DISSERTATION

ASSESSING AND MANAGING URBAN RIVERSCAPES: INTEGRATING PHYSICAL PROCESSES AND SOCIAL-ECOLOGICAL VALUES

Submitted by

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ABSTRACT

ASSESSING AND MANAGING URBAN RIVERSCAPES:

INTEGRATING PHYSICAL PROCESSES AND SOCIAL-ECOLOGICAL VALUES

In the age of the Anthropocene, human influence has spread far and wide across our planet affecting the physical, chemical, and biological condition of the rivers, streams, and floodplains in the urban environment, our "urban riverscapes." The human connection to urban riverscapes includes both the built environment created and accessed by people and the intangible community values that humans place upon flowing water. The value of these benefits encourages stewardship of our waterways by integrating experiential, aesthetic, and cultural attributes that foster appreciation for streams as natural systems in the built environment. However, when poorly managed, human activities adversely impact our natural ecosystems, resulting in less resilient stream systems, poor aesthetics, and unsafe conditions.

The research presented in this dissertation asks the following overarching research question: How can managers and practitioners apply multi-scale social-ecological, hydrologic, geomorphologic, and riparian ecological remote sensing and field data to advance urban riverscape management. Four chapters follow from this hypothesis: urban riverscape problems lie on a spectrum of complexity where solutions are often conceivable but difficult to implement. Integrating diverse perspectives and knowledge extends the scope of stakeholder perspectives so that social-ecological context is considered alongside the physical processes that typically characterize riverscapes. This approach entails leveraging existing and new methods to create frameworks that integrate the multi-scale assessment of physical conditions and social-ecological qualities underlying applied riverscape management.

To study this question, I explore the integration of diverse knowledge to enhance management outcomes through the concept of "wicked problems." I analyze the connections between diverse types of

knowledge and practices through numerous case studies. My analysis shows how systematically characterizing project attributes, such as the prominence of local government and technical knowledge or the weakness of academia and indigenous knowledge, requires an approach that builds capacity and collaboration within transdisciplinary stakeholder groups. I find that the importance of integrating communities, including under-represented knowledge bases, into urban riverscape management can generate equitable and incremental solutions.

To evaluate connections between social values, ecological conditions, and hydrogeomorphic processes, I outline a framework for urban riverscape assessment that advances the practice of managing urban riverscapes facing complex problems. The framework is based upon evaluation across four foundational categories, or facets, critical to the management of urban riverscapes: (1) human connections and values, (2) hydrologic processes and hydraulic characteristics, (3) geomorphic forms and processes, and (4) ecological structure and processes. I structure the framework around three tiers of actionable steps, which tackle the questions: Why are we assessing this riverscape (Tier 1)? What do we need to understand in and along this riverscape (Tier 2)? How will we assess the riverscape to develop that understanding (Tier 3)?

I find that the answer to the first question is context-based and dependent upon integrating diverse types of knowledge, while the response to the second question involves examining the functions and values of urban riverscapes through the lens of the four facets and their inter-related processes. Answering the third question requires developing and testing a novel assessment method – the "Urban Riverscape conditions-Based Assessment for management Needs" (URBAN). I base URBAN on riverscape context and on integrating the assessment of facets at multiple scales. I apply the method to a test data set of publicly available and site-specific data across a study area in the Denver metropolitan region to illustrate its overall performance, including its ability to evaluate specific riverscape physical conditions and social-ecological qualities. I find reach typologies combined with urban riverscape characteristics provide tangible management strategies that managers can use to inform planning and decision making.

The overarching conclusion of this dissertation is that managing urban riverscapes requires assessment methods that consider scale (spatial, temporal, and topical) and context (both physical and social characteristics), and the use of indicators and metrics that directly support decision-making among interdisciplinary stakeholders. It is possible to move toward this vision by using remote-sensed and field data, that provides both social and physical information, to assess the relationship between physical condition and social-ecological values, and to use that information to determine where and how to prioritize management strategies for urban riverscapes.

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When I first started on this journey, I read somewhere that getting a Ph.D. is like climbing a mountain. I am an avid hiker and mountaineer, so that analogy resonated with me. I did not realize that the "Ph.D. Mountain" is akin to climbing Mount Everest. Once I came to terms with the challenge that lay ahead, I realized I would need a lot of support through all the different routes, setting up milestone basecamps, and providing supplemental chai tea and wine as I made the final push towards the summit. To Kera, you moved mountains for me and are the strongest person I know. Every time I struggled, you made me laugh and "told me to hurry up and finish." You supported me even when it took me away from my family. Thank you for your patience and love. And to my children – Eden Raine, August Redding, and Macallum River – your smiles, warm hearts, and senses of humor bring me hope during these strange times.

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DEDICATION

To Kera Jane, Eden, August, and Mac

"And still, pressed deep into my mind, the river
keeps coming, touching me, passing by on its
long journey, its pale, infallible voice
singing"

- Mary Oliver

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INTRODUCTION

In the age of the Anthropocene, urban riverscapes – rivers, streams, and their floodplains in the urban environment – are exceedingly important novel ecosystems, within which numerous facets interact at multiple scales (Polvi et al. 2020). But as human alterations continue to modify the landscape and hydrology, pronounced spatial and temporal variability in response to these disturbances reflects divergent catchment characteristics and urbanization processes (Chin 2006). Different land use practices, levels of imperviousness, and vegetative cover produce unique combinations of factors that directly affect watershed hydrology and stream physical condition (Karr 1999). A consistent suite of effects degrades streams draining urbanized watersheds, in a process known as the "urban stream syndrome" (Walsh et al. 2005; Booth et al. 2016; Smith et al. 2016). The urban stream syndrome is of ongoing concern because stream functions and ecosystems services continue to deteriorate when in-stream conditions diverge from the range of dynamism typical of natural streams (Hale et al. 2016). The symptoms of the urban stream syndrome are well known – altered hydrologic regime (Poff 2018; Bhaskar et al. 2016), geomorphic novelty (Russell et al. 2020; Vietz et al 2016), reduced biodiversity (Paul and Meyer 2001), and impaired physicochemical environment (Parr et al. 2016). Despite these impairments, these dynamic systems still deliver ecosystem services, such as flood attenuation and drinking water, although at reduced rates (Manning et al. 2018). These benefits, however, require societal trade-offs (Thieme et al. 2021) and sequencing the change from a transactional dominion management approach to distributed watershed and riverscape management. Thus, urban riverscapes occupy an unusual space in the hydrologic, geomorphic, ecological, and cultural landscapes of cities (Francis 2014).

The human connection to urban riverscapes includes both the built environment created and accessed by people and the intangible community values that humans place upon flowing water. The value of these benefits encourages stewardship of our waterways by integrating experiential, aesthetic, and cultural attributes that foster appreciation for streams as natural systems in the built environment.

However, when poorly managed, human activities adversely impact our natural ecosystems, resulting in less resilient stream systems, poor aesthetics, and unsafe conditions. The many socioecological complexities of urban rivers and streams complicate their management, particularly when it comes to finding appropriate interventions to improve physical condition and ecological quality, rather than simply water quality or the river esthetic (Francis 2014). It is vital, therefore, to take these constraints into account when conceptualizing the evolution of urban riverscapes.

Identifying and investigating the multi-causal mechanisms that influence the physical condition of urban riverscapes requires methods to assess the various processes and values at play across multiple scales, including hydrologic and fluvial geomorphologic processes, ecological processes, and social values. Numerous types of data collection and evaluation approaches have been created to develop a conceptual or detailed understanding of river and stream conditions in a variety of settings (Somerville 2010; Belletti et al. 2015; Fryirs 2015; Gurnell et al. 2016). Many of the assessment frameworks and methods include indicators of human pressures and their impacts (e.g., Smith et al. 2008; Kline 2010; Harman et al. 2012; Nadeau et al. 2018; Wheaton et al. 2019; Polvi et al. 2020). Yet, despite the prevalence of assessment methods and frameworks, few integrate fully across the relevant riverscape facets of human values, hydrology and hydraulics, geomorphology, and ecology, and at multiple scales. This is due to insufficient data and the logistical difficulty of investigating context, stressors, physical conditions, and social-ecological values within an urban riverscape. Even fewer consider the social-ecological context prevalent in urban riverscapes. This dissertation fills these knowledge and research gaps, providing conceptual frameworks and an assessment method that:

1. Integrates diverse perspectives and knowledge to enhance social and ecological outcomes of urban stream restoration by setting manageable objectives for complex problems through incremental solutions.
2. Considers the social-ecological context and human values alongside physical processes.

3. Evaluates the physical conditions and social-ecological values of urban riverscapes underlying applied riverscape management and broad-scale preservation and renovation planning.

In Chapter 1, I explore the first point, the integration of diverse knowledge to enhance management outcomes, through the concept of an unsolvable, “wicked” problem (Rittel and Webber 1973). In these instances of urban stream restoration, formulating the problem statement itself can be highly problematic. In practice, stressors affecting urban streams exist on a spectrum of complexity, in which solutions are often conceivable in theory but difficult to implement successfully in practice. For these reasons, urban stream problems are unique when compared to problems affecting streams in natural environments, which exhibit comparably fewer human modifications and less intense interactions among the local community and the stream channel and catchment (Roy et al. 2008; Dhakal and Chevalier 2017; Qiao et al. 2018). I examined a selection of diverse case studies that vary in setting, scope, costs, spatial scale, and restoration goals. When taken together, the case studies provide a modest cross section of potential “wicked” problems in urban stream restoration, characterized by scientific uncertainty, values disagreement, undefined success criteria, or a failure to consider incremental solutions. With several colleagues, I applied semi-quantitative gap analysis to describe the linkages – strengths and weakness – of institutional and community involvement across the case studies. We also analyzed the connections of diverse types of knowledge and practices in the case studies. My analysis showed how systematically characterizing project attributes, such as the prominence of local government and technical knowledge or the weakness of academia and indigenous knowledge, creates an accounting of potential roadblocks to solving the complex problems exhibited by the project, and may give the appearance that solutions are impractical if not impossible. The study accentuates the importance of integrating communities, including under-represented knowledge bases, into urban stream restoration such that transformative approaches to complex or “wicked” problems can generate equitable and effective solutions with tangible benefits to the community and ecosystems.

In Chapter 2, I describe the foundation and outline a framework for urban riverscape assessment to advance the practice of managing urban riverscapes facing “wicked” problems. The framework is based upon evaluation across four foundational categories, or “facets,” critical to the management of urban riverscapes, which include: human connections and values, hydrologic processes and hydraulic characteristics, geomorphic forms and processes, and ecological structure and processes. The framework can be conceptualized in three tiers of actionable steps, which tackle the following questions in turn: Why are we assessing this riverscape? What do we need to understand in and along this riverscape? And, how will we assess the riverscape to develop that understanding? Tier 1 of the framework hones the intent of the assessment before identifying the values and functions in need of evaluation, while Tier 2 determines which social-ecological values and urban riverscape physical functions to include in the assessment. The third tier describes how to measure the riverscape functions and values given urbanization and existing management practices. The overall framework provides watershed managers and practitioners working on urban riverscapes an inclusive framing of the interrelationships by incorporating social, ecological, and hydrogeomorphic facets.

In Chapter 3, I summarize the most relevant assessment methods and frameworks that I reviewed in developing this methodology. This review focuses on those frameworks that concentrate on physical processes and are implemented with multi-scale methods, and specifically investigates their potential applicability to streams in the urban environment. The range of application of the methods considered in the review varies from those applicable to small, ephemeral streams to those suited to moderately-sized, wadeable, perennial streams. It is restricted, however, to physical-based assessments, those methods that address all or some of the physical elements required for a hydrogeomorphological evaluation of urban riverscapes. This summary provides a broad cross-section of representative methods used across the scientific field and reviews their commonalities and differences.

Finally, in Chapter 4 I describe and test a novel assessment method – the “Urban Riverscape Conditions-Based Assessment for management Needs” (URBAN) that fits under the technical domain described in Chapter 2. URBAN is based upon and informed by the frameworks defined in Chapters 2 and 3. It is organized into three steps: (1) characterization, (2) assessment, and (3) management. In this chapter, I apply the method to a test data set of publicly available and site-specific data across a study area in the Denver metropolitan region to illustrate its performance, and I demonstrate how it can be used to evaluate riverscape physical conditions across varying scales. The case study provides insights into evaluating the interconnections and disconnections between reach typing; hydrologic, geomorphic, and ecological conditions; and human connections and values. I demonstrate that the process of identifying stream values links social, hydrologic, and geomorphic features to environmental factors that may influence the restoration, resilience, and viability of urban riverscapes.

The four chapters of this dissertation build from one to another to provide a holistic urban riverscape management approach that is science-based—replicable, consistent, and defensible—and considers both the physical conditions and social-ecological values relevant to urban streams. These chapters provide new insight into the complex relationships between the physical conditions and the social-ecological values prevalent in urban riverscape environments. Managing urban riverscapes requires assessment methods that consider scale (spatial, temporal, and topical), and context (both physical and social characteristics), and the use of indicators and metrics that directly support decision-making among interdisciplinary stakeholders. Integrating community values into urban riverscape assessments provides managers with the necessary tools to improve riverscape health and the livability of the surrounding communities for the foreseeable future.

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CHAPTER 1

Closing the gap on wicked urban stream restoration problems: A framework to integrate science and community values[1]

Summary

Restoring the health of urban streams has many of the characteristics of a wicked problem. Addressing a wicked problem requires managers, academics, practitioners, and community members to make negotiated tradeoffs and compromises to satisfy the values and perspectives of diverse stakeholders involved in setting restoration project goals and objectives. We conducted a gap analysis on 11 urban stream restoration projects to identify disconnections, underperformance issues, and missing processes in the project structures used to develop restoration project goals and objectives. We examined the gap analysis results to investigate whether managers appropriately identified problem statements and met stated objectives. Projects that aimed to restore overall stream health commonly fell short for various reasons, including limited stakeholder and community input and buy-in, revealing potential limitations in the breadth of objectives, values, and stakeholder perspectives and knowledge types. Projects that

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[1] Murphy, B.M., Russell, K., Stillwell, C.C., Hawley, R., Scoggins, M., Hopkins, K.G., Burns, M.J., Taniguchi-Quan, K.T., Macneale, K.H., Smith, R.F. (2022, accepted 4 February 2022). Closing the gap on wicked urban stream restoration problems: Integrating science and social-ecological values. Freshwater Science XX:XXXX-XXXX.

Brian M Murphy initiated this study and conceived the original idea to evaluate restoration case studies and invited colleagues from the 5th Symposium on Urbanization and Stream Ecology (SUSE5) to collaborate on the study. He also provided two case studies and filled out the gap analysis survey for those case studies. Robert F Smith, Kathryn L Russell, Brian M Murphy, and Charles C Stillwell designed the gap analysis to expand on the qualitative assessments and to describe the strengths of institutional and community involvement and linkages. Robert F Smith evaluated the gap analysis data and the linkages of diverse types of knowledge and practices in each project. Kathryn L Russell prepared the Likert plots and network graph. Brian M Murphy and Charles C Stillwell lead the literature review. Brian M Murphy, Robert F Smith, Kathryn L Russell, and Charles C Stillwell developed the conceptual framework and knowledge cloud figures.

emphasized integrating community values and diverse knowledge types tended to meet the expected outcomes of restoring stream processes through incremental solutions. Managers implementing more holistic solutions and values-driven approaches are more likely to consider diverse viewpoints from a variety of community local institutions. Based on these and other results, we propose a conceptual framework that integrates diverse perspectives and knowledge to enhance social and ecological outcomes of urban stream restoration. The framework also emphasizes the importance of setting objectives that support incremental solutions to foster more realistic expectations amongst stakeholders.

Introduction

1 Introduction

Streams in urban environments are unable to provide the same functions and ecosystem services typical of streams in undeveloped landscapes (Walsh et al. 2005, Kondolf and Yang 2008). Human actions continually shape hydrologic, chemical, and geomorphic conditions of urban streams that degrade the biological conditions of aquatic and riparian ecosystems (Roy et al. 2016, Van Metre et al. 2019). Restoring urban streams is a common practice to improve water quality, enhance aquatic habitat, and protect infrastructure (Kenney et al. 2012). The ecological and social challenges of restoring urban streams are complex and confounded by regulatory hurdles, funding limitations, and property right conflicts (Bernhardt and Palmer 2011). Tractable problem statements to guide restoration rarely address the collective dynamic, interdisciplinary, and multifaceted challenges that plague urban streams (Wenger et al. 2009).

Rittel and Webber (1973) introduced the concept of an unsolvable, wicked problem in where formulating the problem statement is itself highly problematic. Wicked problems are defined as being unsolvable, untamed problems (Turnbull and Hoppe 2019) and are rooted in a deep disagreement of underlying values between stakeholders (Ballint et al. 2011). Approaching a wicked social problem by attempting to reduce it to a rational scientific problem fails to achieve a viable solution and often results in repetitive rounds of trying to reduce scientific uncertainty and improve public understanding of the problem (Rein and Schon 1996, Ballint et al. 2011).

Restoring urban streams aligns with certain premises of a wicked problem (Rittel and Webber 1973). In practice, urban stream problems lie on a spectrum of complexity where solutions are often conceivable but difficult to implement. The set of possible solutions, or solution space, is often poorly defined for projects with complex, compounding, and often interacting components (e.g., regional climate, infrastructure, geomorphological characteristics, local ordinances, community needs, etc.). Urban design, development policies, environmental regulations, social norms, and systemic racism and classism shape contemporary urban conditions (Schell et al. 2020). For these reasons, urban stream problems are generally more complex than stream issues found in more natural environments with comparably fewer human modifications and less intense interactions among residents and the stream channel and catchment (Roy et al. 2008, Dhakal and Chevalier 2017, Qiao et al. 2018).

Gaining community support is important for the success of stream restoration efforts (Bos and Brown 2015, Smith et al. 2016, Moran et al. 2019). To successfully achieve ecological and social outcomes within a complex solution space, managers must prioritize local community engagement (Kondolf and Yang 2008, Dhakal and Chevalier 2016, Smith et al. 2016). Also, managers need to use value judgements in the decision-making process to select an appropriate solution from many options. Solution spaces defined using incomplete knowledge of community values likely prevent managers from defining reasonable restoration potential for urban streams. The inability to define restoration potential commonly leads to inconsistent success criteria between projects (Stoddard et al. 2006), piecemeal strategies (e.g., addressing individual stressors such as flooding, water quality, or erosion), or poorly defined approaches that can all contribute to ineffective interactions among stakeholders.

Including diverse community values and perspectives in the context of complex and possibly wicked urban stream restoration problems is challenging and requires that all stakeholders are willing to make compromises through negotiated tradeoffs (Scoggins et al. 2022). Social dimensions, however, can restrict how experiential and empirical knowledge moves between geographic locations and across institutions, changing how stakeholders perceive tradeoffs.

The co-authors for this Bridges article participated in the 5th Symposium on Urbanization and Stream Ecology (SUSE5), where symposium participants discussed multidisciplinary solutions to wicked problems in urban stream restoration (Scoggins et al. 2022). Following SUSE5, an international working group of scientists and engineers from academic, government, and private institutions selected a set of urban stream restoration case studies to study: 1) how managers, academics, practitioners, and community members perceive success in urban stream restoration; 2) to what extent managers and practitioners integrate community members into projects; and 3) how project planning and implementation structures contribute to success or failure.

2 Methods

2.1 Urban restoration case studies

We examined diverse case studies that vary in environmental setting, scope, costs, spatial scale, and restoration goals (Table 1.1). When taken together, the case studies provide a modest cross section of potentially wicked problems in urban stream restoration characterized by scientific uncertainty, values disagreement, or undefined success criteria.

Using a narrative approach, case-study co-authors (i.e., a subset of this study's authors with direct knowledge of case studies) described how project goals were defined and if structured criteria and stopping rules potentially tamed the project's wickedness. Case-study co-authors also described project successes against their stated goals (i.e., not wicked) or if unintended consequences or unknowns impeded achieving stated goals that emerged in the "one-shot operation" (p. 163) of stream restoration practices typical of wicked problems (Rittel and Webber 1973). Case-study co-authors also identified shortcomings in project actions to define problems and stated whether problem definitions led to solutions that, in hindsight, missed important components or root causes of the actual problem.

Table 1.1 Urban stream studies included in the gap analysis.

Study	Stream	Location	Project motivation	Stream restoration goals	Community engagement efforts	Perceived successes and shortcomings
Big Thompson Watershed Coalition 2015	Big Thompson River	Colorado, USA	Plan, design, and implement restoration measures and strategies that address adverse changes to river dynamics, aquatic habitat, and recreation following a major flood in 2013	Improve riverine functions (habitat, fish passage, floodplain connection, etc.), address water user needs, and provide recreational opportunities	Users provided input and feedback via public outreach surveys, correspondence with a coalition of citizen stakeholders, and facilitator-led community meetings	Restored river processes (e.g., floodplain connectivity and sediment continuity) and aquatic habitat. Catchment drivers not addressed, limited community engagement
Hopkins et al. 2022	Clarksburg, Little Seneca Creek	Maryland, USA	Inform impervious cover limits and stormwater management guidelines for new development within the Clarksburg special protection area	Protect water quality and biology using impervious limits, stormwater controls, and riparian buffers	Planned development, community meetings during planning, minimal engagement efforts throughout the project's lifetime	Mitigated catchment drivers related to flow regime (e.g., peak flows and runoff volumes), but water quality degraded (e.g., increase in specific conductance) and sensitive taxa were lost. Limited community engagement post-development
Sammonds and Vietz 2015	Gum Scrub Creek	Melbourne, AUS	A 100-m wide riparian corridor was required under federal legislation to support a vulnerable frog species, creating an opportunity to revitalize the waterway corridor and support other social and ecological values	Protect natural stream via buffer preservation and stream and wetland enhancements	Planned development: developers anticipated the future residents' social values	Stream corridor protected, but catchment drivers were not addressed
City of Austin 2016a	J.J. Seabrook Reach	Texas, USA	Erosion and water-quality problems associated with upstream development spurred a collaborative approach with multiple community benefits	Restore aquatic and riparian functions by improving bank habitat and floodplain connectivity	Community engagement efforts during planning decreased over the course of the project	Structurally and ecologically successful, limited community buy-in
Walsh et al. 2015	Little Stringybark Creek	Melbourne, AUS	Research-driven project to test the real-world feasibility and effectiveness of distributed stormwater	Restore natural flow and water-quality regimes to improve instream ecological condition in all the watershed's headwater streams	Hundreds of stormwater controls installed on private residential land required community and landowner buy-in, achieved with support from many stakeholders	Community uptake improved as engagement processes were adjusted and incentives simplified. Outcomes fell short of targets due, in part, to lack of space for structures and lack

Study	Stream	Location	Project motivation	Stream restoration goals	Community engagement efforts	Perceived successes and shortcomings
			control measures for stream restoration			of demand for harvested stormwater
Stein et al. 2021	Los Angeles River	California, USA	Evaluate the effect of potential flow reductions on beneficial uses of the Los Angeles River and inform decisions regarding proposed wastewater change petitions	Develop tools to establish flow recommendations that balance goals for wastewater reuse, aquatic health, and recreational purposes	Facilitated public meetings (quarterly) were hosted by project leaders to gather stakeholder and community feedback on project scope and outcomes	Overall community and stakeholder buy-in on decision support tools to understand the effects of wastewater reuse on instream flows, water quality, and stream temperature. Unable to integrate the combined effects of multiple stressors on aquatic health
City of Austin 2016b	Lower Waller Creek	Texas, USA	Historic downtown flooding and the potential for economic reinvestment created an incentive to rethink the creek and corridor	Remove developed areas from floodplain, restore channel form and ecological function, and improve the look and feel in corridor	Little community engagement during floodplain restoration efforts, but heavy involvement during aesthetic improvements	Massive public works effort and flood mitigation success, hydrologic and ecological components were stalled
USACE 2018	South Platte River	Colorado, USA	Create an active river corridor that restores and improves the natural habitat and function of the South Platte River and enhance the connection between the river and the community	Restore channel flows, features, and functions to enhance foraging, spawning, and protective cover habitat for indigenous fish species. Improve public recreation opportunities, connectivity, and accessibility along River.	Consistent formal and informal outreach to community during the design process. Local stakeholders and nonprofit representatives provided input at public meetings during planning. Local government stakeholders participated in meetings throughout the project	Increase in recreational access and community stewardship of the river, fishery rebounded. Catchment drivers not addressed, vegetation not established limiting riparian function and habitat, secondary channels silted in
Franklin Soil and Water Conservation District 2015	Spring Run*	Ohio, USA	Chronic bank erosion and property loss in a residential stream threatened patios and other structures, impaired habitat, and impacted water quality	Improve stream habitat, bank stability, and water quality in a residential headwater stream	Project started with little effort to engage the community. A grassroots approach to integrate community values revived the project	Inadequate engagement led to property owner rejection of the original design and loss of grant funding. Grassroots approach revived the project, which is awaiting funding
Bakke et al. 2021	Thornton Creek	Washington, USA	Frequent flooding of residential properties and desire to improve habitat and water quality for endangered salmon	Provide flood storage in floodplain, mitigate peak flows, improve water quality, and enhance hyporheic exchange	Heavy community involvement in all project stages, highlighted by film to document project successes	Collaborative project that resulted in some water-quality improvements within restored reach

2.2 Gap analysis

Survey co-authors (i.e., a subset of this study's co-authors that differed, in part, from the case-study co-authors) designed a gap analysis to describe the strengths and linkages of institutional and community involvement, and the connections of diverse types of knowledge and practices in the project. Gap analysis employs qualitative and quantitative methods to characterize why realized and intended or desired outcomes differ (Parasuraman et al. 1985). When combined with the case-study narrative, this analysis allows us to identify which project approaches were associated with success or shortcomings in the case-study projects. We also used the gap analysis to characterize gaps in project planning and implementation frameworks that restricted interdisciplinary approaches to restoration. Using this systematic approach provided opportunities to holistically examine all components and linkages (see Table 1.2) of project planning, design, and community involvement. The gap analysis also introduces a novel method to ask questions about how to improve restoration projects.

The survey co-authors created a perceived set of components and linkages (see Table 1.2 and Appendix A for expanded descriptions of components and linkages as presented in the survey to case-study co-authors) for interdisciplinary stream restoration projects that were translated into a survey for the case-study co-authors (n = 11 case studies, where the 2 phases of the Spring Run case study [Franklin Soil and Water Conservation District 2015] were considered as 2 replicates). Survey co-authors used survey responses to systematically identify potential gaps using a semi-quantitative rather than narrative approach. To guide case-study author through the gap analysis, we defined a desired outcome as a system that integrated diverse ecological and social components in urban stream restoration projects. The list of specific components and subcomponents (Table 1.2) and linkages among them created by the survey co-authors represented the desired system specifically to suit the needs of this study (i.e., our components and linkages are specific to the experiences conveyed through the case-study co-author narratives).

Table 1.2 Components and subcomponents of urban stream restoration case studies assessed in the gap analysis (further explanation is provided in Appendix A).

Component	Component description	Subcomponents
Institutions	Governmental or nongovernmental organizations (i.e., an organized group) that contribute to the project planning, design, or implementation through a formal or informal process	Local government State government Federal government Consultant Academia Nongovernmental organization Utility Private company
Community	Individuals, groups, or collectives that benefit from (or are affected by) the restoration work	Action groups Place-based groups Individual community leader Individual based on interest Individual based on place
Knowledge	Conceptual, historical, empirical, and theoretical representations of contextualized information and place-based wisdom (Hillman 2009) associated with the project context, design, goals, and outcomes	Physical/ecological science Community wants and needs Engineering design Restoration process Social science Policy and regulations Land-use planning Community planning Landscape architecture or structural architecture Funding procurement and management Indigenous culture relevant to project scope
Strategies and practices	Actions that occur as part of the project through all phases (design, implementation, monitoring, etc.)	Restoration: biophysical Restoration: social/cultural/economic/political Ecological monitoring Community survey Outreach and education Participant natural or social science training Citizen science Community planning Community empowerment and capacity building

Case-study co-authors scored strengths of individual components and subcomponents (Table 1.2) and all pairwise linkages (i.e., a single linkage between 2 separate components or subcomponents) among all 4 main components (institutions, community, knowledge, and strategies and practices) and ≤8 institution subcomponents (Table 1.2) using the same scale to relativize responses. Survey respondents scored each component, subcomponent, and linkage on a scale of 1 (weak) through 5 (strong) for their case study based solely on their judgement and experiences with their specific case study. A value of 0 indicated no involvement. Case-study co-authors were instructed to interpret values of 1 and 5 as an idealistic level of potential strength that may be purely conceptual and rarely (if ever) realized in real-world projects. The component need not reach its pinnacle to be considered a 5. The survey co-authors used the analogy of an "A" grade representing ≥93% to help demonstrate the meaning for a 5 score (See Appendix A for further explanation). We summarized numerical responses with Likert-scale plots of scores and network graphs of score averages (Figure 1.1).

3 Results

Among the 4 main components, case-study co-authors rated institutions the strongest and community the weakest. Institution subcomponent ratings varied in strength, but local government and consultants were generally the strongest and involved in every selected case study. Academia, nongovernmental organizations, and state government were the weakest. The number of institution types involved in each project varied from 4 (e.g., the Spring Run case study, a reach-scale backyard stream restoration project) to 8 (e.g., the Los Angeles River case study [Stein et al. 2021], a planning study in a large and highly altered watershed). Community subcomponents were ranked moderate to weak except for the Thornton Creek case study, which had strong involvement from all community subcomponents, and the South Platte River case study, which hosted various public meetings and community engagement strategies throughout the project (Figure 1.1).

Respondents rated knowledge of physical and ecological science and engineering design (from the knowledge component) as moderate to strong for all case studies (Figure 1.1). Respondents considered knowledge of social science and community planning to be weaker than other knowledge subcomponents. Almost half of respondents did not believe knowledge of indigenous culture was considered at all and 4 other respondents rated indigenous culture as weak (see Figure 1.1).

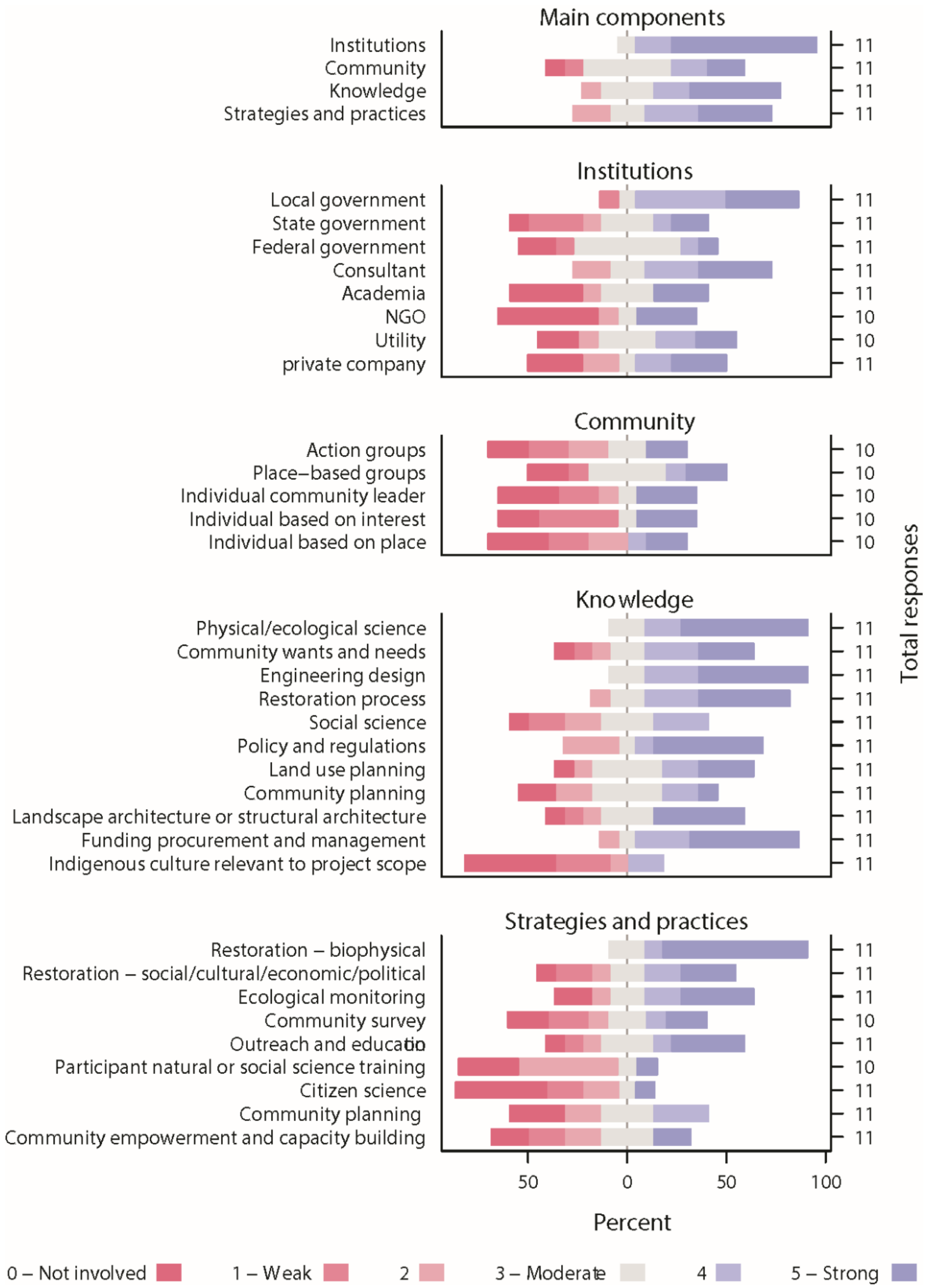

Figure 1.1 Case-study survey results plotted with a Likert scale showing relative strength of main components and subcomponents from 0 to 5. The % of responses with each rating is shown by bar color and horizontal position, centered on moderate (gray bars). The darkest blue bars that extend furthest to the right represent components and subcomponents with the strongest ranking. Row count totals on the right side of each diagram indicate the number of responses to each question. See Table 1 in Appendix A for full survey results. NGO = nongovernmental organization.

Responses on strategies and practices followed similar patterns. Survey respondents ranked strengths of biophysical restoration strategies and practices and ecological monitoring as moderate to strong (Figure 1.1), whereas respondents ranked strategies and practices referencing the community as weaker than most other subcomponents. Respondents considered all linkages between community and the other 3 main components to be weaker than all pairwise connections not including community (Figure 1.2). Connections among consultants and local government were rated the strongest, and both were commonly well connected to utilities (e.g., stormwater and flood control providers). Numerous other connections were overall weak including academia to nongovernmental organizations (NGO), NGO to State Government, and Federal Government to Utility (Figure 1.2).

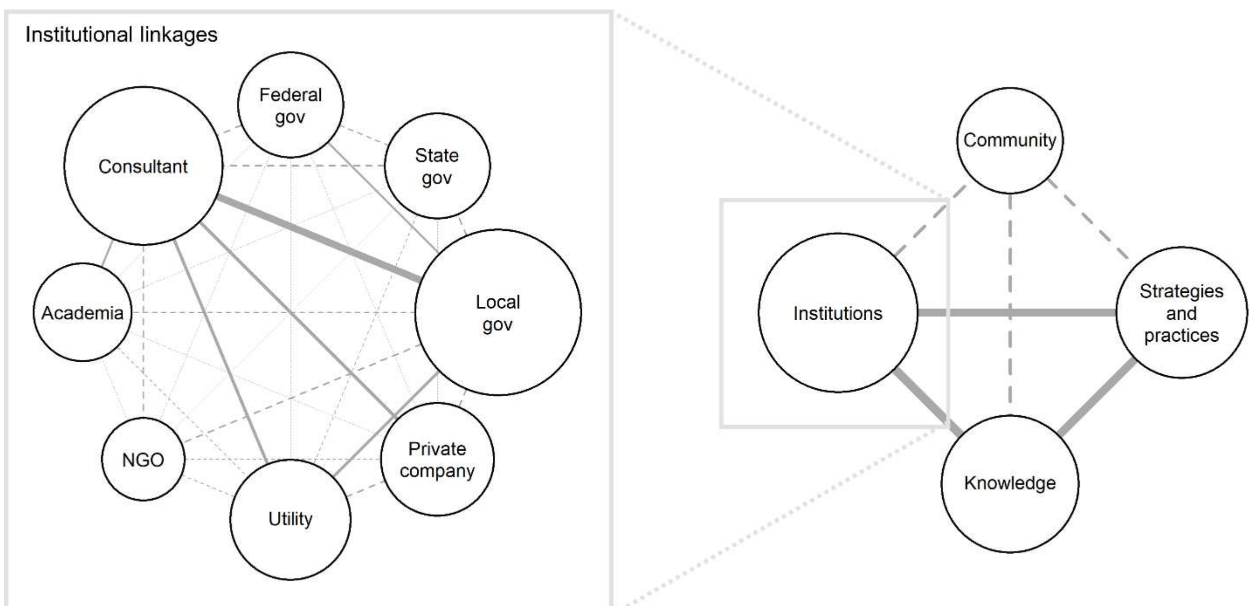

Figure 1.2: Network graph showing how the case-study co-authors rated strength of representation of institutions, community, knowledge, and strategies and practices and the connections between them. Strengths and connections within institution subcomponents were also analyzed. Relative strength of each component or subcomponent is shown by circle diameter, and strength of connections is shown by line weight (i.e., solid and thicker lines represent stronger connections, dashed and thinner lines represent weaker connections). Full results of the survey are presented in Tables 1 and 2 in Appendix A. Institutions, knowledge, and strategies and practices were strongly represented and interconnected while community was weakly represented and relatively unconnected to the other components. Case-study co-authors rated consultants and local government the strongest and most-linked institutions. Gov = government, NGO = nongovernmental organization.

4 Discussion

The case-study narratives and gap analysis highlighted potential areas for improvement in developing problem statements and solution spaces. The shortcomings in problem definition, for example, seemingly prevented achieving stated goals or produced unintended consequences that culminated in solutions that failed to reach the full potential of community or ecological benefit. These shortcomings may have also led to inconsistent interpretations of success, which may not align with community needs and values. The gap analysis and supporting narratives demonstrated how qualitatively designated successes can fall short of the actual potential restoration outcomes possible (see Appendix A for further information).

In addition, the gap analysis suggested that community groups and representatives had weak roles in case-study projects and were not well connected to institutions, knowledge, and the strategies and practices employed by managers. This result aligned with themes developed during SUSE5 that focus on how communities may not be well integrated into project designs, goal setting, or evaluation (Scoggins et al. 2022, Cross and Chappell 2022). Moreover, the results contradicted qualitative outcome statements regarding community involvement (Table 1.1) that generally included community engagement efforts for all projects (also see Appendix A for information about gap analysis results unrelated to the community components).

Difficulties defining problems and identifying potential solution spaces may make problems seem intractable. Conversely, supporting knowledge transfer and interactions among stakeholders and communities may lead to better defined solution spaces. For instance, the gap analysis suggested that the Gum Scrub Creek (Sammonds and Vietz 2015), Little Stringybark (Walsh et al. 2015), and Big Thompson River (Big Thompson Watershed Coalition 2015) case studies each lacked inclusion of community stakeholders. A lack of broad community engagement likely limited the potential of projects to achieve community benefits in these examples where they were noted as a project goal or contributed to the omission of community-oriented goals where they were absent from these case studies. Furthermore, only 2 case studies (Thornton Creek [Bakke et al. 2021] and South Platte River [USACE 2018]) included indigenous culture when scoping and implementing the projects, emphasizing the substantial omissions of incorporated scientific and indigenous ecological knowledge (Kimmerer 2011). Inadequate community engagement efforts for the Spring Run project suspended work to the degree of returning grant funding. A subsequent grassroots effort to integrate community values led to increased recognition of the value of community knowledge, which allowed re-implementation of the project. The narrative and gap analysis approaches suggested that ineffectively characterizing potential components of restoration actions in this case study likely contributed to a lack of engagement, which in turn may have obstructed the development of an inclusive and collaborative solution space.

We propose a conceptual framework to guide urban stream management towards problem definitions and solution spaces that encourage adaptive, collaborative, and transdisciplinary approaches to tackle complex problems and enhance societal and ecological outcomes (Figure 1.3). Our framework identifies gaps in status-quo project arrangements (Figure 1.3 Before) that prevent integration of diverse knowledge across fields (or clouds). Integrating all stakeholders as equal participants with strong linkages across knowledge bases and personal experiences creates a single knowledge cloud space that can employ holistic strategies and practices to address complex or wicked problems (Figure 1.3 After).

The framework focuses on how project structures relate to interdisciplinary knowledge transfer necessary to address a complex problem. Specifically, communities are recognized as central holders of place-based experiential knowledge critical to developing appropriate problem statements and equitable solution spaces. Examples of centrally held place-based knowledge in our study included the Thornton Creek case study (Bakke et al. 2021), which emphasized the importance of community and institutional arrangements, and the South Platte River case study (USACE 2018), which focused on social outcomes in addition to ecological objectives. These projects demonstrate that attempting to solve a complex urban stream restoration problem requires an approach that builds capacity and collaboration within transdisciplinary stakeholder groups. The framework aligns with outcomes of other SUSE5 papers (Cross and Chappell 2022, Pascacio et al. 2022, Scoggins et al. 2022) that demonstrated the need for approaches to set realistic expectations and consider the social context for managing urban streams in constrained urban environments.

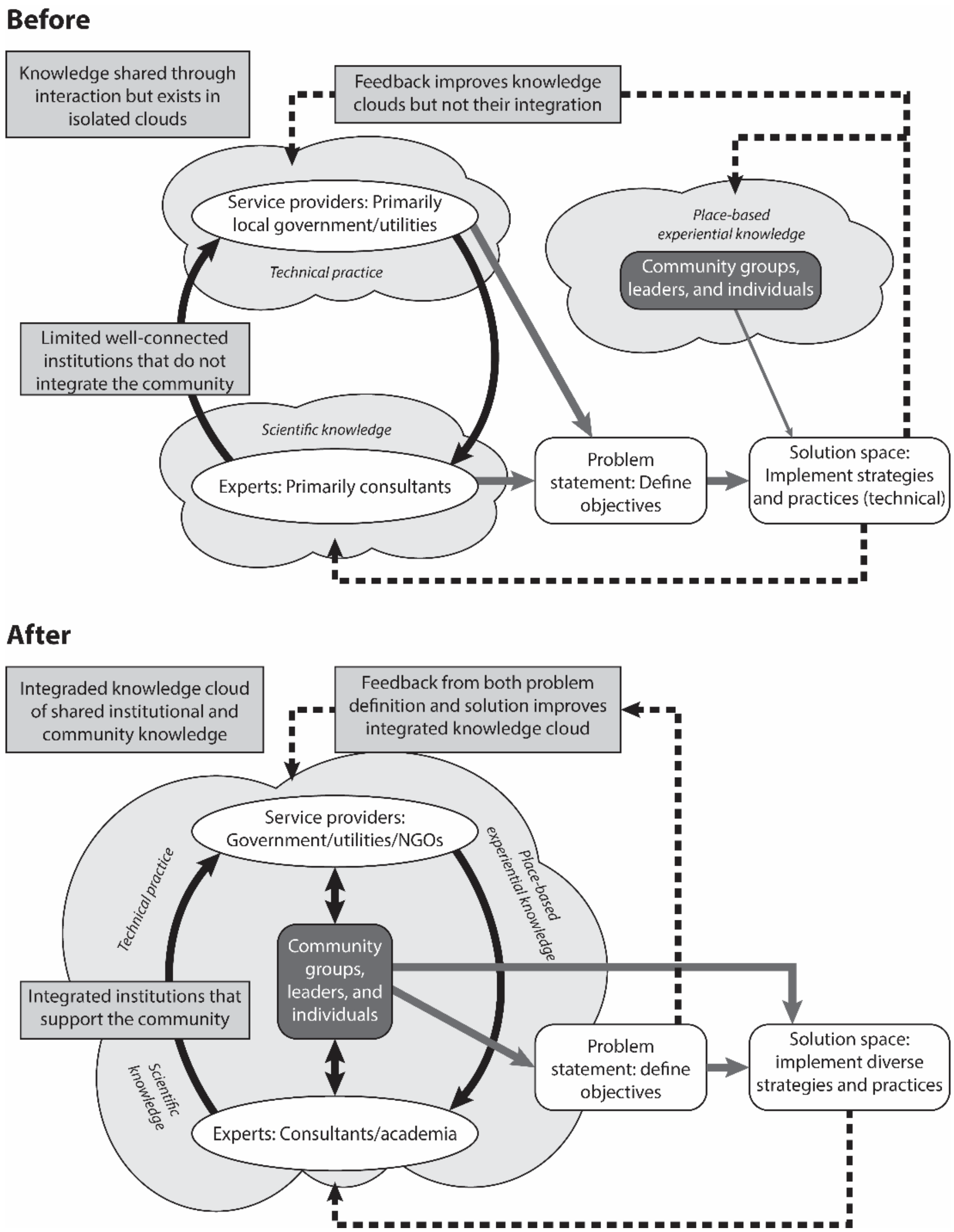

Figure 1.3 Before—Historical interdisciplinary knowledge is shared among groups but is not integrated to support holistic multidisciplinary approaches to restoration. Community groups are narrowly linked to the solution space. The problem statement generally excludes community input and knowledge, and the solution space is driven by how the problem is defined. After—We propose a new framework that integrates interdisciplinary knowledge, including input from community stakeholders. The problem statement integrates diverse perspectives and types of knowledge, and the solution space is driven by an appropriate problem statement and integrated community and institutional perspectives, values, and knowledge.

Our analysis also highlights how a systematic approach (e.g., the gap analysis) has the potential to explicitly identify components and linkages in complex systems, although the gap analysis was most informative when performed in conjunction with the narrative-based approach. The study's findings are limited due to a small sample size of case studies and survey responses. Additionally, the selected case studies were familiar to case-study co-authors but were not a comprehensive representative sample of urban stream restoration projects. Further, case-study co-authors were highly knowledgeable but viewed their case study through a certain lens depending on their involvement. Also, the gap analysis approach to ranking linkage strength failed to capture linkage types that may vary in strength over time.

The qualitative narrative and the gap analysis need to be interpreted together to identify which project approaches may limit restoration outcomes and community involvement. For example, in Little Stringybark Creek (Walsh et al. 2015) community actions (e.g., ongoing construction of impervious surfaces, excavation of creek channels) appeared to threaten the success of the design. However, we were able to identify this component more easily with the narrative analysis. Additionally, in Gum Scrub Creek (Sammonds and Vietz 2015), identities of strong and weak institutional components were revealed by the gap analysis even though community components were not involved. Yet, the narrative described how institutional arrangements produced a solution that protected the corridor but did not address causes of stream degradation in the catchment. The gap analysis also revealed overall patterns that were not apparent in the case study narratives such as how local government and consultants commonly played a central role in defining and delivering projects.

5 Broader Implications

Urban streams are socioecological systems and restoration work can affect the local community. Advances in urban stream restoration that achieve equitable and effective outcomes may come from project-based experimentation of new approaches in management, knowledge sharing (e.g., SUSE5), outreach, and other activities. These approaches improve integration of stakeholders and knowledge clouds to tackle complex and wicked urban stream restoration problems. By broadening the scope of stakeholder perspectives and knowledge types considered, we can uncover complexities inherent to the socioecological systems of urban streams and better develop incremental solutions to complex problems (Parsons et al. 2016). The combined narrative from SUSE5 and our gap analysis provide a foundation to tackle wicked urban stream restoration problems. Our analysis shows how systematically characterizing project attributes (e.g., prominence of local government and technical knowledge and weakness of academia and knowledge of indigenous culture) can reveal potential limitations in the solution space. Such limitations can create the appearance that solutions are impractical if not impossible. Our methods could support future urban stream restoration research with greater depth, funding, and scope than our study.

Understanding gaps in restoration systems represents a major opportunity to improve problem definitions and achieve tractable solutions. The conceptual framework we propose provides a structure to integrate diverse perspectives and knowledge and enhance social and ecological outcomes. Future work to incorporate communities likely needs leadership from local government agencies and consultants given their apparent dominant roles in projects; however, accomplishing this goal will require further defining the role community groups play in restoration projects. Integrating communities and under-represented knowledge into urban stream restoration could lead to transformative approaches to complex or wicked problems that generate equitable and effective solutions with tangible benefits to the community and ecosystems. We encourage expansion of the framework beyond a conceptual vision into a structured approach that managers can use to integrate community into restoration projects.

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CHAPTER 2

Managing urban riverscapes: An assessment framework to integrate social-ecological values and physical processes[1]

Summary

The services that rivers provide and how they affect the landscape plays a dominate role in urban planning and development. Urban riverscapes, which consist of stream channels, their floodplains, biotic communities, and manmade features, are complex social-ecological and hydrogeomorphic systems. Yet, despite recognition of their place and value, rivers are often degraded in urban settings. Successfully managing urban riverscapes requires improved methods to assess them and to more effectively link stressors to values, and to incorporate these considerations in planning. Assessment of urban riverscapes' physical condition and function—a hydrogeomorphic assessment—is necessary to inform more appropriate management strategies for sustainable and valued riverscape systems. The framework and methods used for such an assessment should be appropriate to the urban context, insofar as they are applicable to a range of streams from lightly degraded to highly utilized or constructed. Above all, the framework must prioritize the connection of human communities to riverscapes. In this article, we outline a framework for urban riverscape assessment which considers four facets of urban riverscapes: human values, hydrology, geomorphology, and ecology. The four facets, assessed across multiple nested scales,

[1]Murphy, B., K. Russell, S. Mould, G. Vietz, and P. Nelson (in review). Managing urban riverscapes: An assessment framework to integrate social-ecological values and physical processes, Journal of Environmental Management, XX:XX.

Brian M Murphy conceived the concepts and original ideas as presented in the paper. He drafted the narrative for the urban riverscapes tenets, framework, and the three tiers, and prepared all figures. Kathryn L Russell contributed content to each section and wrote the narrative on urban riverscape indicators and targets. Simon Mould developed the principles for incorporating socio-political context into urban riverscape assessments. Geoff Vietz and Peter A Nelson assisted in developing, discussed results, contributed to discussion and implications, and edited the manuscript.

provide a flexible basis for human-centered hydrogeomorphic assessment. Evaluating connections between social values, ecological conditions, and hydrogeomorphic processes is vital to informing better planning and management of urban riverscapes. By linking intrinsic, relational, and use-based values to physical conditions, watershed managers can select relevant and measurable indicators that directly inform interventions in the riverscape, catchment, or urban zones to improve riverscape function and urban vitality through planning mechanisms. Dialogue between managers, practitioners, scientists, and the community is thus a core component of urban riverscape assessment; it provides technical and non-technical input into the development of assessment criteria and establishes a shared vision to inform targets and other goals.

1 Introduction

Riverscapes are an integral part of both the natural landscape and urban environments. They include the river channel, its connected floodplain, and the biotic communities that together constitute the river valley bottom (Wheaton et al. 2019), as well as infrastructure and recreational corridors. In cities, riverscapes often exhibit particularly poor ecological health (Paul and Meyer 2001) and highly altered morphologies (Vietz et al. 2016a; Vietz et al. 2016b). Human-induced changes to the boundary conditions within which urban riverscapes function create a myriad of problems, which result in non-uniform responses to the nature and rate of urban riverscape and landscape adjustments. Some noted features of urban riverscapes include increased quantity and degraded quality of runoff as well as sediment starvation, which cause physical alterations upon the riverscape, including channelization, urban encroachment on floodplains, erodible corridors, and the conversion of riparian areas (Brown et al., 2009). While these actions inconsistently impact urban riverscapes, in general they adversely influence the physical and ecological integrity of streams (Chin 2006; Walsh et al, 2005). Despite this, local communities often maintain strong social interconnections with urban riverscapes (Capps et al. 2016).

Several authors have described riverscapes in concept, assessment, management, and restoration. Carbonneau et al. (2012) examined the ways in which recent technical and methodological developments in remote sensing have enabled the quantitative documentation and analysis of riverscapes. Wheaton et al. (2019) focused on several hallmarks of healthy riverscapes, which include space for floodplain engagement and dynamic behavior, as well as structures that add complexity and resilience—large wood or beaver dams—and hydraulic inefficiency. Wohl (2016) found that, while context is widely variable (Wohl 2018) and should guide expectations (Brierley and Fryirs 2009), messy rivers tend to be healthy rivers. Fausch et al. (2002) also confirmed the importance of discrete structural or habitat elements to river health, while their primary focus was the importance of scale in riverscapes: it is critical to consider and manage the complex interactions of processes and degradation effects across multiple scales.

Recently, multi-scale, hierarchical assessment approaches have been developed and implemented to support a better understanding of river and stream systems (Belletti et al. 2015; Fryirs 2015). More current iterations include the incorporation of hydrogeomorphic evaluation methods into urban riverscape assessment (Grabowski and Gurnell 2016; Gurnell et al. 2016; Rinaldi et al. 2015; Newson and Large 2006). "Hydrogeomorphology" refers to the suite of hydrological and geomorphological processes and forms that occur within catchments and their stream systems. Hydrogeomorphology's nascent stream assessment methods analyze the physical basis of a stream ecosystem and can directly inform restoration and enhancement measures that address causes rather than symptoms of degradation (Fryirs 2015; Vaughan et al. 2009; Somerville and Pruitt 2004; Poole 2010; Somerville, 2010). Hydrogeomorphic assessments contribute critical information about the underlying watershed system status and stream evolution trajectory (Brierley and Fryirs 2015). Given its importance, the European Union (EU) enshrined hydrogeomorphology as integral to 'good ecological quality' in its *EU Water Framework Directive* (European Parliament and Council 2000), a dictate that has focused European efforts on understanding the interactions between hydrogeomorphology and stream ecology (Vaughan et al. 2009; Newson and Large 2006).

Concurrently, the push to investigate relationships between social and physical processes has resulted in the development of two relatively new fields, "sociohydrology" and "sociogeomorphology" (e.g. Lane 2014; Ashmore 2015), that frame social and natural systems as inherently integrated. The inclusion of the social aspect in river assessment frameworks has not yet been realized at the scale seen in hydrogeomorphic assessment, but social values are increasingly incorporated into urban stream assessments. For example, recent assessment methods (Vietz et al. 2018; Gurnell et al. 2020; MHFD 2021) have demonstrated how altered physical and hydrological processes due to urbanization can be linked to the loss of stream values, which in turn acts as a driver for improving management actions. Each method emphasized the identification of social values associated with stream function and developed rational approaches to quantify linkages between these values, the physical processes of the riverscape, and flow metrics. These types of integrated procedures, however, are still in early development and application. Further, few of the assessment frameworks are specifically targeted for, or suited to, assessing riverscapes in the urban environment; they tend not to consider the relationship between demographics, socioeconomic processes, social values, ecological conditions, and riverscapes processes (Zhou et al. 2021). The failure of discipline-specific assessment methods to integrate social values into the front-end of their approaches for stream protection and restoration has been highlighted as a core reason for their ineffectiveness (Smith et al. 2016).

In general, the disparate approaches to incorporating multi-scale, hierarchical methods that are sensitive to interventions and social-ecological linkages, and applying such methods to urban environments, have not yet crystallized into an effective overarching framework for the assessment of urban riverscapes. Further, researchers and practitioners alike find it difficult to isolate critical stressors and their relationship to sustainable management within a social-ecological paradigm.

In this paper we outline specific foundational tenets for conceptualizing and understanding urban riverscapes in this context. We present four functional facets to evaluate within a practical and flexible assessment framework. The framework considers the social-ecological context alongside physical processes and forms. We discuss how to establish useful objectives and indicators, and how to evaluate connections amid different attributes between and within facets. We focus on how relationships between riverscapes and human values and uses might be better understood and incorporated into riverscape assessment and management.

2 Urban riverscapes foundational tenets

Human beings are innately drawn to water. Thus, as cities continue to grow, urban riverscapes are exceedingly important to communities working, living, and recreating adjacent to them. In this paper, we propose four foundational tenets—beliefs or ideas honored by a group—that underpin the conceptualization and understanding of riverscapes in the urban environment:

1. Urban riverscapes perform essential functions and provide vital services.
2. Anthropogenic uses of riverscapes affect their physical characteristics and behavior.
3. Urban riverscape conditions vary within space, and change with time, depending on adjacent land use and community values.
4. Social, economic, and political views shape riverscape management.

These four tenets, visualized in Figure 2.1, articulate key aspects of urban riverscapes that should guide any assessment of them and effective management practices. Specifically, the four tenets are intended to shepherd the development of an urban riverscape assessment framework that fills the current social-ecological gap in riverscape management.

We chose to anchor these tenets directly to reasoning derived from riverscape science and social-ecological system thinking (e.g., Brierley and Fryirs, 2005; Wheaton et al, 2019; Kondolf and Pinto, 2017; Mould et al., 2020a). Of critical importance, these tenets are not only grounded in scientific reasoning but have been refined from and build off common river management practices. They are not new ideas, yet most riverscape managers and practitioners do not actively observe them, particularly when competing values and interests dominate management decisions. These tenets, however, can inform assessment, planning, and management through an understanding of what influences functioning urban riverscapes in particular, and therefore what values drive decision-making, but have been refined from and build off common river management practices. They are not new ideas, yet most riverscape managers and practitioners do not actively observe them, particularly when competing values and interests dominate management decisions. These tenets, however, can inform assessment, planning, and management through an understanding of what influences functioning urban riverscapes in particular, and therefore what values drive decision-making.

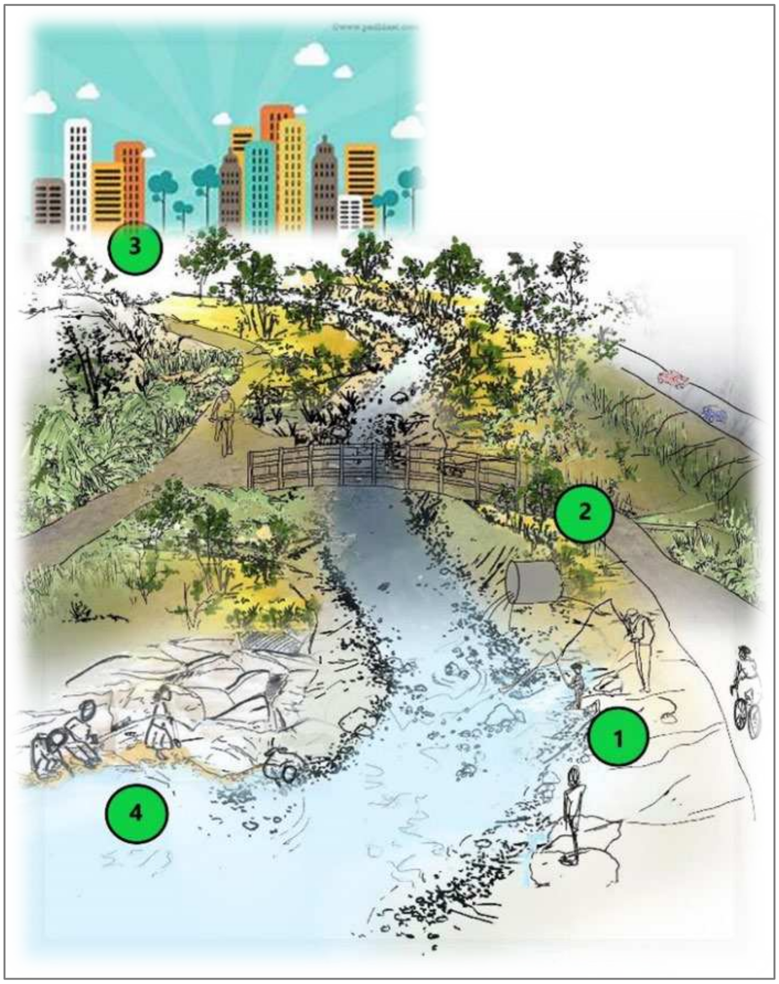

Figure 2.1 Illustration of the four urban riverscape tenets. (1) Urban riverscapes perform essential functions and provide vital services. (2) Anthropogenic uses of riverscapes affect their physical characteristics and behavior. (3) Urban riverscape condition varies and changes depending on land use. (4) Social, economic, and political views shape riverscape management.

The tenets have been developed based on riverscapes with real anthropogenic constraints in mind, those that intersect multiple urban zones. In other words, the application of these tenets to the assessment of urban riverscapes helps not only to create healthier riverscapes, but also sets realistic management expectations for sustaining dynamic riverscapes that provide instrumental (use-based), intrinsic, and relational values. Two of the tenets (1 and 2) directly address the value urban riverscapes provide to humans and the resulting impacts, often adverse, that those uses cause upon riverscapes. The third tenet recognizes the ability of a riverscape to adjust to the anthropogenic uses due to its assimilative capacity.

The last tenet suggests that managers directing restoration and rehabilitation should use identified riverscape values to guide decision-making in order to appropriately address the degradation of river health, and not rely exclusively on economic drivers or political levers, such as regulatory guidelines and standards. Table 2.1 outlines the premise for each tenet followed by its potential management applications.

Table 2.1 Foundational tenets for the effective assessment and management of urban riverscapes

Tenets	Premise	Management application
1. Urban riverscapes perform essential functions and provide vital services.	Urban streams provide opportunities for human interaction and are the subject of instrumental (use-based), intrinsic, and relational values. These systems also provide access to food resources, water supply, and navigable channels.	Identifying the valued attributes of urban riverscapes and understanding their dependencies and interdependencies provides a basis for the selection of relevant stream attributes and targets for assessment (Ives and Kendal 2014). The interdependence of human wellbeing and stream ecosystems can be summarized in the concept of 'river culture' (Wantzen et al. 2016), a useful basis for understanding, conserving, and preserving ecological health and cultural diversity along urban riverscapes.
2. Anthropogenic uses of riverscapes affect their physical characteristics and behavior.	Human impacts on urban riverscapes (e.g. stormwater discharge, waste disposal into streams, and human development along the floodplain) bring about the functional degradation of freshwater systems and a corresponding reduction in the potential value that urban riverscapes provide for humans.	Understanding of contemporary hydrology, morphology, and riverscape processes, tied to conceptualizations of natural variability and longer-term evolution, provide a basis to assess river responses to human disturbances (Fryirs and Brierley 2013).
3: Urban riverscape conditions vary within space, and change with time, depending on adjacent land use and community values.	Rivers are dynamic systems. Detecting human impacts on riverine systems is challenging because of the diverse biological, chemical, hydrological, and geophysical components at play (Gergel et al. 2002), as well as the social and economic variables. Additionally, human-induced alterations to river boundary conditions generate irregular responses to the rate and type of riverscape adjustments (Fryirs and Brierley 2013).	Stream responses are complex, with interacting effects and thresholds across scales, such that linkages between anthropogenic change and loss or degradation of valued stream attributes are often indirect, unpredictable, and non-linear, which is critical to note in any assessment. Thus, riverscape assessment should take into account both diffuse and direct influences of urbanization through scale and spatial organization in the catchment (King et al. 2005).
4. Social, economic, and political views shape riverscape management.	Decision-making for riverscape protection, rehabilitation, and restoration is based on social values and culture (Norris and Thoms 1999; Dunham et al. 2018). Whose values are represented (e.g. local community, broader community, stream managers) depends on governance systems (Dunham et al. 2018) and the processes and biases of stream managers (Ives and Kendal 2014). Furthermore, political influences across multiple layers of government can result in a complex web of legislation and policy that can both protect and harm urban riverscapes and communities (Findlay and Taylor 2006).	Managers directing riverscape restoration and rehabilitation should use identified riverscape values to guide decision-making. Identification of values in a deliberate and holistic way allows managers to appropriately address degradation of river health rather than focusing on solving single issues (e.g. flooding, erosion).

3 Urban riverscapes assessment framework

With these four foundational tenets in mind, we propose a framework for the assessment of urban riverscapes that prioritizes social values alongside ecological and physical processes. This framework recognizes that assessments of urban riverscapes must adjust expectations for health and function because urban streams are responding to numerous anthropogenic as well as natural stressors (U.S. EPA, 2017). These ecosystems reflect a unique combination of efforts to balance flood control, recreation, water supply, and other stream uses with the need to protect riverscapes and stream values, and this requires an understanding of urban stream systems' physical processes. Disparate land uses and land cover in urban areas produce distinct combinations of factors that directly affect watershed hydrology and stream conditions.

Historically, riverscape intervention has often focused on highly specific elements, such as water quality or the river aesthetic. This framework, instead, encapsulates new ideas of social-ecological systems that are at the forefront of urban stream management. The many social-ecological complexities of urban riverscapes confound their management, particularly when it comes to determining the appropriate interventions to improve their physical condition and ecological integrity more generally. It is vital to account for these urban complexities through an assessment framework that is underpinned by the urban riverscapes tenets (see Table 2.1). By assessing hydrogeomorphic processes against an understanding of what constitutes healthy, functioning riverscapes, riverscape assessments can inform urban planning, stream management and restoration that better supports human values, which in turn bodes well for their success.

Recent research and planning projects (Murphy et al. 2022) have found that engaging local communities in the assessment process achieves a shared understanding of riverscape function and associated tradeoffs. Under a values-based paradigm, assessment is conducted to ascertain the physical condition and stream values given the riverscape context, which leverages both social and hydrogeomorphic indicators. The framework can be conceptualized in three tiers, which tackle the following questions in turn: why are we assessing the riverscape?, what do we need to understand in and along the riverscape?, and how will we assess the riverscape to develop that understanding? (Figure 2.2).

Tier 1 of the framework hones the intent of the assessment before identifying the values and functions to assess (Figure 2.2). It establishes the context for assessment by asking, what are we assessing, and subsequently managing towards? Critical to this tier is incorporating the socio-political context into urban riverscape assessments and integrating diverse types of knowledge in the procedure. The process of setting the scene in this first tier ensures that the assessment is driven by appropriate goals and objectives, and also is inclusive of community values. Through a series of understanding and learning questions, such as “What community values and policies influence the condition of the urban riverscape?” and “How do we leverage the assessment to effectively balance riverscape condition and community values?”, we can facilitate the integration process.

The second tier of the framework determines which social-ecological values and urban riverscape physical functions to include in the assessment (Figure 2.2). This tier expands on the specific attributes and relationships, including pressure-response relationships or feedback loops and human-riverscape linkages, that should be understood in order to assess riverscape physical condition and use. Assessing the physical aspects of urban riverscapes requires attention to the connections between hydrologic, geomorphic, ecological, and social facets that drive riverscape processes. These facets are sensitive to riverscape management; understanding them through assessment can help to define potential solutions and build a financial case for protection or renovation programs, ultimately improving the likelihood of funding (Smith et al. 2016).

Finally, the third tier of the framework describes how to measure the riverscape functions and values given urbanization and existing management practices (Figure 2.2). Tier 3 is the technical domain in which models, metrics, tools, and processes are developed and tested. The technical domain in this framework differs from what often occurs in the development of other riverscape assessment schemes, where the hydrological and ecological facets become the programmatic focus (i.e., Fitzpatrick et al. 1998;

Somerville and Pruitt 2004; Poff and Zimmerman 2015); this framework advocates a more holistic approach that begins with the social-ecological processes that underpin management decisions (Murphy et al. 2022). It is not until the social-ecological context has been set that suitable technical elements can be determined. In the subsequent sections, we describe each tier in more detail.

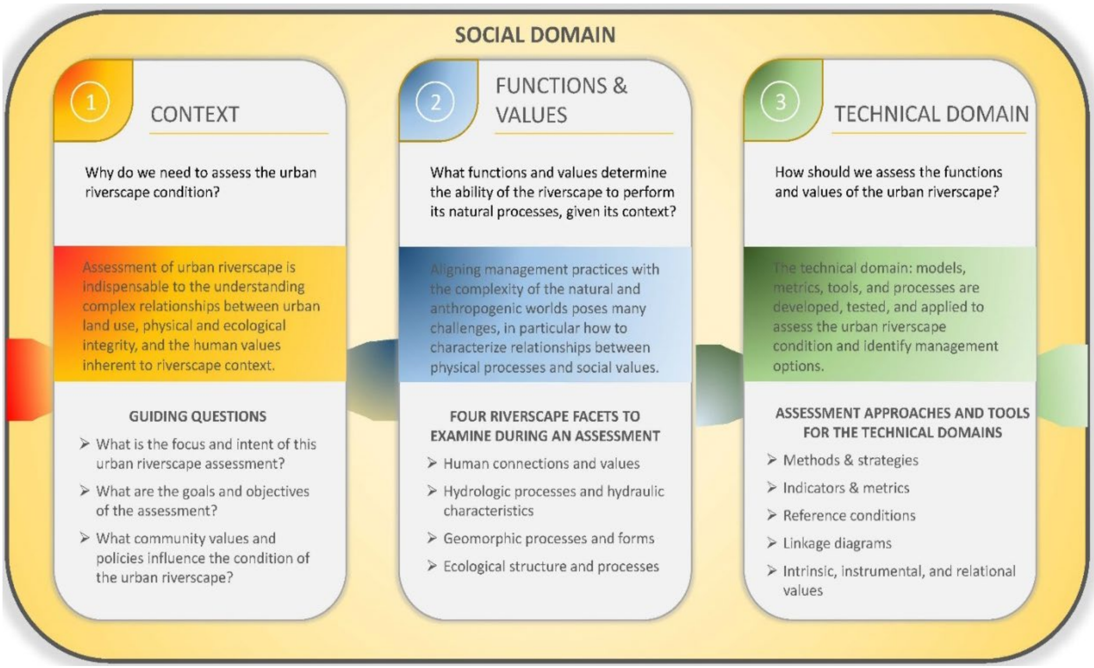

Figure 2.2 A tiered framework for urban riverscape assessment that incorporates social-ecological values. When devising assessment methods, the process works from left to right. When assessing and drawing conclusions, the process works from right to left. Understanding and learning occurs throughout the process.

4 Tier 1 – Why assess this urban riverscape? Focus and intent

Assessment of urban riverscapes is indispensable to understanding the complex relationships between urban land use, riverscape management, physical and ecological integrity, and the human values inherent to appropriate planning and management. The primary objective of Tier 1 is to provide watershed managers with an approach to improve understanding of the physical condition of an urban riverscape and support future visions for the watershed on a localized and regional scale. Assessment can demonstrate the condition of a riverscape relative to baseline or target conditions and/or reveal the trajectory of the system (Fryirs 2015). Adopting the continuous, multi-scale, spatially heterogeneous “riverscape” as the primary unit of assessment extends the scope of the framework beyond streams at site or reach scales, and allows interacting elements to be assessed as a larger system (Fausch et al., 2002). Riverscape-scale approaches thus provide a holistic basis to assess the capacity of streams to support ecological communities and social values at multiple scales, from small niches within the riverscape to the catchment scale (Fausch et al. 2002).

Increasing awareness of human connections and linkages to urban riverscapes elevates the value of urban riverscapes within society. However, the linkages between riverscape alteration and human values are often opaque, making it difficult to develop, justify, and fund appropriate restoration approaches and mitigation actions. Communities value riverscapes in many ways, from their experiential to aesthetic to cultural attributes. Urban planners use the rural-to-urban "transect" concept (Duany and Falk 2020) to describe the gradient of development that can occur on land, from predevelopment landscapes and undisturbed ecosystems to constructed industrial, urban, and suburban spaces. These transects can be spatially or temporally distributed throughout a city, and each reflect characteristic differences in the complex interactions between natural and human systems (Figure 2.3).

These gradients of riverscape human connections and riverscape characteristics are clearly applicable to urban as much as non-urban riverscapes, but they lack consideration of the human connections to riverscapes beyond uni-directional degradation and management actions. Recognizing this, Dunham et al. (2018) urged the consideration of riverscapes as social-ecological systems, including both the study of interactions within social systems that influence human-riverscape interactions, such as values, politics, and culture, as well as elements like ecological services that emanate from riverscapes to the benefit of humans. Perhaps nowhere are these human dimensions more important than in cities, where people inevitably interact in various ways with riverscapes (Smith et al. 2016) and where government officials and non-profit organizations are consistently seeking opportunities to connect people with nature. For example, UNEP (2020) aims "to create a platform for societies globally to put their relationships with nature on a new trajectory for centuries to come."

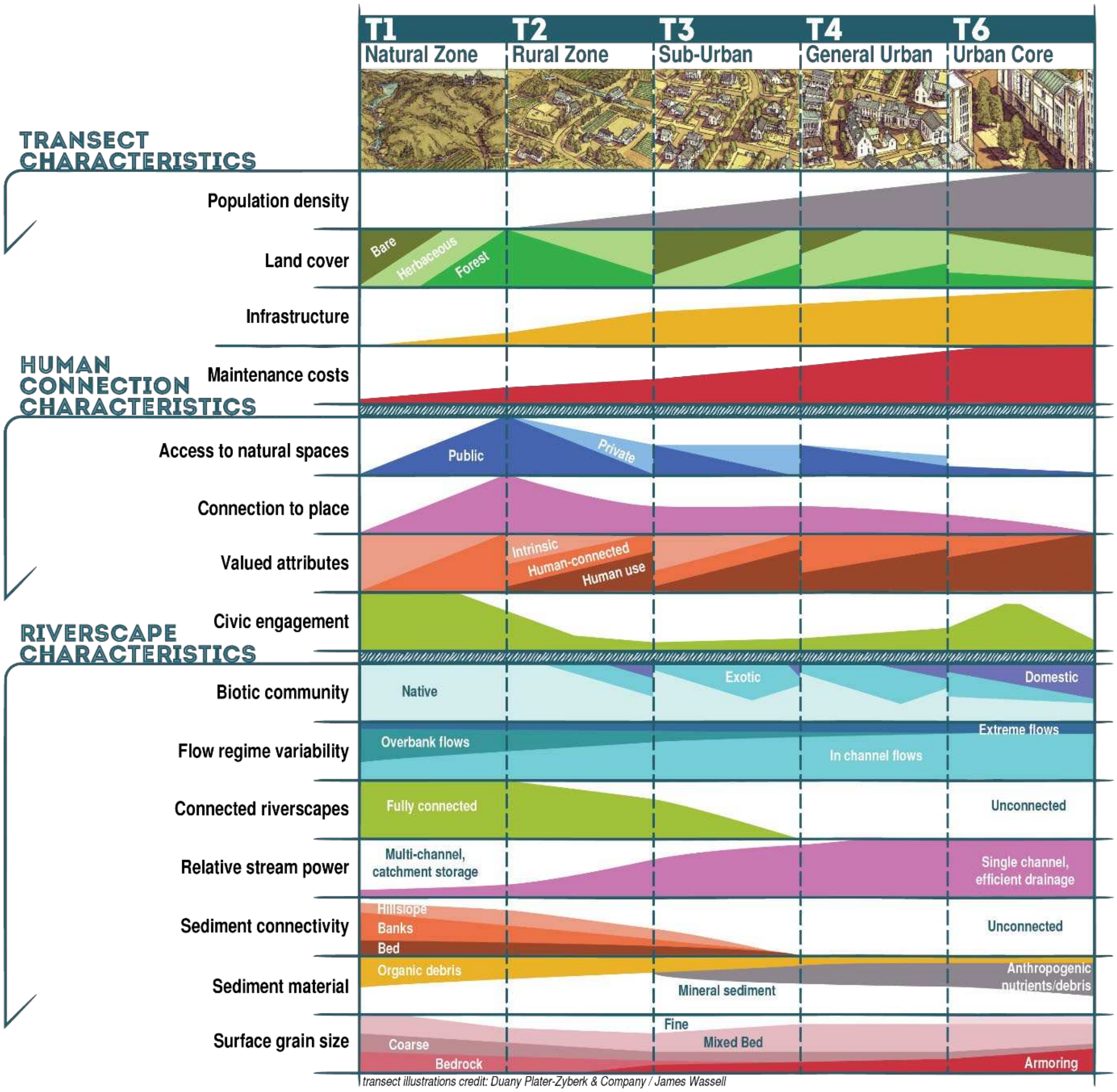

Figure 2.3 Gradients of riverscape human connections and riverscape characteristics associated with various urban transects, or T-zones. The urban transect is a cut or path through part of the environment showing a range of different habitats or anthropogenic biomes. The transect is divided into six zones: natural (T1), rural (T2), sub-urban (T3), general urban (T4), center (T5), and core (T6). T5 is omitted for purposes of clarity. Modified from Ellis 2011 and Johnson et al. 2020. Urban transects reproduced by permission from the Center for Applied Transect Studies).

To address the core question of "why," we see a need to consider and define optimal connections between stream health and socio-political context, and then to determine how these connections can be realized through diverse knowledge sharing. Interdisciplinary knowledge transfer is necessary to understand riverscape processes and the social-valued attributes that underpin appropriate problem definition and assessment.

4.1 Principles for incorporating socio-political context into urban riverscape assessments

The socio-political context can strongly influence the focus of river corridor management. Case studies examining values in stream rehabilitation indicate the importance of human relationships for helping assessors and practitioners understand the range of values that exist in a community and in enabling those values to inform how communities participate in stream management (e.g. Mould et al. 2020a). Values may be intrinsic, instrumental, or relational. Intrinsic value is the value that an entity possesses as itself, simply for what it is, for example, valuing biodiversity for its own sake. Instrumental value is the value that something holds as a means to a desired end; natural resources and ecosystem services, for example, offer instrumental value in what they provide (Sandler 2012).

In addition to intrinsic and instrumental values, relational values—the existing or desired relationships among people and between people and their environments (Chan et al. 2018)—can be used to enhance practitioners' understanding of what communities want in a landscape and why (Arias-Arévalo et al. 2017; Chan et al. 2018; Tadaki et al. 2017). Relational values can contribute meaningfully to stream management in a way that is specifically suited to the social context of the work (Tadaki et al. 2017; Bremer et al. 2018), by more fully addressing the underlying reasons that people become involved. Community participation in stream restoration may take the form of assisting river management practitioners in the design phase, or of participating in on-the-ground action to implement and maintain works. Potential participants may be motivated by a desire to connect with their neighbors or to take part in shared work, rather than by a desire to see specific ecological outcomes realized. In other cases, participants who were initially motivated to engage because of intrinsic ecological values may be encouraged to continue their involvement over time as they develop or deepen relationships with others.

Connecting community motivation with participation requires understanding the enablers and barriers to involvement (Scoggins et al. 2022), many of which may be social and relational. Enablers may include informal social networks, organized engagement activities, sufficient time and resources, and a proactive and adaptive approach from facilitators (Bos and Brown 2015; Jami and Walsh 2017). Barriers may include social isolation, poor community-government relationships (Jones 2003; Rodriguez-

Izquierdo et al. 2010), lack of time or financial resources (Lall et al 2004), or differences in identities and politics within a community (Kenter et al. 2019; Njoh 2002). Taking into account relational enablers and barriers, facilitators and knowledge brokers can play a significant role by recognizing and investing in relationship-building (Jami and Walsh 2017). Investing in relationships and prioritizing dialogue can help skilled practitioners access and understand the latent values that exist in a community and to mobilize them to inform project design and effectively facilitate participation (Mould et al. 2020a). Securing this kind of community buy-in tends to ensure more successful outcomes.

Recognizing that the specific methods used in developing an assessment approach will be dependent on the socio-political context in which assessors are working, we propose several general principles that can underpin this work. These principles include:

- **Focus on building trust** between participants by adopting a transparent approach to defining values and linking them to appropriate indicators and measures. Collaborative mapping of these relationships avoids the problem of a 'black box' when designing river management projects, and provides a shared basis for input into decision-making.
- **Prioritize dialogue** in gathering technical and non-technical input into the development of goals and assessment criteria, and involve communities, where possible, in the selection of methods that will be used to investigate their values and understand their connections to place.
- **Recognize that values are dynamic** and can change over time, through shared learning when participants share knowledge.
- **Recognize relational values** alongside more traditional conceptualizations of value, such as intrinsic or instrumental. While relational values can be more difficult to define, they tend to be powerful motivators driving people to action. Their recognition allows for a more complete articulation of the elements of a riverscape that contribute to a sense of place (Tadaki et al. 2017; West et al 2018; Mould et al. 2020a).

These principles are intended to create spaces for collaboration between assessors, resource managers, and communities, through which participants can share knowledge, learn from each other, and construct logic that reflects a broad range of values.

4.2 Integrating diverse types of knowledge to establish goals and objectives

Connecting social values to those riverscape processes that may be assessed requires a blending of social, ecological, and physical sciences, highlighting the need for interdisciplinary approaches to urban riverscape assessment (Figure 2.4). For example, Tippler et al. (2015) linked special-interest community groups in an urbanizing area to the iconic species and ecological communities they valued for their 'life-fulfilling' functions (Daily 1999). Then, they identified the specific ecological and environmental needs of each icon. In like fashion, for urban riverscapes, indicators and detailed parameters such as flow, water quality, or physical habitat could be identified for assessment to support social values. However, emphasis on "icon functions" should be accompanied by expert knowledge to ensure that ecologically important–but less charismatic–attributes are also supported. Feedback of that scientific knowledge into community education and outreach can then help to improve public understanding of how such keystone attributes support broader community values (e.g. Dahdouh-Guebas et al. 2020).

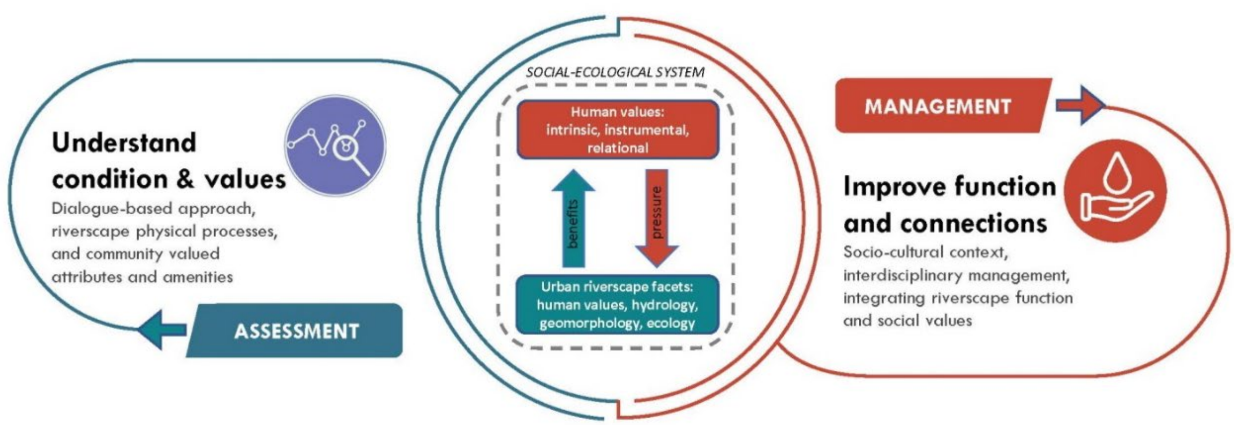

Figure 2.4 Urban riverscapes as a social-ecological system. Interactions between riverscape facets and human values within the system can be better understood through assessment. Assessment informs improved urban riverscape management to enhance riverscape function and resultant human benefits.

Adaptive, collaborative, and transdisciplinary approaches enhance understanding of the social-ecological system in such a way that project goals and objectives can be systematically characterized (Murphy et al. 2022). Methodically and purposefully transferring knowledge amongst a diverse multi- or trans-disciplinary team ensures comprehensive understanding of riverscape processes and the social values that improve assessment and management. Place-based experiential knowledge further fosters appropriate goal setting and clear objectives for the local context. Creating an inclusive approach to identifying goals and objectives and to establishing assessment strategies will make it easier to formulate feasible management outcomes, which are likely to yield increased function and reduced maintenance costs. Skidmore et al. (2011) noted that objectives should be well-defined, clearly relate to and support the assessment process by considering historical and anticipated future conditions, and achievable given the context of the riverscape.

5 Tier 2 – What functions and values determine the ability of the riverscape to perform its natural processes, given its context? The four facets

The outcome of Tier 1–defining the catchment context, the assessment goals and objectives, and a dialogue-based approach–informs the properties and relationships between physical processes, ecological conditions, and social values in Tier 2. The ability of a riverscape and its associated physical processes to perform their natural functions given the surrounding social-ecological context requires an understanding of urban riverscape functions and values. Aligning management practices, however, with the complexity of the natural and anthropogenic worlds requires understanding these functions and values and their linkages.

5.1 Understanding urban riverscape functions and values through the four facets

Examining urban riverscapes through a number of inter-related processes, which we have categorized into four "facets," provides a template for conceptualizing the many aspects of a riverscape and its connection to human communities (Figure 2.5). Given that physical and social-ecological processes influence stream character and behavior directly, we developed the following four facets for consideration in urban riverscape assessments: "human connections and values," "hydrologic processes and hydraulic characteristics," "geomorphic forms and processes," and "ecological structure and functions." These four facets generally align with those proposed by Polvi et al. (2020), with the exception of their biogeochemical properties and processes facet and the addition of human values to our framework. We chose to exclude the biogeochemical facet, which examines overall river 'health' through biologic and chemical lenses such as water quality assessments or associated aquatic life criteria, due to our focus on the physical condition and because it is the main focus of many other existing stream assessment procedures. The four urban riverscape facets are described in further detail below.

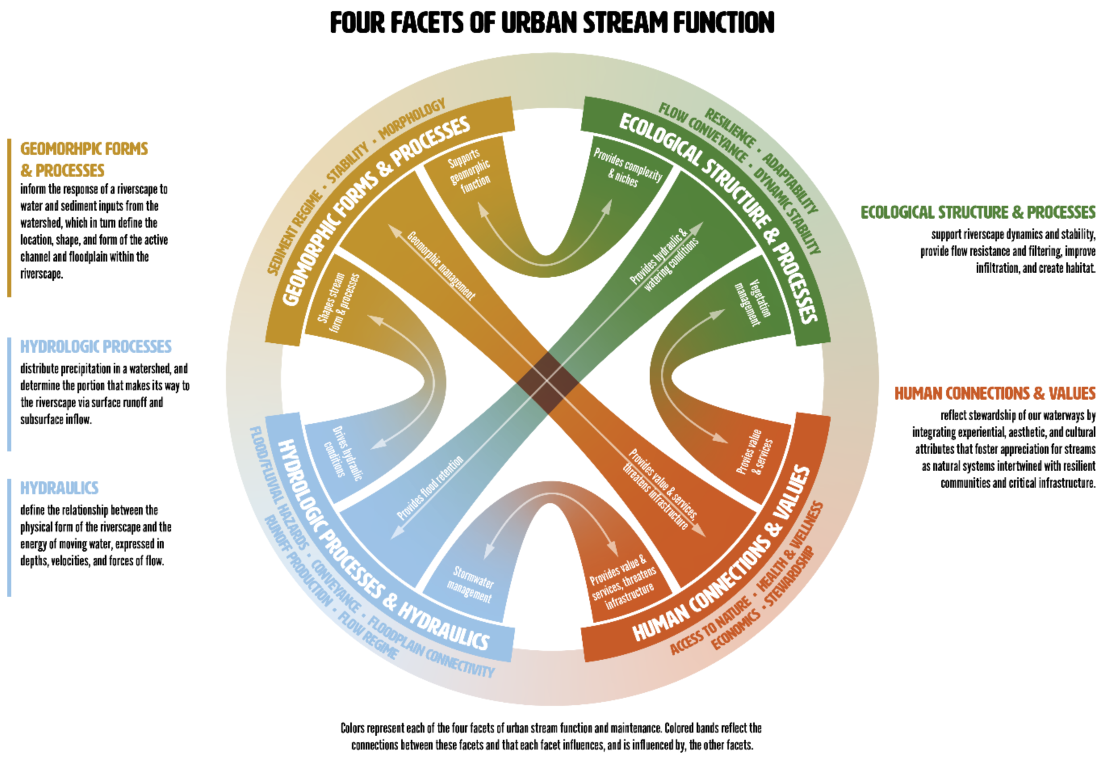

Figure 2.5 The four facets of urban riverscapes: human connections and values, hydrology and hydraulics, geomorphology, and ecology. Two-way connections exist between all urban riverscape facets. Examples are provided on the arrows for each connection.

Table 2.2 provides a synthesis of the "why" in Tier 1, the "what" in Tier 2, and the "how" in Tier 3 of this urban riverscapes assessment framework. The table includes the questions and answers at the core of the framework that explain what function each facet provides, why that facet is important to both the riverscape and to society, and what the management goals are for each facet.

Table 2.2 A matrix that includes four questions to support multi-disciplinary teams in ensuring the four urban riverscape facets are all integrated into an assessment.

	URBAN RIVERSCAPE FACETS			
	Human connections and values	**Hydrologic processes and hydraulic characteristics**	**Geomorphic form and processes**	**Ecological structure and processes**
Why is this facet important?	Management of urban riverscapes in a way that aligns with community values and allows human connections will improve urban quality of life. Understanding community values also helps to define project goals that meet human needs and foster stewardship of the riverscape.	The flow regime (peak, volume, duration, frequency, and timing of streamflow) establishes hydraulic conditions that directly affect stream form, riparian vegetation, aquatic and riparian habitat, water availability, water quality, sediment transport, and flood and erosion hazards.	A riverscape that has a self-sustaining form given its water, sediment, and wood inputs, and a high degree of physical complexity, facilitates natural riverscape functions and supports human values.	The integrity and function of a riverscape is reflected in its ecological communities. Healthy vegetation is integral to geomorphologically resilient stream corridors, reducing maintenance costs and providing aesthetic value and habitat.
What function does the facet perform in urban streams?	Human connections and values encourage stewardship of riverscapes by integrating experiential, aesthetic, and cultural attributes that foster appreciation for riverscapes as natural systems in the built environment.	Hydrologic processes control surface runoff and subsurface inflow to riverscapes. The flow produces in-stream hydraulic conditions, which can support or degrade riverscape functioning.	Geomorphic processes dictate the response of a stream to water and sediment inputs from the watershed, which in turn define the location, size, and form of the river channel and floodplain.	Vegetation supports stream dynamics and stability, flow resistance and filtering, infiltration, organic matter and wood input, human connections, and habitat. In-stream physical habitat provides the physical niches for ecological communities to inhabit.
How does a riverscape assessment characterize the facet?	Society increasingly values urban riverscapes. If poorly managed, human activities can adversely impact riverscape functions, and human-valued stream services and benefits can be lost. Human overuse of ecosystem services can degrade riverscapes, resulting in less resilient riverscapes, loss of habitat, and reduced natural and beneficial functions.	Increased urban runoff and other modifications to the flow regime may adversely impact riverscapes by producing in-stream hydraulic conditions that cause erosion, habitat simplification, and ecosystem alteration.	Anthropogenic stressors upset geomorphic equilibrium and natural amenities of a riverscape thereby increasing the risk of property loss and the need for infrastructure protection, which increases the need for maintenance.	Vegetation along urban riverscapes is disturbed by management practices and social uses. Pruning, thinning, and mowing are common responses to aesthetic and safety concerns, but can reduce the functions of vegetation. Instream physical habitat is threatened by instability and adverse hydraulic conditions.
What is the overarching management goal of the facet?	Riverscapes that enhance urban areas and improve quality of life while performing essential riverscape functions and providing flood attenuation.	A flow regime that supports geomorphic equilibrium and complexity, physical habitat, and riparian vegetation.	A riverscape that supports fluvial processes (conveys and retains water, sediment, and wood; allows channel adjustment; and fosters physical complexity) that are compatible with adjacent land uses.	A complex and self-sustaining instream physical habitat, including self-sustaining vegetation communities that provide erosion resistance and wood input, and improve infiltration and filtering while not impeding flood conveyance.

5.1.1 Human connections and values

Communities greatly value riverscapes and exhibit a strong sense of place associated with streams (e.g. Kendal and Farra 2016). The importance of riverscapes to communities provides waterway managers with license to restore stream health (Boyd 2021). Thus, understanding a community's specific values, including determining the community-valued amenities and anticipated social benefits of a riverscape as well as the potential concerns, can guide the selection of assessment metrics for urban riverscapes. Ignoring social-ecological connections, on the other hand, can lead to assessment and management outcomes that provide little value to people, or may even conflict with community benefits. Unless eco-centric projects reinforce some high-level, broadly-supported strategic goal, such as the protection of an endangered species or creating landscape-scale connectivity, they are unlikely to be successful. When communities are invited to co-design the future of urban waterways, they center themselves in the landscape, with their aspirations for better ecological health going hand in hand with better access and amenities for the community (e.g. McAuley and Knights 2021).

Identifying community-valued riverscape amenities requires managers and practitioners to consider the range of values that make riverscapes important to communities and to produce a conceptualization of "value" that is inclusive. These complexities convey that riverscape assessments benefit from social science expertise in order to devise community engagement strategies, questionnaires, or other means of identifying valued attributes (e.g. Kendal et al. 2015). A particular challenge exists in newly developing areas where some of the greatest gains in stream protection can be made, but where the community does not yet exist (Sammonds and Vietz 2015; Birtles et al. 2015); in such scenarios project stakeholders must advocate for the rights of the future community to form the kinds of relationships with riverscapes that they wish, while ensuring that those relationships are compatible with a functioning and healthy ecosystem.

5.1.2 Hydrologic processes and hydraulic characteristics

It is well known that runoff is a master variable that controls many aspects of the hydraulic and geomorphic conditions of receiving streams and rivers, as well as ecological processes (Poff et al. 1997;

Doyle et al. 2005; Bunn and Arthington 2002; Vietz et al. 2016b). An urban riverscape assessment therefore must include evaluation of aspects of the hydrologic processes that maintain resilient physical form, sustain in-stream biota and riparian vegetation, and support human uses and benefits provided by the riverscape (Fletcher et al. 2014). For example, overbank flows are critical to watering floodplain vegetation (Piegay 1997), moderate peak flows can be important for flushing fine sediment and channel maintenance (Poff et al. 2010; Piegay 1997), and baseflows are essential to providing persistent in-stream physical habitat (Smakhtin 2001) and in some cases an environment amenable to recreation (e.g. Willis and Garrod 1999).

Urbanization can have varying impacts on hydrology (Booth et al. 2016; Brown et al. 2009), depending on factors including urban design and the pre-development hydrologic regime. Most commonly, in urban areas peak flows increase in magnitude and frequency due to elevated runoff from impervious surfaces through efficient drainage pathways (Fletcher et al. 2013) and/or combined sewer overflows (Tetzlaff et al. 2005). Effects on low flows can be highly variable (Bhaskar et al. 2016): they can decrease because water is diverted to surface runoff rather than recharging groundwater, or they can increase due to leaks in water supply infrastructure, increased dry-weather irrigation, and wastewater discharges. Thus, overall flow volumes in urban riverscapes are quite variable (Konrad and Booth 2005). And while they commonly become increasingly flashy, this pattern is not necessarily the case in naturally flashy systems such as arid lands (McPhillips et al. 2019) or tropical environments (Ramirez et al. 2009). Given this variability, assessment methods need to allow for both excesses and deficits in relevant flow components depending on local climate and urban design context.

"Hydraulics" refers to the movement of water through the channels and floodplains of riverscapes, as expressed in depths, velocities, and forces of flows (i.e., stream power or shear stress), as well as the interactions between sediment, water, and wood (Niezgoda and Johnson, 2005; Anim and Banahene 2021). The hydrological processes of a riverscape, specifically alterations to flows, create changes to the hydraulic processes of the riverscape. The movement of water through the landscape influences the geomorphology and vegetation of riverscapes across a broad range of spatial and temporal scales. The shape and size of stream channels, the distribution of vegetation, the stability of channel bed and banks, and the physical in-stream habitat for aquatic biota are all largely determined by the interaction between the flow regime and local geology and landform. It is these relationships that assessment frameworks must understand in order to define flow requirements for an urban riverscape that support its geomorphic and ecological characteristics and community benefits. In doing so, relevant flow metrics can be defined, assessed, and used to guide policy towards more functional flow regimes, in similar fashion to the ecohydrologic approach used in environmental flow assessment (Fletcher et al., 2014; Poff et al. 2017).

5.1.3 Geomorphic forms and processes

The location, shape, and form of a riverscape is determined by geomorphic processes, such as erosion, sediment transport, and large wood dynamics produced by water and sediment moving through the system. But these physical elements can also be constrained or even defined by direct modification, like constructed channels or rock protection. Adjustments to bed, bank, and channel morphology and riverscape processes have important implications for ecosystem functioning and hazards associated with river dynamics (Bollati et al. 2014). Development has significantly altered physical habitat (Violin et al., 2011) and sediment transport rates (Papangelakis et al. 2019; Russell et al. 2020), which contribute to the degradation of stream ecosystems (Vietz et al. 2016a; Hawley et al. 2013; Vietz et al. 2014). The simplification of river structure that results from erosion, sedimentation, and direct channel modification reduces the geomorphic complexity of channels and alters channel-floodplain connectivity, diminishing the diversity of habitat and the availability of refugia (Brierley and Fryirs 2009).

Assessment of the geomorphology of urban riverscapes typically focuses on the channel, due to the encroachment of human development on parts of the riverscape that would, under more pristine circumstances, be more fully connected with the channel, including floodplains. Connectivity between the channel and its floodplain reflects the two-way transfer of water, sediment, and nutrients between them, and is critical for maintaining riparian vegetation and habitat and creating flow inefficiencies and a resilient river system (Brierley and Fryirs 2005). Poorly connected floodplains often reflect impairments to stream health and function due to hydromodification, channel modification, and/or anthropogenic land use within the floodplain, which limit hydrogeomorphic processes and biologic interactions between the channel and its floodplain. These anthropogenic stressors create constraints and evolutionary trajectories that can hamper or preclude re-connection in urban environments so that investigating those stressors and their associated impacts is central to assessing urban riverscapes. It has been argued that protecting floodplain space will afford the greatest possible success for rivers in an urbanizing world, and should be a priority in greenfield or urbanizing catchments (Vietz et al. 2016a).

The important processes of channel and floodplain interactions, and their associated spatial and temporal variability, are a focus of this framework because they are fundamental to successful riverscape management strategies (Kline 2010; Wohl 2017; Blazewicz et al. 2020; Melbourne Water 2018). Temporal variability describes the frequency and duration of specific processes influencing the riverscape, from outside the corridor and within the riverscape, as well as the history of formative events that continue to influence form and process (Wohl et al. 2018). The trajectory of geomorphic change can be directly related to the level of urbanization and/or to the timeframe of response (Hawley et al. 2013).

Assessing at various scales the physical attributes, such as connectivity, stability, dimensions, and physical complexity, will help to illustrate relevant aspects of morphologic character, their importance in supporting human values and benefits, and their sensitivity to degradation or management influences. Thus, catchment-scale conceptual models of process interactions, connectivity, and evolutionary traits provide a basis to predict responses to management interventions (Mika et al. 2019; Wohl et al. 2019).

5.1.4 Ecological structure and processes

The ecological condition of urban riverscapes affects the value they provide to society (Gonzalez del Tango and Garcia de Jalon 2013). In turn, changes in flow and sediment regimes, as well as and channel and riparian zone characteristics, affect the ecology (Gurnell et al. 2007). In an assessment framework that focuses on the hydrogeomorphic context, emphasis is placed on the flow regime and geomorphic conditions as the physical template that supports ecological functioning (Grabowski and Gurnell 2016). Thus, valued ecological attributes are not necessarily directly monitored in a riverscape assessment, but their requirements can be interrogated to define relevant flow and physical conditions for assessment.

Hydrologic changes in particular considerably influence the ecological function of urban riverscapes, and their significance depends on the riverscape's context and the spatial and temporal patterns of urban development (Konrad and Booth 2005). In urban riverscapes with altered hydrology, the ecological benefits of improving physical habitat and water quality may be tempered by the persistent effects of altered streamflow. Identifying the primary mechanisms of physical and ecological degradation requires rethinking how we assess urban riverscapes.

Furthermore, the interactions between ecological processes and hydrogeomorphic processes are an important component of hydrogeomorphic assessment (Grabowski and Gurnell 2016). Urban riverscape vegetation, for example, supports stream dynamics and stability, provides flow resistance and filtering, improves sediment and organic matter retention, and provides large wood which fosters structural complexity (Gurnell 2014). Forman and Godron (1986) identified the four main ecological functions of river corridors as habitat, conduit, barrier (or filter), and source. Urban riverscapes should strive to provide these ecological functions and support the social values held by communities that rely on those ecological functions. Thus, assessing those functions is paramount to identifying and deploying management actions to address the stressors degrading them.

5.2 Linking facets: Inter-related properties and processes

Characterizing relationships between hydrogeomorphic riverscape processes, ecological conditions, and social values is important because (a) physical processes interact to produce complex effects on the social-ecological system; (b) processes which represent management levers, such as flow regime or sediment transport, may be several steps removed from the attributes that are most valued by people, like support of significant species, recreation, or aesthetics; and (c) some processes are easier to assess than others, therefore it may be preferable to evaluate a surrogate indicator of riverscape physical condition rather than directly assessing the most valued riverscape attributes (e.g. appraising physical habitat rather than surveying biota). In the urban riverscape context, all assessed physical facets ultimately link to social values–instrumental, intrinsic, and relational–that define the goals of riverscape assessment and management (Figure 2.5).

Typically, natural resource agencies tend to focus on ecological resilience rather than societal benefit as an end-goal (Benson and Garmestani 2011), emphasizing the biophysical resource rather than the social system that cares for, governs, and benefits from the resource (McMillen et al. 2019). We posit that ecological resilience and social benefit do not have to be mutually exclusive. Our framework helps facilitate treating stream restoration and management as an optimization problem, where the different facets are evaluated and used to define the objective function, which should be informed by dialogue and relational values. The relationships between society and riverscapes need to be better illuminated to support the adoption of eco-centric goals, or to support alternative goals which balance different types of values.

Numerous existing methods and frameworks have already been developed and applied to describe and assess linkages between ecological and hydrogeomorphic facets (Gurnell et al. 2020; Polvi et al. 2020; Beck et al. 2019; Nadeau et al. 2018). These methods require: (i) the best available science on pressure-response relationships; (ii) mechanisms to fill knowledge gaps with better science, such as research partnerships; and (iii) expert opinion to provisionally fill gaps with best available knowledge or estimates. While expert opinion is often the optimal resource to synthesize scarce information in such studies (e.g. environmental flow studies, Acreman et al. (2014); urban hydrogeomorphology, Vietz et al. 2016b), its fallibilities should be examined (Burgman 1981). Formal expert elicitation practices that reduce cognitive biases and better account for uncertainty (e.g. Hemming et al. 2018; Webb et al. 2015) could improve the robustness of hydrogeomorphic assessments. Furthermore, knowledge gaps revealed by the expert elicitation process could be adopted as research priorities to improve future assessments.

The linkages between human connections and values and the other facets (see Figure 2.5) require social science and community participation. These relationships are not readily quantifiable; they may be dynamic over time, and are likely highly variable between and within cases. They are of primary importance in defining what is important in riverscape systems, particularly in urban areas, and can guide the selection of relevant, measurable indicators of riverscape health (see Tier 3). Dialogue between managers, practitioners, and the community provides a basis for mapping this conceptual logic that incorporates diverse perspectives and knowledge types (Murphy et al. 2022). Indicators chosen in this manner would represent the hydrogeomorphic conditions that support healthy riverscape functioning and also meet the wants and needs of urban communities and broader society.

The process of linking human values, riverscape ecology, and hydrogeomorphic conditions can be facilitated by the development of conceptual diagrams and mental models. Using this type of conceptual logic to define the relationships between goals or intended outcomes and the values that inform them will determine if assessment outcomes are achieved, and what measures could drive metrics of achievement (e.g. MHFD 2021; Vietz et al. 2018; Melbourne Water 2018). These diagrams also provide valuable communication tools to identify associations and the reasoning behind a particular focus, such as how nature-based solutions with plantings might better facilitate human health.

6 Tier 3 – How should we assess the values and functions of this urban riverscape? Strategies, indicators, and targets

Tier 3 contains the technical domain, including strategies and methods, indicators and metrics, and targets applied to assess the urban riverscape conditions and trajectory and to identify management options. Techniques applied under this tier are not solely scientific (related to ecological, hydrological, or geomorphic components), but also include social science techniques and community engagement strategies. The assessment of the four facets includes selecting a diverse set of indicators and metrics for every element in turn, based on each value (activity) linked to Tier 1.

6.1 Urban riverscape assessment strategies

Once Tier 1 (the "Why?") and Tier 2 (the "What?") have been applied, the defined objectives and the corresponding understanding of the important elements and linkages in the riverscape system that have been developed can guide the selection of a workable set of strategies and techniques (the "How?" of Tier 3). An assessment framework with a flexible yet parsimonious approach to formulating methods (neither “one size fits all” nor overly comprehensive) makes it easier to formulate feasible management outcomes, which are likely to improve function and reduce maintenance costs. Example assessment strategies at the three scales—watershed, riverscape, and reach—for all four facets described in Table 2.3 provide researchers and watershed managers tools to meet that objective.

Table 2.3 Reach, riverscape, and watershed-scale strategies for the assessment of the four facets of urban riverscapes.

Stream Facet	**SPATIAL SCALE**		
	Reach	**Riverscape**	**Watershed**
Human connections and values	• Consider social-ecological aspects such as equitable access to nature, enhanced health and wellbeing, safety and security, community development, First Nations cultural values, and stewardship of natural resources. • Evaluate local riverscape attributes that are significant to human communities (e.g. waterholes, fishing spots, cultural sites, and habitat for iconic species). • Consider the adjacent context, such as neighbourhood values, aesthetic and experiential characteristics, and historical management practices.	• Evaluate interactions of riverscapes with regional plans for transportation, trails, open spaces, land-use, and economic development. • Assess current maintenance regime and legacies of past management (e.g. concrete-lining, rock armoring). • Assess community wants and needs with regards to functional, connected riverscapes. • Evaluate tenure, access, and land-use within riverscape and associated risks to life and property from fluvial hazards. • Evaluate local communities’ understanding of riverscape health and hazards.	• Understand and respond to current conditions and support future visions on a regional scale. • Consider regional strategic priorities for environmental protection and improvement that are supported by the broader community. • Identify education and outreach programs for unrecognized community relational values tied to the watershed.
Hydrologic process and hydraulic characteristics	• Evaluate the full spectrum of flows, including geomorphically-relevant discharges and base flows. • Identify discharge points into the reach as well as diversion structures. • Evaluate how alterations to the flow regime, resulting from development in the watershed, manifest at the reach scale. • Determine hydraulic characteristics for runoff events to establish depths, velocities, and shear stress, and evaluate associated impacts to reach morphology. • Determine if restoration or renovation strategies can affect quantity or quality of flows through the reach.	• Consider how high and low flows provide lateral connectivity with groundwater and floodplains. • Evaluate impacts of past and future hydrologic changes to the riverscape function (e.g. flood attenuation). • Determine areas of high and low flood and fluvial hazard and evaluate risks to ecological and hydromorphic floodplain function (e.g. loss of riparian vegetation to bank erosion, change in floodplain vegetation watering regime).	• Delineate the stream network and opportunities to preserve /recreate /mimic headwater streams. • Identify impacts to the stream network due to changes in hydrology resulting from urbanization. • Identify watershed-scale factors and management measures (regional detention, stream network, land use patterns, etc.) that influence the hydrologic regime. • Evaluate how existing and future flow storage/detention is distributed across the watershed. • Evaluate the energy spectrum (i.e. stream power/shear stress) along the stream network.
Geomorphic forms and processes	• Place reach-scale geomorphology in context of processes occurring in the riverscape and watershed. • Evaluate physical processes observed at the reach scale. • Determine sediment transport capacity of the flow regime to identify erosion/deposition hotspots. • Determine if the reach is stable or trending towards aggradation/ degradation and the factors that contribute to anticipated future changes • Evaluate in-channel geomorphic complexity and physical habitat. • Understand geomorphic hazards and determine whether instability may threaten infrastructure, property, or public safety.	• Place riverscape-scale geomorphology in context of processes occurring in the watershed to identify larger-scale/offsite drivers of change. • Determine locations where the channel’s ability to adjust (e.g. migrate laterally or recover from past incision) is limited through natural and/or anthropogenic constraints and areas where adjustment is incompatible with land use. • Evaluate the geomorphic function of the riverscape including space for channel adjustments and sediment supply. • Analyze geomorphic trajectory and the likely future responses given flow alteration and land use practices.	• Identify dominant land uses in the watershed to understand influences that shape the land and the stream network. • Determine areas within the watershed where the sediment supply/ transport regime is changing or is out of balance due to natural and/or anthropogenic stressors or anticipated future flow conditions. • Understand sediment continuity along the stream network, including significant sediment sources/sinks. • Place watershed-scale geomorphology in context of natural and anthropogenic constraints (climate, geology, urban infrastructure, etc.).

Stream Facet	SPATIAL SCALE		
	Reach	Riverscape	Watershed
Ecological structure and processes	• Understand the existing in-stream and bank vegetation communities and species. • Identify the hydrogeomorphic functions of vegetation (e.g. erosion resistance). • Evaluate the quantity and function of large wood. • Evaluate physical habitat in the context of necessary habitat types for significant species/communities and general habitat diversity.	• Understand the existing riverscape vegetation communities. • Determine network-scale impacts of vegetation on flood conveyance (both its potential detrimental impact on local flood risk and its value in attenuating floods downstream). • Understand the ecological resilience of the existing vegetation communities. • Identify areas of invasive, sparse, or stressed vegetation; investigate causes.	• Understand landscape-scale riparian vegetation communities and connectivity. • Determine existing or potential gaps in, or encroachments on, riparian vegetation. • Understand the wildlife corridors for iconic, endangered, and keystone species.

6.2 Urban riverscape indicators and targets

An effective assessment framework relies upon the process of selecting appropriate indicators for evaluation. Indicators are summary variables that provide a gauge or meter, and often they are indicative of a suite of more complicated, interactive processes, patterns, or conditions. Indicators are useful because they offer a simpler way to communicate and describe overall trends or levels. They also serve to foster an understanding of cause-and-response relationships at and between the various scales present in complex urban stream systems. In this way, indicators provide comprehensive baseline data from which to assess a stream's physical condition and its potential trajectories, and to develop a clear understanding of stressor-impairment (i.e., cause-effect) relationships. When evaluated collectively, indicators comprehensively describe stream condition by diagnosing the severity, extent, and causes of impairment. For urban riverscapes, indicators should be (i) sensitive to degradation due to urbanization, (ii) relevant to riverscape function, and (iii) applicable to management objectives and timeframes. While the specific indicators chosen for a given project will depend on the watershed and the riverscape geographic context (both human and physical), indicators should generally cover the four riverscape facets across a range of spatial scales, from sub-reach-scale up to and beyond the watershed scale (see examples in Figure 2.6). Almost innumerable indicators are possible to characterize a riverscape, and such indicators have been reviewed elsewhere (e.g., hydrological indices, Olden and Poff 2003; channel geomorphic indices, Vietz et al. 2014). Here we provide a few examples of the broad categories of indicators of each facet that may be covered by an urban riverscape assessment (Figure 2.6).

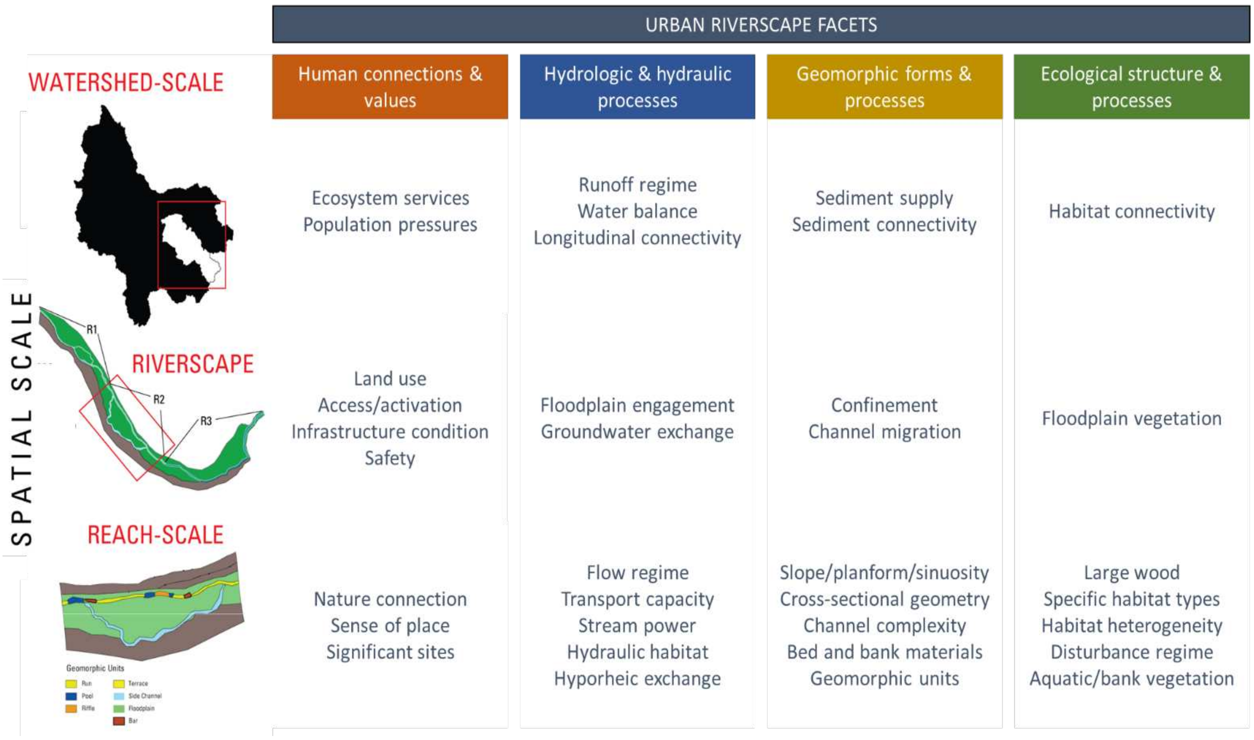

Figure 2.6 Possible indicators of urban riverscape function, at a range of spatial scales. Spatial scale diagrams adapted from Wheaton et al. (2019).

Once broad objectives (Tier 1) and indicators (Tier 3) have been defined, consideration should be given to appropriate targets which guide the ideal or desired value of riverscape indicators and thus the ideal or desired state of the riverscape. It can also be of interest to understand how a riverscape has altered from a pre-disturbed or least-disturbed 'reference' state. It is common for non-urban river assessments to adopt reference conditions as target conditions; however, the concept and application of reference conditions has been critiqued widely (Stoddard et al. 2006; Fryirs 2015; Poff 2018; Dufour and Piégay 2009). No stream can truly be considered undisturbed, and the process of stream degradation often creates constraints and circumstances that mean a return to reference conditions is not possible. Inappropriate or narrowly defined targets often lead to misdirected efforts (Hiers et al. 2016). Such issues are even more significant in urban riverscapes than their rural counterparts.

Many urban streams have been modified to such a degree that pre-development conditions no longer provide a realistic or meaningful benchmark for stream condition (Dufour and Piégay 2009; Erba et al. 2019). Rather, a best attainable condition (Stoddard et al. 2006) may be a more appropriate benchmark from which to assess riverscape condition in the context of current constraints. Moving beyond the simple consideration of benchmark conditions, it can be useful to use multiple, adaptive targets. The 'moving targets' approach (Brierley and Fryirs 2016) has great utility in urban riverscapes where natural or historic conditions are unlikely to be helpful indicators of current restoration potential, and where rapidly changing conditions and multiple management levers create a wide range of potential future trajectories.

Decisions about targets require both an appreciation of eco-hydromorphic science (to understand historic evolution and thresholds) and value judgments (to decide what is 'worth doing'). The latter creates an opportunity to involve community stakeholders in the technical domain, using social science and community engagement techniques to create a bridge between high-level community vision-setting endeavors (Tier 1) and detailed targets (Tier 3). In a degraded system, interventions which focus more on community benefits than stream health improvement may be preferable, for example pursuing stream renovation rather than restoration or rehabilitation (Smith et al. 2016).

7 Conclusions

Urban riverscapes are integral to the livability and sustainability of future cities and suburbs. To safeguard the social and ecological values of these riverscapes, appropriate planning and practices must recognize the physical form and functioning of the riverscape, and the relationship to catchment activities. Hydrogeomorphic assessments link hydrologic changes, and direct intervention in riverscapes, to the form and functioning that supports values. While there are many hydrogeomorphic assessment approaches, few integrate fully across the riverscape facets of human values, hydrology and hydraulics, geomorphology, and ecology, and at multiple scales. Even fewer consider the social-ecological complexities that are common in urban riverscapes.

The urban riverscape assessment framework provides watershed managers and practitioners working on urban riverscapes an inclusive framing of river system relationships that incorporates social, ecological, and hydrogeomorphic elements and processes. The framework integrates riverscape form and function with social values, facilitates the identification of target conditions, and assists in outlining desired trajectories, even for highly modified catchments.

While the framework contributes the key tenets, facets, objectives, and practices relevant to evaluating urban riverscapes, it will evolve over time as stream managers and practitioners apply the process across varied urban environs, with their unique socio-cultural and hydrogeomorphic contexts. The framework process will also advance over time, and the selection of indicators will develop, further supporting the integration of human values into urban riverscape assessments. The framework is intended to better support and guide planning and management of urban riverscapes, in order to improve the ecological health and livability of the communities worldwide that fundamentally rely on riverscapes.

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CHAPTER 3

An overview of stream assessment frameworks

1 Introduction

There is an increasing interest throughout the world in quantifying stream health through a variety of assessments and tools (Karr 1999, Finkbine 2000, Bledsoe 2012, Somerville 2010, Harman et al. 2012, Nadeau et al. 2018, Belletti et al. 2015, Fryirs 2015, Gurnell et al. 2020). Assessment types include, but are not limited to, biological, chemical, physical habitat, riparian habitat, morphological, and hydrologic assessments. Biological assessments (e.g. indices of the diversity and abundance of aquatic species) have been used in the United States since the 1970s to evaluate and characterize biologic integrity and stream health following the passage of the Clean Water Act (CWA), mirrored by advances in environmental law in other countries. More recently, multi-scale, hierarchical assessment approaches that support a better understanding of river systems have emerged, including several hydrogeomorphological assessment methods (Gurnell et al. 2020, Gurnell et al. 2016), which exhibit varying aims, scales, and approaches (Belletti et al. 2015, Fryirs 2015).

Two comprehensive reviews of the published literature on hydrogeomorphic assessment methods have been completed in the last decade. The first, by Somerville (2010), focused primarily on literature published in the United States, while the second, by Belletti et al. (2015), reviewed literature published throughout the world. The former reviewed 45 stream assessment and stream mitigation protocols to determine the degree to which they presented unique, comprehensive procedures to assess stream and riparian functions. The latter examined 121 articles that reported the approach of various assessment techniques. In only two of these articles did the methods focus on streams in the urban environment, and most techniques lacked a social-ecological assessment component which is critical for urban settings.

2 Literature review

In Table 3.1, we summarize the most relevant assessment methods and frameworks (i.e. those that focus on physical processes and multi-scale methods) and specifically focus on their potential applicability to streams in the urban environment. The range of application of the methods considered in this review varies from those applicable to small, ephemeral streams to those suited to moderately sized wadeable perennial streams. It is restricted, however, to physical-based assessments (i.e., methods that address all or some of the physical elements required for a hydrogeomorphological evaluation of urban riverscapes). Therefore, methods for the assessment of water quality, aquatic life, or biological function are generally not included. Our review also excludes physical habitat simulation models and environmental flows methods, as they differ in structure and approach from hydrogeomorphological assessments considered here.

Criteria for inclusion in this review included, but was not necessarily limited to, the following:

- Verifiable use of hydrogeomorphic assessment methods or procedures that have formed the basis for protocols that could be applied to urban riverscapes.
- Inclusion of multiple assessment attributes at varying scales as indicators of interlinked stream or riverscape functions.
- Emphasis on objective stream physical attributes based on desktop measurements and/or estimation in the field.
- Reliance upon, or inclusion of a hierarchical typology that requires assessment undertaken at watershed, riverscape, and stream-reach scale.
- Reference to or possible inclusion of urban riverscape social ecological characteristics, such as community values, ecosystem benefits and services, or stewardship.
- The methods and frameworks are generally in wide use and are peer-reviewed.

This summary is not a comprehensive review of every stream assessment approach, but rather a representative compilation that highlights the range of methods used across the scientific field, their commonalities, and differences. Nor is it a compilation and review of hydrogeomorphic assessment programs in use by governmental agencies as part of programs for regulatory purposes.

Table 3.1: Examples of stream assessment methods and frameworks and their application to urban streams and incorporation of social-ecological context. The methods are in chronological order.

Assessment Name	Purpose	Spatial scales	Data requirements	Process/form indicators	Social-ecological context	Applicable to urban streams	Source
River Styles Framework	A hierarchical, multi-scale classification scheme for describing river character and behavior.	Catchment, riverscape, reach, sub-reach	Field, remote-sensing and other GIS data on geology, hydrology, and stream geomorphic setting to identify broad-scale to local controls on river character and behavior.	Channel attributes (size, shape, bank morphology, etc.) channel planform (lateral stability, riparian vegetation), bed character (grain size, bed stability, sediment regime)	Not included	River Styles can be used to understand urban rivers condition, recovery potential and prioritize management but is not explicitly tied to urban riverscapes.	Brierley and Fryirs 2005
Urban River Survey	Semiquantitative indices and classifications as well as simple decision and scenario modelling system for the initial exploration of urban river habitat and rehabilitation potential that is appropriate for application to entire urban catchments	Applicable to reaches of urban river of approx. 500m length that are of a single engineering type (a combination of cross-profile type, planform type and level of reinforcement). The method allows a broad overview at the catchment scale.	Field, remote-sensing, and other GIS data	Synthetic indices derived from the urban river survey relating to three different sets of characteristics of urban river stretches: (A) 'Materials'; (B) 'Physical Habitat' and (C) 'Vegetation'	Not included	URS is concerned entirely with the quality, diversity and complexity of physical habitat within and between urban river stretches.	Boitsidis et al. 2006
Watershed Assessment of River Stability and Sediment Supply (WARSSS)	A three-level approach including reconnaissance, screening, and prediction. The WARSSS method leads to a prediction of channel changes due to aggradation, degradation, or bank erosion. It is designed to identify the location, nature, extent, and consequences of various past, existing, and proposed, land use impacts.	Assesses large watersheds with a rapid screening component	Measured bankfull sediment data, sediment delivery data, field observations, desktop analysis, modeling	WARSSS integrates hillslope, hydrologic, and channel processes. The model does not evaluate floodplain or biological processes.	Not included.	While not specifically developed for urban or urbanizing watersheds, WARSSS can be used to analyze known or suspected sediment problems, develop sediment remediation and management components of watershed plans, and develop sediment Total Maximum Daily Loads.	Rosgen 2007
Rivers as Ecosystems	A framework for the interdisciplinary study of river ecosystems with parallel hierarchies in the geomorphology, hydrology and ecology of a river with different organizational elements and levels of organization for each discipline.	Assigns spatial and temporal scales for each level of organization for the different discipline hierarchies to distinguished different frequencies of occurrence and/or rates of change; environmental flows should match the appropriate scales of physical and hydrological Processes	Hydrologic and hydraulic analyses, desktop analysis, remote sensing, hierarchical discrimination.	Ecological and physical (geomorphology and hydrology) processes that encompass the entire mosaic of patches relevant to the organism under consideration; environmental flow strategies, biological indicators	Not included.	Limited connection to urban rivers and streams although the physical and ecological hierarchies are applicable to streams in the urban environment.	Dollar et al. 2007

Assessment Name	Purpose	Spatial scales	Data requirements	Process/form indicators	Social-ecological context	Applicable to urban streams	Source
The Active River Area	The active river area (ARA) provides a spatially-explicit framework based on watershed position and key geomorphic components to provide a tool to inform conservation, restoration and management and to broaden work on river conservation.	Regional, watershed, multiple to single reach, local unit.	Remote-sensing and other GIS data, hydrologic and hydraulic models, desktop analysis.	Five primary components of the active river area: 1) material contribution areas; 2) meander belts; 3) floodplains; 4) terraces; and 5) riparian wetlands. These areas are defined primarily by the type and frequency of interaction with the river.	Protection, restoration, and management of ARA is undertaken to meet the needs of both people and nature. Range of important benefits to society include providing habitat values, the reduction of risk from flood and erosion hazards, water quality protection, and providing scenic and recreation amenities.	The ARA can be used to understand urban river function, conservation, restoration and management but is not explicitly tied to urban streams.	Smith et al. 2008
River Corridor Planning Guide	The Vermont, USA Agency of Natural prepared the River Corridor Planning Guide to identify underlying causes of channel instability and encourage a stream's return to equilibrium conditions. The Guide is also a tool to assemble and integrate information from assessments, planning efforts, and river corridor protection and restoration projects.	Watershed, river corridors, and reach-scale.	Previous river studies, physical data, watershed natural resource inventories, biological surveys, water quality monitoring data, windshield surveys, remote-sensing and other GIS data.	Applies Vermont Stream Geomorphic Assessment Phase 1 and Phase protocols, including land cover and reach hydrology, instream channel modifications, planform changes and floodplain modifications.	The goal of the Planning Guide is to resolve conflicts between human investments and river dynamics. Project development is broken down into technical and social components of project feasibility.	The Planning Guide can be used to study the effects of urbanization using multiple indicators such as altered hydrology, land use, and sediment loading.	Kline 2010
Level 1-2-3 Assessment Framework	A multi-tiered monitoring approach integrating various types of data collected at three intensities of monitoring effort in order to identify possible causal relationships affecting overall wetland condition and provide conclusions on how multiple tiers of monitoring data can be used to target and prioritize wetland management activities at the watershed-scale.	Watershed, river corridors, and reach-scale.	Remote-sensing and other GIS data, historical ecology, contemporary wetland mapping, rapid assessment, and site-specific monitoring.	Inventory of historical and contemporary wetlands; California Rapid Assessment Method for Wetlands (CRAM) for buffer and landscape context, hydrology, physical structure, and biotic structure; land develop intensity index (LDI), Level 3 monitoring included measures of water column chemistry, aquatic toxicity, the benthic macroinvertebrate community, and stream physical habitat.	Not included.	Provides a framework for resource managers need a means to integrate various types of spatial and temporal watershed data to make more informed management decisions A coordinated approach using standardized tools for data collection and information management can minimize the aggregate costs for multiple programs while improving public access to monitoring and assessment results that better reflect management priorities.	Solek et al. 2011

Assessment Name	Purpose	Spatial scales	Data requirements	Process/form indicators	Social-ecological context	Applicable to urban streams	Source
Ecological Performance Index	An analytical framework that improves understanding of the interrelationships among health indicators, among stressors, and between the two.	Catchment, local, reach scales, and stream network.	Data generated by fieldwork and GIS techniques.	Land use land cover stress indicators (population density, imperviousness, and tree cover metrics), stream health indicators (macroinvertebrates and water temperature signals).	Not included.	The method measures the ecological performance of urban stream sites in achieving maximum stream health given the constraints imposed by land-use stressors.	Millington et al. 2015
REFORM (Restoring rivers FOR effective catchment Management)	A process-based, multi-scale, hierarchical framework to support river managers in assessing the hydromorphological character of rivers, exploring the causes of hydromorphological problems, and devising sustainable management solutions. Includes Morphological Quality (MQI) and Morphological Dynamic Index (MDI).	The framework includes spatial units at region, catchment, landscape unit, segment, reach, geomorphic unit, hydraulic unit and river element scales.	Field, remote-sensing using historical aerial photographs, DEMs/LiDAR, and other GIS data on topography, aerial imagery, river networks and catchments, geology, land cover, soils, and groundwater resources to support delineation and characterization of spatial units.	Water production, runoff production/retention, sediment production, valley features, flow regime, sediment delivery, riparian corridor functions, wood delivery, stream power, constraints on channel adjustments, vegetation dynamics. MQI assesses the present geomorphological conditions of a stream reach and the deviation of such conditions from reference conditions. MDI is a methodological framework for hydromorphological assessment, analysis and monitoring to support the management of river processes.	REFORM includes a communication and dissemination strategy by holding interactive stakeholder workshops; interaction with the Advisory Board of REFORM whose members are part of the stakeholder community; and interaction with other ongoing activities with established relevant stakeholder networks.	Reflecting the long history of human interventions on European rivers, the framework incorporates human pressures as well as natural processes and forms at all included spatial scales and gives them equal weighting. Artificial elements along a reach such as embankments and levees are considered as part of several indicators. Specific urban stream indicators are not included in MQI or MDI.	Gurnell et al. 2016 Rinaldi et al. 2013; Rinaldi et al. 2015
Colorado Stream Health Assessment Framework (COSHAF)	A holistic health assessment tool and a hierarchical information framework for stream management and restoration planning.	Watershed, riparian corridor, stream reach.	Desktop analysis, rapid field assessment, and intensive field data collection.	Hydrology, sediment, chemistry, floodplain connection, riparian condition, organics, channel morphology, resilience, habitat structure, biota.	Social values and needs can be incorporated into COSHAF through stakeholder engagement as part of evaluating alternatives and adaptive management.	COSAF can be applied to understand urban river condition, alternatives, ecological outcomes and social outcomes but it is not explicitly tied to urban streams.	Johnson and Beardsley 2016
Urban channel adjustment and management	A geomorphological approach to evaluating urban channel adjustment and management using a channel classification.	Reach scale predominantly.	Field, remote-sensing, and other site-specific data.	Channel classification based on degree of modification and change based on seven categories, ranging from near natural (1) to those washes which have been completely enclosed (7), according to disturbance by direct effects of human activity, vegetation characteristics, adjustment to urban runoff by erosion and deposition, and appearance.	Not included.	Emphasizes assessment of urban channel adjustments and guided watershed management, to conduct geomorphological evaluations of urban channel systems.	Gregory and Chin 2018

Assessment Name	Purpose	Spatial scales	Data requirements	Process/form indicators	Social-ecological context	Applicable to urban streams	Source
Stream Function Assessment Method	The Stream functions Assessment Method (SFMA) is used for assessing the functions and values of wadable, non-tidal streams for the purposes of Oregon, USA. regulatory purposes related to Section 404 of the federal Clean Water Act.	Watershed and local (reach) scale.	Field observations, remote-sensing and other GIS data including NHD, land use, soils, etc.	SFAM includes a suite of function and value measures: 20 measures of function and 14 measures of value. Function group includes Hydrologic (Surface Water Storage Sub/Surface Transfer Flow. Variation). Geomorphic (Sediment Continuity Substrate Mobility), Biologic (Maintain Biodiversity Create and Maintain Habitat Sustain Trophic Structure), and Water Quality (Nutrient Cycling, Chemical Regulation, Thermal Regulation).	SFAM distinguishes between values and functions. Values (i.e. ecosystem services) are assessed separately from function, and are defined as the ecological and societal benefits that riverine systems provide such as water storage, biodiversity, nutrient cycling, and thermal and chemical regulation. Social connections to rivers and streams are not included.	Anthropogenic factors such as urbanization, flood control, and irrigation are considered through multiple functions such as surface water storage, nutrient cycling, and chemical regulation.	Nadeau et al. 2018
USIA (Urban Streamflow Impact Assessment)	USIA assesses the impacts of altered streamflows on social, ecological, and geomorphic values of streams in urban catchments.	Reach scale.	Hydrologic and hydraulic models, desktop analysis and literature review, field assessment.	Annual flow volume, duration of zero flow periods, baseflow index, frequency and duration of freshes, total duration of flows above channel erosion threshold, floodplain engagement flows.	USIA includes a social-ecological system framework proposed by (Tippler et al., 2016) to inform infrastructure planning and decision making.	USIA was specifically developed to assess the role of streamflow in degrading waterways in urban catchments.	Vietz et al. 2018
Stream Quality Index	The Stream Quality Index (SQI) assesses overall stream health using biological indicators and physical and chemical measures, combining the three indicators in a way that would preserve the types of information provided by each.	SQI recognizes large scale patterns in data from multiple indicators. It also supports exploration of the data at both regional and site scales, encouraging users to explore results in different spatial contexts.	SQI synthesizes large amounts of physical, chemical, and biological data such as water quality measures (TN, TP, conductivity) and physical habitat and IPI.	The indicators provide direct measures of aquatic life, while physical and chemical measures provide supporting information about the stressors that may affect aquatic life and supporting information about the stressors that may affect all three indicators.	Not included.	SQI assessment and results can be applied in urban channel with impacted biology.	Beck et al. 2019
Riverscapes Principles	Riverscapes represent an understanding of what constitutes healthy riverscapes to help define what restoration should be aiming for; articulate key aspects of healthy riverscapes that inform the low-tech process-based restoration approach.	Region, watershed (catchment), network, riverscape, reach, geomorphic unit. Follows River Styles (Brierly and Fryirs, 2005) methods for classifying and assessing river processes.	Field, remote-sensing and other GIS data on geology, hydrology, and stream geomorphic setting to identify broad-scale to local controls on river character and behavior.	Riverscape principles 1. Streams need space (floodplain connectivity) 2. Structure forces complexity and builds resilience (riparian condition, structure, complexity) 3. The importance of structure varies 4. Inefficient conveyance of water is healthy (flow regime).	Riverscapes can include a fifth principle to account for specific project objectives to be considered during the assessment; additional indicators may be warranted in the context of local existing conditions and/or for project-specific purposes.	Riverscapes can be used to understand urban river condition, recovery potential and prioritize management but it is not explicitly tied to urban riverscapes.	Wheaton et al. 2019

Assessment Name	Purpose	Spatial scales	Data requirements	Process/form indicators	Social-ecological context	Applicable to urban streams	Source
River condition assessment tool	The river condition assessment adopts a bottom-up multi-scale approach that integrates field observations of physical habitats and of features indicative of geomorphic processes to deliver assessments of longer subreaches, whose condition is then evaluated within the context of the reach-scale geomorphic type of river.	The assessment method designed to deliver one component of Biodiversity Metric 2.0 (BM2, Crosher et al., 2019) that includes three-tiered spatial assessment of river condition: "module" (river length approx. twice the river width); "subreach" (river length approx. 10 times the river width); and "reach" (river length typically >5 km).	Field (MoRPh module) surveys and a desk-based assessment of the indicative geomorphic type of the river reach containing the project site.	Each surveyed subreach is assessed using more than 30 condition indicators extracted from the field survey data, including riparian and aquatic vegetation structure and the variety and abundance of riparian and channel physical materials and features. An on-line information system supports input and storage of MoRPh survey data, calculation and mapping of indicators extracted from survey data.	BM2 "provides developers, planners, land managers and others with a tool to help limit damage to nature in the first place and to help it thrive. The metric uses habitat features as a proxy measure for capturing the value and importance of nature. Utilizes a field survey designed for application by trained citizen scientists.	The river condition assessment assesses the variety and abundance of human physical (direct) interventions and (indirect) pressures.	Gurnell et al. 2020
River Facets	Addresses the influence of the four river facets and their (inter-) dependence at various spatial scales and a nine-step checklist for managers to follow when holistically restoring rivers by taking into account how the facets interact at different spatial scales	Catchment, reach, sub-reach. Scales influence one another in different orders and directions depending on the prevailing processes resulting from the principal degradations.	Field, remote-sensing, and other GIS data	River processes, as defined by the four facets—hydrological, geomorphic, ecological, and biogeochemical processes in rivers.	Different scales of anthropogenic disturbance are accounted for when addressing the four facets.	Planners can use the four facets to demonstrate the effects of different types of anthropogenic pressures within non-negotiable constraints of land-ownership and infrastructure (e.g., urban areas) but it is not explicitly tied to urban riverscapes.	Polvi et al. 2020
Stream Quantification Tool/ Stream Functions Pyramid	Stream Quantification Tool (SQT) is a spreadsheet based tool designed to inform permitting and compensatory mitigation decisions related to Section 404 of the federal Clean Water Act. SQT leverages the stream functions pyramid, a five-level hierarchical framework that categorizes stream functions and parameters that describe those functions.	Watershed and reach scale (emphasis on reach scale)	Desktop analysis and literature review of databases, field data collection	The hierarchical levels in the framework include hydrology, hydraulics, geomorphology, physiochemical, and biology. Indicators include discharge, flood frequency, flow duration, floodplain connectivity, flow dynamics, sediment transport competency/transport, large wood transport and storage, channel evolution, bank migration, riparian vegetation, bed form diversity, bed material characterization, water quality, nutrients, biological communities	Not included	SQT is not appropriate for assessing more complex or dynamic stream systems accurately, especially streams in urban or highly altered riverscapes.	USACE 2021; Harman et al. 2012

3 Summary

Although the list of frameworks and methods presented in Table 3.1 is far from comprehensive, it illustrates that many types of data collection and evaluation approaches have been created to gain a conceptual or detailed understanding of stream conditions in a variety of settings. The analysis of stream assessment methods has built upon and extended existing reviews (Somerville 2010, Belletti et al. 2015, Fryirs 2015, Gurnell et al. 2016) providing the following new insights that are useful when applied to urban riverscapes.

1. Utilizing hydrogeomorphic methods of assessing stream condition can maximize the effectiveness of management and restoration actions when applied to urban streams. Particularly effective attempts at integrating hydrogeomorphic methods into common frameworks include the Stream Quantification Tool (SQT) and Stream Functions Assessment Method in the United States (Harman et al. 2012, Nadeau et al. 2018, respectively) and REstoring rivers FOR effective catchment Management (REFORM) framework (Gurnell et al. 2016). The hydrogeomorphic approach allows consideration of physical drivers and constraints and their interaction across multiple scales and can therefore aid design and delivery of sustainable river management solutions.
2. Most recent frameworks are quantitative, generating one or more indices or health scores for streams and/or watersheds (e.g., Vietz et al 2018; Harman et al. 2012; Beck et al. 2019; Kline 2010; Millington et al. 2015). Conversely, some frameworks are conceptual, providing a hierarchical way of thinking about or structuring assessment of stream systems, and interpreting their processes and function (e.g., Smith et al. 2008; Wheaton et al. 2019, Johnson and Beardsley 2016). However, some frameworks follow an intermediate course, generating relatively open-ended indices or classes that can be interpreted flexibly (e.g., Brierley and Fryirs 2005; Polvi et al. 2020).

3. Frameworks necessarily balance simplicity (i.e. ease of use) with complexity (i.e. ability to extract real-world insight) and such simplifications are honed for a particular purpose. For example, simple flow metrics such as channel forming discharges and peak flows which are useful in natural and rural settings (e.g. MQI; Rinaldi et al. 2015) may not adequately characterize the profound changes in flow regime in urban streams (Fletcher et al. 2014) or the potential flow regime manipulations that could be used as a restoration tool. In these cases, detailed flow regime assessment methods, which consider linkages between flows and their socio-ecological functions (sensu environmental flow methods; Acreman and Dunbar 2004; Poff et al. 2017) could be useful for urban stream assessment (e.g. USIA; Vietz et al. 2018).
4. The indicators and metrics of the frameworks reflect the data requirements as well as the spatial and temporal scales of assessment. Much of the data and information on urban streams is related to hydrological, biological, and chemical assessments and the associated effects of watershed urbanization such as changes to the hydrologic regime and degradation of water quality (Beck et al. 2019).
5. Most assessment frameworks lack an emphasis on evaluating historical data on stream evolutionary processes and drivers, which makes it difficult to establish a meaningful baseline for assessing stream change within a developing watershed (Norris and Thoms 1999; Solek et al. 2011). Understanding historical changes is particularly important to assessing stream condition because it helps to define the range of past conditions and can prevent imposing a form that climatic and geologic conditions do not support (Wohl and Merritts 2007).
6. Many of the assessment frameworks and methods include indicators of human pressures and their impacts (e.g., Smith et al. 2008; Kline 2010; Harman et al. 2012, Nadeau et al. 2018; Wheaton et al. 2019; Polvi et al. 2020), but few specifically consider social values or context. Two notable exceptions are USIA (Vietz et al. 2018) and REFORM (Gurnell et al. 2016). Both methods identified the human uses and values connected to riverscapes, the challenges in linking values to

ecological and physical conditions and addressed social aspects through an emphasis on stakeholder integration processes and structures.

Despite the prevalence of assessment methods and frameworks described in Table 3.1, few integrate fully across the riverscape facets of human values, hydrology and hydraulics, geomorphology, and ecology, and at multiple scales. Even fewer consider the social-ecological context that are common in urban riverscapes.

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CHAPTER 4

Assessing urban riverscapes: A multiscale approach designed for management application

Summary

Urban riverscapes are integral to the livability and sustainability of cities and suburbs. Conserving and restoring riverscapes requires assessing their condition over a broad range of spatial scales, including watershed, planning segments, and reaches. Assessments of hydrogeomorphic and ecological characteristics and behavior of riverscapes provide critical information about their physical condition and social-ecological values. The novel assessment method – Urban Riverscape conditions-Based Assessment for management Needs (URBAN) – provides a broad and moderate scale characterization of the physiographic and topographic setting and the anthropogenic impacts affecting functions and values that can inform restoration planning and riverscape management. URBAN is founded upon Tier 3 of the Urban Riverscapes Assessment Framework (see Chapter 2) – "How should we assess the values and functions of an urban riverscape?" Assessment of physical conditions and characteristics in urban riverscapes using the URBAN indicators and metrics provides critical information about the underlying watershed system status and stream evolution trajectory. URBAN includes both data collection and the evaluation of desktop and field data to determine the stream characteristics. Data collection emphasizes reach typing (or stream classification) and related or relevant aspects of stream physical condition. URBAN is unique in that it emphasizes stream values, which links the physical processes and social-ecological values to anthropogenic stressors that may influence the long-term recovery of degraded streams. These links also provide critical data for planning instruments, regulatory requirements, and community conversations. Coupled with GIS tools, urban riverscape studies at multiple-scales provide objective methods to understand and interpret multi-causal mechanisms and trends that influence the physical condition and potential recovery of degraded urban riverscapes. This chapter provides a

summary of those methods and the tools applied by way of remote and rapid field assessments through the lens of an evaluation of an urban watershed in the Colorado Front Range. The outcome of this study will advance the scientific basis underlying applied riverscape management and broad-scale preservation and renovation planning.

1 Introduction

The many social-ecological complexities of streams in an urban landscape—"urban riverscapes" (Chapter 2)—complicate their management, particularly when it comes to finding appropriate interventions to improve physical condition and ecological integrity, rather than considering water quality or river esthetic alone (Francis 2014). Further, although similarities among urban streams may be observed, each are unique (Gurnell et al. 2016), and the similarities among them tend to obscure meaningful differences between them (Booth et al. 2016) when it comes to management. As Vietz et al. (2016) point out, the phrase "urban stream" often conjures images of concrete-lined channels and culverts and fails to effectively recognize the gradient of urban riverscapes. Descriptions of urban riverscape characteristics that include engineering nature for anthropogenic benefits at the expense of physical and ecological processes have long been the guiding image for managers of urban streams (Murphy, in review).

The longitudinal nature of urban riverscapes provides an ideal corridor for human infrastructure, which might include floodplain hazard mitigation works (levees, dams, and reservoirs), streamside infrastructure (roads, trails, pipelines, and streambank protection), and stream crossing infrastructure (bridges, culverts, pipelines, grade control structures, and surface water diversion structures), among other built features (Sholtes et al. 2018). This infrastructure is critical to public safety and provides vital anthropogenic services, but it is often detrimental to stream systems; it can create hazardous conditions (e.g., levee breaching) and incur significant maintenance costs. When much of the existing infrastructure was built in the early- to mid-twentieth century, engineers generally prioritized stream hydrology and hydraulics, and designed hard engineering structures and protection measures with little understanding of fluvial processes and stream ecology. This approach, coupled with aging infrastructure, results in high maintenance costs and adverse ecological impacts. It can become a straitjacket on the river's physical and ecological processes. Thus, streams in the urban environment tend to be managed by external constraints and context, rather than a sought-after, long-term, ecological equilibrium, which often governs streams in less developed areas (Yli-Pelkonen et al. 2006; Wohl 2018). It is vital, therefore, to take these constraints and each unique context into account when assessing the physical condition of urban riverscapes.

In this chapter, I explain the operational approach to assessing the physical conditions and social-ecological values of urban riverscapes using a novel method, the Urban Riverscape conditions-Based Assessment for management Needs (URBAN). URBAN is founded on the interdisciplinary "solution space" framework defined in Chapter 1 and the Urban Riverscapes Assessment Framework outlined in Chapter 2. In particular, I expanded and tested Tier 3 of the Urban Riverscapes Assessment Framework – "How should I assess the values and functions of [an] urban riverscape?" based on four primary motivations that are supported by the review of assessment methods in Chapter 3. First, the paradigm shift in riverscape management (Brierley and Fryirs, 2022; Gurnell et al. 2016) highlights the need for advances in science-based assessment methods that evaluate both physical condition and social-ecological values. Second, urban riverscapes require that assessment methods consider scale (spatial, temporal, and topical) and context (physical and social characteristics). Third, establishing relationships between urban riverscape conditions and social-ecological values requires using indicators and metrics that directly support decision-making among interdisciplinary stakeholders. Finally, to integrate community values into urban riverscape assessments, managers require tools that evaluate condition, and its relationship to human activities, at varying scales.

Section 2 outlines the method itself in detail, describing the specifics of how I developed URBAN. And then, the method is applied to a test data set of publicly available and site-specific data across a study area in the Denver metropolitan region to illustrate its performance and how it can be used to evaluate riverscape physical conditions across varying scales (Section 3). Section 4 of this chapter discusses the potential future evolution and broader applications of the method, and section 5 offers brief concluding remarks.

2 Methods

2.1 Urban Riverscape conditions-Based Assessment for management Needs (URBAN)

URBAN is informed by many previous frameworks and methods, most notably the Restoring Rivers for Effective Catchment Management (REFORM; Gurnell et al. 2016), the Morphological Quality Index (MQI; Rinaldi et al. 2013), the Colorado Stream Health Assessment Framework (COSHAF; Johnson and Beardsley 2016), and the Urban Stream Impact Assessment (USIA; Vietz et al. 2018). Similar to those frameworks, URBAN leverages a multi-scale, science-based hierarchical framework that incorporates context and physical conditions (i.e., character and behavior) as well as the social-ecological values relevant to urban riverscapes, through the lens of the four facets of the Urban Riverscapes Assessment Framework – community values, hydrologic processes and hydraulic characteristics, geomorphic forms and processes, and ecological structure and processes. [1] The four facets support improved understanding of the structural and functional changes caused by established urban and urbanizing watersheds, a knowledge base that is necessary to move beyond the common management philosophy of imposing channel form toward one that seeks to preserve natural watershed and streams processes, where possible (Wohl et al. 2015).

URBAN follows a top down (region, watershed, and valley-scale controls) perspective rather than a bottom-up approach (geomorphic units as building blocks) so analyses are ‘nested’ across a range of spatial scales relevant to regional contextual attributes, watershed characterization, riverscape broad-scale assessments, and reach-scale rapid assessments. This stratification provides the foundational framework for assessing the physical condition and social-ecological qualities based on variations in the dominant landforms, geomorphic processes, and community values that shape urban riverscapes. The assessment,

[1] See Chapter 3 for additional information on the four facets.

therefore, reveals a combination of facets across multiple scales in need of consideration in order to protect or improve riverscape condition.

URBAN is organized into three steps (Figure 4.1): 1) characterization, 2) assessment, and 3) management. The initial step relies on a multi-scale delineation and characterization of the riverscape in its current condition at the regional and watershed scale, focusing on watershed processes, stressors, and land use modifications. This requires developing an understanding of the physical and social context of the study area and uncovering stressors, historical changes (natural or anthropogenic), and possible thresholds at which point the onset of riverscape degradation or vegetation loss occurred.

Step 2 involves the assessment of current conditions at the riverscape and reach scales, which requires defining indicators and metrics. The suite of chosen indicators and metrics describes the physical conditions and social-ecological values across the study area, as well as upstream and downstream, through desktop and field analyses. Step 2 also includes identifying functional characteristics and qualities for each metric as well as scoring guidelines. Scores will either be based on discrete criteria or on expert opinion, calibrated by scoring guidelines, and supported by the best available evidence, including professional judgment. Implementing URBAN requires investigators to apply the indicators, metrics, and scoring guidelines across riverscapes and reaches. Grouping the metric scores for the indicators under each facet provides a diagnostic tool that synthesizes the physical conditions and social-ecological qualities. These data are interpreted geospatially such that the condition of each facet can be mapped across the study area to compare different riverscapes and reaches. The reach-scale assessment provides more detailed, stand-alone scores that support design and implementation projects.

The final step is synthesizing the scores and linking them to stressors that overwhelm the functional conditions of the four facets. Managers interpret those results to identify management strategies that support decision-making efforts. For example, do reaches show moderate geomorphic function as a result of downcutting, or good lateral migration as a result of very limited channel reinforcement and a wide erodible corridor? In combination, such conclusions can lead to problem identification and an understanding of the possible management scenarios.

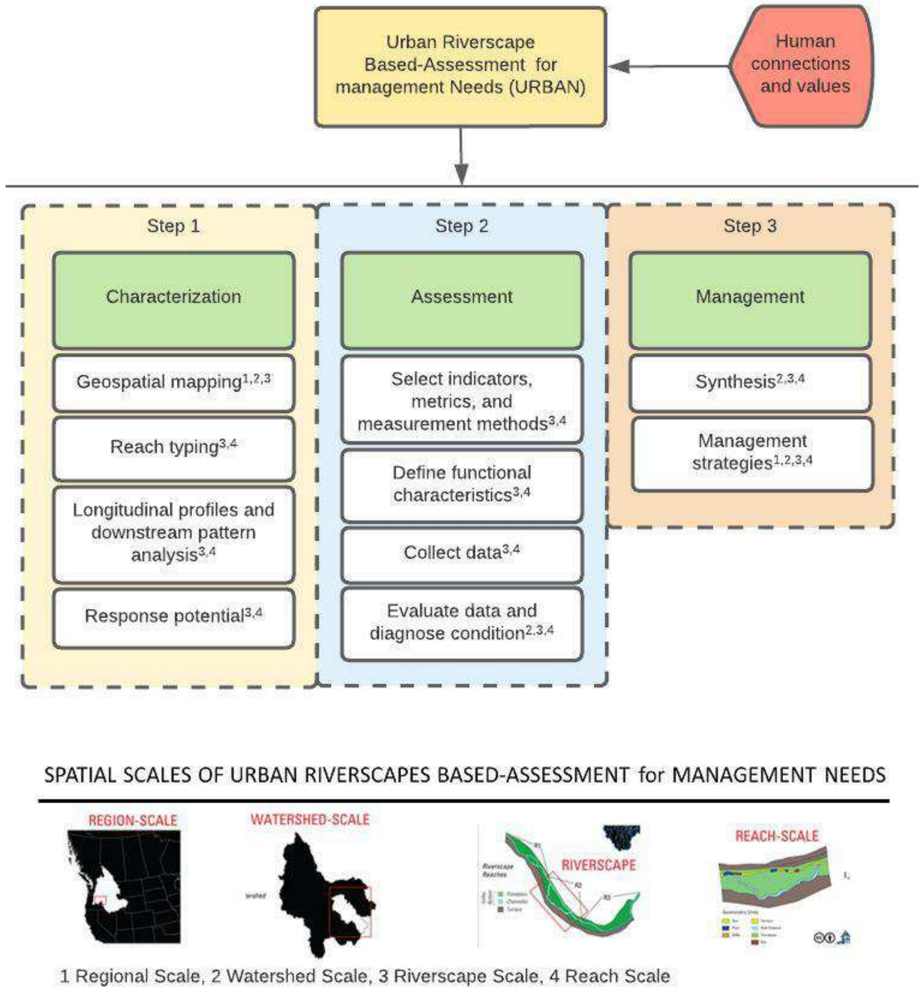

Figure 4.1: Flow chart of the three steps of URBAN, and accompanying scales at which analysis is undertaken. Superscripts note the hierarchical scale at which the activity under each step is performed.

2.2 Characterization

The characterization of the watershed, riverscape, or reach in its current condition should focus on physical processes, causes of degradation (i.e., stressors), and community values. The regional-scale contextual attributes provide a basin-scale characterization of the dominant physiographic (i.e., geologic, topographic, and climatic) conditions that influence stream type, hydrology, physical and ecological processes, and other factors that drive the characteristics of a watershed and riverscape. Geology, ecology, and hydrology determine an area's physiographic setting and drive physical processes that shape and influence landscapes and riverscapes.

Studying riverscape processes, behavior, and patterns at the watershed scale requires characterizing physiographic, hypsometric, geomorphic, vegetation, and social-ecological data (O'Brien et al. 2017). The watershed characterization, therefore, considers the flow, sediment, and vegetation connectivity and anthropogenic stressors (human activity, land-use intensity, and water infrastructure) that affect physical functions. The riverscape, broad-scale assessments provide an overall evaluation of physical conditions leveraging reach typology to evaluate downstream patterns, response potential, and evolutionary trajectory. The reach-scale assessment considers the adjacent context, such as neighborhood values, aesthetic and experiential characteristics, and historical management practices, as well as geomorphic hazards (e.g., bank erosion, avulsion) to determine whether instability may threaten infrastructure, property, or public safety.

2.2.1 Geospatial mapping

URBAN relies on a geospatial mapping of the area of interest (AOI) and establishing the watershed and associated riverscapes context leveraging publicly available data. Herein, I refer to a riverscape as a river corridor, typically comprised of one or more reaches, with channel, hillslopes, floodplain, and social–ecological processes that are complex, dynamic, and interactive (see Chapter 2). This definition is modeled after Ward's (1998) original concept of a riverscape as a holistic perspective of the broadscale patterns and processes associated with fluvial systems. Each riverscape is therefore a product of a suite of processes that operates across various spatio-temporal scales (Brierly and Fryirs 2022). Similar to Wohl (2018), I define a reach as a length of riverscape with consistent valley setting, channel geometry, and geomorphic units. A "reach" is also the scale at which humans view and interact with a stream, such that management and restoration work typically occur at this scale (Grabowski et al. 2014). I occasionally use the terms riverscape and reach interchangeably when a reach and riverscape are similar in length and physical and social-ecological characteristics and/or conditions.

Describing the extent of the area under review requires developing an understanding of the physical and social context of the study area. Central to geospatial mapping is the regional and watershed context, including its ecoregions, climate, hydrology, and geology, as well as its stressors such land use changes and infrastructure encroachment. Many readily available geospatial datasets will cover the full geographical extent of an urban riverscape. For example, the United States Geological Survey (USGS), U.S. Environmental Protection Agency (USEPA), and other regional agencies provide access to various public databases and data sources (digital datasets such as stream networks, digital elevation models, and LiDAR coverage), resource maps and GIS databases (i.e., for ecoregions, geology, soils, and vegetation), and flood history records and gauge station data. A desktop analysis leverages this historical information, the publicly available geospatial datasets, and curated data from GIS tools to identify and map contextual elements such as physiographic setting and social-ecological values, in addition to anthropogenic stressors. The datasets can also be utilized within a suite of remote assessment tools, over a range of scales, to allow for the selection of riverscape indicators and metrics.

It may be the case for a given riverscape that data relating to the impacts on processes or vegetation communities is sparse or absent. When this is the case, stressors or regional factors known to be critical to the viability of processes and vegetation communities in like environments may be used as surrogates to extrapolate predicted impacts on identified stream values. An example of this may be the use of geology and topography to inform the functional characteristics associated with a stream of a specific valley confinement type, or using vegetation type to identify communities that are most susceptible to climate change in order to deduce potential outcomes for management scenarios.

2.2.2 Context

Context includes the spatial and temporal dimensions of the “frequency and duration of specific processes” influencing the stream (Wohl 2018 p. 842), as well as the social-ecological values that drive management and maintenance decisions (Chapter 2). These physical and social characteristics interact to create a context that governs the process of defining a problem statement and identifying solutions. In short, context underpins any assessment of urban riverscapes.

While the context for every project will be different, every project has a context (see Table 4.1). Some aspects of the context might be viewed positively by one stakeholder group and negatively by another. For example, a concrete channel might be advantageous to a homeowner adjacent to a stream but seen as destructive by a local watershed group. Thus, descriptions of the context should use objective, value-neutral language to reflect the perspectives of all stakeholders without judgment (FHWA 2007).

Table 4.1: Examples of context and types of inventories to define the project area's context

Context examples	**Type of inventory**
The area's natural environment	• Physiographic setting, topographic features, • Does the project area include natural features such as a park, an open space, or a riparian area? • Is there a connection to the stream for fishing, walking, or boating? • What are the land uses in the area?
The area's social environment	• How do stakeholders perceive the community and its strengths and weaknesses? • Are there major gathering places in the project area? • What are the area's demographics? • Are there elderly, low-income, or minority communities in the area?
The area's cultural characteristics	• What aspects of the community are important to stakeholders? • What significant features define the community?

** Adapted from FHWA (2007) Context Sensitive Solutions (CSS)

Physiographic setting

Within URBAN, context refers to the physiographic setting of the watershed, riverscape, and/or reach. Geology, ecology, and hydrology define an area's physiographic setting and drive physical processes that shape and influence watersheds and riverscapes. The geologic context influences a suite of variables that drive the geomorphic responses of riverscapes, including sediment supply, valley setting, the erodibility of the channel bed and valley margins, vegetation, and hydrology (Brierley and Fryirs 2005). Variability in the erosional resistance of various rock units can significantly constrain the formation and evolution of riverscapes, with stronger rocks forming peaks, ridges, and canyons, and weaker rocks underlying the broad wide valleys and intermontane basins (Alba et al. 2022). For example, unconsolidated Pleistocene, Quaternary, and Anthropocene surficial material that deposits within valley bottoms and on low to moderate gradient hillslopes by alluvial, landslide, and glacial processes often form the foundation of the floodplain and riparian corridor.

The ecological context refers to a series of nested environments, with each level of contextual influence embedded within a larger level (Steinberg 2001). URBAN leverages ecoregions to describe these nested environments. An ecoregion is an attempt to characterize a region based on physical characteristics (Chapman et al. 2006) that are similar in type, quality, and quantity. Level III and Level IV ecoregions provide broad-scale information on the endemic and introduced vegetation, which is pertinent context for the assessment and management of urban riverscapes. Ecoregions are also effective for integrating watershed and riverscape management activities as another line of evidence for conservation or restoration. However, as urbanization changes land uses "there is a continuum of human uses and influences in all of the ecoregions" (Omernik and Griffith 2014, p. 1256). This means that urban riverscapes are a tapestry of ecological context and anthropogenic stressors. Understanding both is foundational to assessing physical conditions and social-ecological qualities.

The climate of a watershed influences the hydrology of a riverscape. Contextualizing both climate and hydrology provides important characteristics regarding the source and pattern of flows within the watershed or riverscape. For example, the predominant hydrologic regime – whether that is groundwater-dominated, snow and rain mix, snow with rain, or snowmelt-dominated – provides watershed-scale hydrologic context and underpins physical processes that influence riverscape character and behavior. Anthropogenic drivers such as increases in stormwater runoff from development also influence a riverscape's hydrology, often leading to erosion, incision, and channel widening (Vietz et al. 2016) while reductions in flow due to abstractions or impoundments from water infrastructure typically results in a stream that is narrow upstream of the infrastructure and overwide downstream. These hydrologic and geomorphic changes influence ecological patterns and structure as well as recreation and placemaking opportunities.

Social-ecological values

As discussed in Chapter 1 and Chapter 2, social-ecological values are paramount to understanding stream conditions and they often drive decision-making. URBAN leverages publicly available data on ecosystem services, the social vulnerability index (Cutter et al 2003), and access to nature (TPL 2017) to collectively underpin a values-based management paradigm. The assumption driving this particular aspect of URBAN is that functional degradation brings about a corresponding reduction in access to nature and ecosystem goods and services, and it increases social vulnerability hazards.

Natural capital assessment is the valuing of ecosystem services and natural assets. A natural capital assessment analyzes datasets ranging from forest resources, wildlife habitat types, agricultural production, parks and open space locations, and stream health to inform and shape urban riverscape management decisions. For example, overlaying available data on park and open space locations, stream health, and environmental quality can help decision-makers consciously address competition between short- and longer-term riverscape management by considering social, economic, and environmental concerns (Benami and Wilkinson 2013). URBAN leverages publicly available ecosystem services resource assessment and project outputs, such as natural capital asset maps and ecosystem services valuation (ESV; Ecosystem Sciences Foundation 2017), to reflect the value of the riverscapes and prioritize management decisions.

Social vulnerability is the susceptibility of social groups to the adverse impacts of natural hazards. Social vulnerability considers the social, economic, demographic, and housing characteristics of a community that influence its ability to prepare for, respond to, cope with, recover from, and adapt to environmental hazards (FEMA 2022). The Social Vulnerability Index (SoVI®) is a nationally adopted statistical methodology (Cutter et al 2003) for evaluating demographic variables to create a social vulnerability score at a defined geographic level that is comparative, for example across neighborhood boundaries (Michael Baker International 2021). FEMA adopted the official SoVI methodology to enhance their National Risk Index. URBAN incorporates SoVI data to prioritize riverscape assessment and management for communities with reduced ability to prepare for, respond to, and recover from natural hazards, in particular floods.

Access to green spaces, natural areas, parks, trails, and waterways is highly-valued in many urban communities because nature has benefits for both physical and psychological human well-being (Schertz and Berman 2019). URBAN emphasizes this contextual element by considering three characteristics: 1) park and open space availability, 2) natural space opportunities, 3) and universal access. Gaps in park and open space availability considers the equity of services and experiences associated with a riverscape. Are there trails, for example, and other means of accessing natural spaces reasonably spaced along the riverscape, and if not, what gaps can be identified across the landscape? Determining natural space opportunities is a desktop mapping exercise to locate proposed parks and open spaces, vacant lands, natural land cover, and riparian corridor in an effort to cultivate and integrate them amongst development. Universal access measures the composition of a watershed or riverscape to understand how it can be accessed, understood, and used to the greatest extent possible by all people regardless of their age, size, or ability (TPL 2017).

2.2.3 Stressors

Current and historical anthropogenic impacts, or stressors, also provide context. It is important to contextualize a condition in terms of anthropogenic features and impacts. It is easy to assume that mapping and quantifying anthropogenic impacts like land use, infrastructure, water extractions, pollution, and/or climate change should simply relate linearly to condition (i.e., the greater the degree of anthropogenic modification, the worse the condition). However, this assumption is too simplistic; the significance of these impacts varies depending on the sensitivity of the riverscape. So, the magnitude of anthropogenic impact also depends on its context, for example, the condition's sensitivity to anthropogenic disturbance. On the contrary, the riverscape's ability to accommodate and recover from disturbance events reflects its resilience, the inverse of sensitivity (Silverman et al. 2019).

Stressors are historical or present-day human activities that impact stream health and contribute to impairment. Stressors and the associated limiting factors are a potential barrier to preserving a riverscape's condition or to its recovery potential. Limiting factors include the impacts of broader stressors, such as climate warming, land development, agricultural operations, water diversions, and road building and maintenance. These stressors influence the condition of reaches throughout a watershed. Recovery potential is determined by assessing the stressors and limiting factors in the watershed along with a riverscape's position in the watershed and its context.

While it is understood that adjustments in stream function arise from the influence of numerous stressors, operating at multiple spatial and temporal scales, causal understanding requires knowledge of a suite of drivers for change rather than a focus on a single causal influence, whether natural or human in origin (Fitzpatrick and Knox 2000). Given similar stressors or limiting factors, disparate evolutionary trajectories may be observed in different reaches as a consequence of distinct characteristics and processes (Brierley and Fryirs 2005; Wheaton and O'Brien 2014). Thus, URBAN emphasizes identifying and measuring stressors across broad spatial extents (e.g., region, watershed, or network scales) and using that information in the evaluation of physical condition at individual riverscape or reach scales. These stressors are described in the section below.

Land-Use Intensity

Measures of land-use intensity recognize the spectrum that ranges from a natural, intact landscape to a landscape that has been highly or entirely altered by anthropogenic disturbance. URBAN leverages the land development intensity (LDI) index (Brown and Vivas 2005) to quantify spatiotemporal changes to land use. The LDI index is a land use-based index of potential human disturbance. It is spatially calculated based on coefficients applied to various land use types within watersheds. Land uses within an area of interest were assigned an LDI coefficient from Table 4.2, and then an overall LDI ranking was calculated as an area weighted average. Using GIS, the total area and percent of total area occupied by each of the land uses is determined, and then the LDI is calculated as follows:

$$LDI_{total} = \Sigma \%LU_i \text{ x } LDI_i$$

where,

LDI_{total} = LDI ranking for landscape unit

$\%LU_i$ = percent of the total area of interest in land use i

LDI_i = landscape develop intensity coefficient for land use i

Table 4.2 Land use classification and LDI coefficients

NLCD land use classification	USGS land use classification	LDI land use classification	LDI coefficients
Open Water	Water	Natural open water	1.00
Woody Wetlands	Vegetation, Natural	Natural system	1.00
Shrub/Scrub	Vegetation, Natural	Natural system	1.00
Deciduous Forest	Vegetation, Natural	Natural system	1.00
Evergreen Forest	Vegetation, Natural	Natural system	1.00
Mixed Forest	Vegetation, Natural	Natural system	1.00
Herbaceous	Vegetation, Natural	Natural system	1.00
Grassland	Vegetation, Natural	Natural system	1.00
Emergent Herbaceous Wetland	Vegetation, Natural	Natural system	1.00
Barren Land	Bare, Natural	Natural system	1.00
Barren Land	Bare, Transitional		1.83
Developed, Open Space	Vegetation, Natural	Recreational/open space – low intensity	1.83
Pasture/Hay	Agriculture	Improved pasture – high-intensity (with livestock)	3.74
Cultivated Crops	Agriculture	Row crops	4.54
Developed, Low Intensity	Residential	Single family residential – low density	6.90
Developed, Medium Intensity	Residential	Single family residential – high density	7.55
N/A	Mining and other Extraction	Industrial	8.32
Developed, High Intensity	Urban and other Developed	High-intensity commercial	9.18

These data are then grouped into five general LDI index classifications for assessment at watershed scale: natural (< 1.2), minimal disturbance (1.2 – 1.83), light disturbance (1.83 – 4.5), heavy disturbance (4.5 – 7), and developed (> 7).

Proximity to and Presence of Water and Transportation Infrastructure

Water infrastructure has the potential to have significant impacts on a stream network by modifying flows, realigning or “pinning in” the channel, or altering hydrology, sediment transport, and water quality. Transportation networks also present a significant detriment to riverscape condition by fragmenting floodplains and creating barriers to channel and floodplain continuity. While a wide range of water infrastructure types exist, URBAN focuses on in-river diversion structures and transportation networks because they provide a consistent and readily measurable feature known to result in impairments to riverscape processes. Although the impact of water diversion structures, road crossings, or other infrastructure can vary widely (both spatially and temporally), and not every diversion or road crossing was created equal, assessing the number and density of diversions and road crossings along a riverscape or reach acts as a proxy measure of their potential cumulative impact on physical processes, such as sediment continuity and riparian vegetation structure (Hupp and Osterkamp 1996). This requires the use of geospatial data on diversion structure locations, roadway networks, and other infrastructure to determine the potential cumulative impact on sediment continuity and instream flows.

2.2.4 Reach typologies

An understanding of the broad geomorphic type of a given riverscape is useful for defining the changes that the riverscape exhibits in its urban environment, or may display due to urbanization. Thus, a motivation for conducting a reach typology exercise is its utility for informing watershed-scale studies of urban environments with a focus on hydrologic modifications that affect geomorphic and vegetation processes (Polvi et al. 2011; Reid et al. 2008). The relationship of reach types to urban riverscapes is based on multi-scalar, hierarchical approach to regional and watershed characteristics. This provides insight into physical conditions that may be directly impacted by anthropogenic stressors to the stream network (O'Brien et al. 2017; Reid et al 2008). Reach typology is a way to account for the effects of these natural and anthropogenic induced variations in riverscapes. The exercise of assigning reach types creates a picture of riverscape character (its geomorphic attributes) and behavior (the range or capacity for adjustments given boundary conditions) for each one (Fryirs 2015). Accurately classifying a riverscape via reach typology in an AOI is important for assessing the current condition of that particular riverscape. Additionally, understanding the reach type dissuades scientists and managers from comparing reaches that are not geomorphologically similar (Brierely and Fryirs 2022).

Step 1 to assigning reach typology includes conducting a hierarchical assessment following a modified River Style® (Brierley and Fryirs 2005) approach in order to characterize an AOI. Reach types are identified by the spatial extent of the valley-bottom (i.e., valley confinement), and longitudinally based on geologic controls, variations in ecoregion and vegetation, and similarities or differences in geomorphic characteristics and drainage network patterns such as stream order. URBAN emphasizes evaluating geology and topography to inform the physical characteristics associated with a riverscape of a specific valley confinement type (confined, partly confined, or laterally unconfined). The degree of valley confinement controls the ability of a channel to adjust laterally and, to some extent, vertically on the valley floor. Measures of confinement are used to differentiate valley settings (Brierley & Fryirs 2005; Fryirs et al. 2016). Less than 10% of the channel abuts confining margins in a "laterally unconfined" valley setting, while greater than 90% of the channel abuts confining margins in a "confined valley" setting. A "partially confined" valley setting is when between 10% and 90% of the channel abuts the confining margins (Fryirs et al. 2016).

The other features used in reach typing included planform, floodplain features, bed material, and urban riverscape functional characteristics. These functional characteristics follow the urban channel types developed by Gregory and Chin (2018). I included the characteristics in the reach typing process because urban riverscapes manifest unique functions (Table 4.3) that are not part of the standard River Styles® approach. The functional characteristics are also useful for deciding management strategies (see Section 2.4). This approach is different than previous studies that did not consider anthropogenic elements or urban riverscape characteristics in the decision tree (Brierly and Fryirs 2022; O'Brien et al. 2017; Reid et al. 2008).

Table 4.3 Urban riverscape characteristics and the associated management strategies

Urban riverscape naming conventions	**Characteristics**	**Management strategy**
Near Natural	No clear evidence of channel change so that bed and banks appear stable, appropriate geomorphic units, and natural interaction of channel and floodplain. Vegetation is appropriate for the ecoregion.	**Conservation reach**
Adjusting but could recover naturally	Signs of an adjusting channel, which could be due to increased runoff from impervious urban areas, include bank erosion (possibly on both sides), undercut trees, channel widening or deepening, silting in channel, sediment accretion above crossings, or buried structures. No culverts or crossing structures. Vegetation is appropriate for the ecoregion.	**Strategic reach** or connected reach with high recovery potential
Adjusting – unable to recover naturally	Clear signs of channel change often by enlargement, undercut or collapsed banks, active erosion in channel, and scour at instream structures. Channel cannot recover without human intervention (e.g., bank stabilization, grade control). Vegetation has been altered in composition and active maintenance is required.	**Strategic reach** or connected reach with high recovery potential
Channelized – channel altered	Shape of channel has been altered by natural processes or anthropogenic means, channel has been straightened, some or all vegetation removed, and storm drains in banks. Vegetation has been altered in composition and active maintenance is required.	Moderate recovery potential or isolated reach with high recovery potential- **moderate priority**
Channelized – channel partially engineered	One bank or part of both banks modified or stabilized with riprap or concrete, altered bed forms due to grade control structures, crossing structures are prevalent, and vegetation significantly changed.	Moderate recovery potential-**moderate priority**
Channelized – channel completely engineered	Riprap or concrete on both banks, artificial channel bed. Significant stormwater runoff discharges into channel. No connection to floodplain and denuded of natural vegetation. Moderate maintenance is required.	Poor recovery potential- **low priority**
Channelized - enclosed	Channel completely enclosed in a culvert or underground structure. No indication of channel and floodplain.	Poor recovery potential- **low priority**

* Modified from Gregory and Chin (2018)

Section 3 offers several reach-typing example trees for the Cherry Creek Watershed streams, in confined, partly confined, and laterally unconfined valley settings. The trees document the key attributes of these reach types, ordered in a hierarchical fashion.

2.2.5 Longitudinal profiles and downstream pattern analysis

Longitudinal profile plots provide a key tool for understanding and interpreting the downstream patterns of riverscapes in each watershed, as well as the controls that govern their form and function (O’Brien et al. 2017). Controls on the longitudinal profile of a stream are dominated by the strength of the geologic units over which the stream flows, the relief, and the slope of the channel (Pederson and Tressler 2012). This data display allows for efficient analysis of downstream variations in types of riverscapes and sediment process zones, the upstream watershed area, the slope, and unit stream power, and the relationship of each to valley setting and reach types (see example in Section 3 for the Cherry Creek mainstem). Unit stream power, the measured value of work being done on the bed and banks of the channel by the flowing stream per unit width (Yochum et al. 2017), drives changes in channel gradient and discharge, which relates to the upstream drainage area.

Recognition of downstream patterns of reach types in any individual riverscape forms the basis for analyzing conditions operating in separate sub-watersheds, and for understanding the physical controls governing those patterns (Brierley and Fryirs 2022). Further, combining patterns of ecoregions, lithology, unit stream power, and drainage basin area define riverscape character and behavior (Brierley and Fryirs 2005). These parameters converge in patterns throughout the watershed and are the basis for defining river styles on the reach scale. Valley setting, channel slope, and lithology are imposed boundary conditions, parameters that are effectively set on millennial timescales, whereas flux boundary conditions indicate the limits of a river's natural capacity for adjustment in terms of its planform, sediment caliber, and the configuration of its geomorphic units.

2.2.6 Response potential

Riverscape or stream response potential (National Academies of Sciences, Engineering, and Medicine 2017) is the range of channel and floodplain changes that are possible given current flow and sediment inputs to a system. The response potential of a stream or riverscape is the gauge of sensitivity to local and system-wide disturbances in the watershed. Stream response potential also relate directly to the risk characteristics and management needs. Reach types possessing low response potential are resistant to natural or anthropogenic disturbances, whereas those with significant response potential are susceptible to the effects of disturbances (Table 4.4). For example, confined riverscapes tend to have low capacity for adjustment because they flow within narrow bedrock walls and possess very limited or absent floodplains, whereas laterally unconfined and partly-confined reach types have moderate to high adjustment potential because their broad, fine-grained floodplains promote dynamically shifting, meandering planforms (Khan and Fryirs 2020; O'Brien and Wheaton 2014). URBAN considers these sensitivity characteristics by evaluating the risks associated with degradation or adverse impacts on the community's connections and values to riverscapes (Table 4.4).

Table 4.4 Characteristics associated with risk of degradation and response potential due to anthropogenic changes and socio-political factors (after Bledsoe 2007) evaluated at the riverscape or reach scale.

Facet	Metric	High-risk characteristics	Low-risk characteristics
Human connections and values	**Access to nature**	• Large gaps in access to natural spaces from adjacent neighborhood • Low to no opportunities within the watershed to provide access to natural spaces	• No gaps in access to natural spaces from adjacent neighborhood • Significant opportunities within the watershed to provide access to natural spaces
	Ecosystem services	• Watershed offers little to no equitable levels of service or experience	• Watershed offers equitable levels of service and experience
	Social vulnerability index (SOVI)	• Numerous demographic metrics affect a community's ability to prepare for, respond to, cope with, recover from, and adapt to environmental hazards	• Minimal demographic metrics affect a community's ability to prepare for, respond to, cope with, recover from, and adapt to environmental hazards
Hydrologic processes and Hydraulic characteristics	**Flow regime**	• Flashy flows	• Flow regime results in gradual bank wetting and drawdown
	Flood and fluvial hazards	• Significant presence of structures within active stream corridor extent	• Absence or negligible presence of structures within maximum potential accessible floodplain extent or 500-year floodplain.
Geomorphic forms and processes	**Sediment Supply/Transport**	• Capacity limited	• Supply limited
	Confinement	• Near an energy threshold associated with initiation of incision • Entrenched channel – minimum floodplain energy dissipation • Floodplain susceptible to chute cutoffs and avulsions	• Channel well-connected to floodplain that resists chute cutoffs and avulsions • Floodplain provides substantial overbank energy dissipation at $Q > Q_{1.5}$
	Bed and bank materials	• Little or no grade control (geologic, wood, or artificial) • Non-cohesive, fine grained, sparsely vegetated banks	• Grade control sufficient to check incision (geologic, wood, or artificial) • Coarse bed material with potential for armoring
	Slope/planform	• High specific stream power • Near an energy threshold associated with abrupt changes in planform	• Low specific stream power • Energy levels not proximal to geomorphic threshold
	Cross-sectional geometry	• Trapezoidal channel with steep bank angles	• Multi-stage channel with shallow bank angles
Ecological structure and processes	**Riparian vegetation**	• Low density of vegetation root volume in banks • Low roughness	• High vegetation root volume density in banks or cohesive/consolidated bank sediments • Instream form roughness and vegetation roughness on banks • Channel well-connected with rough riparian zone
	Large wood	• Increased woody debris input may destabilize banks and/or enhance vertical stability	• Small ratio of woody material size to channel width

2.3 Assessment

The assessment step involves identifying appropriate metrics and defining the functional characteristics associated with each indicator. Desktop and field techniques are used to collect and evaluate data that provide the basis for interpreting and diagnosing the condition of each facet.

2.3.1 Indicators and metrics

Riverscapes encompass countless functions that can be measured, mapped, or estimated (Alba Watershed Consulting 2022). These functions include hydrologic, geomorphic, and ecological processes and community values associated with the riverscape. Often in the assessment of streams and rivers, managers ask scientists to measure functions because that is the way it has always been done, rather than a more well-rounded set of measurements that are fundamentally important to understanding what constitutes a competent urban riverscape. Under a values-based paradigm (Chapter 2), the assessment is conducted to ascertain the physical condition and community values given the context, which leverages both social-ecological and physical indicators. Indicators are summary variables that are indicative of a suite of more complicated, interacting processes, patterns, and/or conditions measured by metrics (Wheaton et al. 2019).

Indicators are useful because they offer a more straightforward means of communicating and describing overall trends than the supporting metrics. Metrics provide the measurement and observation data for indicators. Many metrics can be useful in specific contexts, especially for describing the details, but most do not rise to the importance of an indicator. It is essential, however, to recognize that no single indicator can explain riverscape function alone, and that multiple indicators are typically needed to provide an overall picture of physical condition.

The key to the development of effective indicators of physical condition and social-ecological values is differentiating the indicator from the context used to estimate a condition (Wheaton et al. 2019). Thus, while the selection of specific indicators will depend upon the watershed and riverscape geographic context (both human and physical), in general indicators should cover the four facets across a range of spatial scales, from reach-scale up to and beyond the watershed scale. By identifying and defining indicators and metrics for urban riverscapes, stream-type specific thresholds and reference conditions can be suggested according to the physical condition (i.e., character and behavior) of the riverscape. These indicators, alongside a comparison to standard functional characteristics (as reference conditions), can be the foundation of stream management planning efforts, by informing managers, stakeholders, and the local community of the consequences of water and land use policies.

I have delineated 14 indicators that influence stream condition, which together cover the spectrum of URBAN's four facets. The metrics associated with each indicator, detailed in Table 4.5, are measurable features or attributes that allow for a reasonable and practical means of identifying the presence or absence of a particular function (Fischenich 2006). Each metric is assigned a recommended range of conditions necessary to achieve a functional stream, while individual measurements and observations are used to calculate metric values. It is critical in this process to isolate evaluation of the indicators, as an interpretation of condition, from the metrics that are logically useful for measuring differences between riverscapes or reaches.

The URBAN indicators and metrics aim to describe limiting factors that impact physical conditions and community values and are barriers to recovery potential. Therefore, they provide comprehensive baseline data from which to assess a riverscape's physical condition and its potential trajectories, and to develop a clear understanding of stressor-impairment (i.e., cause-effect) relationships. When the same indicators and metrics are compared to standard functional characteristics, URBAN allows for the assessment of whether and how much hydrological alteration, morphological adjustments, and vegetation has changed over time. This in turn provides insight into a riverscape's condition and maintenance requirements. When evaluated collectively, these indicators comprehensively describe riverscape condition by diagnosing the severity, extent, and causes of impairment and the response gradient compared to a reference condition (i.e., the expected character and behavior).

Table 4.5 Summary table of URBAN's indicators and metrics that are applied across multiple scales to assess stream physical conditions and community values

Facet	Indicators	Metrics	Assessment methods	Example references
Human connections and values	Access to nature	Universal access	• Remote sensing: measurement of proximity to natural areas	TPL 2017
	Vitality	Environmental and health hazards	• Remote sensing: evaluation of SoVI data.	CDPHE 2020
	Economic	Ecosystem services	• Remote sensing: evaluation of natural capital data	Ecosystem Sciences Foundation 2017
	Stewardship of natural resources	Compliance with water quality standards	• Remote sensing: evaluation of 303d listings and local WQ data	CDPHE 2020
		Riverscape protection	• Field observations	TPL 2017
Hydrologic processes and Hydraulic characteristics	Runoff production	Land-use gradient	• Remote sensing: evaluation of land-use changes considering LDI index and imperviousness	Brown and Vivas 2005
	Flow regime	Flow regime change	• Remote sensing: evaluation of urbanization	Poff et al. 2010
		Rate/magnitude	• Hydrologic data and analyses	USGS 2019
		Volume	• Hydrologic data and analyses	USGS 2019
		Flashiness Index	• Hydrologic data and analyses	Baker et al 2014
	Flood/fluvial hazards	Structures in broad floodplain	• Remote sensing: flood and fluvial hazard data • Hydraulic analyses • FHZ protocol	MHFD 2021
		Structures in the regulatory floodplain		MHFD 2021
		Structures in the fluvial hazard zone		Blazewicz et al. 2020
	Floodplain connectivity	Floodplain connectivity ratio	• Remote sensing: valley bottom data and modeling	Macfarlane et al. 2018
Geomorphic forms & processes	Sediment regime	Sediment continuity	• Remote sensing • Field survey • Database of CS structures	USACE 2021
	Stability	Stream power gradient	• Calculations and Modeling	Yochum et al. 2017
		Channel stability index	• Remote sensing and field survey using rapid geomorphic assessment techniques	Simon and Downs 1995; Kline and Cahoon 2010
	Morphology	Response potential	• Remote sensing • Field survey • Database of structures • Modeling • Historical / bibliographic information, cross sections / longitudinal profiles	National Academy of Sciences 2017
		Geomorphic functionality		Rinaldi et al. 2013
		Artificiality		Rinaldi et al. 2013
		Channel adjustments		Rinaldi et al. 2013; Cluer & Thorne 2014
Ecological structure & processes	Dynamic stability	Riparian vegetation width	• Remote sensing	Merritt et al. 2017
		Vegetation vigor	• Field survey and observations	USFWS 2009
	Adaptability	Structural diversity	• Remote sensing and field survey and observations	TPL 2017
	Resiliency	Vegetation assemblages	• Field survey of structural layers	

The linkages between human connections and values and the other facets require social science and community participation. These relationships are not readily quantifiable; they may be dynamic over time, and are likely highly variable between – and within – cases. They are of primary significance in defining what is important in riverscape systems, particularly in urban areas, and can guide the selection of relevant, measurable indicators of riverscape condition. Indicators chosen in this manner would represent the hydrogeomorphic conditions that support healthy riverscape functioning and also meet the needs of the local community. Underlying this statement is the premise that the resilience of water resources to disturbances like floods, droughts, and anthropogenic stressors is fundamental to sustainable communities.

The selected indicators should account for stakeholder priorities, project objectives, data availability, urban riverscape tenets, and the ability of remote sensing and rapid field methods to accurately characterize trends in riverscape condition. The varying inputs and decision points in selecting indicators and metrics should also include incorporating the 'voices' of a diverse population and should consider questions of environmental justice and equity such as equitable access to nature and ecosystems services.

2.3.2 Riverscape functional scores and social-ecological qualities

Given the natural diversity of urban riverscapes, it is critical to identify appropriate reference conditions and targets to ensure that management and maintenance actions are consistent with the local context (Bennett et al. 2019). Reference conditions provide the context with which the condition or outcome of any observation or measurement can be compared to other similar observations (Somerville 2010). Conceptually, this is simply comparing what can be measured to the range of variability you might expect to find naturally. Thus, assessments of riverscape condition must be framed in relation to what is expected for any given type of reach (Brierley and Fryirs 2005). Two common ways that riverine scientists express this context include, (1) O to E (observed to expected) models (e.g., Hawkins et al. 2000; USEPA 2006), which consider the departure of existing conditions from an intact system, and (2) intrinsic potential (e.g., Burnett et al. 2007; Beechie et al. 2007; Fryirs and Brierley 2005), which compares prevalent conditions to the best achievable condition within anthropogenic constraints (i.e., what improvements are possible given existing roads, development, agriculture, etc., that cannot be removed). Using an intrinsic potential approach is the logical choice for urban riverscapes because it accounts for the anthropogenic constraints and relies on both geospatial data and field observations of existing, "on the ground" conditions. Furthermore, the range of conditions varies depending on the severity of stressors degrading the function as well as the amount of maintenance required to sustain or improve physical conditions. The coupling of riverscape and reach-scale condition data fosters a better understanding of the ‘‘best achievable’’ conditions relating local site condition to its riverscape perspective (Solek et al. 2011).

URBAN applies a four-point scoring system to describe the varying degrees of functionality (Table 4.6) or quality (Table 4.7). Scores are based on discrete criteria or on expert opinion and supported by multiple lines of evidence, such as correlation between metrics and field verification. Multiple lines of evidence together provide a more complete understanding of the factors affecting overall riverscape condition in an AOI (Solek et al. 2011). The scoring also includes the relative severity of stressors degrading the reach as well as the amount of maintenance required to sustain or improve physical conditions. Required maintenance is a cornerstone concept in URBAN reference conditions. A lack of maintenance implies a self-sustaining, dynamic equilibrium in the system. When active maintenance is required to reestablish or restore functions of the natural system, the river condition is impaired, which has both direct and intrinsic (ecosystem service) costs.

The functional characteristics follow a simple scoring scheme of “fully functional” (3 points), “functional” (2 points), “partly functional” (1 point), or “not functional” (0 points). The scoring scheme for the human connections and values facet is similar, although the qualities of the values are scored as “high” (3 points), “moderate” (2 points), “low” (1 points), and “none” (0 points).

Table 4.6 Reference condition guidelines used to calibrate the criteria of URBAN physical condition indicators and metrics

Guideline	Description
Fully functional riverscape with no maintenance	The condition of the metric is self-sustaining with negligible alterations, and supports functional characteristics appropriate to sustain stream physical condition. Minimal, if any, management is required to sustain and protect this level of function given stressors from the modern riverscape/landscape and climate. The variable retains its essential qualities and fully supports physical functions.
Functional riverscape with moderate alterations and limited maintenance	The condition of the metric is moderately altered and/or degraded by stressors that substantially influence the variable's functionality. The variable still supports natural physical and social-ecological functioning. Frequent management and maintenance are required to sustain the characteristic functional role of the variable.
Partly Functional riverscape with altered conditions and active maintenance	The condition of the metric is significantly altered by stressors that impair the indicator variable' s ability to support characteristic function and the overall physical condition of the stream. Extensive, consistent, active management and maintenance are required to sustain the characteristic functional role of the variable.
Not functional with novel condition and intensive maintenance	The condition of the metric is under the influence of severe adverse alterations/stressors. The level of alteration generally results in an inability of the indicator variable to support characteristic functions and/or it otherwise makes the area physically and social-ecologically unsuitable.

Table 4.7 Reference condition guidelines used to calibrate the scoring criteria of URBAN human connections and values indicators and metrics, also referred to in this chapter as social-ecological qualities.

Guideline	Description
High quality and fully supports community values	The quality of the metric indicates significant benefit to the surrounding community. The identity of the riverscape or reach provides a sense of place that honors the importance of the riverscape to the character and heritage of surrounding neighborhoods. Local development patterns encourage sustained natural riverscape functions and indications of positive aesthetic and experience types (presence of desirable amenities/services) are excellent.
Moderate quality and supports community values	The quality of the metric indicates moderate benefit to the surrounding community; the identity of the riverscape mostly provides a sense of place that honors the importance of the riverscape to the character and heritage of surrounding neighborhoods. Local development patterns support high functioning riverscape systems and indications of positive aesthetic and experience types are good.
Low quality and limited support of community values	The quality of the metric indicates minimal benefit to the surrounding community; the identity of the riverscape somewhat provides a sense of place that honors the importance of the riverscape to the character and heritage of surrounding neighborhoods. Local development patterns impact natural riverscape functions and indications of positive aesthetic and experience types are marginal.
Poor quality and does not support community values	The quality of the metric indicates adverse impacts to the surrounding community; the identity of the riverscape does not provide a sense of place that honors the importance of the riverscape to the character and heritage of surrounding neighborhoods. Local development patterns degrade natural riverscape functions, significantly impacting landscape/riverscape processes, and do not provide positive aesthetic and experience types.

2.3.3 Data collection

This section outlines the three “levels of detail" for data collection efforts (i.e., Level 1-2-3; USEPA 2006; Stein et al. 2007), and the process for gathering information for each level through a multi-disciplinary approach. The three-tiered approach provides a structured framework for conducting integrated assessments of physical condition across multiple scales (Solek et al. 2011). Level 1 analysis consists of inventories and mapping at the watershed-scale and riverscape-scale while Level 2 consists of desktop and rapid assessment methods based on diagnostic indicators to assess physical conditions and community-associated values. Level 3 consists of intensive assessment methods that provide detailed information on the functionality of specific reaches. The various levels of assessment are further explained in Table 4.8. The process can be cumulative or independent at each level; however, each level builds on the previous level and provides a basic framework of knowledge about a given facet. For instance, the knowledge gained from Level 1 and Level 2 “provides greater interpretive power” for the intensive Level 3 data collected at the reach-scale (Solek et al. 2011, pg. 472). Level 1, therefore, is typically completed before Level 2 and Level 3, although Level 1 is not a prerequisite for the others. Whether Level 2 or Level 3 methods are used to collect data will depend on project goals and circumstances. The objectives, procedures, and applications are discussed below for each level of assessment.

Level l is a desktop procedure that begins by assembling and interpreting existing maps, publicly available data, and stream classification information. The intended use of the desktop assessment is to determine watershed context and characteristics. Level 2 is a combination of desktop and rapid field assessment that (1) identifies and maps observable physical features using qualitative and semi-quantitative measures; (2) delineate reaches; (3) defines reach types; and (4) prioritize reaches for which more detailed information is required. Reach delineation is based on geomorphic landforms, riverscape classification, gradient, and anthropogenic factors such as roadway crossings and water infrastructure. Practitioners delineate physical features based on easily identifiable characteristics that correspond to the riverscape-scale strategies (see Table 2.3 in Chapter 2). The intended use of the field portion is to verify results from Level 1 and the Level 2 desktop analysis or to quickly measure and document conditions in the field.

Table 4.8 URBAN levels of assessment summary

Evaluation Level	Description	Kinds of Data Curated	Management Applications
Level 1	Desktop analyses using existing publicly available data	• Land use changes • natural space opportunities • Urban heat island index • Environmental and health hazards • Social vulnerability index • Infrastructure risk • Structures in floodplain and/or FHZ • Riverscape capacity • Vegetation cover types • Geomorphic character (e.g., valley bottom type)	• Documents existing information • Displays resource values and management gaps • Provides basis for prioritization for higher level evaluation (2 or 3)
Level 2	Rapid field work curating new data	• Universal access • Maintenance requirements • Reach type(s) • Flow regime type • Flow alterations due to diversions • Floodplain connectivity • Sediment sources • Geomorphic properties (e.g., depositional reaches) • Bank stability • Vegetation community type and diversity • Vegetation structural layers	• Identifies and maps geomorphic properties and riparian condition • Verifies resource values and management/maintenance gaps • Characterizes existing riverscape condition in relation to functional characteristics • Results in mapping of functional areas • Identifies areas for Level 3 assessment • Evaluates current management/maintenance effects • Provides a basis for management decisions
Level 3	Detailed field investigation, reach or site specific	• User experience • Neighborhood identify and placemaking • Community stewardship efforts • Location of stormwater control measures • Flow regime analysis • Riverscape and crossing structure capacity • Channel stability index • Mapping and analysis of channel adjustments • Bank protection locations • SEM stages • Foliage height/volume • Vegetation community assemblages and composition • Dominant plant associations	• Select monitoring procedures • Identifies "watch" zones • Refines the relationship between natural processes and land use changes or management activities • Quantifies current status and potential recovery • Quantifies/validates resource values • Identifies limiting factors • Provides detailed project design criteria based on site characteristics • Quantitatively validates Level I or Level II assessment results

Level 3 involves more intensive, site-specific field data collection to address specific questions, issues, or needs. Quantitative data are collected at the reach-scale to: (1) characterize existing and potential riverscape or reach conditions; and (2) to monitor changes in those conditions. Level 3 typically relies on field surveys, including topographic, geomorphic, water quality, and biologic surveys. Information from Level 3 surveys is used to assess the impacts of stressors such as land use changes and hydromodification on the reach-scale flow regime, geomorphic functionality, and vegetation patterns. The detailed assessment integrates reach-scale metrics (e.g., Table 4.5) with additional analyses using higher-resolution datasets to better understand riverscape and reach physical conditions, help target potential management or recovery opportunities, and identify future assessment needs.

2.3.4 Evaluate data and diagnose condition

The final activity in Step 2 (see Figure 4.1) is assigning and evaluating the metric scores for the four facets and aggregating those scores by indicator in order to interpret and diagnose conditions and values across the riverscape and/or reach scales. Depending on data extent and resolution, scoring may entail qualitative assessment of metrics based on best professional judgment, which has an inherent degree of subjectivity. To minimize error, analysis should be carried out in a systematic manner by the same investigator.

Metrics are grouped to summarize the measurements by indicator and then facet, and then aggregated to determine the overall condition. Assigning condition-based hydrologic, geomorphic, and ecological scores and social-ecological qualities to a riverscape or reach is based on the current physical functions and social-ecological qualities. The scoring of indicators and overall conditions allows for identification and characterization of primary stressors on the system that are impairing existing conditions and/or driving evolutionary changes, as well as the identification of high functioning areas that should be protected or preserved. These results, in conjunction with watershed characterization maps, offer managers a resource for more effectively identifying problem areas and opportunities (O'Brien et al. 2017).

Indicator and overall condition scores are calculated and mapped across riverscape-to-reach scales, depending on the indicator (Table 4.5). The mapping approach generally follow O'Brien et al.'s (2017) data visualization and condition ranking scheme with the addition of the urban reach characteristics and response potential. The condition maps display the scoring results for each facets. The maps help establish a physically realistic understanding of the functional characteristics and provide the input for acutely interpreting and synthesizing riverscape or reach conditions. Maps also provide consistent, study area-wide visual representations of the assessments to inform strategic riverscape management.

2.4 Management

2.4.1 Synthesis

The synthesis of Step 1 and Step 2 summarizes the assessment of the relevant physical and biological conditions across the AOI. The indicators and metrics' scores, based on Level 1, Level 2, and/or Level 3 data, provide a holistic understanding of riverscape function and the related social-ecological values. The summation and averaging of scoring results from Step 2 also provide a concise synthesis of the overall riverscape or reach condition score across all four facets, which provide a baseline reference for creating management strategies. Comparing the relative results across riverscapes and reaches is also an option, although verifying the four facets' conditions and overall scores is encouraged before making planning or design decisions.

Averaging the results applies a baseline weighting of 25% for each facet. However, weighting the overall score by facet is encouraged to account for watershed or riverscape-specific considerations or limiting factors. For example, reducing the weight for hydrology and hydraulics to 5% due to an upstream reservoir that alters the flow regime and no long-term solution to that stressor, thus rendering that facet unlikely to drive management decisions towards the overall assessment. The additional weighting would be added to the other three facets, although human connections and values could be rated higher than geomorphology and ecology because the primary driver for a project could be improving social vulnerability.

Applying a multi-criterion decision analysis (MCDA) to weight the lines of evidence for each facet is also recommended as a way to engage stakeholders and the local community. MCDA is a method to support decision-making, by exploring different alternatives with stakeholders. It assists in framing decision problems, illustrating the performance of alternatives across criteria, exploring trade-offs, formulating a decision and testing its robustness (Esmail and Geneletti 2018). MCDA is particularly useful when reducing a multi-objective problem into a single-objective problem that is either unfeasible or undesirable, especially with diverse stakeholders and objectives (Linkov et al., 2006).

After the weights for each facet are determined, and scores are calculated, the reach types, urban reach characteristics, response potential, condition for all four facets, and overall condition are mapped across the AOI. The maps help set visual bounds on what might be possible for managers to achieve through appropriate planning and maintenance practices. For example, using the results of reach types, hydrologic, geomorphic, and ecological condition, and recovery potential, managers can develop a watershed-framed riverscape management plan with strategies to achieve short- and long-term goals.

2.4.2 Management strategies

The characterization and assessment steps, and the synthesis, provide the information and data to develop management strategies that inform decision-making for and implementing of management plans. URBAN's management objectives are framed by the hydrologic, geomorphic, and ecological conditions scores and the community values qualities. The results of the assessment combined with the urban riverscape characteristics (Table 4.3) and response potential (Table 4.4) set up five possible management strategies: 1) conservation reach; 2) strategic reach, or connected reach with high recovery potential; 3) high priority reach that is functional, or partly functional reaches with high recovery potential; 4) moderate priority reach with partly functional physical conditions and functional or fully functional human connections and values; and 5) low priority reach that is partly or not functional, or reaches with poor recovery potential. These strategies are defined as follows:

- <u>Conservation reaches</u>: Conserve fully functional reaches to preserve physical functions and social ecological values. Includes reaches coded as "near natural" and with functional human connections and values.

- Strategic reaches: Near natural or adjusting reaches that could recover naturally with functional hydrologic, geomorphic, or ecological conditions and high response potential; mitigate stressors that may spread adverse effects to fully functional and functional reaches. Typically includes high response potential reaches.
- High priority: Connected functional and partly functional reaches with high recovery potential to maximize the physical condition and social-ecological values of fully functional and functional reaches. Typically includes high and moderate response potential reaches.
- Moderate priority: Partly functional physical conditions with functional or fully functional human connections and values (moderate priority-values) or a partially engineered channel. Typically includes moderate response potential reaches that are isolated functional and partly functional reaches with high recovery potential. Restore or protect individual functional or partly functional reaches that are isolated between non functional reaches. Typically includes moderate or low response potential reaches.
- Low priority: Partly and not functional reaches with poor recovery potential: where resources allow, rehabilitate or develop long-term restoration strategy that addresses stressors and reoccurring maintenance issues in reaches with moderate to poor recovery potential, such as a completely engineered channel (e.g., Cherry Creek walled section near downtown Denver), enclosed pipe, or a reservoir. Typically includes low response potential reaches.

These provide a balance between protecting and enhancing riverscape condition, recognizing diverse community values, and supporting resilient riverscapes. The strategies also encourage conservation of remaining natural areas, followed by restoration and rehabilitation efforts that support and promote function, such as natural flow regime (Poff et al. 1997), sediment flux, and riparian vegetation. The management strategies should be driven by the various relevant institutions and supported by the community to meet their values, objectives, and needs.

3 Testing urban riverscape-based conditions assessment for management needs (URBAN)

I designed URBAN for urban riverscapes in the Denver, Colorado metropolitan area (Figure 4.2), focusing on the multi-jurisdictional boundary of the Mile High Flood District (MHFD). The MHFD concentrates its resources on over 1,600 miles of riverscapes (i.e., major streams) that are in Denver, portions of the six surrounding counties, and 35 incorporated cities and towns nearby, and it serves a population of approximately 2.8 million. In order to test and validate the URBAN method, I applied the three steps (Figure 4.2) to the Cherry Creek watershed south of Denver, CO, USA. The MHFD management area acted as the regional-scale boundary; it includes approximately half of the Cherry Creek watershed (Figure 4.2), referenced in this study as the lower and middle sub-watersheds.

To test and validate URBAN, I assessed the Cherry Creek mainstem and its major tributaries based on physiographic characteristics, social-ecological data, reach types, and a suite of indicators and metrics. I focused the testing and validating of URBAN on remote sensing and rapid field techniques (i.e., Level 1 and Level 2) due to the efficiency of using desktop and rapid assessment techniques that use cost-effective remote sensing and field-based diagnostic indicators to assess physical conditions and the linkages to community values. Level 3 methods could be applied in future studies to verify the condition of specific reaches or to provide more robust evaluations of overall condition prior to implementing restoration or rehabilitation actions.

I utilized the publicly available dataset within a suite of geographic information system (GIS) tools, over a range of scales, to describe the regional context and provide the characterization of the Cherry Creek watershed within the MHFD boundary. For the condition assessment, I applied moderate-resolution geospatial data (e.g., aerial imagery and 10-meter DEM) to evaluate and score the indicators and metrics. Higher-resolution data (e.g., 1-meter LiDAR) and site-specific field data were incorporated into the assessment to verify the remote sensing curated data.

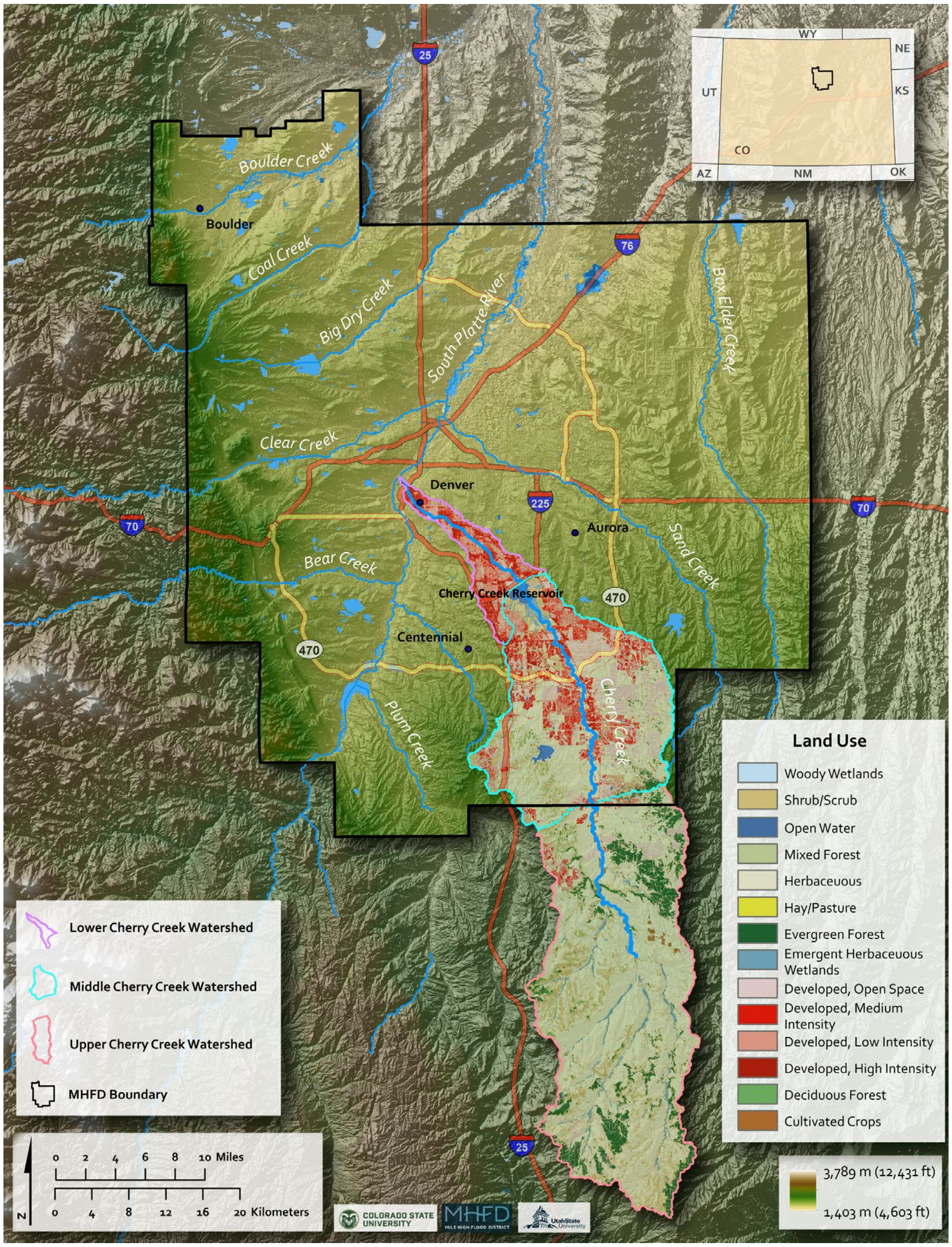

Figure 4.2 Cherry Creek Watershed in the Denver metropolitan area with the MHFD service area boundary.

3.1 Characterization of the Cherry Creek watershed

3.1.1 Geospatial mapping

The Cherry Creek watershed within the MHFD boundary is spatially diverse and varies in land cover and development patterns. It has been the focus of numerous studies by the MHFD and other local agencies, which make it a data-rich area for illustrating the potential utility of URBAN. Collectively, these past studies on Cherry Creek in combination with the inventory of low-, moderate-, and high-resolution geospatial data offered an excellent backdrop in which to develop and test URBAN as a novel method for assessing urban riverscapes.

The Cherry Creek watershed drains approximately 414 square miles (1,070 km^2) to the confluence with the South Platte River (Figure 4.2). Elevations range from a maximum of 8,000 feet (2,438 meters) in the upper watershed to 5,000 feet (1,524 meters) near downtown Denver, CO, USA. Cherry Creek has its headwaters on the Palmer Divide on the western margin of the Colorado Piedmont, east of the Rampart Range, and flows northerly through Castlewood Canyon State Park into Cherry Creek Reservoir at the downstream extent of the middle sub-watershed (Figure 4.2). The 850-acre Cherry Creek Reservoir was built by the U.S. Army Corps of Engineers for flood control, but its proximity to the Denver metropolitan area makes it a popular destination for swimming, boating, and other recreational activities. Downstream of the reservoir, the creek flows northwest through Denver, transitions from a "natural" stream to an urban riverscape upstream of its confluence with the South Platte River. The mainstem of Cherry Creek is a perennial stream that has a wide, shallow, well-defined channel that meanders through a majority of its corridor.

The hydro-climate of the Cherry Creek watershed is primarily semi-arid; mean annual precipitation is approximately 14 inches (360 mm). High intensity rainfall events, which tend to occur from May to August, along with a highly asymmetric (linear) drainage network cause very flashy river responses, which is why the U.S. Army Corps of Engineers constructed the Cherry Creek dam (completed in 1950) at the south end of the middle sub-watershed. Land cover is dominated by shrublands, grasslands, and ponderosa pine in the sub-watershed upstream of the Cherry Creek reservoir (Chapman et al. 2006). The land uses, once natural vegetation, were converted to agriculture and are now primarily open space, residential, or dense urban except in the upper sub-watershed, where most of the landscape is undeveloped forestland. Downstream of the reservoir, land cover is dominated by urban land uses with occasional mixed grasslands and riparian vegetation along the corridor. Floodplain and valley bottoms in the middle and upper sub-watershed are still relatively intact while the lower sub-watershed floodplain has been reclaimed primarily for urban development over the course of the past 150 years. Figure 4.3 provides a chronology of the Cherry Creek watershed characteristics.

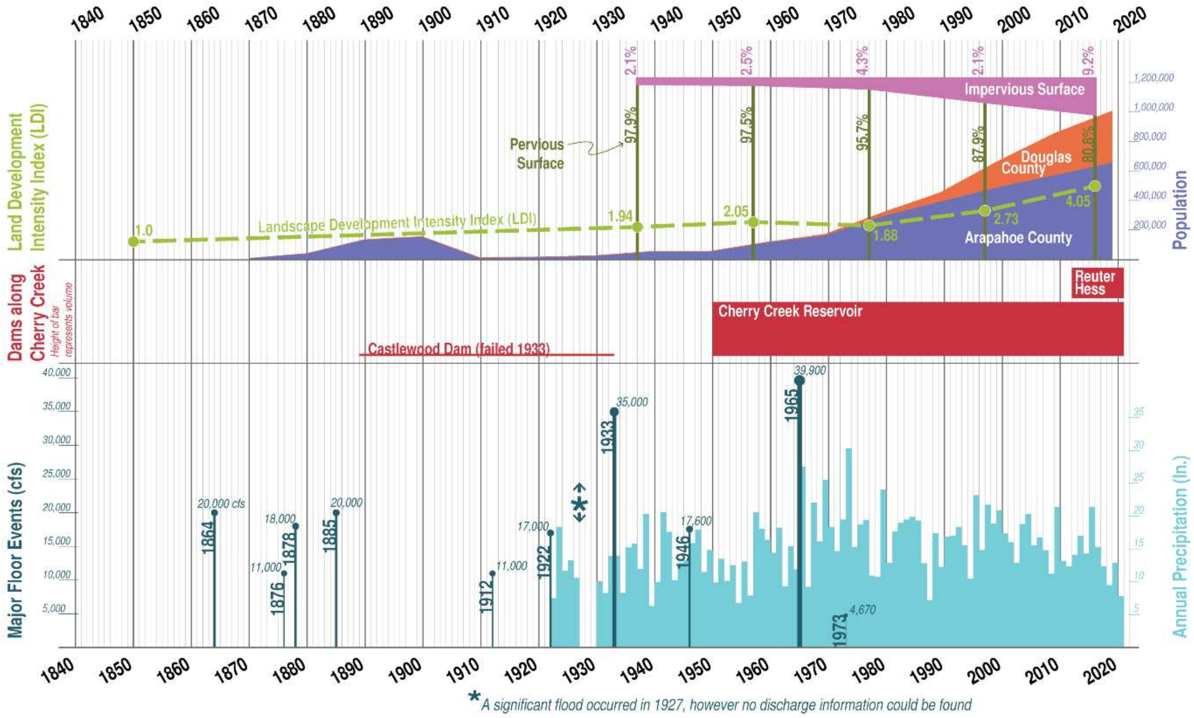

Figure 4.3 Chronology of human and natural disturbances in the Cherry Creek watershed since the mid-1800s. Note the LDI, impervious surface, and pervious surface values are for the entire watershed.

3.1.2 Context

This section describes Cherry Creek's physiographic setting in terms of its underlying geology, ecoregions, and hydrologic regime as well as the social-ecological values and anthropogenic stressors.

Physiographic setting of the Cheery Creek watershed

I used Google Earth Pro (v. 7.3.4.8573, 2022), Nearmap (2022), and other high-resolution GIS imagery, in conjunction with the 10-meter DEMs and NHP+ HR Dataset (NHD; Moore 2019), to document the watershed-scale physiographic attributes such as underlying geology, vegetation patterns and composition, relief, drainage density, and visual interpretation of the stream channel, floodplain, and valley attributes. For this study, I used the "segments" in the MHFD stream network database to define reaches, valley setting, condition, and management strategies for the Cherry Creek lower and middle sub-watersheds. The segments were delineated based on the ArcHydro GIS extension and elevation data provided by DRCOG (2.5-ft resolution DEM based on 2013 LiDAR). In most cases, the segments align with reach breaks that are based on physical signatures such as confluences and anthropogenic features.

Geology

The Cherry Creek watershed straddles the western slope of the Rampart Range Mountains and the eastern boundary of the Colorado Piedmont. The Rampart Range refers to the mountains east of the South Platte River in the south half of Figure 4.4 and is a southern extension of the Colorado Front Range. The watershed encompasses a wide range of geologic units (Figure 4.4, Trible and Machette 1979). The Cherry Creek basin primarily is underlain by tertiary sedimentary rocks, including sandstone, conglomerate, siltstone, claystone, and shale (Tweto 1979). Unconsolidated surficial deposits, originating in the Pleistocene and Holocene eras and derived from aeolian (wind-blown), colluvial (superficial deposit), and fluvial (flowing water) processes, cover much of the basin. Unconsolidated Pleistocene, Quaternary, and Anthropocene surficial material has been deposited within the valley bottoms and on low-to-moderate gradient hillslopes by alluvial, landslide, and glacial processes. These surficial deposits are the foundation of the floodplain and riparian corridor.

Each side of the Cherry Creek valley has distinctly different geologic characteristics. Near the floodplain, the east side of the valley is composed of aeolian sands (Qes) that are more uniform in nature than alluvial sediments. Upper portions of the east valley are within the Dawson formation (Tkd and Tkda), which formed as a series of ancient coalesced alluvial fans that overlie the Denver formation. The west side of the valley consists of colluvial deposits that are derived from the erosion of the Castle Rock conglomerate (Tkr) and Denver formation (Tkd). The Louviers alluvium (Qlo) borders much of the west valley and forms a gravelly terrace that is about 60 feet above the modern valley of Cherry Creek. With the exception of the aeolian sands, erosion of these base formations produces mostly coarse sand with some gravel sediment (Cotton 2004).

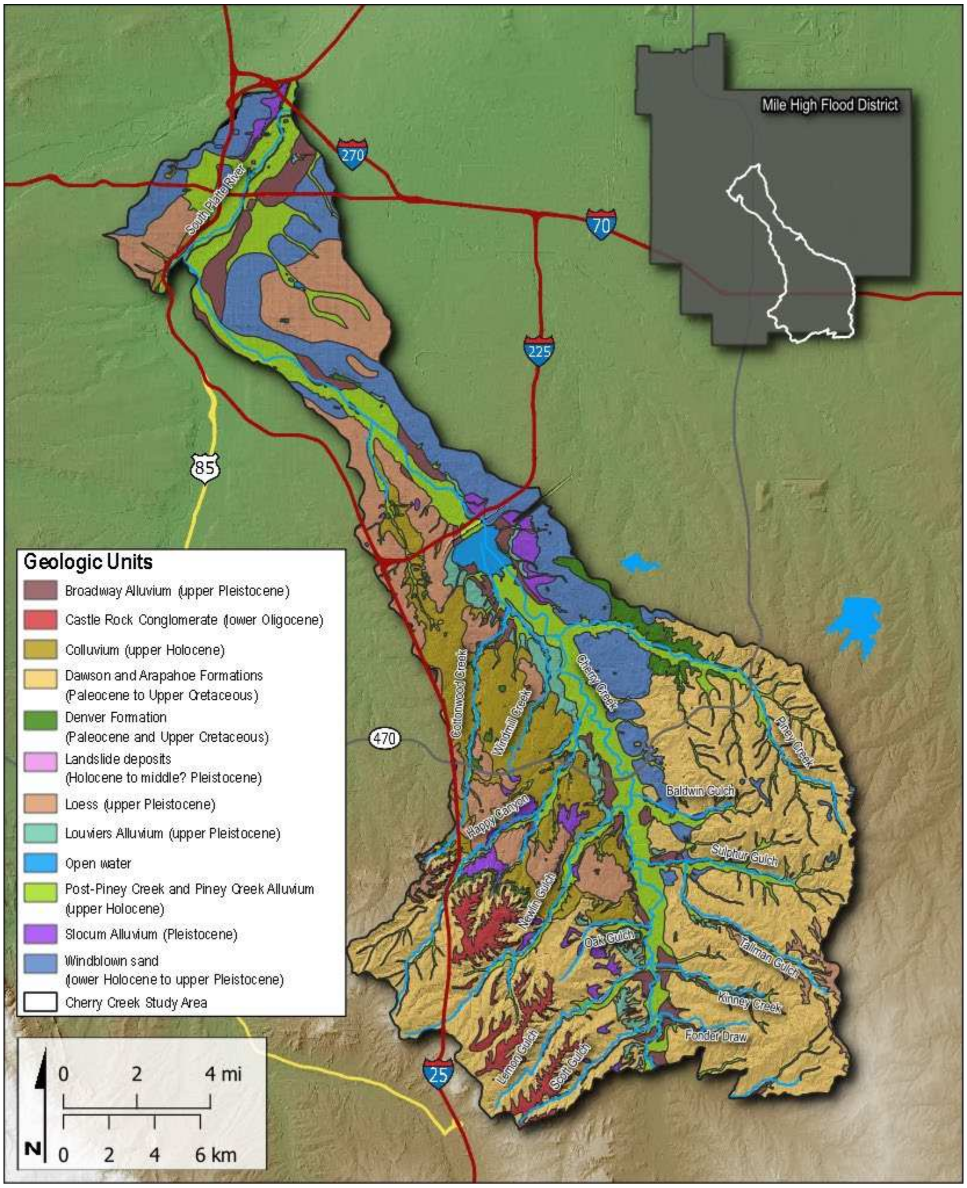

Figure 4.4 Geology of the Cherry Creek Watershed

The geographical extent of the Cherry Creek watershed is divided between two Level III ecoregions: the “Southwest Tablelands” ecoregion in the southern, upstream portion of the watershed and the “High Plains” in the northern, downstream portion. The watershed includes the following four Level IV ecoregions: “Pine-Oak Woodlands,” “Foothill Grasslands,” “Moderate Relief Plains,” and “Flat to Rolling Plains” (Figure 4.5).

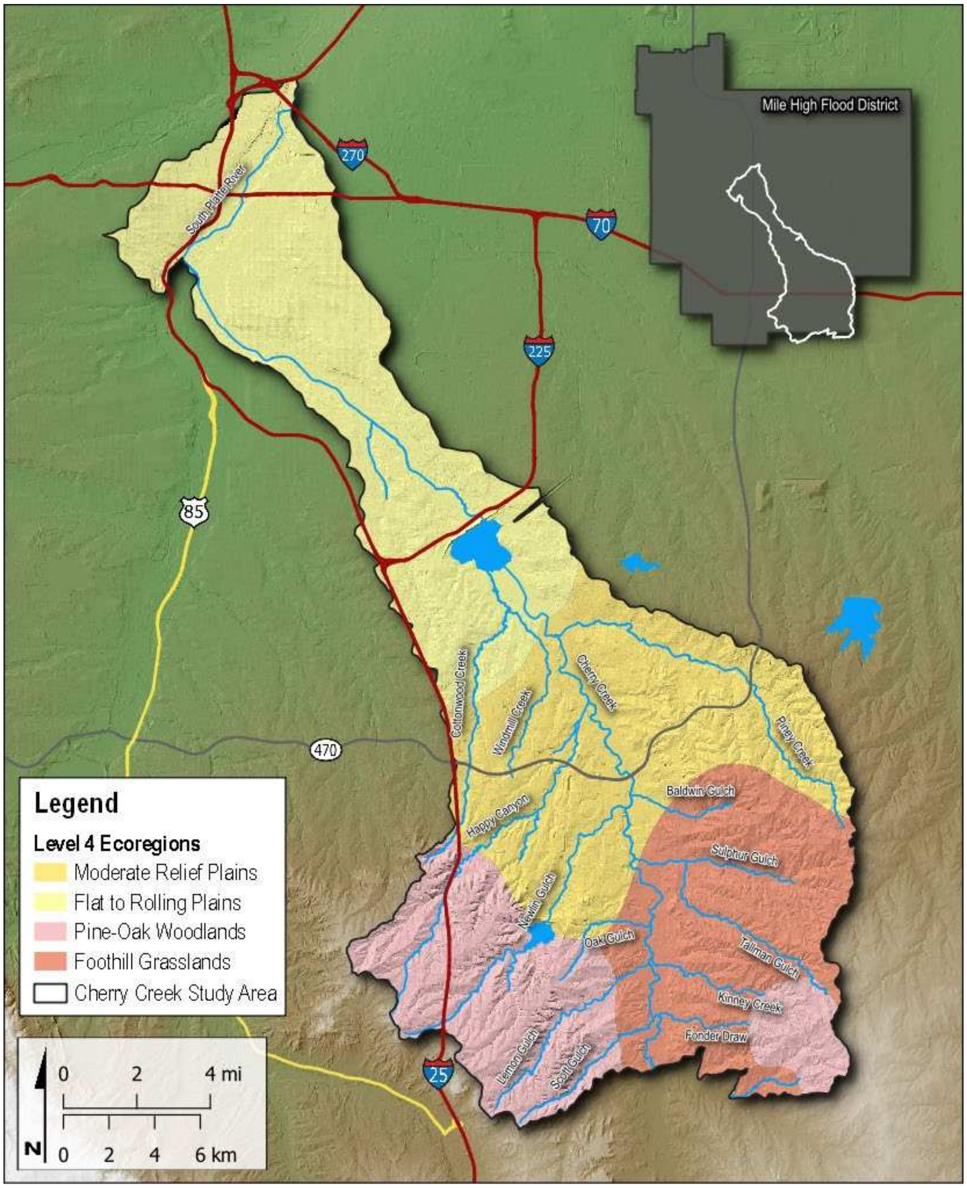

Figure 4.5 Level IV Ecoregions of the Cherry Creek Watershed

The Southwestern Tablelands flank the High Plains with red hued canyons, mesas, badlands, and dissected river breaks. Unlike most adjacent Great Plains ecological regions, little of the Southwestern Tablelands is in cropland. Much of this region is in sub-humid grassland and semiarid rangeland. The Pine-Oak Woodlands Level IV ecoregion is a dissected plain with dense oak brush and deciduous oak woodlands combined with ponderosa pine woodlands. Although woodlands dominate, the region is a mosaic of woodlands and grasslands. Soils are formed from weathered sandstone and shale with some outwash on uplands. The Foothill Grasslands Level IV ecoregion contains a mix of grassland types, with some small areas of isolated tallgrass prairie species that are more common much further east. The proximity to runoff and moisture from the Front Range and the more loamy, gravelly, and deeper soils are able to support tallgrass and midgrass species better than neighboring ecoregions. The mesic soils are formed from weathered arkosic sedimentary rock, gravelly alluvium, and materials weathered from sandstone and shales. Rangeland and pasture are common, with small areas of cropland (Chapman et al. 2006).

The High Plains comprises smooth to slightly irregular plains featuring a high percentage of cropland. Grama-buffalo grass is the likely natural vegetation in this region. The Moderate Relief Plains Level IV ecoregion is typified by irregular plains with slopes greater than the surrounding rolling plains. Land use is predominantly rangeland. Soils are silty and clayey loams, formed from aeolian sediments. The Flat to Rolling Plains Level IV ecoregion is more level and less dissected than the adjacent Moderate Relief Plains (Chapman et al. 2006).

Hydrology

The streams in Cherry Creek lower and middle sub-watersheds vary in stream order (Strahler, 1952) and flow regime (Figure 4.6). The middle sub-watershed includes many intermittent headwater first order streams; the lower sub-watershed likely had numerous first order streams but most of those streams are enclosed in pipes now. The perennial streams in both sub-watersheds that are tributary to mainstem Cherry Creek are third or fourth order streams while the mainstem is a fifth order stream. Stream order characteristics of the Cherry Creek sub-watersheds produce a high density of intermittent third order or less streams of partly confined (53%) and confined (33%) valley settings, comprising more than 80% of all reaches. These streams are often impacted significantly when land use changes due to urbanization. Therefore, preserving and protecting the riverscapes of third order or less streams is a key consideration in the management strategies.

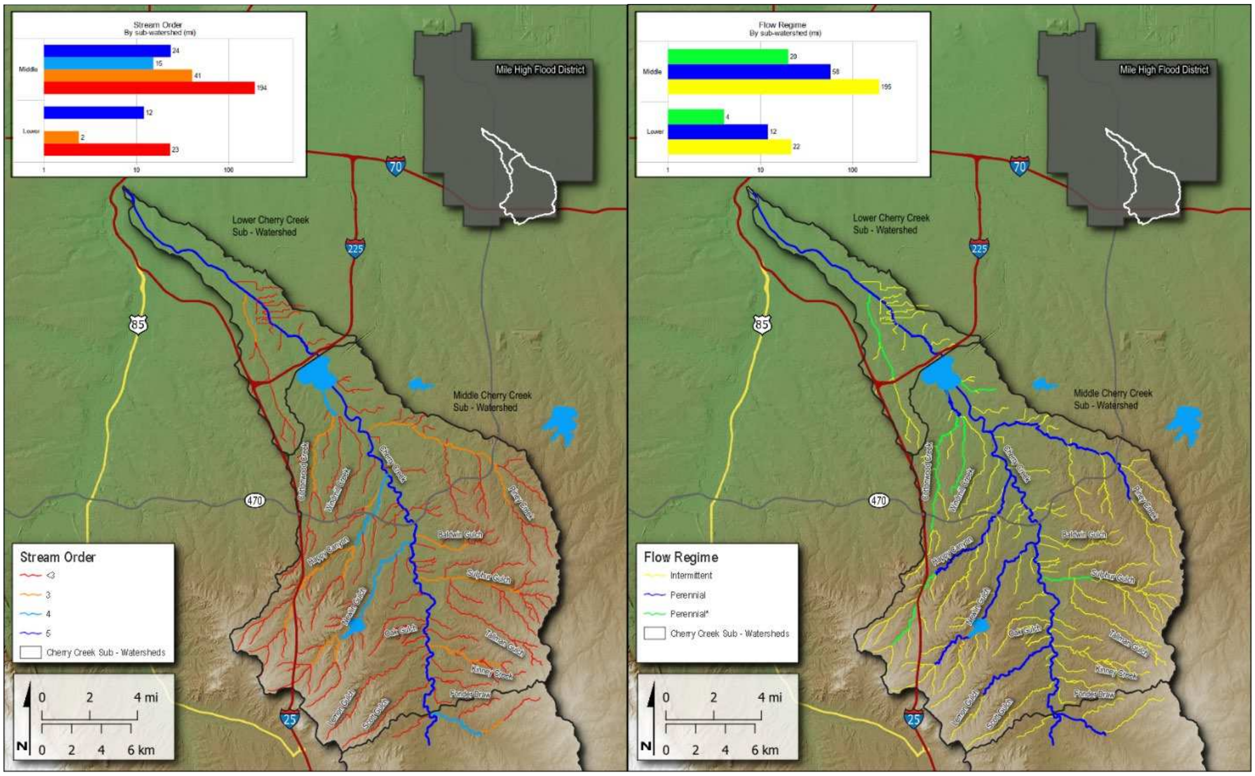

Figure 4.6 Stream order and flow regime in the Cherry Creek lower and middle sub-watersheds. Perennial* indicates streams that were intermittent but are currently considered perennial due to hydromodification.

The U.S. Geological Survey (USGS) operates two gaging stations on Cherry Creek upstream of the Reservoir. The "Cherry Creek Near Franktown, CO" station (0671200) has an 80-year period of record (POR) and the "Cherry Creek near Parker, CO" station (393109104464500) has a 29-year POR. The USGS Cherry Creek near Franktown station is located in Castlewood Canyon State Park. This station has a drainage area of 169 mi^2 (438 km^2). The USGS WY 2020 summary statistics list annual daily mean flow rates of 4.74 cfs (0.13 cms). Figure 4.7 shows the estimated daily discharge along with the median daily statistic from the last 80 years (CCWQBA 2020). The USGS Cherry Creek near Parker station is located downstream from mouth of Sulphur Gulch near Parker, CO, USA. The station has a drainage area of 287 mi^2 (743 km^2) The USGS WY 2020 summary statistics list an annual daily mean flow rate of 10 cfs (0.28 cms). Figure 4.8 shows the estimated daily discharge along with the median daily statistic from the last 29 years (CCWQBA 2020).

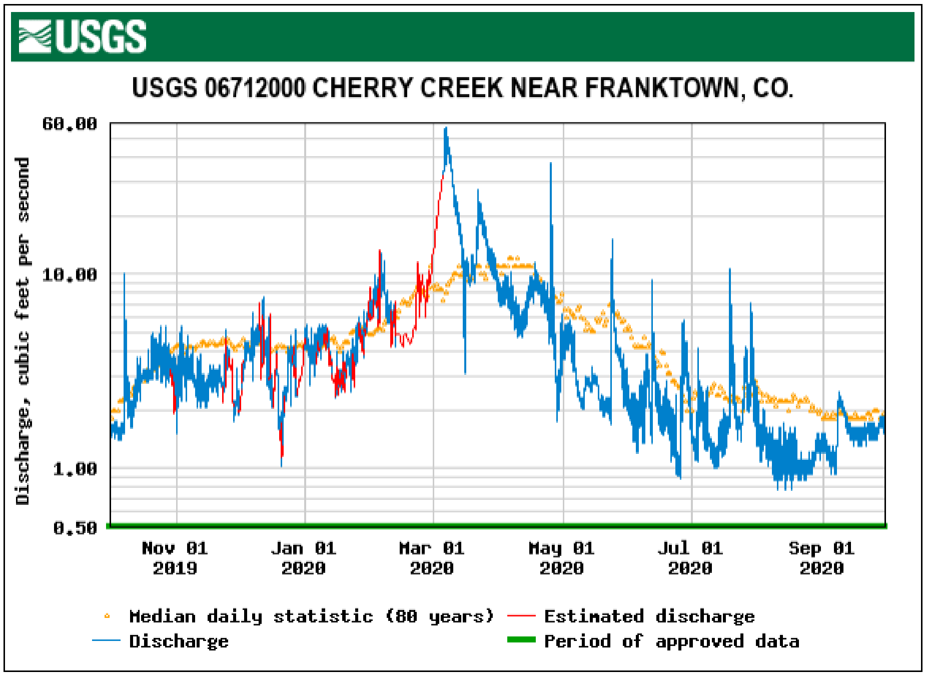

Figure 4.7 WY 2020 daily mean discharge and historical median flows for USGS gage near Franktown, CO USA.

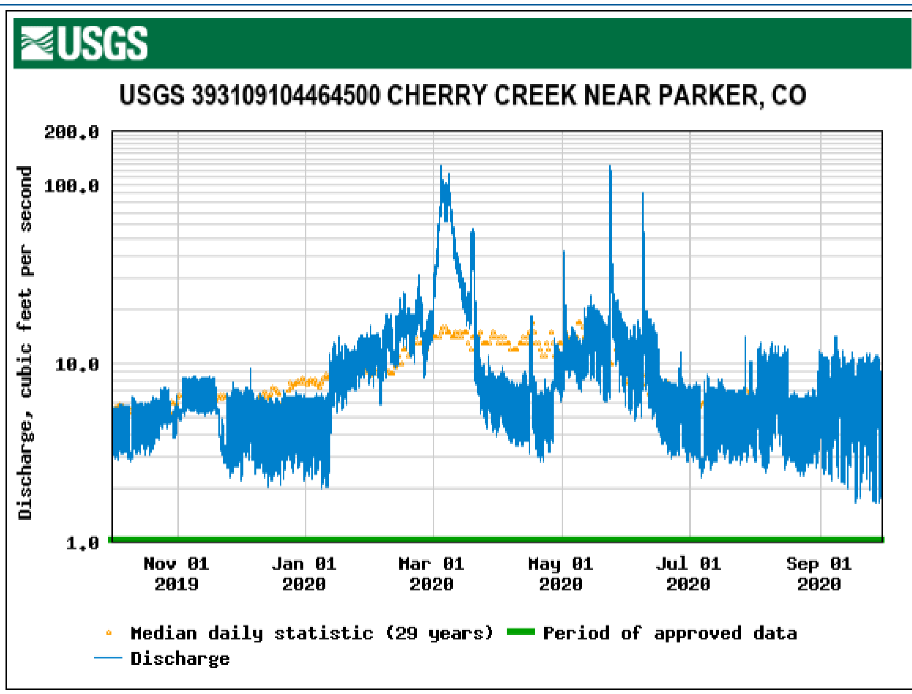

Figure 4.8 WY 2020 daily mean discharge and historical median flows for USGS gage near Parker, CO USA.

Prior to land use changes in the watershed, Cherry Creek was an intermittent stream with a hydraulically connected alluvial aquifer. As land use shifted and groundwater pumping began, changes in water table elevations affected morphology and the vegetation. Currently, several reaches dry up as a result of groundwater well pumping. Cherry Creek baseflow typically peaks during snowmelt runoff period, March through May.

Social-ecological values in the Cherry Creek watershed

Within the Cherry Creek watershed, community-valued riverscape amenities were identified by reviewing natural capital (Ecosystems Science Foundation 2017), the Social Vulnerability Index (SoVI®; Michael Baker International 2021), and access to natural spaces (Trust for Public Land 2017) data.

Natural Capital Resource Assessment

The South Platte Natural Capital Assessment is a collaborative natural capital assessment that "catalogued existing data sources, identified the most important natural assets in the watershed and then mapped the natural capital and valued the ecosystem services produced throughout the watershed" (Ecosystems Science Foundation 2017, p. 1) to assist stakeholders with prioritizing future investments in the watershed. The natural capital asset map and ESV Map developed by the Ecosystem Sciences Foundation (2017) shows the ecosystem services produced by the natural assets present across the Cherry Creek Watershed as expressed in dollar per acre per year (Figure 4.9). The stream corridors, forested areas, and urban parks hold the highest ecosystem services value. Ultra-urban areas exhibited the lowest ecosystem services value. The ESV information provides important context for the assessment and was used to identify management scenarios (restoration, preservation, and conservation) in Section 3.3.

Social Vulnerability Index

MHFD commissioned an SoVI study for the Denver metropolitan region (Michael Baker 2021). While the SoVI score is represented as a numeric value, it has no inherent mathematical properties; rather, the SoVI methodology is intended to show the relative placement of a census block to others in the study. I evaluated the MHFD SoVI data to understand the social context relative to riverscape conditions. The

SoVI results generally indicate that the Cherry Creek Watershed has average-to-low social vulnerability with a portion in the lowest category (Figure 4.10). Similar to the ESV data, this information provides important context for management scenarios.

Access to Nature

The Trust for Public Land Access to Natural Spaces analyzed access to existing parks and open space (TPL 2017) in the Denver metropolitan area. The analysis incorporated a two-step approach: 1) it determines where there are gaps in public park availability across the landscape and constructs a demographic profile to identify gaps with the most urgent need for public parkland, and 2) it incorporates natural space opportunities based on land use and cover characteristics, schools, community gardens, and potential for certified backyard wildlife habitat areas. The two components are combined using an equal weighted sum computation.

The map in Figure 4.11 was created using a weighted overlay analysis based on the following criteria:

- Park needs
- Proposed parks and open space
- Vacant lands
- Natural land cover
- School grounds
- Potential for certified backyard wildlife habitat areas
- Community gardens

The Access to Nature model results generally indicate that the Cherry Creek watershed has opportunities to provide access to natural spaces in the middle sub-watershed along the eastern and western tributaries and in almost the entire upper sub-watershed (Figure 4.11). I also incorporate this information into the management scenarios.

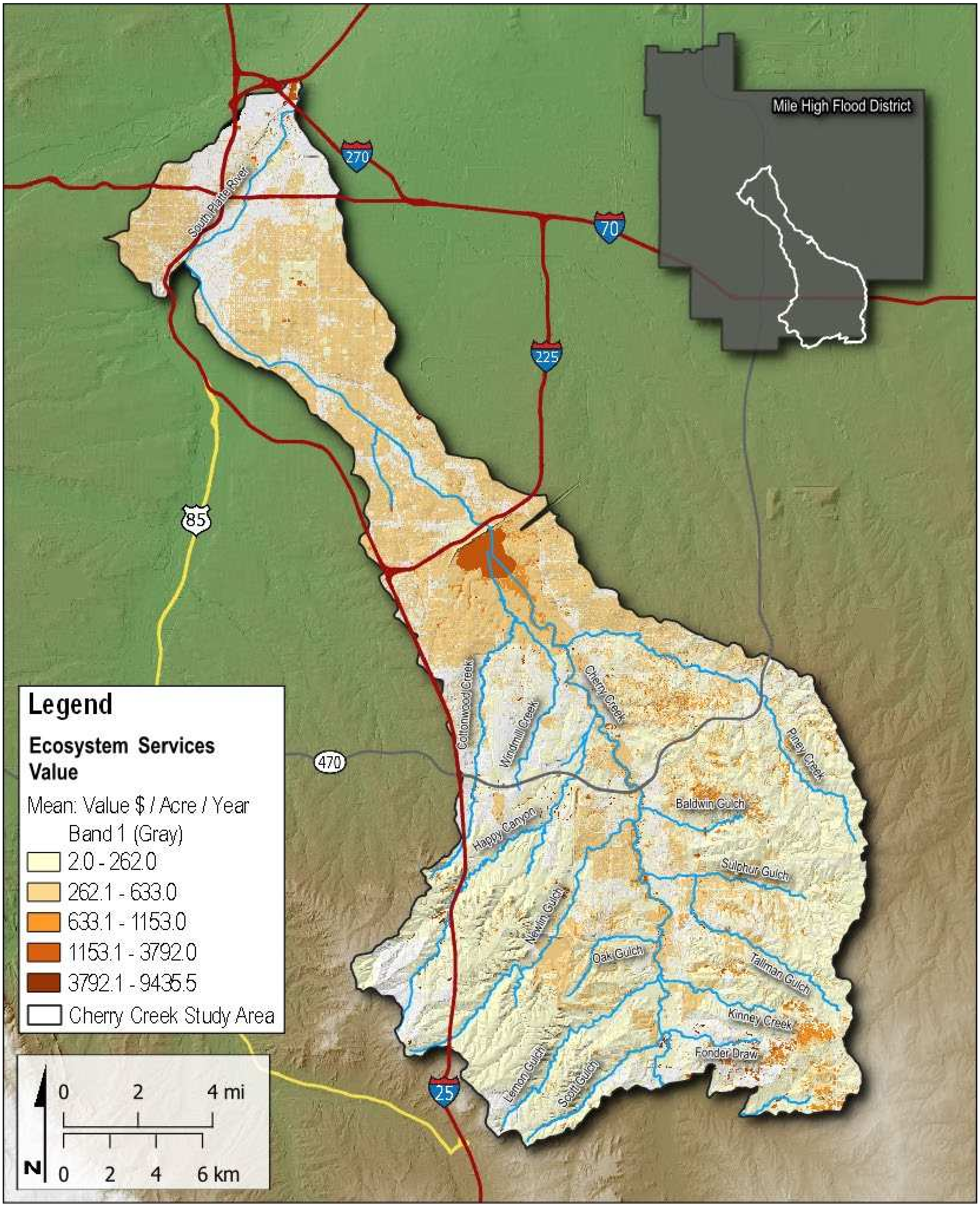

Figure 4.9 Ecosystem services value for the Cherry Creek Watershed

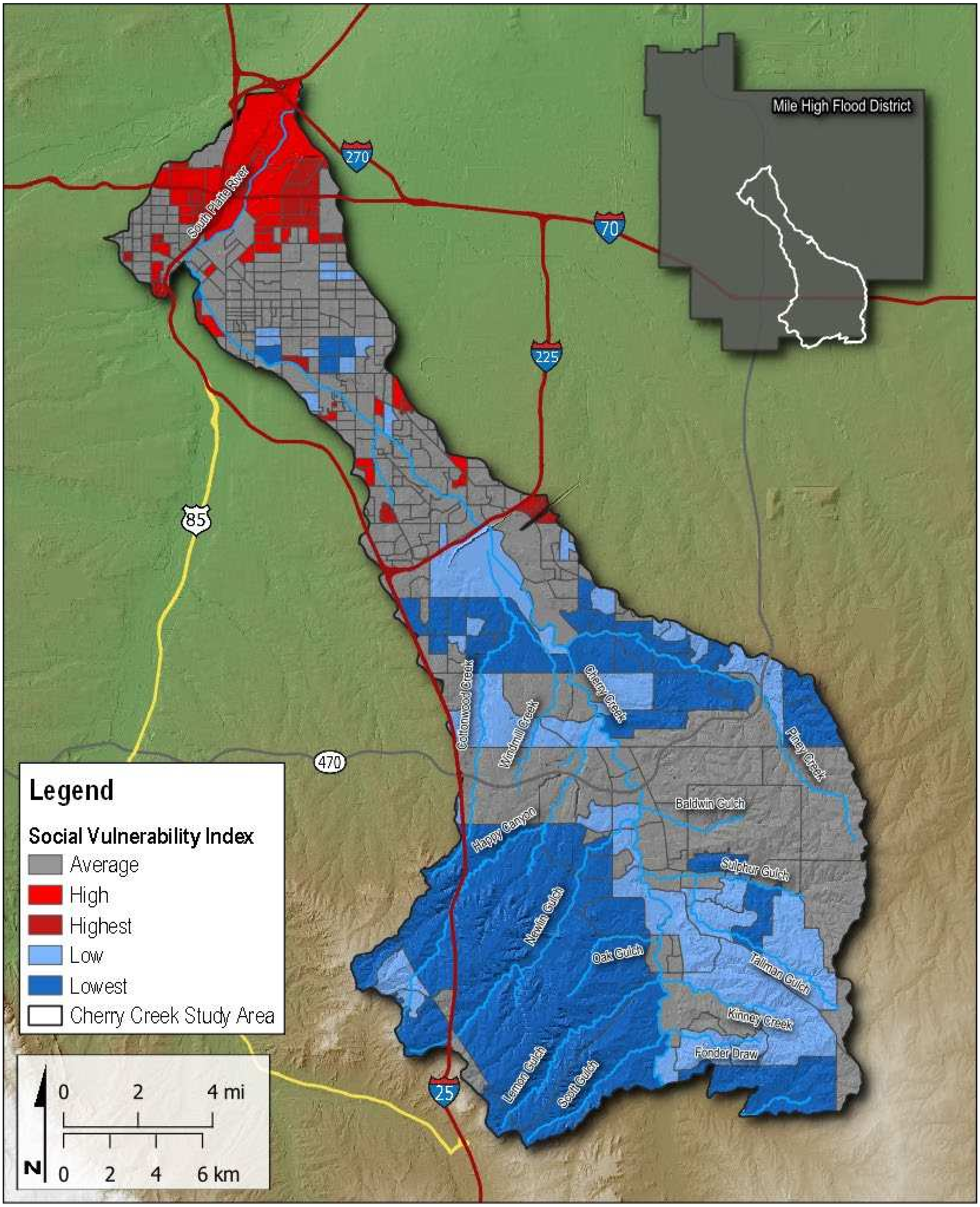

Figure 4.10 SoVI ratings for the lower and middle Cherry Creek sub-watersheds

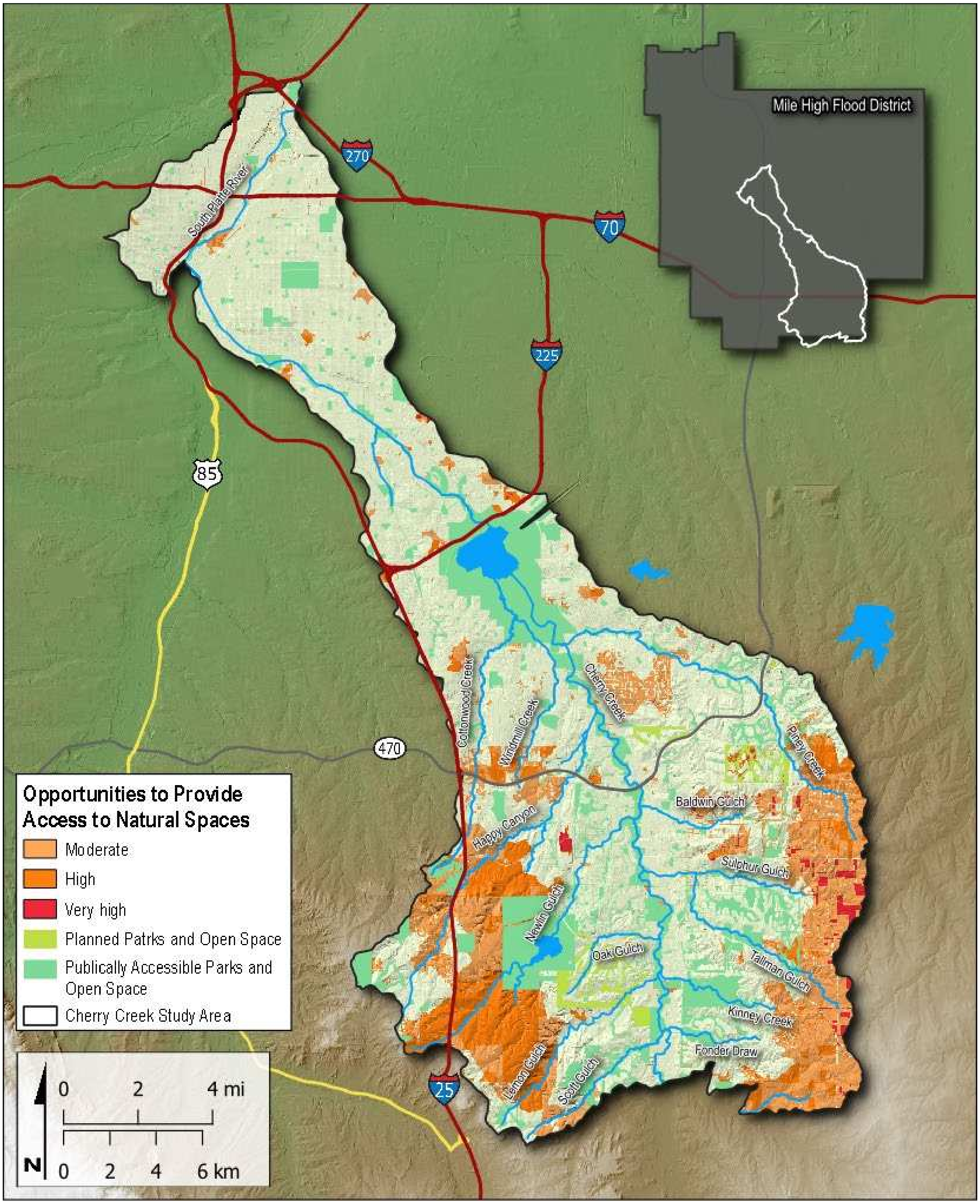

Figure 4.11 Opportunities to provide access to natural spaces map for the Cherry Creek watershed (TPL 2017). The tan color over much of the watershed corresponds with developed areas that are not considered natural spaces.

3.1.3 Stressors

For centuries indigenous peoples, trappers, traders, and adventurers traversed the Cherry Creek corridor (CCBWQA 2020). The watershed also maintained important agricultural value from the late 1800s through the 1930s, due to its rich soil and flat land. There were numerous dairy farms, truck farms, orchards, and potato fields from Franktown to downtown Denver. Water was supplied from the Castlewood Reservoir, built in 1890. Cherry Creek was the focus of the early part of the Pikes Peak Gold Rush in 1858 and 1859. For most of the 20th century, ranching and farming were the economic bases of the watershed. Thus, anthropogenic stressors occur in the Cherry Creek watershed, such as land-use changes due to urbanization, surface water diversions, and reservoirs, which results in the degradation of riverscape function. The most profound and documented change began following the arrival of settlers in the Cherry Creek watershed when grazing, ranching, and farming were implemented. More recently, urban and suburban development in the lower watershed have transformed the landscape.

Below, we attempt to map and quantify the degree of anthropogenic impact at the watershed scale through land-development intensity and proximity to and presence of water and transportation infrastructure.

Land-development intensity

I evaluated the effects of anthropogenic stressors on the Cherry Creek watershed by calculating LDI index values (Table 4.9) using data from five different years following the procedure outlined in Section 2. Derived LDI index values were then used to score the hydrologic processes and hydraulic characteristics facet condition (see Section 3.2). The LDI index values were grouped into five general LDI index classifications for assessment at watershed scales: near natural (< 1.2), minimal disturbance (1.2 – 1.83), light disturbance (1.83 – 4.5), heavy disturbance (4.5 – 7), and significant disturbance (> 7; fully urban). Figure 4.12 shows the results of an assessment of land-use intensity at the watershed scale leveraging the 2016 NLCD data (Dewitz and USGS 2019) and multi-year USGS datasets (Drummond et al. 2019), which identify a wide array of land cover types. For each cell in the USGS data, I assigned an LDI index score and aggregated the results (Table 4.9 and Figure 4.12).

Table 4.9 LDI values for the lower and middle Cherry Creek sub-watersheds

Imagery data	Natural (LDI < 1.2) acres	Minimal disturbance (LDI 1.2 – 1.83) acres	Light disturbance (LDI 1.83 – 4.5) acres	Heavy disturbance (LDI 4.5 – 7) acres	Significant disturbance (LDI > 7) acres
1937 USGS	5,106	42,105	64,201	13,972	6,452
1957 USGS	6,371	35,665	66,682	11,299	11,820
1977 USGS	13,217	43,317	44,423	7,870	23,009
1997 USGS	6,193	16,285	71,246	7,233	30,880
2016 NLCD	2,645	14,164	75,791	19,113	20,124

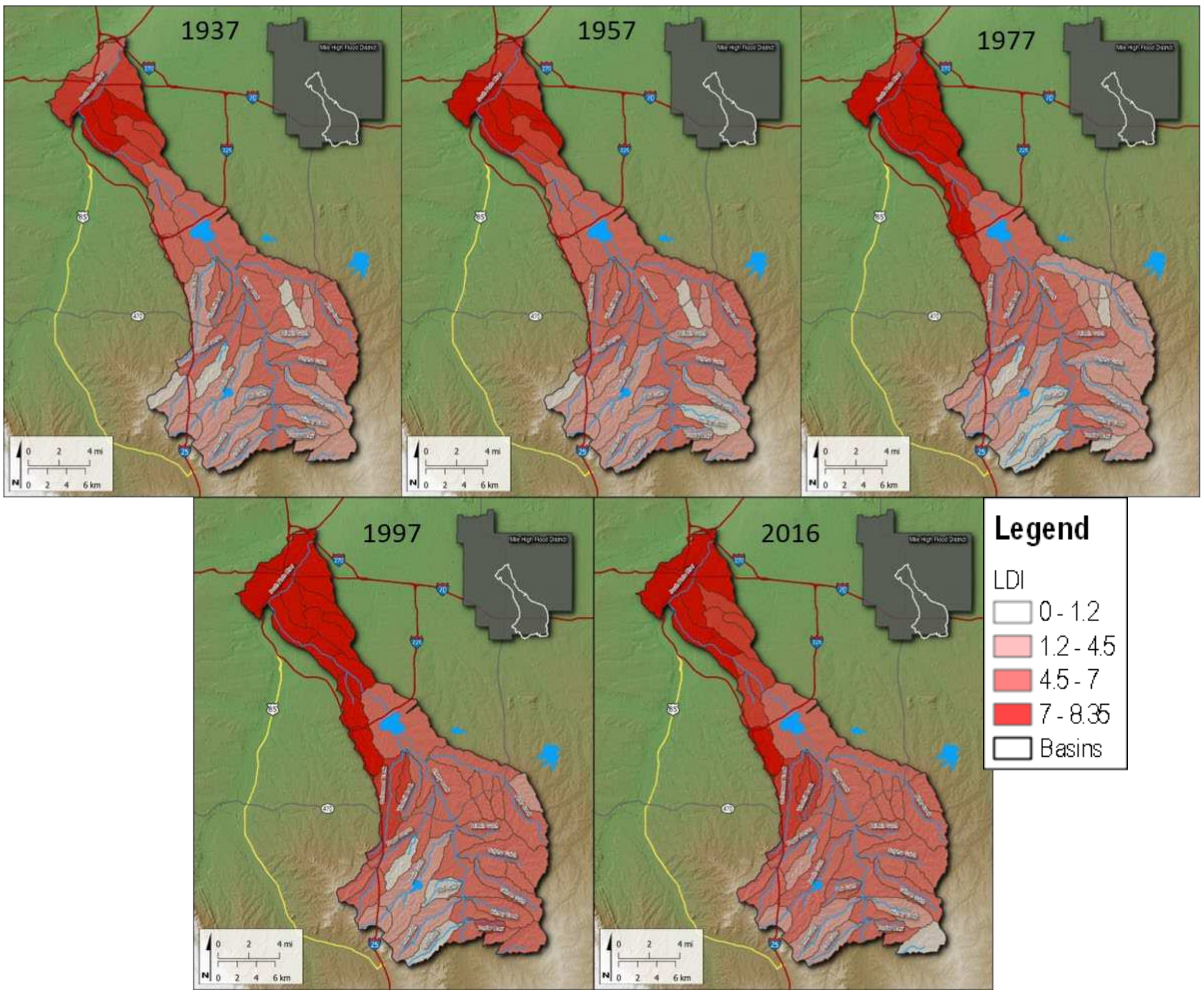

Figure 4.12 USGS land use land cover time series for the Cherry Creek Watershed

The LDI data suggests land use activities began transforming the landscape as urbanization occurred over time, the lower sub-watershed, which includes a portion of downtown Denver, transitioned from heavily disturbed to significantly disturbed while the land use in the middle sub-watershed generally remained lightly disturbed. However, over that time agricultural lands changed to open space with pockets of interspersed developed land. The resolution and land use categories of the USGS data and NLCD data is an important consideration in calculating LDI. For example, the decrease in LDI in areas in the lower sub-watershed is due to the difference in classes from NLCD to USGS: NLCD has three urban classes, whereas USGS only has two.

Proximity to and Presence of Water Infrastructure

A vast network of infrastructure exists within the Cherry Creek watershed, which includes flood hazard mitigation works (levees, diversion structures, and reservoirs) and streamside infrastructure such as streambank protection. I used the diversion structures identified by the Colorado Water Conservation Board (2022) to calculate the number of diversion structures along the mainstem Cherry Creek and perennial tributaries (Figure 4.13). A total of 16 diversion structures were identified with the majority located along the mainstem of Cherry Creek in the middle sub-watershed. Collectively, these structures adversely impact sediment continuity and instream flows, although they also provide vertical grade control that prevents incision.

Groundwater wells are pervasive in the lower and middle sub-watersheds with over 1,500 active wells. The groundwater pumping has lowered the water table along the several reaches of the Cherry Creek mainstem, which effects the riparian vegetation and stability of channel banks. However, as the groundwater in the Denver Basin area has been developed, groundwater discharge to Cherry Creek has increased, and streamflow has changed from flowing only during wet seasons to flowing year-round (Bauch 2014). The discharge of treated wastewater effluent into the Cherry Creek mainstem also influences the stream flows. Four publicly owned wastewater treatment plans currently discharge into Cherry Creek mainstem upstream of the reservoir. The perennial flow in the mainstem provides a consistent water source for riparian vegetation, although the water quality tends to be poor (CCBWQA 2020).

Proximity to and Presence of Transportation Infrastructure

I performed a similar analysis for the transportation infrastructure (roads, bridges, etc.) that crosses the mainstem and perennial tributaries (Figure 4.14). A total of 1,186 road crossings were identified with the majority located along the mainstem of Cherry Creek in the lower sub-watershed. These road crossings present a significant detriment to riverscape function by fragmenting floodplains thereby disconnecting portions of the valley bottom and creating impediments to sediment continuity. The distance of roads to the channel in the valley bottom is also a key consideration. Approximately 50% of the roads in the middle watersheds are within 300 ft (100 m) or less to the stream corridor while nearly all roads are within 300 ft (100 m) or less to the lower sub-watershed stream corridor. The proximity of roads to the channel limits the width of the riparian vegetation. Conversely, the closer the roads, conceivably the more access for pedestrians to recreate and experience nature in those corridors, which is an important factor I considered when evaluating the management scenarios.

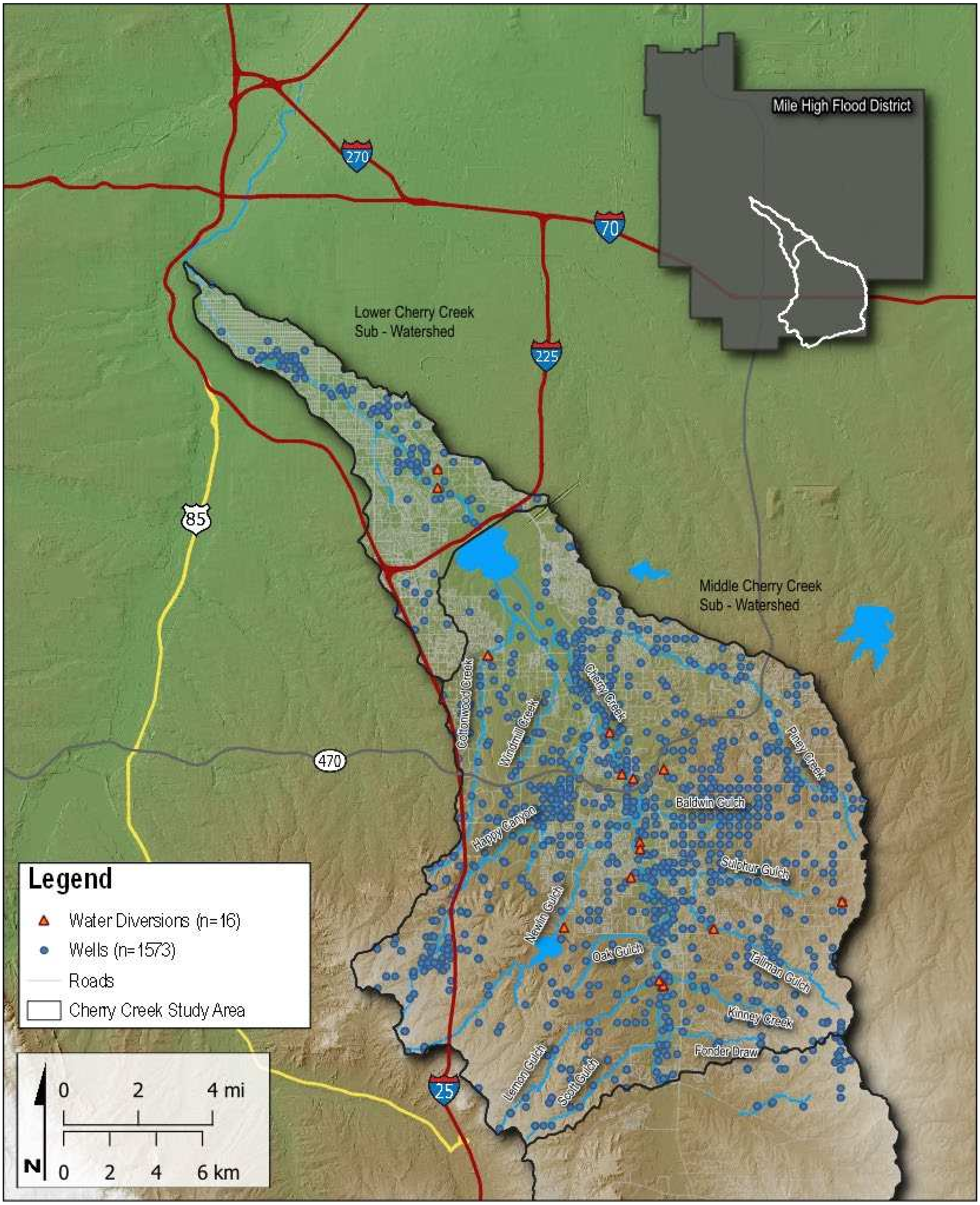

Figure 4.13 Water infrastructure (diversion structures and groundwater ells) in the Cherry Creek Watershed

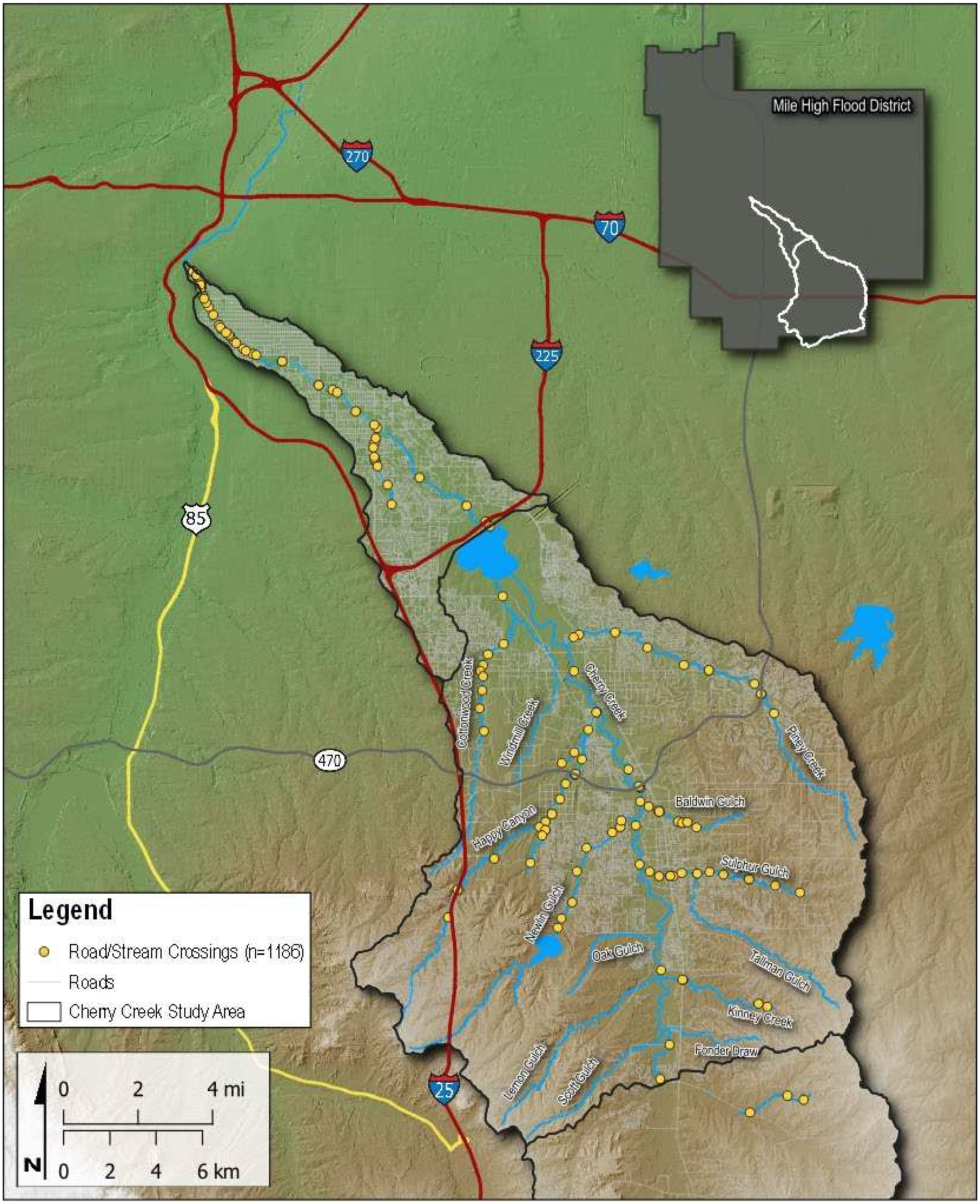

Figure 4.14 Road crossings in the Cherry Creek lower and middle sub-watersheds.

3.1.4 Reach typologies in the Cherry Creek watershed

I developed reach types across the Cherry Creek watershed following the process described in Section 2 and inspired by River Style® (Brierly and Fryirs 2005). For this study, I grouped reaches based on valley setting (confined, partly confined, or unconfined). We established valley setting using the valley bottom extraction tool (VBET) platform (Gilbert et al. 2016). This was followed by review of aerial photographs and rapid field analysis to validate the automated mapping of the valley bottom, channel, and accessible floodplain. I applied the height above nearest drainage, spatial raster data (derived from 10-meter and 1-meter DEM data), and relative elevation model (REM; Blazewicz et al. 2020) to further investigate riverscape physical properties.

I identified 14 different reach types, spanning the range of confined, partly confined, and laterally unconfined valley settings. This included perennial and intermittent streams. I considered six variables to assign a reach type within a decision tree. Variables leading to the typology are listed in organizational trees that include explicit, objective, and/or quantitative criteria (Figure 4.15, Figure 4.16, and Figure 4.17). Five of the reach type variables were derived from maps or digital elevation models and aerial imagery: valley confinement, presence/extent of floodplain, presence/absence of channel, channel pattern (number of channels and sinuosity), and urban riverscape characteristics (Table 4.3 and Figure 4.18).

I summarized the frequency of stream length by reach types and valley settings for all streams within the Cherry Creek Watershed. These data are critical for understanding the variable nature of the riverscapes and to track attributes that are helpful for a variety of hydrologic, geomorphic, and ecological-related analyses. Field characterization of geomorphic and vegetation attributes for each reach type was conducted at representative sites to verify those types and to determine bed material texture (see Appendix 2). Figure 4.19 shows the distribution of valley confinement and stream length data for the streams mapped on the MHFD stream network in the Cherry Creek middle and lower sub-watersheds. Figure 4.20 illustrates the reach types found in the Cherry Creek middle and lower sub-watersheds.

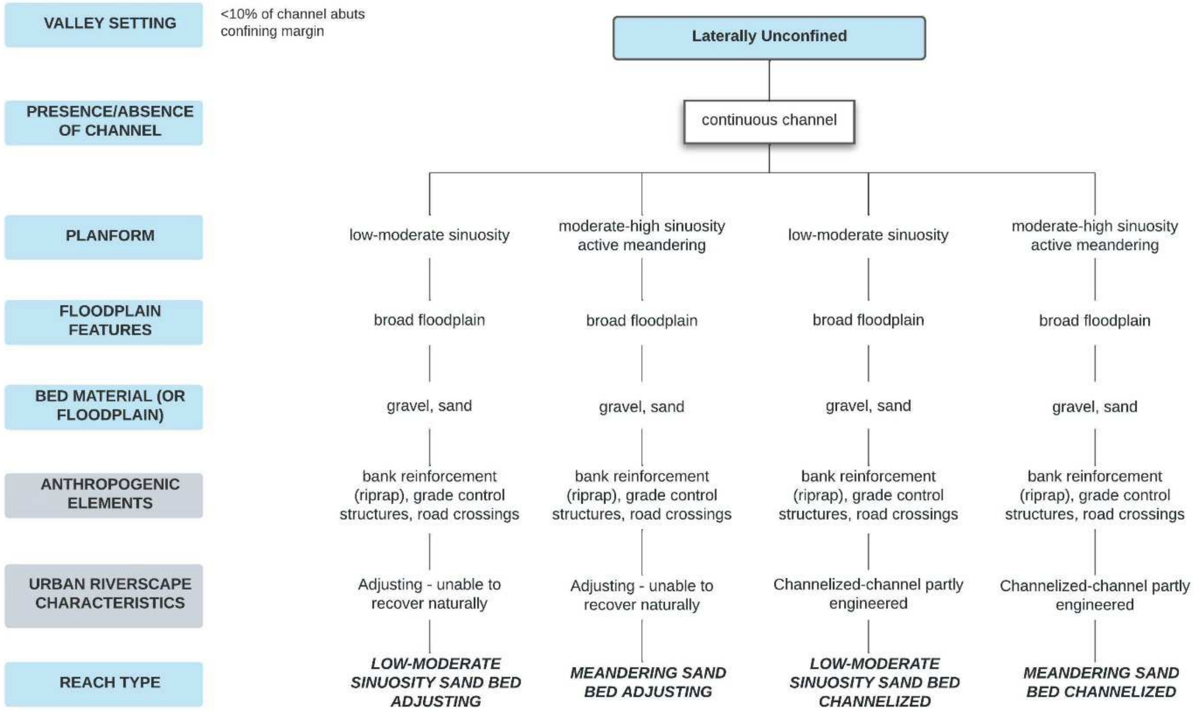

Figure 4.15 Reach typing tree for lower and middle Cherry Creek sub-watersheds in laterally unconfined valley setting

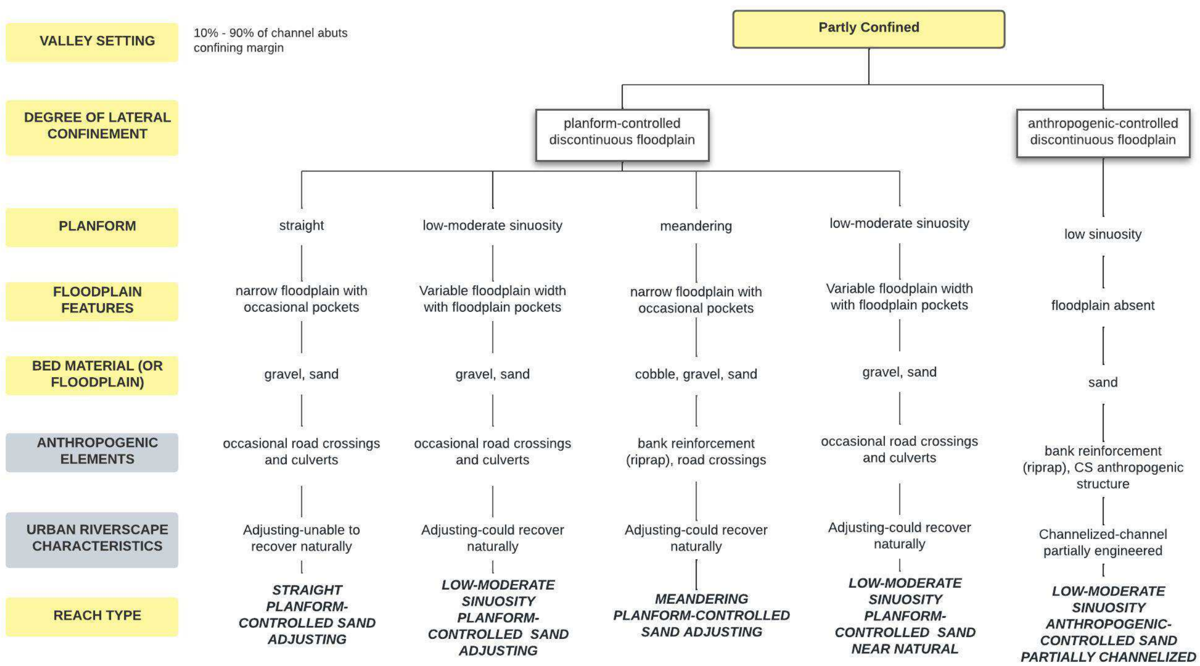

Figure 4.16 Reach typing tree for lower and middle Cherry Creek sub-watersheds in partly confined valley setting

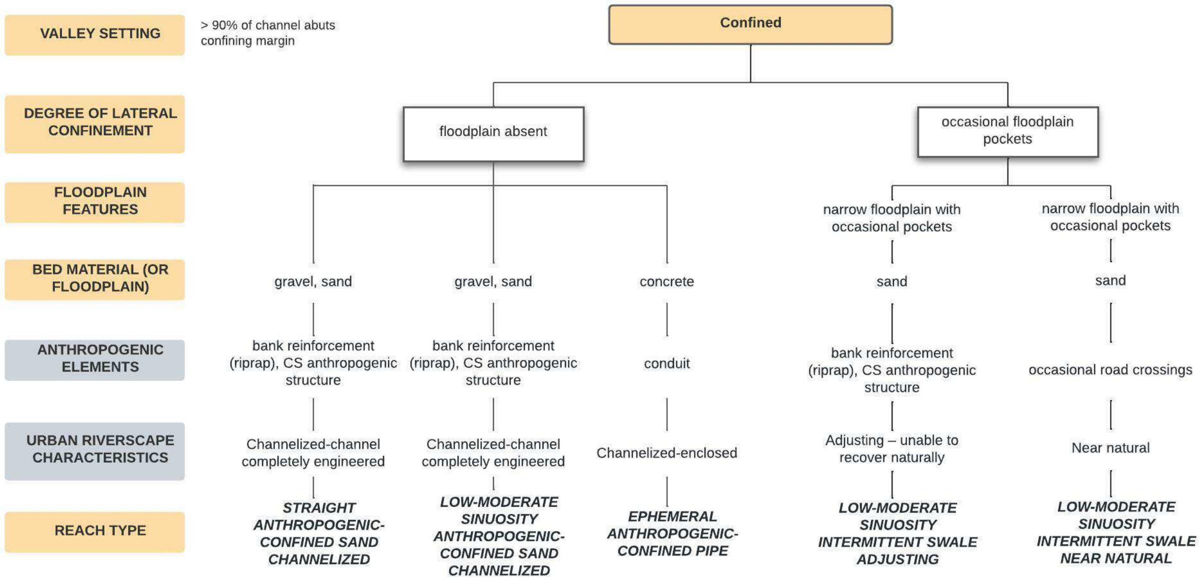

Figure 4.17 Reach typing tree for lower and middle Cherry Creek sub-watersheds in confined valley setting

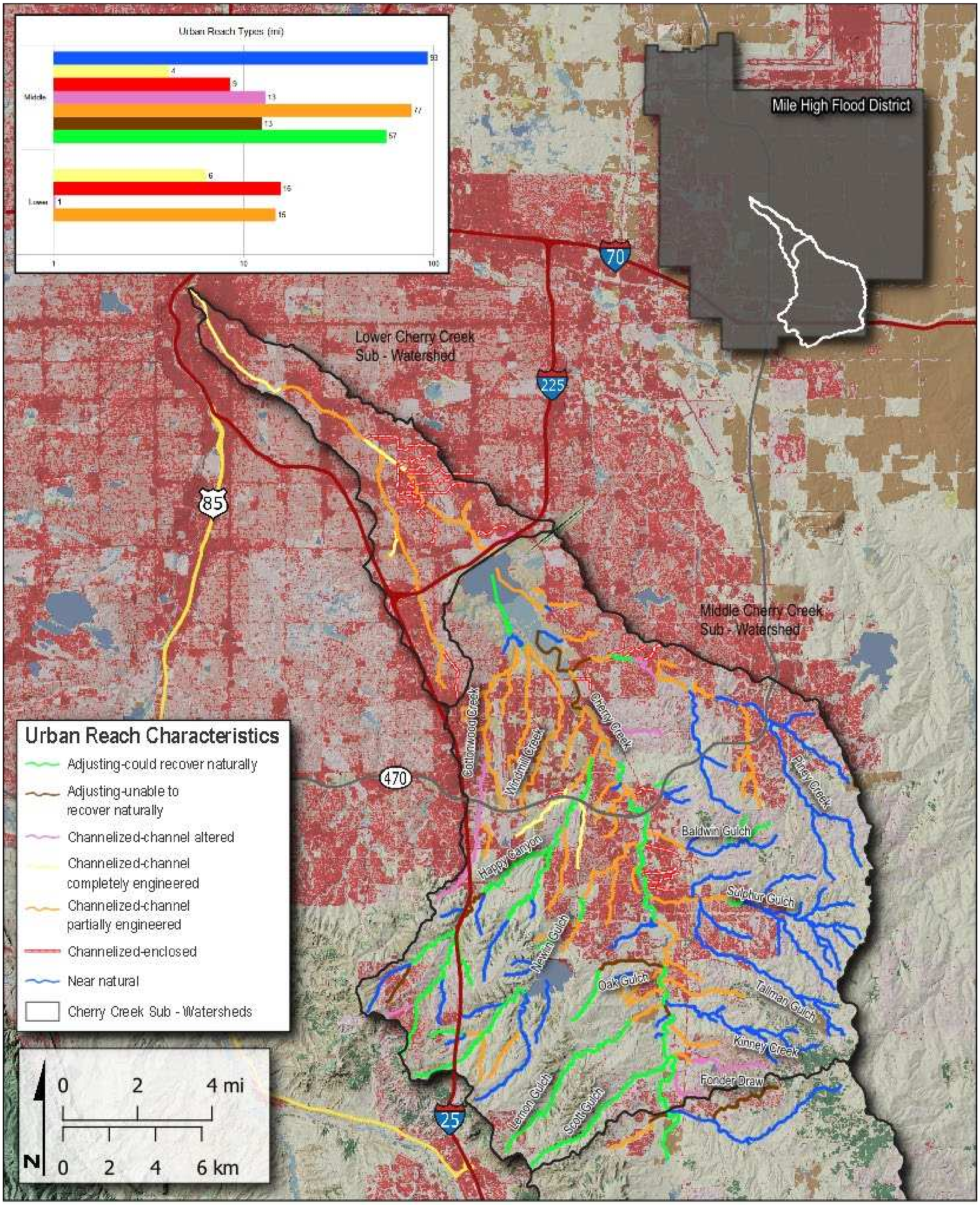

Figure 4.18: Urban reach types of streams in terms of stream length and valley confinement, in context of the lower and middle Cherry Creek sub-watersheds

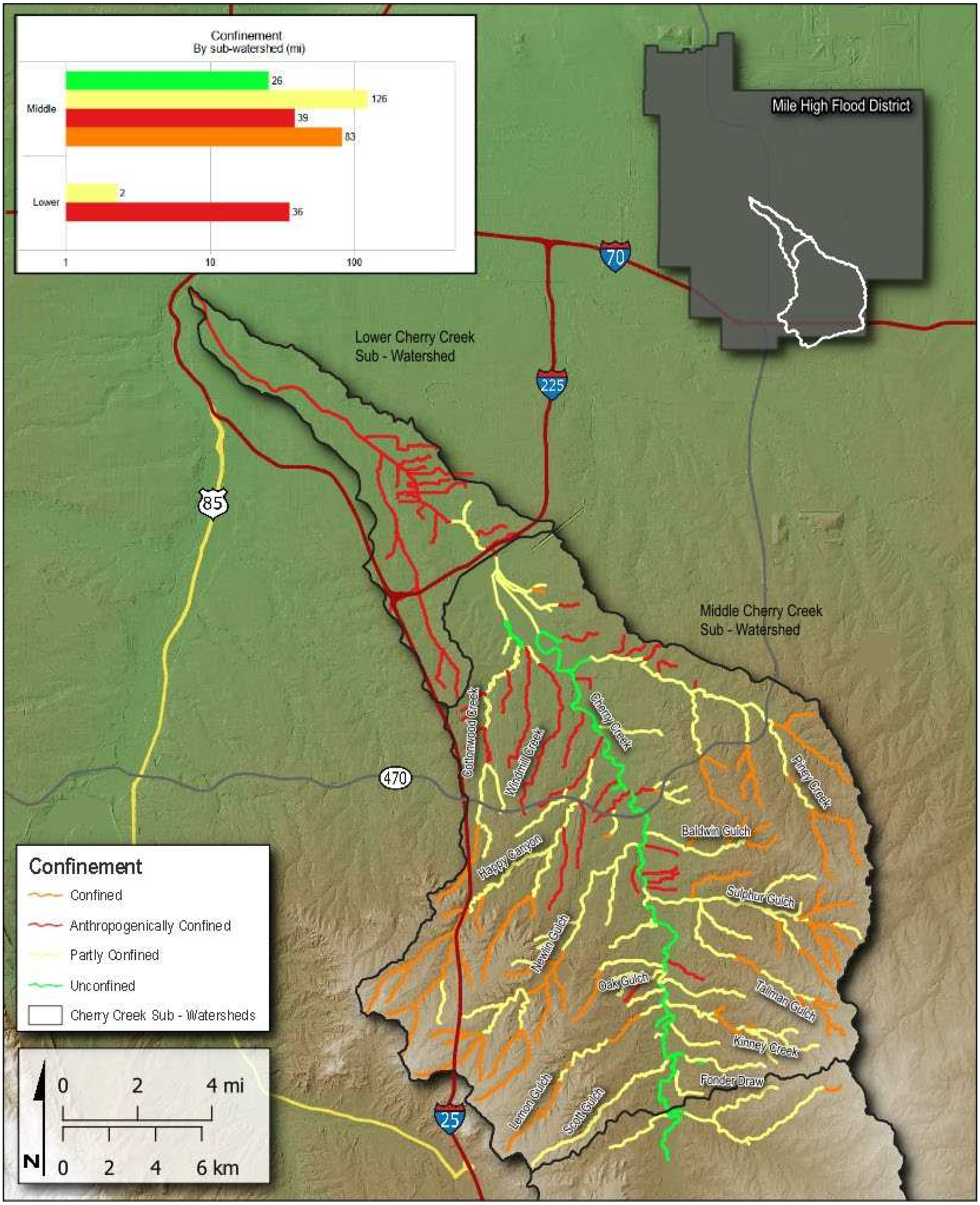

Figure 4.19 Valley confinement and length for the riverscapes in the Cherry Creek middle and lower sub-watersheds.

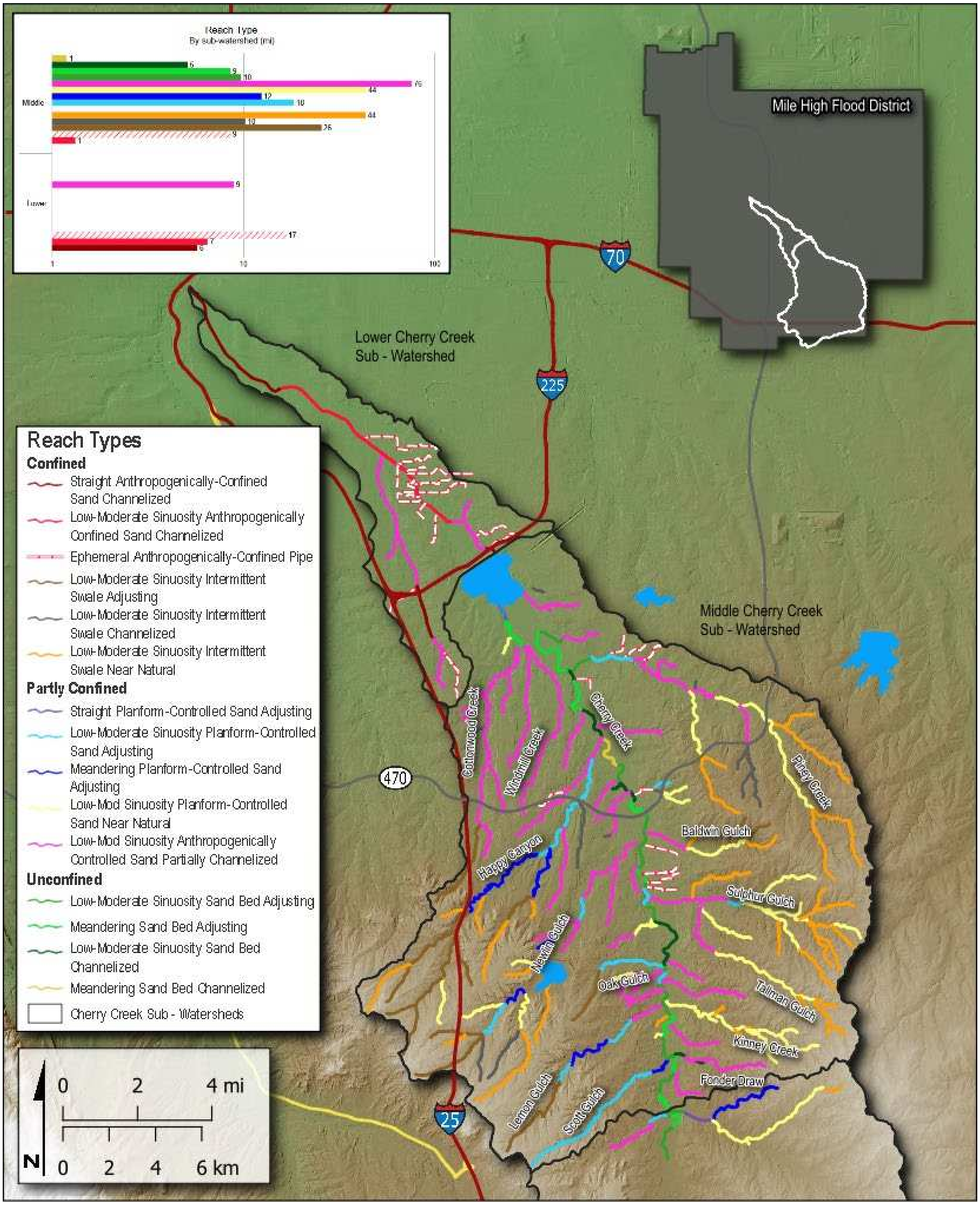

Figure 4.20 Reach types of riverscapes and associated length for the Cherry Creek lower and middle sub-watersheds.

Summary of reach types in laterally unconfined valley settings

Four reach types were identified within laterally unconfined valley settings, where the channel is in contact with the valley margins between less than 10% of the reach length (Figure 4.15 and Appendix 2). The low-moderate sinuosity sand bed adjusting and meandering sand bed adjusting reach types have broad, fine-grained floodplains, and comprise a large portion of the alluvial-filled valley segments along the mainstem Cherry Creek in the middle sub-watershed. The low-moderate sinuosity sand bed channelized and meandering sand bed channelized reach types have narrower floodplains due to anthropogenic features yet the reaches still comprise a portion of the alluvial-filled valley segments along the mainstem Cherry Creek in the middle sub-watershed.

The low-moderate sinuosity sand bed adjusting reach type and meandering sand bed adjusting reach type occur in reaches of the Cherry Creek within the middle sub-watershed where valley expansion or floodplain preservation has created lateral space and a wide, uniform floodplain. The channel is free to adjust across the floodplain unimpeded and is laterally unstable unless constrained by anthropogenic features. The channel interacts with foothills or low relief alluvial fans less than 10% of the time along its length. The channel is primarily single thread with occasional side channels. The bed is underlain by sand and occasional gravels and cobbles; instream geomorphic units include runs and glides in straight sections, and short pool-riffle sequences developed at meander bends or at grade control locations. Point bars are common, with occasional diagonal and lateral bars present. The banks are stable and steep-sided (1 horizontal:1 vertical), with a moderate width to depth ratio ($6 < W/D < 10$). The floodplain is composed of fine-grained materials deposited by overbank floods. The channels are adjusting to natural processes or anthropogenic features such as occasional road crossings or bank reinforcement.

The low-moderate sinuosity sand bed channelized reach type and meandering sand bed channelized reach type occur in reaches of the Cherry Creek within the middle sub-watershed where flood hazard reduction projects have reduced the valley-wide floodplain. However, the channel is still free to adjust across the floodplain, although it is constrained by anthropogenic features. The channel interacts with foothills or anthropogenic features less than 10% of the time along its length. The channel is primarily single thread with occasional side channels. The bed is underlain by sand and occasional gravels and cobbles; instream geomorphic units include runs and glides in straight sections, and short pool-riffle sequences developed at meander bends or at grade control locations. Point bars are common, with occasional diagonal and lateral bars present. The floodplain is composed of fine-grained materials deposited by overbank flows.

Summary of reach types in partly confined valley settings

Five reach types were defined within partly confined valley settings, where the channel is in contact with the valley margins between 10 and 90% of the reach length (Figure 4.16 and Appendix 2). These riverscapes start as headwater streams and are found downstream of confined valley settings. They represent narrow to broad floodplain with varying diversity of in-channel and floodplain geomorphic units. The low-moderate sinuosity planform-controlled sand bed near natural, straight planform-controlled sand bed adjusting, low-moderate sinuosity planform-controlled sand bed adjusting, and meandering planform-controlled sand bed adjusting have narrow to variable discontinuous floodplains. The low-moderate sinuosity anthropogenic-controlled sand bed partially channelized have minimal floodplain due to anthropogenic features such as concrete or riprap banks and have been partially channelized for flood control purposes.

The low-moderate sinuosity planform-controlled sand bed near natural occurs in intermittent headwater and mid-valley streams tributary to Cherry Creek within the middle sub-watershed. The straight planform-controlled sand bed adjusting, the low-moderate sinuosity planform-controlled sand bed adjusting, and meandering planform-controlled sand bed adjusting generally occur in intermittent streams also within the middle sub-watershed. The moderate to low slope (< 4%) reach types are found in partly confined valley settings with topographic ridges and occasional floodplain space for accumulation of stream bed materials, primarily sands and gravels. The channel is primarily single thread with sand bed substrate mixed with occasional gravels and cobbles. The planform is controlled by alluvial deposits and hillslope terraces. Instream geomorphic units are mostly absent due to the episodic flow regime and lack of large wood along the stream banks. The floodplain topography may have been influenced by ranching and farming.

The low-moderate sinuosity anthropogenic-controlled sand bed partially channelized reach types occur in intermittent streams tributary to Cherry Creek within the middle sub-watershed. The single thread moderate to low slope (< 2%) reach type is found in partly confined valley settings with minimal floodplain space outside of a larger flood control channel. The substrate is generally sand mixed with occasional gravels and cobbles. Floodplain geomorphic units are homogenous alluvial flats with occasional ridges. The planform is strongly controlled by alluvial deposits and hillslope terraces. Instream geomorphic units are mostly absent due to the episodic flow regime and lack of large wood along the stream banks. The floodplain topography has influenced by urbanization.

Summary of reach types in confined valley settings

Five reach types were defined within partly confined valley settings, where the channel is in contact with the valley margins greater than 90% of the reach length (Figure 4.17 and Appendix 2). The low-moderate sinuosity intermittent swale adjusting and low-moderate sinuosity intermittent swale near natural reach types are typically headwater riverscapes in the Cherry Creek middle sub-watershed. Generally, the first and second order streams begin as gulches on moderate to steep hillslopes in non-forested or sparsely forested areas of the middle sub-watershed. The imposed-form stream is in nearly continuous contact with valley walls, which is composed of consolidated colluvium or bedrock outcroppings. These channels have no visible floodplain or terrace surfaces and contain a narrow range of geomorphic units: primarily shallow thalweg swale or bedrock steps. Large wood is mostly absent and willows, cottonwoods and grasses line the channel. Streams of this reach type tend to collect snowmelt and overland flow from spring and summer storms in their channels. Channel lengths are commonly influenced by deposits from small mass wasting failures, agricultural encroachment, and by road crossings. Channels areas tend to have well-developed soil profiles with a gentle "U-shaped" channel shape obscured by bedrock outcroppings and steep hillslopes. Once established in confined valleys, the stream network gradually becomes more diverse in terms of instream geomorphic units and vegetation, but is directly connected to hillslopes with occasional floodplain pockets.

The straight anthropogenic-confined sand bed channelized, the low-moderate anthropogenic-confined sand bed channelized, and ephemeral anthropogenic-confined pipe reach types are found in the lower sub-watershed where urban development converted the once natural channels to stormwater and flood conveyance systems. Floods often turned Cherry Creek, from an “inconsequential dry channel into an enemy for the city to defeat.” In 1948, Cherry Creek Dam became the first of the three dams the Corps would build to lower the risks to the Denver region from catastrophic South Platte River floodwaters that plagued the area for more than 100 years. The once unconfined sand bed channel from the confluence with the South Platte upstream three miles was converted to a rectangular concrete-lined channel to efficiently convey flood flows (Figure 4.21). All of the tributaries to Cherry Creek in the lower sub-watershed were converted to stormwater systems. I defined those reach types as ephemeral anthropogenic-confined pipes due to their lack of connection to groundwater and episodic conveyance of runoff from rain and snow events.

Figure 4.21: 1933 aerial photograph (King 1933) of Cherry Creek in the lower sub-watershed through the City and County of Denver. The anthropogenic-confined trapezoidal straight channel is visible near the confluence with the South Platte River (upper left). Prior to urban development the creek was an unconfined meandering sand bed channel (lower right).

3.1.5 Longitudinal profiles and downstream pattern analysis along the Cherry Creek mainstem

As discussed in section 2.2.3, controls on the longitudinal profile of a stream are dominated by the geology, the relief, and the slope of the channel (Pederson and Tressler 2012). To investigate those controls in the Cherry Creek watershed, I constructed a longitudinal profile (Figure 4.22) of the Cherry Creek main stem within the upper, middle, and lower sub-watersheds. In the profile, I plotted (a) elevation with the longitudinal profile reflecting valley slope; (b) upstream drainage area using data from a 1-dimension HEC-RAS model and NHD+ HR data (Moore et al. 2019) to derive upstream watershed area; (c) Level IV ecoregions, as they intersect the longitudinal profile; and (d) unit stream power from the HEC-RAS model for the 10-year discharge. Valley setting and reach types are also shown on Figure 4.22.

Cherry Creek has a relatively smooth profile with some notable features. For example, the channel descends rapidly from its headwaters, but thereafter assumes a relatively constant gradient along the course toward its confluence with the South Platte River. The drainage area profile is also relatively smooth although, as expected, it rapidly increases at the confluence with major tributaries and downstream of the reservoir due to stormwater inflows from urban areas that are highly impervious. The unit stream power varies considerably along the channel. Significant spikes in the middle sub-watershed are generally due to increases in discharge at confluences and rapid changes in slope and width at grade control structures while sudden change in width at bridges primarily drives the spikes in the lower sub-watershed. Figure 4.22 includes threshold lines for two unit stream powers: 1) 230 w/m^2 and 2) 480 w/m^2. Yochum et al. (2017) suggested channel widening initiates at 230 w/m^2 and avulsions and braiding processes start at 480 w/m^2. The unit stream power values along the Cherry Creek mainstem frequently exceed the 230 w/m^2 threshold in both the middle and lower sub-watersheds, and occasionally exceeds the 480 w/m^2 threshold in lower sub-watershed. These exceedances indicate high-risk of potential rapid geomorphic changes.

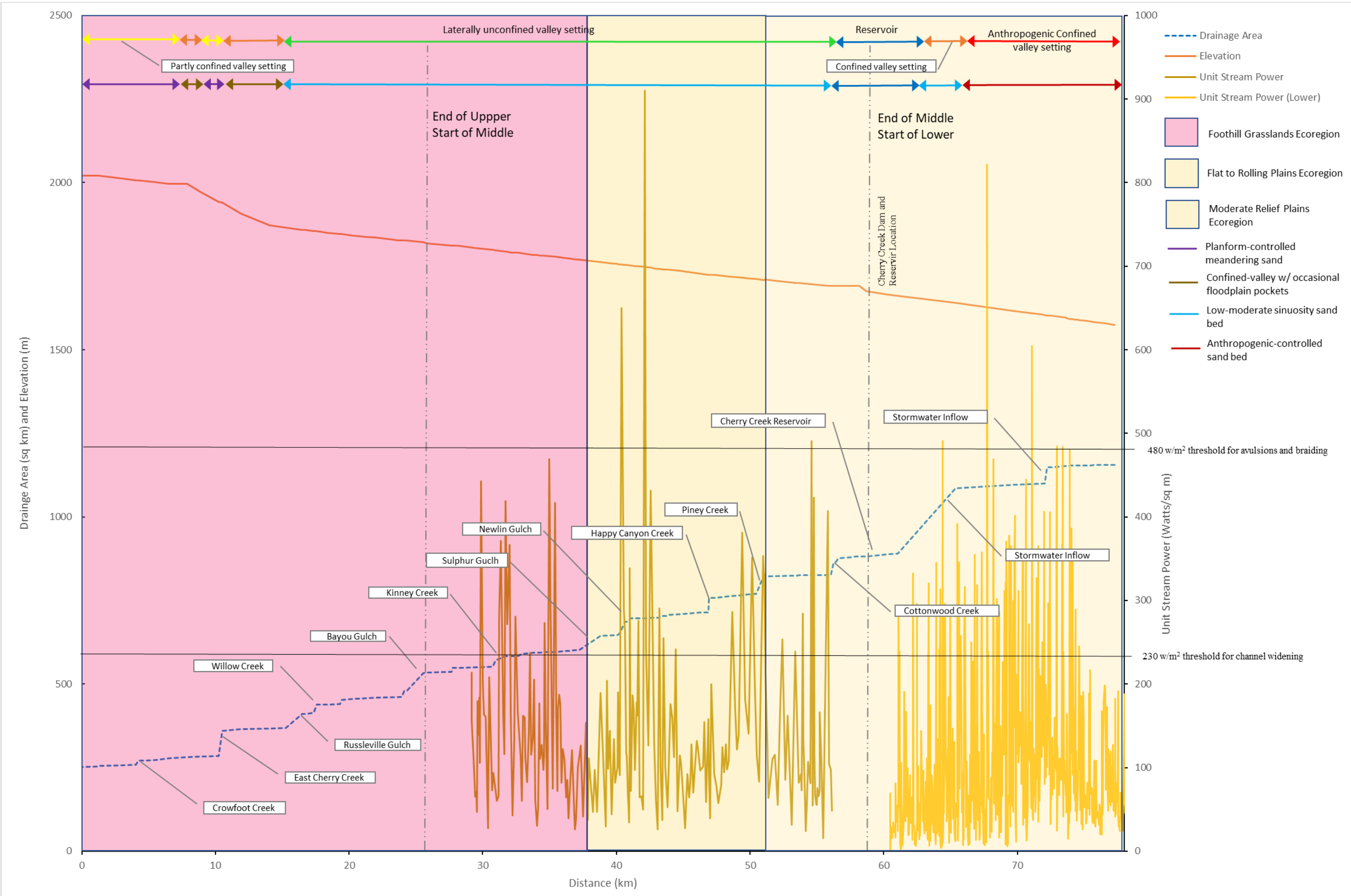

Figure 4.22 Examples of controls on downstream patterns of reach types on Cherry Creek mainstem

The valley setting generally follows a typical downstream pattern from the upper sub-watershed through the middle sub-watershed – confined to partly confined to laterally unconfined (Cherry Creek is confined in its headwaters, which are not shown on Figure 4.22). The reservoir, urban development, and channelization change that pattern, introducing an atypical valley setting – anthropogenic-confined riverscape. The same pattern is generally consistent with reach types where a confined-valley with occasional floodplain pockets transitions to planform-controlled meandering sand bed channel then to a low-to-moderate sinuosity sand bed riverscape upstream of the reservoir. Downstream of the reservoir, the riverscape of low-to-moderate sinuosity sand bed channel transitions to an anthropogenic-controlled sand bed riverscape that is a mix of riprap-lined and concrete-lined channels designed with a singular purpose: flood conveyance.

3.1.6 Response potential of riverscapes and reaches in the Cherry Creek watershed

The response potential of each reach type (Table 4.10 and Figure 4.23) is based on the geomorphic risk characteristics described in Section 2.2.4 (Table 4.4), which are linked to reach types (Figure 4.20) and downstream patterns. The response potential is a proxy for riverscape or reach sensitivity to disturbances, which is used as a basis for measures of geomorphic and ecological condition for each reach type and to guide the selection of management strategies. In the case of the Cherry Creek lower and middle sub-watersheds, I designated the laterally unconfined reach types along the Cherry Creek mainstem with a high response potential due to the sand bed channel and flow regime flashiness. The partly confined planform-controlled reach types were defined as high response potential as well due to their slope, bed and bank material, and lack of a broad floodplain. They are also characterized as "adjusting" to natural processes and anthropogenic stressors. The partly confined anthropogenic-controlled reach types were assigned a moderate response potential rating based on the anthropogenic features, including riprap, constructed riffles, and irrigated vegetation, that maintain\ stability, except during extreme storm events. Both the adjusting and near natural confined intermittent swales reach types were classified as moderate response potential based on their slope and sparse vegetation. If a reach was classified as channelized (indicating that the channel was completely engineered) or pipe, the response potential shifted from moderate to low. Note that a higher the stream response potential relates directly to an increased assessment and management effort. If the reach type indicates a high response potential, then a Level 3 data collection and analysis is recommended.

Table 4.10 Response potential as a proxy for sensitivity to disturbances applying risk characteristics found in Table 4.4.

Reach Type	Response potential	Reach Type	Response potential	Reach Type	Response potential
CONFINED VALLEY SETTING		**PARTLY CONFINED VALLEY SETTING**		**LATERALLY UNCONFINED VALLEY SETTING**	
Low-moderate sinuosity intermittent swale adjusting	Moderate	Straight planform-controlled sand adjusting	Moderate	Low-moderate sinuosity sand bed adjusting	High
Low-moderate sinuosity intermittent swale near natural	Moderate	Low-moderate sinuosity planform-controlled sand adjusting	Moderate	Meandering sand bed adjusting	High
Straight anthropogenic-confined sand bed channelized	Low	Meandering planform-controlled sand adjusting	High	Low-moderate sinuosity sand bed channelized	Moderate
Low-moderate sinuosity anthropogenic-confined sand bed channelized	Low	Low-moderate sinuosity planform-controlled sand near natural	High	Meandering sand bed channelized	Moderate
Ephemeral anthropogenic-confined pipe	Low	Low-moderate sinuosity anthropogenic-controlled sand partially channelized	High		

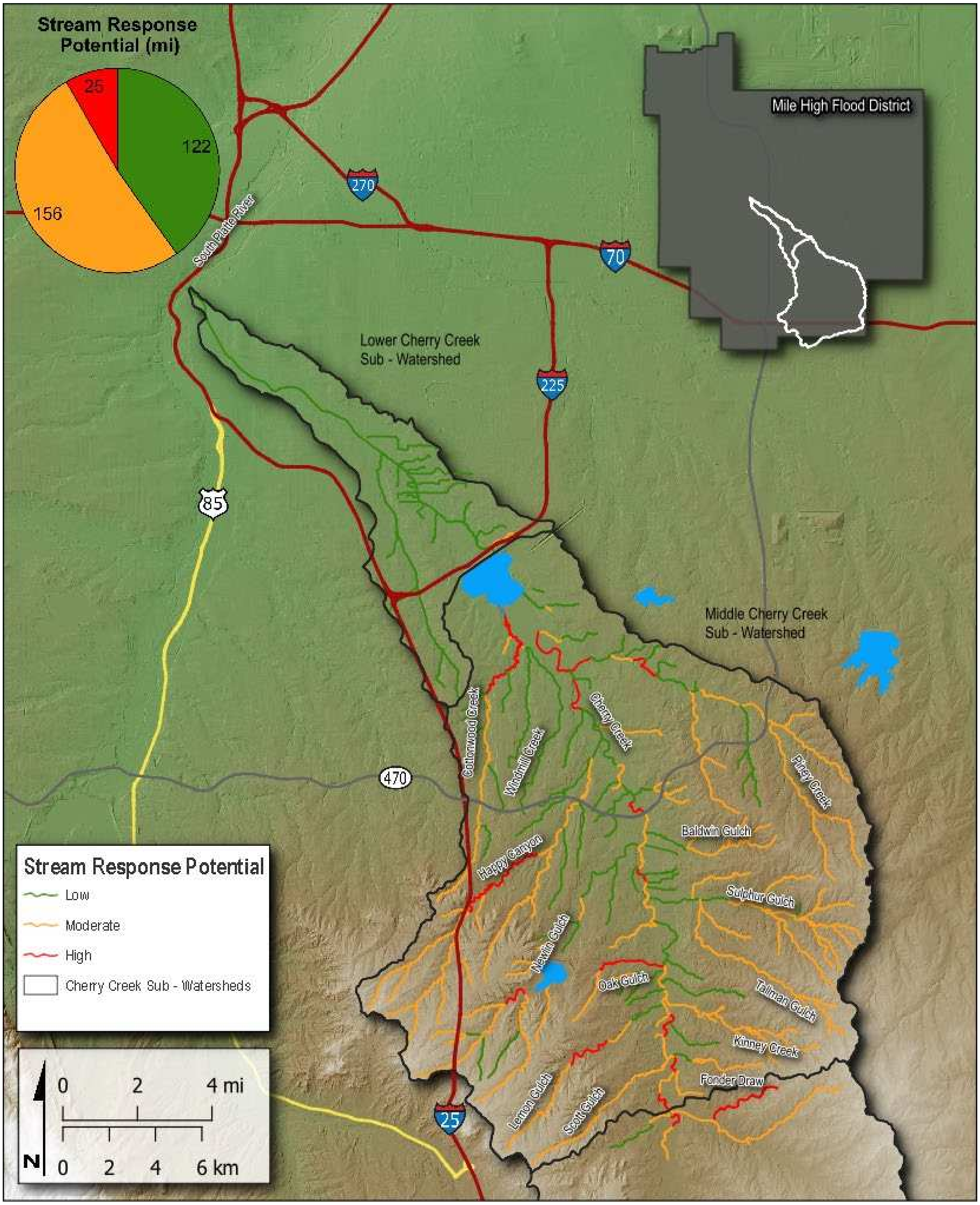

Figure 4.23 Response potential of the streams in the lower and middle Cherry Creek sub-watersheds.

3.2 Assessment of the Cherry Creek watershed

3.2.1 Indicators, metrics, functional scores, and social-ecological qualities

I implemented the URBAN method on the riverscapes in the Cherry Creek lower and middle sub-watersheds to assess hydrologic, geomorphic, and ecologic (i.e. vegetation) condition and the link to human connections and values using the indicators and metrics in Table 4.11. The Level 2 analysis produced an output of functional characteristics for each facet at the riverscape and reach scales. Criteria used to appraise each metric are semi-quantitative measures, such that fully functional, functional, partly functional, and not functional categories can be determined for reach types. The flexibility of this approach enables the overall category of condition that is determined for a reach to be broken down into its physical template and anthropogenic stressors. This allows management applications that use these procedures to target the specific attribute(s) that resulted in the riverscape being classified as partly functional or not functional.

URBAN also includes Level 3 metrics designed for fine scale assessment using high resolution data. I did not apply those in this study due to my focus on testing and validating the Level 1 and Level 2 metrics (i.e., remote sensing and rapid field data collection); however, I have provided a list of potential indicators and metrics for Level 3 assessment in Appendix 3.

Table 4.11 Summary table of URBAN's indicators, metrics, and scoring criteria that were applied on the riverscapes in Cherry Creek middle and lower sub-watersheds to assess physical conditions and community values.

Facet	Indicators	Metrics	Social-ecological values and functional characteristics
Human connections and values	Access to nature	Universal access	(A) High quality: riverscape or reach offers diverse access to experience nature (B) Moderate quality: riverscape or reach provides moderately diverse access to experience nature (C) Moderate quality: riverscape or reach provides limited access to experience nature (D) Poor quality: riverscape or reach provides no access to experience nature
	Economics	Ecosystem services	(A) High quality: riverscape or reach offers equitable levels of service and sustained natural and anthropogenic functions, resilient landscapes, and lower routine maintenance costs. (B) Moderate quality: riverscape or reach offers moderate equitable levels of service and supports natural and anthropogenic functions and moderate routine maintenance costs. (C) Moderate quality: riverscape or reach offers limited equitable levels of service and limited natural functions, moderate anthropogenic services, and high routine maintenance costs. (D) Poor quality: riverscape or reach offers limited equitable levels of service and the natural not function, limited anthropogenic services, and high routine and long-term maintenance costs.
	Stewardship	Compliance with water quality standards	(A) High quality: riverscape or reach exceeds all local, state, and federal water quality standards. (B) Moderate quality: riverscape or reach meets all local, state, and federal water quality standards. (C) Moderate quality: riverscape or reach partly meets all local, state, and federal water quality standards. (D) Poor quality: riverscape or reach does not meet all local, state, and federal water quality standards.
Hydrologic processes and Hydraulic characteristics	Runoff production	Land-use gradient	(A) Fully functional: no alteration of natural runoff processes (no stressors) (B) Functional: limited alteration of natural runoff processes (minimal stressors) (C) Partly functional: moderate alteration of natural runoff processes (multiple stressors) (D) Not functional: significant alteration of natural runoff processes (large dam/reservoir, multiple diversions)
	Flow regime	Flow regime change	(A) Fully functional: no alterations of natural runoff processes and no in-channel structures (no stressors). (B) Functional: limited alterations of natural runoff processes and in-channel structures (minimal stressors). (C) Partly functional: multiple alterations of natural runoff processes and in-channel structures (multiple stressors). (D) Not functional: significant alterations of natural runoff processes and in-channel structures (significant stressors).
	Flood/fluvial hazards	Structures in broad floodplain	(A) Fully functional: absence or negligible presence of structures within maximum potential accessible floodplain extent or 500-year floodplain. (B) Functional: absence or negligible presence of structures within active floodplain extent or 500-year floodplain. (C) Partly functional: limited presence of structures within active floodplain extent or 500-year floodplain. (D) Not functional: presence of structures within active floodplain extent or 500-year floodplain.
Geomorphic forms & processes	Sediment regime	Sediment continuity	(A) Fully functional: absence of alteration in the continuity of sediment and wood, and no crossing structures (bridges, diversions, culverts) (B) Functional: slight alteration (minor obstacles to the flux but with no interception) requiring limited maintenance. Presence of some crossing structure (≤1 every 2000 m on average) (C) Partly functional: moderate alteration (major obstacles to the flux but with no interception). Presence of numerous crossing structures (>1 every 2000 m on average) (D) Not functional: significant alteration (complete interception of sediment and wood). Presence of numerous crossing structures (>1 every 1000 m on average along the corridor)
	Stability	Stream power gradient	(A) Fully functional: the unit stream power (USP) gradient along the is corridor self-sustainable with no management or maintenance required. Limited, if any, major fluctuations in the ratio between upstream and downstream unit power. (B) Functional: moderate fluctuations in USP may exist, but they are either insignificant or they localized to only a small portion of the overall corridor. (C) Partly functional: major fluctuations in USP, and they impact more than 33% of the corridor. (D) Not functional: major fluctuations in USP exist, and they impact more than 50% of the corridor. Erosion and sedimentation are significant to a level that results in an inability to support functional processes.
	Morphology	Response potential	(A) Fully functional: dynamically meta-stable riverscape featuring historical natural planform connected to a frequently inundated floodplain that supports riparian vegetation; SEM Stages 0 and 8 (B) Functional: dynamically stable and laterally active channel within a floodplain complex; SEM Stages 1 and 7 (C) Partly functional: quasi-equilibrium channel with two-stage cross-section featuring regime channel inset within larger, degraded channel; SEM Stage 6 (D) Not functional: incising with unstable, retreating banks and abandoned floodplain or bed rising, aggrading, widening channel with unstable; SEM Stages 2, 3, 3s, 4, 4-3, and 5
Ecological structure & processes	Dynamic stability	Riparian vegetation width	(A) Fully functional: wide connected functional riparian vegetation (>nW, where n=1 or 2 for wandering—braided or for single thread channels, respectively, and W=channel width) (B) Functional: intermediate width of connected functional riparian vegetation (0.5W to nW) (C) Partly functional: intermediate width of connected functional riparian vegetation (0.2W to .5W) (D) Not functional: narrow connected functional riparian vegetation (≤0.2W)

3.2.2 Data collection

A wealth of "Level 1" data exists for the Cherry Creek watershed, making it important to balance the need to incorporate relevant and valuable data into this study with the scale that data is applicable. I leveraged the Riverscapes Consortium tools including the Riverscapes Context Tool (Riverscape Consortium 2022) that aggregates contextual layers such as 10-meter digital elevation models (DEMs) from the National Elevation Dataset (NED; USGS 2019), LANDFIRE vegetation (LANDFIRE 2021), hydrology from the National Hydrography Dataset (NHD+ HR; Moore et al. 2022), and transport networks. I also acquired other relevant, publicly available hydrogeomorphic, vegetation, and social-ecological data, including LiDAR (DRCOG 2020, 2013), FEMA National Flood Hazard Layer (NFHL; FEMA 2022), land use land cover data (Drummond et al. 2017; Dewitz and USGS 2021), etc. Table 4.12 lists the geospatial data I used to develop the regional context and watershed characteristics in addition to assessing riverscapes and reaches.

Table 4.12 Geospatial data sources relevant to the Cherry Creek watershed leveraged for the testing and validation of URBAN.

Data	Description	Source(s)
Aerial photography	Google Earth (1937-2021), NearMap, (2014-2022)	Google Earth 2022, Nearmap 2022
Topography	USGS (10 meter DEM), Denver Regional Council of Governments 1-metter LiDAR (DRCOG)	USGS 2022; DRCOG 2013, 2020
Drainage network	USGS NHD+ HR, MHFD	Dewitz and USGS 2021; MHFD 2022
Vegetation	Colorado Parks and Wildlife (CPW) vegetation type mapping, CPW riparian corridors (2012), NLCD (2016), LANDFIRE existing and historical vegetation	CPW 2012, Dewitz and USGS 2021
Hydrology	USGS gages (1950s and later), Cherry Creek Water Quality Basin Authority (CCWQBA) annual reports	CCWQBA 2020
Land use land cover	USGS (1937, 1957, 1977, 1997), DRCOG, NLCD	Drummond et al. 2019; DRCOG 2022,
Imperviousness	NLCD (2019)	Dewitz, J. and USGS, 2021
Geology	USGS, Colorado Geologic Society	Moore et al. 2001
Ecoregions	EPA Level III and Level IV ecoregions	Chapman et al. 2006
Transportation	TIGER, Colorado Department of Transportation shapefiles	
SoVI	MHFD dataset	Michael Baker 2021
Access to Nature	Metro Denver Nature Alliance analysis	TPL 2017
Ecosystem services	EPA Natural Capital Resources	Ecosystem Sciences Foundation 2017

In the Front Range of Colorado, the temporal scale of investigation generally corresponds to the past 100 to 150 years. However, reliable data on stream morphology and riparian types are usually unavailable on longer time scales. Thus, reconstruction of historical change is highly subject to the quantity and type of information that is available, and this is certainly the case for the Cherry Creek watershed. Historical reconstruction of lateral dynamics, for example, depended entirely upon aerial photographs (1937 to present day).

Field verification for each reach type, and social-ecological qualities and physical conditions scores was conducted at representative sites. Rapid field analysis (i.e., "Level 2") consisted of completing proforma for reach type to confirm or modify reach type designations and boundaries. Information documented in the proformas includes stream character, structural elements, anthropogenic features, floodplain geomorphic units, vegetation associations, and stream behavior. Proformas describing characteristics of each representative reach type are provided along with site photographs in Appendix 2. For this study, I did not identify geomorphic unit assemblages due to the focus on broad to moderate resolution data.

As many of the physical conditions and social-ecological values metrics as possible were verified in the field, and scores were refined where warranted. Field verification prioritized checking metrics that can be difficult to score using aerial photographs, such as geomorphic properties (e.g., depositional reaches), bank stability, and riparian vegetation width. Field verification was also used to clear up instances of uncertainty and served to calibrate scoring guidelines. I visited as many locations as possible within time and private property access constraints between October 2019 and May 2022.

3.2.3 Data evaluation and diagnosis of conditions

I applied the riverscape-scale metrics (Table 4.11) across the Cherry Creek lower and middle sub-watersheds. Available data were used for interpreting the present-day conditions with regards to each of the four facets at the riverscape and reach-scales. The Cherry Creek lower and middle sub-watersheds contain a range of riverscape conditions. Figure 4.24 partitions the stream network into categories of fully functional, functional, partly functional, and not functional conditions for each of the four facets based on the functional characteristics and social-ecological values in Table 4.11. I also derived stream length metrics for each of the four facets, which are shown in Figure 4.24.

In the lower sub-watershed, the riverscapes were generally rated functional and partly functional for the human connections and values facet based on the metric scoring of the access to nature and ecosystem services indicators. The stewardship indicator was ranked as partly functional along the mainstem because the stream is on the 303d list and only partly meets federal and state water quality standards. The condition of hydrologic processes and hydraulic characteristics facet were rated partly functional along the mainstem due to the reservoir's influence on the flow regime and the effect of increased runoff production from the tributaries to the mainstem. The reservoir prevents flood hazards from effecting adjacent urban areas so the mainstem was rated as partly functional. Geomorphic and ecological conditions were generally rated similar across all reach types in the lower sub-watershed with the mainstem scoring partly functional and the ephemeral anthropogenic-controlled tributaries scoring not functional. The geomorphic and ecological indicators and metrics suggest significant alterations to sediment continuity and limited riparian vegetation width.

The scoring of human connections and values facet in the middle sub-watershed indicate a range of fully functional, functional, and partly functional conditions. The majority of the tributaries offer access to the riverscape and provide ecosystem services with water that meets federal and state water quality regulations. The scoring of the physical conditions showed similar conditions across the three facets with a similar number of stream miles rated as fully functional, functional, and partly functional conditions, although a few reaches ranked as not functional for geomorphic and ecological conditions. Runoff production and flow regime tend to be near natural for many of the tributaries with negligible presence of structures in the broad floodplain. The sediment regime and riparian vegetation are also near natural and the riverscapes are generally stable.

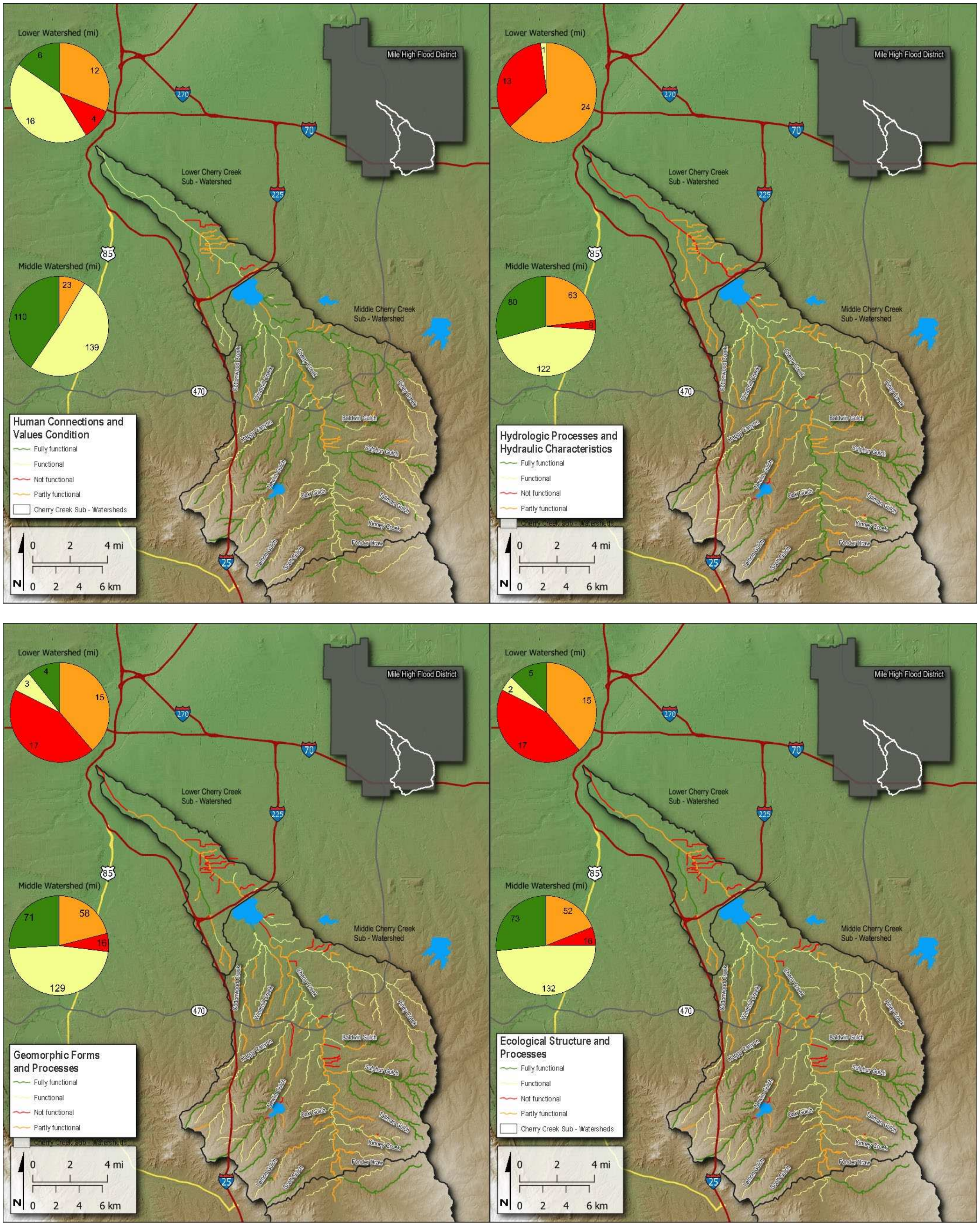

Figure 4.24 Human connections and values qualities, hydrologic, geomorphic, and ecological conditions across the Cherry Creek lower and middle sub-watersheds.

3.3 Management of the Cherry Creek watershed

3.3.1 Synthesis

The overall riverscapes condition (Figure 4.*25*) in the lower sub-watershed primarily was rated not-functional with the exception of one tributary that was scored functional and partly functional. The low scores reflect the poor function of hydrologic, geomorphic, and ecological facets due to land use changes, stormwater management practices, and channelization. However, the mainstem is a valued recreational corridor and provides access to nature for the local community, so the human connections and values facet tends to outweigh the physical conditions in this case.

In the middle sub-watershed, the overall condition analysis shows riverscapes are fully functional and functional in most of the intermittent swales that are in undeveloped areas (those that demonstrate low LDI values), functional and partly functional in the lightly disturbed LDI areas, and partly functional and not functional in the heavily disturbed and significantly disturbed LDI areas (Figure 4.26). Along the Cherry Creek mainstem, the overall alignment and broader channel sinuosity has changed very little, although historical aerial imagery reveals episodic periods of aggradation and degradation/incision in response to hydromodification and flood events, with varying channel responses.

From the assessment of the four facets' specific set of conditions as well as the overall condition, I observed the following:

- A vast majority of the lower, and some of the middle, sub-watershed has concentrated higher land-use intensity areas within the valley bottoms and along riparian corridors, while land downstream of the reservoir is ultra-urban with no apparent remnants of its pre-development land uses. Riverscapes with no diversions and little to no land use changes, typically reflect fully functional or functional geomorphic and ecological (i.e., vegetation) conditions. The spacing of the road crossings also plays an important role in the disconnection of the valley bottom.

- An intact, pristine example of any reach type does not exist in either the lower or middle sub-watersheds. The confined low-moderate sinuosity intermittent swale near natural reach type is the only reach that may resemble a pre-settlement condition.
- Most of the reach types in the middle sub-watershed are adjusting to either (or both) natural processes and anthropogenic stressors. Rapid changes in land use could potentially adversely impact physical the condition due to the risk characteristics and associated response potential.
- The anthropogenic-confined and partly confined anthropogenic-controlled reach types reflect efforts by local agencies and stakeholders to find a balance between mimicking natural processes and protecting people and property, while also providing recreational amenities within heavily and significantly disturbed landscapes and riverscapes.
- Most of the riverscapes and reaches in the lower sub-watershed were likely laterally unconfined low sinuosity or meandering sand bed reach types but were converted to anthropogenic-confined channelized or pipe reach types. This “novel” river style possesses low response potential and high to moderate social-ecological qualities, yet is partly to not functional.
- Varying intermittent reach types of confined and partly confined valley settings are driven by the arid climate , ecoregions, geology, and human influences of the Cherry Creek watershed. These reach types are compelling because they offer an opportunity to implement the conceptual framework described in Chapter 1 that guides urban stream management toward problem definitions and solution spaces that encourage adaptive, collaborative, and transdisciplinary approaches.

The results of the Cherry Creek assessment highlight the importance of protecting and preserving areas that are fully functional and provide the highest social-ecological quality while also not discounting the importance of areas with low physical function yet high to moderate social-ecological qualities.

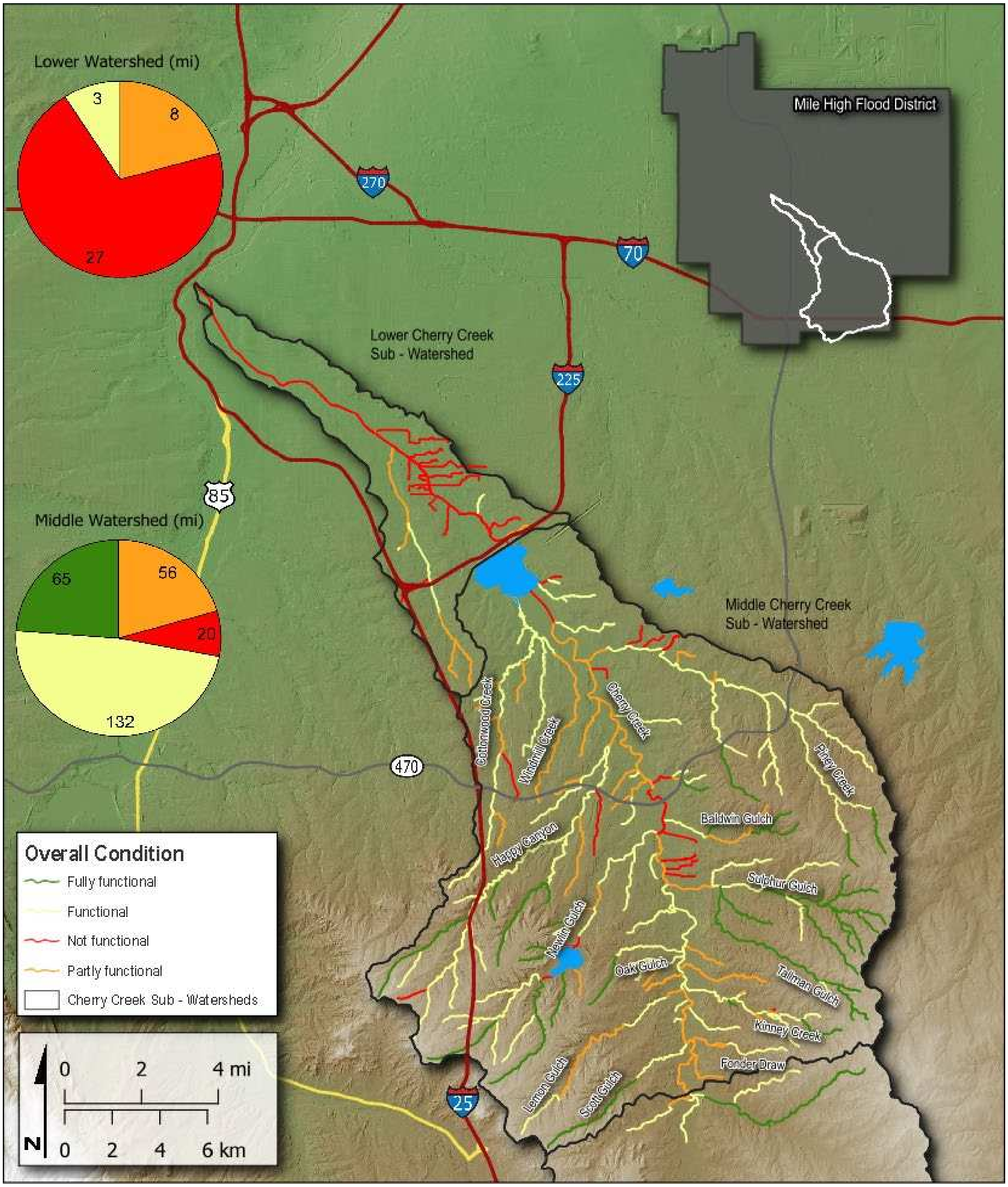

Figure 4.25 Overall condition across the Cherry Creek lower and middle sub-watersheds based on combing the scores from URBAN's four facets.

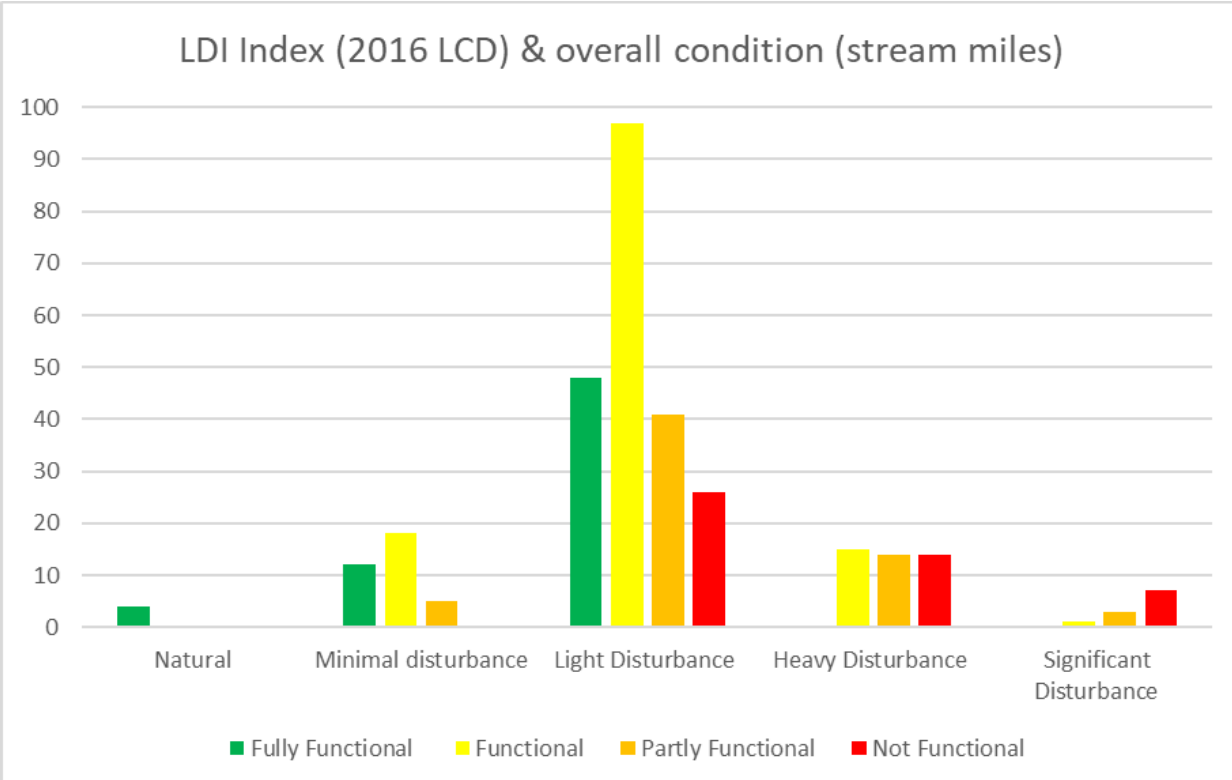

Figure 4.26 LDI values for the overall condition across the Cherry Creek lower and middle sub-watersheds.

3.3.2 Management strategies

Evaluating the interconnections and disconnects between reach typing, hydrologic, geomorphic, and ecological conditions, and human connections and values ratings (Figure 4.24 and Figure 4.25) were used to determine management strategies for the Cherry Creek lower and middle sub-watersheds (Figure 4.27). The management reaches focus on (a) maintaining the highly functional reaches in the middle sub-watersheds, (b) restoring functions of the mainstem and primary tributaries in the middle sub-watershed, and c) maintaining human connections along the lower and middle sub-watershed without further degrading function. The management strategies also recognize the constraints and realities of these urbanized and urbanizing riverscapes:

- Conservation reaches tend to be in the middle sub-watershed intermittent headwater streams and riverscapes that are adjusting or near natural in confined or partly confined valley settings with low to moderate LDI index values (Figure 4.28) and with high human connections and values qualities (existing or potential).

- Strategic reaches along the Cherry Creek mainstem and major tributaries in the middle sub-watershed align with functional hydrologic, geomorphic, or ecological conditions, moderate to high response potential, and adjusting urban reach characteristics that could recover naturally.
- High priority reaches were identified in the middle sub-watershed with functional and partly functional conditions and high to moderate social-ecological values qualities. These reaches tend to be a link between confined low-moderate sinuosity intermittent swales that are adjusting or near natural reach types and partly confined planform-controlled or anthropogenic-controlled reach types. Social-ecological values are considered high to moderate such that a restoration project could maximize the intersection between physical condition and human connections.
- Moderate priority reaches in the lower and middle sub-watersheds include partly functional riverscapes and reaches with high to moderate human connections and values qualities or a partially engineered channel. These reaches also include moderate response potential and isolated physically not functional and high to moderate quality human connections and values reaches.
- Low priority reaches tend to be partly and not functional reaches that are completely engineered channels with high to moderate quality human connections and values and low response potential (e.g., Cherry Creek concrete walled section near downtown Denver).

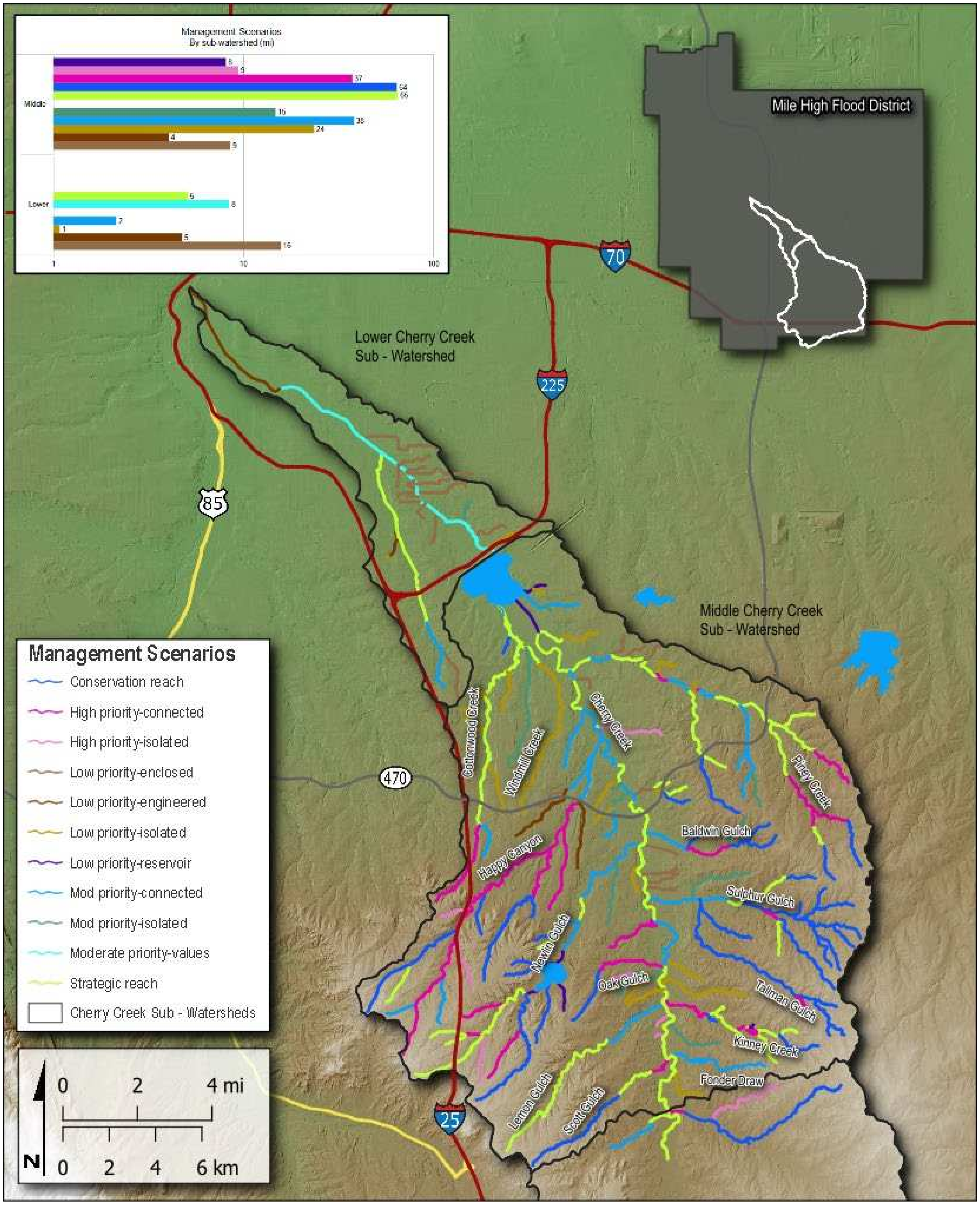

Figure 4.27 Management scenarios for the Cherry Creek lower and middle sub-watersheds.

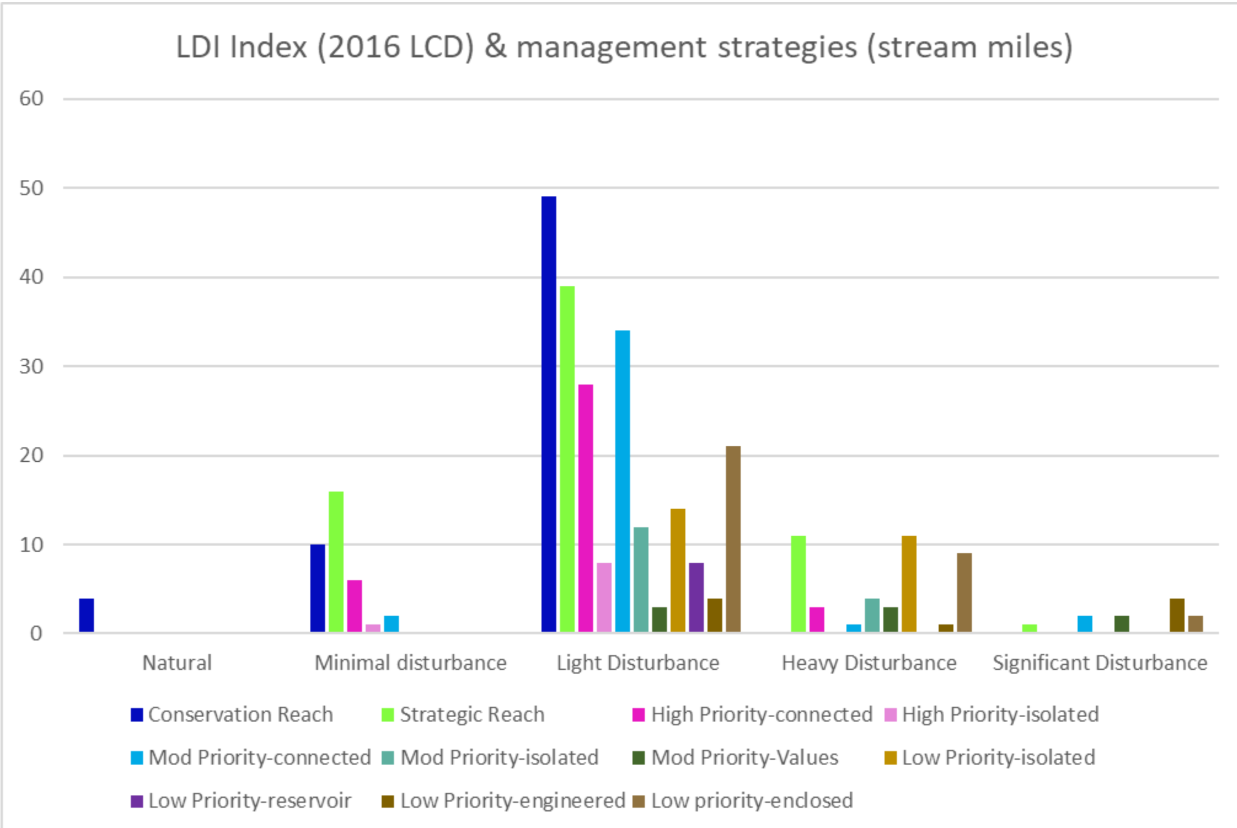

Figure 4.28 LDI values associated with the management scenarios for the Cherry Creek lower and middle sub-watersheds.

4 Discussion

URBAN provides the foundation for the assessment of riverscape condition by employing a consistent method that identifies stressors and defines reach types, using multiple lines of evidence. Although multiple lines of evidence can potentially provide more precision, different metrics do not always align to give an accurate picture of the overall riverscape condition (Solek et al. 2011). Therefore, any conclusions based on these metrics, indicators, and facets must consider the type and number of indicators and metrics used in the assessment. For example, had assessment in the Cherry Creek watershed relied only on the geomorphic and ecological facets of condition, the associated indicators and metrics would indicate that the lower sub-watershed is mostly not functional. If based solely on the human connections and values facet, the associated indicators and metrics would suggest that the lower sub-watershed is mostly functional along the mainstem and a mix of partly functional and fully functional along its tributaries. This indicates that different facets, indicators, and metrics can provide different types of information and address disparate elements of riverscape conditions and qualities. URBAN's use of multiple metrics and indicators provides a method to integrate different types of data, collected at various scales, to wholistically diagnose riverscape condition and identify applicable management strategies.

URBAN follows a top-down, hierarchical perspective that examines regional, watershed, and valley-scale controls, rather than a bottom-up approach using geomorphic units as the building blocks. As a result, analyses are 'nested' across a range of spatial scales relevant to regional contextual attributes, watershed characterization, riverscape broad-scale assessments, and reach-scale rapid assessments. This stratification provides the foundational framework for assessing the physical condition and social-ecological qualities based on variations in the dominant landforms, geomorphic processes, and community values that shape urban riverscapes. Historical data, if available, can also be applied to illustrate the trajectories of the different facets. The assessment, therefore, reveals a combination of facets across multiple scales, and time, in need of consideration in order to protect or improve riverscape condition. The application of URBAN to the Cherry Creek watershed demonstrates the utility of assessing urban riverscapes across multiple scales to identify unmanageable and manageable predictors of physical condition. For example, the physiography, lithology, watershed area, soil type, and slope are all predictors of reach types; however, they are largely unchangeable through management practices. Similarly, anthropogenic stressors such as road density and crossings, hydromodification and stormwater infrastructure, and dams and diversions influence riverscape conditions. These anthropogenic stressors tend to drive management practices, rather than the "levers" that managers can pull to improve riverscape conditions. The results from the Cherry Creek case study identified several manageable predictors – geomorphic condition and riparian condition – that managers can use to inform planning and decision making alongside social-ecological values. The process of identifying those values links hydrologic, geomorphic, and ecological features to socio-political factors that influence the long-term viability of any management strategies. These links also provide critical input into planning instruments, regulation, and legislation.

Application of a multiple metric and indicator approach at different spatial scales promotes a better understanding of the relationships between context, anthropogenic stressors, reach types, and urban riverscape characteristics operating within a riverscape. Reach types based on physical and anthropogenic features intersected with social-ecological values were shown to be an important determinant of overall riverscape condition. This relationship can be extrapolated to a wide range of management strategies and activities. Different anthropogenic stressors, reach types, and community values produce unique combinations of factors that directly affect the four facets and riverscape conditions. URBAN can bridge the gap between physical assessments and the community values that often influence those conditions.

The main strengths of URBAN can be summarized as follows: (i) the methodology builds on a watershed-wide analysis of the hydrologic, hydraulic, geomorphic, and riverscape vegetation characteristics as well as human values, by using a hierarchical, multi-scale approach; (ii) a temporal context is explicitly provided and knowledge of past channel and floodplain evolution is required to assess present and future conditions; (iii) the procedure is firmly based on the consideration and, in many cases, the quantification of physical processes and maintenance requirements; and (iv) the procedure provides a general process that incorporates physical condition into potentially conflicting goals, such as improving floodplain connection and reducing flood risk, and for assessing stream types to identify the best options for stream management.

Reflecting the scope and intent of the application, data availability, and the combination of available cost, time, and effort, URBAN can be applied in different ways. It is flexible enough to be generically applied, but framed to account for landscape and catchment conditions within, and associated geological and climatic influences upon, a given region. And while the application of the method in entirety is recommended, use of just some of its elements (e.g., one or more parameters or assessment at only one scale) for specific purposes is also possible. Furthermore, depending on data availability and the skillset of the user, relatively simple or more sophisticated indicators and metrics can be adopted. Each indicator described in this chapter characterizes specific physical functions and social-ecological values critical to maintaining a healthy and resilient river system. However, each indicator is only one piece of the puzzle; together they provide a holistic understanding of riverscape condition and its degree of functionality or impairment.

While several metrics used in URBAN are simplified, and/or their assessment is typically based on remote sensing data or best professional judgement, other metrics require a rigorous evaluation of various physical processes (e.g., sediment continuity and riparian vegetation width) or some quantitative analyses (e.g., land-use gradient and stream power). Indeed, the method does not account for biological or chemical stream conditions or stressors, but it is easily linked to other methods. A standardized, remote sensing and rapid assessment method such as URBAN provides an efficient, cost-effective, and structured approach to holistically collect data across the four facets to support urban riverscape management.

5 Conclusions

Urban riverscapes are one of the most crucial natural elements that remain in our ever-urbanizing world, and this chapter has described an innovative method for assessing them. The use of the procedure across different space and time scales can be applied to develop understanding of the physical condition of streams in the urban environment. The Cherry Creek case study illustrates the utility of the URBAN method – context and stressors, reach typing, response potential, and metrics and indicators – that provide an understanding of a watershed based on contextual information. Consequently, integrating assessments of spatially hierarchical physical conditions and social-ecological values using desktop and field parameters can diagnose the physical condition of urban riverscapes and define their management strategies. However, integrated multi-scale procedures that can comprehensively assess the physical condition of urban riverscapes are still in early development. This approach, therefore, is deliberately open-ended so that it can be adapted to local context and management issues, and can make the most effective use of available data sets.

URBAN provides a method that embraces the complexities prevalent in urban riverscapes by integrating community values like vitality, public safety, and recreation with physical elements such as flow regime, geomorphic characteristics, and vegetation structure on a localized and regional scale. It offers watershed managers and practitioners a structure to collect and analyze various types of spatial and temporal physical function and social-ecological quality data in order to make more informed management decisions. Although the method is designed for application across arid and semi-arid urban environments, it is presented to a broad audience because implementing an integrated process-based assessment framework that provides a consistent evaluation and synthesis can improve urban riverscape management wherever it is applied. It is possible to move towards this vision by using social and physical remote-sensed and field data to assess the relationship between physical condition and social-ecological values, and to determine where and how to prioritize management strategies. URBAN does precisely this by providing decision-makers a practical tool to understand urban riverscapes.

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CONCLUSIONS

Urban riverscapes are social-ecological systems that benefit and adversely impact local communities. The complexities of urban riverscapes complicate their management, particularly when it comes to finding appropriate interventions to improve physical conditions and social-ecological values. I found identifying and investigating the multi-causal mechanisms that influence the physical condition of urban riverscapes requires assessment methods that scrutinize the various processes and values at play across multiple scales. The question then becomes, how can managers and practitioners apply multi-scale social-ecological, hydrologic, geomorphic, and riparian ecological data to advance urban riverscape management?

This is the question I have attempted to answer in this dissertation. In Chapter 1, I described the advances in urban stream restoration and management that emphasize equitable and effective outcomes. Examples of those advances are project-based experimentation of new approaches in assessment, knowledge sharing (e.g., SUSE5), outreach, and other activities. These approaches improved the integration of stakeholders and knowledge clouds in order to tackle complex and wicked urban stream restoration problems. However, I found that the shortcomings in problem definition prevented solutions that reached the full potential of community or ecological benefit. Further, community groups and local representatives maintained overall weak roles in stream management and restoration, and were not well connected to institutions, knowledge, or strategies and practices. To successfully achieve project outcomes for “wicked” or complex problems, my evaluation of case studies demonstrated that managers must prioritize local community engagement through project planning and implementation structures that relate to the interdisciplinary knowledge transfer that is necessary to address a complex problem. The concept I proposed provides a structure to integrate diverse perspectives and knowledge to enhance social and ecological outcomes.

In Chapter 2, I introduced an assessment framework that provides watershed managers and practitioners an inclusive framing of urban riverscapes relationships that incorporates social, ecological, and hydrogeomorphic facets. The framework provides managers a tool to integrate riverscape context, functions and values, and the technical domain with diverse types of knowledge into assessments. My research explained the critical reasons why managers must include diverse types of knowledge when establishing goals and objectives, and why they must focus on building trust, prioritizing dialogue, and recognizing that values are dynamic. I also found that managing urban riverscapes requires assessment methods that consider values and functions at varying scales. This compels the use of an inclusive framework that utilizes indicators, target conditions, and desired trajectories that incorporate social, ecological, and hydrogeomorphic processes. I proposed using remote-sensed and field data that provides both social and physical information to determine where and how to prioritize management strategies for urban riverscapes.

In Chapter 3, I summarized a review of assessment frameworks and methods that provided new insights that are useful when applied to urban riverscapes. Frameworks and methods, I observed, must balance simplicity with complexity, with the understanding that simplifications are honed for a particular purpose. Further, the indicators and metrics of the frameworks and methods reflected the data requirements as well as the spatial and temporal scales of assessment. I determined that despite the prevalence of assessment methods and frameworks, few considered a well-rounded suite of riverscape facets – human values, hydrology and hydraulics, geomorphology, and riparian ecology – at multiple scales. Even fewer considered the social-ecological context integral to assessing and managing urban riverscapes in particular.

In Chapter 4, I described my innovative assessment method – URBAN – that I developed for managers and practitioners to improve their understanding of the physical condition of riverscapes in the urban environment. The Cherry Creek case study illustrated the utility of the URBAN method, including context and stressors, reach typing, response potential, and metrics and indicators that provided an understanding of the watershed and riverscapes. Consequently, I demonstrated that integrating assessments of spatially hierarchical physical conditions and social-ecological values using indicators and metrics improves decision-making among interdisciplinary stakeholders using a suite of remote sensing and field data. Diagnosing the functions and values of urban riverscapes highlighted a novel approach to defining riverscape specific management strategies. URBAN is presented to a broad audience because implementing an integrated process-based assessment framework, that provides a consistent evaluation and synthesis, can improve urban riverscape management wherever it is applied. URBAN is deliberately open-ended so that it can be adapted to local contexts and management issues, and can make the most effective use of available data sets.

Collectively, the research and methods described in this dissertation provide new insight into the complex relationships between the physical conditions and the social-ecological values prevalent in urban riverscape environments. The compelling relationship between these two realms significantly influence management decisions. Integrating community values with physical elements offers managers a structure to collect and analyze various types of spatial and temporal physical and social-ecological data in order to make more informed management decisions.

Future efforts to better incorporate communities requires leadership from local government agencies and practitioners, given their dominant roles in most urban stream projects. However, this will require further defining the role that community groups can play in assessing, managing, and restoring urban riverscapes. Integrating communities and under-represented knowledge bases could lead to transformative approaches to complex problems, which in turn generate more equitable and effective solutions with tangible benefits to the communities as well as the urban stream systems. While the assessment framework proposed in Chapter 2 contributed the key tenets, facets, objectives, and practices relevant to evaluating urban riverscapes, this framework will progress as assessment and management approaches evolve over time. URBAN will also change as technology influencing data resolution advances, and social and physical scientists recognize the importance of transdisciplinary collaboration to address complex urban riverscapes problems.

APPENDIX A

GAP ANALYSIS COMPONENT DESCRIPTIONS, ADDITIONAL RESULTS, AND DISCUSSION UNRELATED TO COMMUNITY COMPONENTS

APPENDIX A

Closing the gap on wicked urban stream restoration problems: A framework to integrate science and community values

Gap analysis component descriptions

The survey provided to case-study co-authors included descriptions of components and certain subcomponents to assist with survey completion and to improve standardization among case-study analyses. The survey co-authors described the component “institution” as any governmental or non-governmental organization that is external to the restoration project but contributes to the project planning, design, or implementation through a formal or informal process. The survey co-authors described the component “community” as any individual, group, or collective that is affected by the restoration project and restored system. For example, An NGO that includes community members is considered an Institution, but an informal community group should be considered “Community. The distinction between Institution and Community is based on Institution being external to the restored system (even if geographically close) while Community is part of the restored system. In some cases, individuals can be part of a community and an institution. Case-study co-authors were often unfamiliar with many of the community groups that were listed among all the case studies. To assist case-study co-authors with completing the survey, we provided the following examples and descriptions for community subcomponents:

1. Action groups: Watershed organizations, resident action groups, environmental advocacy groups (e.g., Adopt-A-Stream), interest groups (e.g., birdwatching clubs, angler clubs, hiking clubs, school clubs)

2. Place-based groups: Neighborhood associations (including HOA's) and other groups whose interest in the project is solely due to their role in representing the areas directly impacted by the project.
3. Individual community leader: A person who is well respected in the community and speaks for the community in general while part of a formal community group.
4. Individual based on interest: A person who has interest or perceived expertise in the natural or social sciences.
5. Individual based on place: A person interested in the project solely because they live in the area.

Case-study coauthors did not communicate any potential confusion interpreting the descriptive names for subcomponents of other components and no further descriptions were provided. The survey co-authors described "knowledge" as contextualized information and place-based wisdom built on experience and incorporation of cultural values (Hillman 2009). It can include the conceptual, historical, empirical, or theoretical representations of information associated with the project context, design, goals, and outcomes. The survey co-authors described "strategies and practices" as actions that occur as part of the project through all phases (design, implementation, monitoring, etc.).

Gap analysis additional results and discussion unrelated to community components

The survey used to systematically evaluate case studies used a consistent scale for all components and linkages to 'relativize' scores. Narrative-based evaluations of the case study may evaluate components and linkages compared to project expectations of success rather than compared to an ideal outcome (the purpose of the gap analysis). In other words, the strength of a community component may be considered "good" because it exceeded low expectations rather than being objectively "good" compared to an idealized outcome.. Survey results presented in Table A1 (components and subcomponents) and Table A2 (linkages) were used to produce the result summaries presented in the main article, but the focus of the main text was on the community components and linkages. The gap analysis, however, identified additional component and linkage strengths that may be investigated further. For example, the strength of physical/ecological science knowledge and engineering design knowledge was considered strong compared to other areas of knowledge (Table A1). This occurred even though the linkages among academia to other institutions was generally weak (Figure 1.2, Chapter 1), which suggested that technical knowledge is being provided by consultants, or that knowledge transfer is occurring outside of project spaces. A commonly stated persistent shortcoming of academic research is an inability to reach managers and practitioners to influence policy and management (Barbour et al. 2008; Ruhl et al. 2021; Wenger et al. 2008). The gap analysis may suggest that the strength of physical/ecological scientific knowledge and engineering design knowledge was overestimated by the case-study co-authors or this information is reaching intended audiences and the focus needs to be on communicating other forms of relevant information (e.g., social science and stakeholder local knowledge). As noted in the main text of the manuscript, a formal gap analysis done on a representative sample of projects may identify a potentially important ‘gap’ in systems of knowledge transfer. Qualitative assessments of the outcomes of SUSE5’s integration of local stakeholders in case study groups showed that novel methods of knowledge transfer and knowledge from new groups integrated into typical academic ‘learning spaces’ could improve the ‘solution space’ for urban restoration projects (Scoggins et al. 2022 this issue).

Table A1. Gap analysis survey results (*n* = 11 case studies): strength of components and subcomponents (scale of 0 to 5, where 0 is no involvement, 1 is weak involvement and 5 is strong involvement). Blank spaces indicate that the component was not evaluated by the case-study co-author. CLS: Clarksburg, Little Seneca Creek; SR1: Spring Run round 1; SR2: Spring Run round 2; JJS: J.J. Seabrook Reach; LWC: Lower Waller Creek; BTR: Big Thompson River; SPR: South Platte River; LAR: Los Angeles River; TC: Thornton Creek; GSC: Gum Scrub Creek; LSC: Little Stringybark Creek.

	Case study										
Component Subcomponent	CLS	SR1	SR2	JJS	LWC	BTR	SPR	LAR	TC	GSC	LSC
Institution	4	3	5	5	5	5	4	5	5	5	5
Local government	4	3	5	5	5	4	4	4	5	1	4
State government	1	3	3	0	1	2	1	5	3	5	4
Federal government	4	3	3	0	3	1	3	3	5	0	3
Consultant	2	3	5	3	5	4	5	2	5	4	4
Academia	3	0	0	0	2	0	3	5	5	3	5
NGO		0	0	0	5	5	3	2	5	0	0
Utility		0	0	3	3	3	2	4	5	4	5
Private company	2	0	0	3	5	4	5	2	5	0	4
Community groups	3	1	5	3	4	3	3	4	5	0	3
Action groups		1	5	1	3	2	3	2	5	0	0
Place-based groups		1	5	3	3	3	4	3	5	0	0
Individual community leader		1	5	2	3	0	5	1	5	0	0
Individual based on interest		1	5	1	1	0	5	3	5	0	1
Individual based on place		1	5	2	1	0	4	0	5	0	2
Knowledge	3	2	5	3	5	4	5	4	5	3	5
Physical/ecological science	4	3	5	5	5	5	4	5	5	3	5
Community wants and needs	2	1	5	3	4	4	5	3	5	0	4
Engineering design	4	3	5	5	5	4	5	3	5	4	5
Restoration process	3	3	5	5	5	4	4	4	5	2	5
Social science	1	1	4	2	3	3	3	2	4	0	4
Policy and regulations	2	3	5	2	5	2	5	4	5	5	5
Land use planning	3	3	0	3	5	3	4	2	5	5	4
Community planning	3	3	0	2	3	3	4	2	5	0	4
Landscape architecture or	2	3	0	5	5	3	5	1	5	3	5

structural architecture											
Funding procurement and management	2	4	5	4	5	5	3	4	5	5	5
Indigenous culture relevant to project scope	0	0	0	0	1	1	4	2	4	1	0
Strategies and practices	3	2	5	4	5	3	4	4	5	2	5
Restoration approaches - biophysical	3	3	5	5	5	5	4	5	5	5	5
Restoration approaches – social	1	1	5	3	5	2	4	3	4	0	5
Ecological monitoring	4	0	3	4	5	3	2	5	5	0	5
Community survey	0	1	5	2	3	1	3	4		0	5
Outreach and education	1	2	5	3	5	3	3	5	5	0	4
Participant natural or social science training		2	3	0	2	2	2	2	5	0	0
Citizen science	2	0	0	0	3	1	2	1	5	0	0

Table A2. Gap analysis survey results: strength of linkages between components (scale of 0 to 5, where 0 is no connection, 1 is weak connection and 5 is strong connection). Blank spaces indicate that the component could not be evaluated by the case-study co-author. Case-study codes listed in the table are: CLS: Clarksburg, Little Seneca Creek; SR1: Spring Run round 1; SR2: Spring Run round 2; JJS: J.J. Seabrook Reach; LWC: Lower Waller Creek; BTR: Big Thompson River; SPR: South Platte River; LAR: Los Angeles River; TC: Thornton Creek; GSC: Gum Scrub Creek; LSC: Little Stringybark Creek.

	Case study										
Components linked	CLS	SR1	SR2	JJS	LWC	BTR	SPR	LAR	TC	GSC	LSC
Institution and Community	2	1	5	3	4	2	3	4	5	0	19
Institution and knowledge	3	3	5	4	4	5	4	5	5	3	5
Institution and Strategies and practices	3	2	5	4	5	4	5	3	5	3	5
Community and Knowledge		1	5	2	3	3	3	4	5	0	1
Community and Strategies and practices		1	5	2	3	2	3	3	5	0	2
Knowledge and Strategies and practices		2	5	3	5	4	5	5	5	2	5
Institution and Community	2	1	5	3	4	2	3	4	5	0	1

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APPENDIX B

REACH TYPE PROFORMAS

PROFORMA – LOW-MODERATE SINUOSITY INTERMITTENT SWALE ADJUSTING AND NEAR NATURAL (CONFINED)

The low-moderate sinuosity intermittent swale adjusting and low-moderate sinuosity intermittent swale near natural reach types occur in 1st or 2nd-order drainages with confined valleys. The imposed-form stream is in nearly continuous contact with valley walls, which is composed of consolidated colluvium or bedrock outcroppings. These channels have no visible floodplain or terrace surfaces and contain a narrow range of geomorphic units: primarily shallow thalweg swale or bedrock steps. Large wood is mostly absent and willows, cottonwoods and grasses line the channel.

First-order and second-order streams formed in headwaters and uplands of the western and eastern middle sub-watershed are described by the steep ephemeral headwater swale reach type. Streams of this reach type are mapped as ephemeral (Dewitz and USGS 2019) and tend to collect snowmelt and overland flow from spring and summer storms in their channels. Channel lengths are commonly influenced by deposits from small mass wasting failures, agricultural encroachment, and by road crossings. Channels areas tend to have well-developed soil profiles with a gentle “U-shaped” channel shape obscured by bedrock outcroppings and steep hillslopes.

Sub-watersheds where this reach style is observed

Confined-valley steep ephemeral headwater streams are found in every sub-catchment of the Cherry Creek middle sub-watershed.

Details of analysis

Representative reach: Badger Gulch and Tallman Gulch

Map sheets and air photographs used: Google Earth imagery from 1937-2021

Coordinates: Badger Gulch: 39°29'59.43"N 104°51'21.31"W ***Tallman Gulch***: 39°30'22.82"N 104°44'39.08"W

Stream character

Valley setting: confined

Channel planform: straight to low sinuosity with occasional floodplain pockets or no visible floodplain

Channel slope: typically, greater than 0.02 ft/ft

Bed material texture: predominantly consolidated fines overlain by sand deposits

Channel geometry: Narrow single thread channel generally 5 to 10 feet wide. Cross section contains occasional bedrock outcroppings along the channel margin and finer sand and silt deposits in the channel.

Instream geomorphic units

Valley floor deposits: These steep swales carry fine sediment and drain steep erodible surface terrain. They flow over terrain created by bedrock geology and hillslope processes and lack continuous alluvial floodplain deposits or self-formed terrace surfaces. Valley floors are relatively consistent with alluvial deposits from extreme high flow events. Valley walls and bottoms show colonization by willows and cottonwoods, indicating that overbank stage is rarely reached for extended periods of time and deposition of sediment during these periods is limited.

Structural elements: small, steep channels along grasslands and woodlands with minimal wood loading.

Anthropogenic features: In frequent road crossings and structures such as houses, barns, etc.

Vegetation Associations

Instream: largely vegetated with grasses, willows, and shrubs; fallen trees are generally absent and do not obstruct flow or trap sediment.

Valley walls: colonized by riparian and upland species including occasional pine and juniper, indicating a lack of consistent/extended floodplain inundation.

Stream behavior

No to low Flow Stage: At low flows, the swale is contained in a single-thread flow path, and the banks are stable as they are vegetated by mature grasses, shrubs, and willows. Virtually no bank erosion occurs at low flows, given the high degree of bank stability due to bedrock outcroppings and consolidated cohesive material along with the vegetated banks and valley walls.

Bankfull stage: flows reaching this stage have the potential to cause scour of the channel banks, although this may be limited due to the bank material nature and the established valley side/bottom vegetation. It is possible that some of the finer sediment (i.e., sands) on the channel bed may be transported at this stage. Small and large pieces of wood may trap the sand that moves through these streams.

Overbank Stage: at this stage, the valley floor may be completely inundated, given its narrow width, and some degree of bank scour may occur, although these channels lack evidence of recent avulsions or migration, implying that these are quite stable streams. Additionally, bedrock outcrops provide a large degree of stability in these streams. The establishment of riparian and upland riparian vegetation and soil development implies that overbank stages are rarely reached but for a very limited amount of time during spring and summer thunderstorms. Flows which overtop the bank may be capable of mobilizing some larger particles, but it is likely that some particles remain immobile in nearly all flows, especially given the presence of downed trees, established upland vegetation, and colluvial deposits, which may limit the geomorphic effectiveness of any natural flow.

Photos

Figure 1: Badger Gulch headwaters

Figure 2: Tallman Gulch

PROFORMA – LOW-MODERATE SINUOSITY ANTHROPOGENIC-CONFINED SAND BED PARTIALLY-CHANNELIZED REACH TYPE (CONFINED)

The low-moderate sinuosity anthropogenic-confined sand bed partially-channelized reach type occurs on the Cherry Creek mainstem within the lower sub-watershed. The single thread moderate to low slope (< 2%) reach type is found in partly confined valley settings with minimal floodplain space outside of a larger flood control channel. The substrate is generally sand mixed with occasional gravels and cobbles. No floodplain geomorphic units are apparent. The planform is strongly controlled bank revetments and transportation infrastructure. Instream geomorphic units are mostly runs and point bars. The floodplain is narrow and has changed due to channelization, urbanization, and hydromodification.

Sub-watersheds where this reach style is observed

HUC 8: St. Middle South Platte-Cheery Creek (10190003)

HUC 10: Cherry Creek (1019000303)

Details of analysis

Representative reach: Cheery Creek mainstem between Monaco Parkway and Holly Street

Map sheets and air photographs used: Google Earth imagery from 1985-2021

Stream character

Valley setting: confined

Channel planform: low to moderate sinuosity (< 1.3)

Channel slope: Typically less than 0.01 ft/ft

Bed material texture: predominantly sand with pockets of fine deposits

Channel geometry: Continuous single thread "U-shaped" channel generally 20 to 40 feet wide. Channel bed is composed of sand with banks composed of riprap and fine-grained deposits.

Instream geomorphic units

Runs with riffles and pools: The perennial flow regime create sculpted runs with riffles and pools along bends and meanders with occasional bars.

Structural elements: reaches of this type include occasional structural elements due to adjacent willows and cottonwoods.

Floodplain geomorphic units

Narrow to broad floodplain with variable width

Vegetation Associations

Instream: vegetated by willow along channel margins with pockets of aquatic plants in shallow, slow water areas.

Floodplain: overgrown with willows and occasional deciduous trees.

Anthropogenic features and stressors

The reach includes recreational trails that parallel the creek and a pedestrian bridge. Road crossings, diversion structures, grade control structures, and multiple stormwater outfalls are also found in the reach.

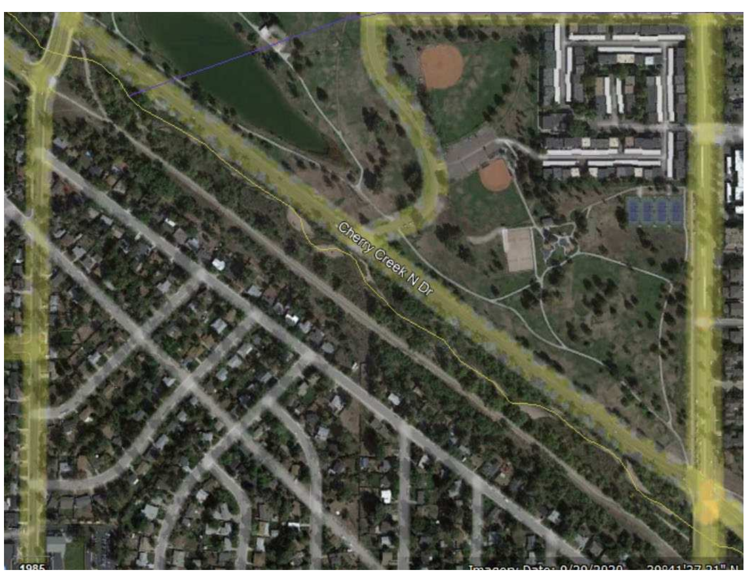
Stream behavior

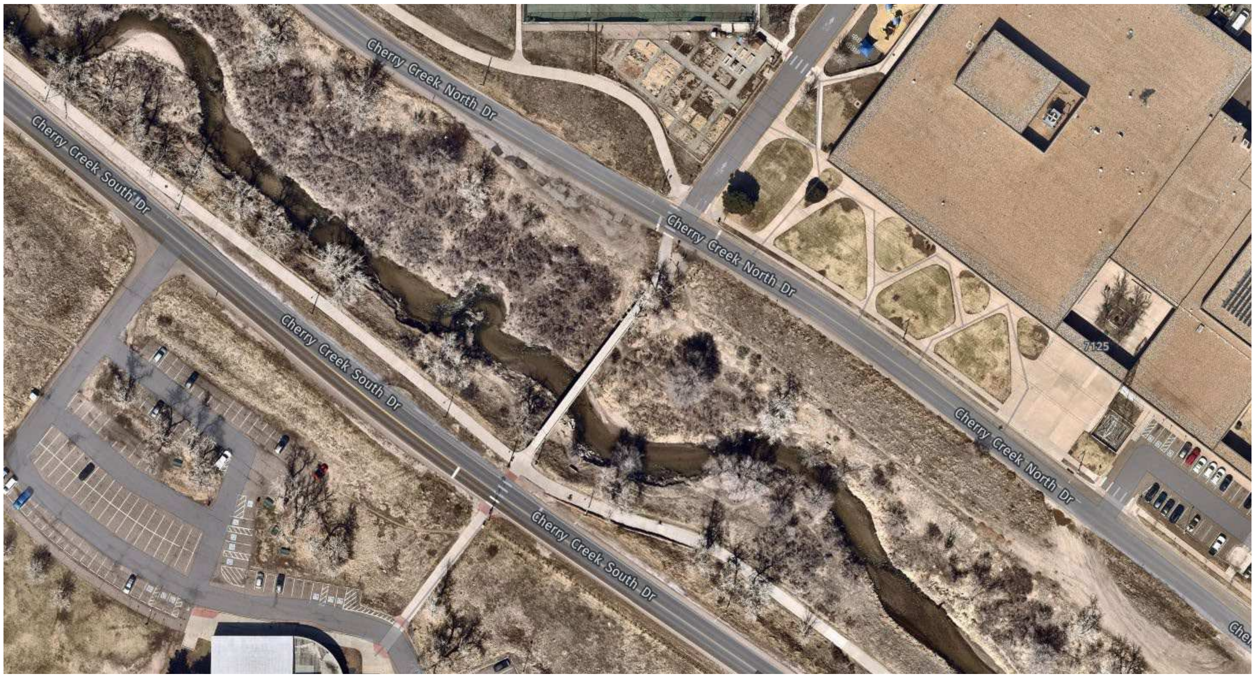
Low flow stage: The perennial flow regime is a result of constant discharge from the Cherry Creek reservoir. At low flows, the discharge is contained in a single-thread channel, and the banks show some lateral bank erosion.

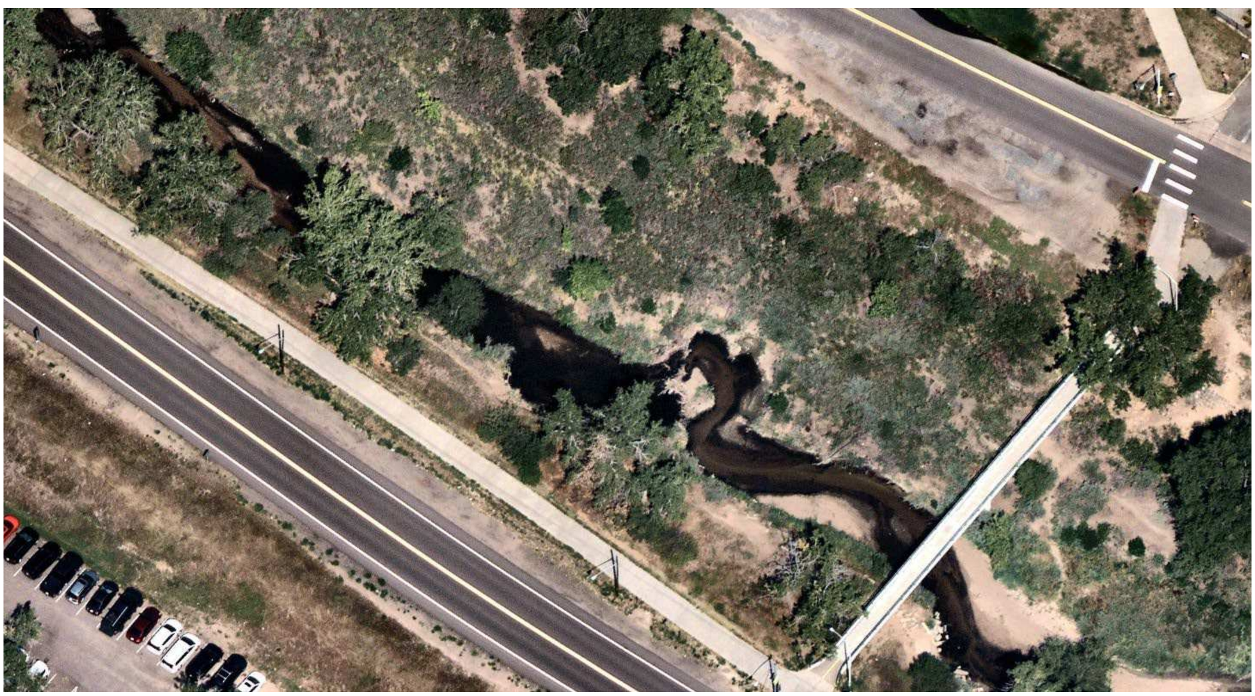
***Bankfull stag*e**: higher flows are capable of reaching the overgrown vegetated narrow floodplain. The floodplain lacks floodplain geomorphic units and migration of the channel does not occur due to the bank revetment.

Overbank Stage: the constrained nature of the channel and its narrow floodplain promotes high stream power that conveys water and sediment above erosion thresholds.

Photos




Cherry Creek North Dr
Cherry Creek South Dr
Cherry Creek North Dr
Cherry Creek South Dr
Cherry Creek North Dr
Cherry Creek South Dr



PROFORMA – STRAIGHT ANTHROPOGENIC-CONFINED SAND BED CHANNELIZED REACH TYPE (CONFINED)

The straight anthropogenic-confined sand bed channelized reach type occurs on the Cherry Creek mainstem within the lower sub-watershed. The single thread moderate to low slope (< 2%) reach type is found in artificially confined valley settings with minimal floodplain space outside of a larger flood control channel. The bed substrate is generally sand mixed with occasional gravels and cobbles. No floodplain geomorphic units are apparent due to concrete banks. The planform is strongly controlled by the rectangular channel section and transportation infrastructure. Instream geomorphic units are mostly runs and with occasional point bars. The floodplain is narrow and has changed substantially due to channelization, urbanization, and hydromodification.

Sub-watersheds where this reach style is observed

HUC 8: St. Middle South Platte-Cheery Creek (10190003)

HUC 10: Cherry Creek (1019000303)

Details of analysis

Representative reach: Cherry Creek mainstem between Wazee Street and Wewatta

Map sheets and air photographs used: Google Earth imagery from 1985-2021

Stream character

Valley setting: partly confined

Channel planform: low to moderate sinuosity (< 1.3)

Channel slope: Typically less than 0.01 ft/ft

Bed material texture: predominantly sand with pockets of fine deposits

Channel geometry: Continuous single thread trapezoidal channel generally 80 to 100 feet wide. Channel bed is composed of sand with banks composed of concrete.

Instream geomorphic units

Runs with riffles and pools: The perennial flow regime create sculpted runs with riffles and pools along bends and meanders with occasional bars.

Structural elements: reaches of this type include occasional structural elements due to adjacent willows and cottonwoods.

Floodplain geomorphic units

Narrow to broad floodplain with variable width

Vegetation Associations

Instream: vegetated by willow along channel margins with pockets of aquatic plants in shallow, slow water areas.

Floodplain: overgrown with willows and occasional deciduous trees.

Anthropogenic features and stressors

The reach includes recreational trails that parallel the creek and a pedestrian bridge. Road crossings, diversion structures, grade control structures, and multiple stormwater outfalls are also found in the reach.

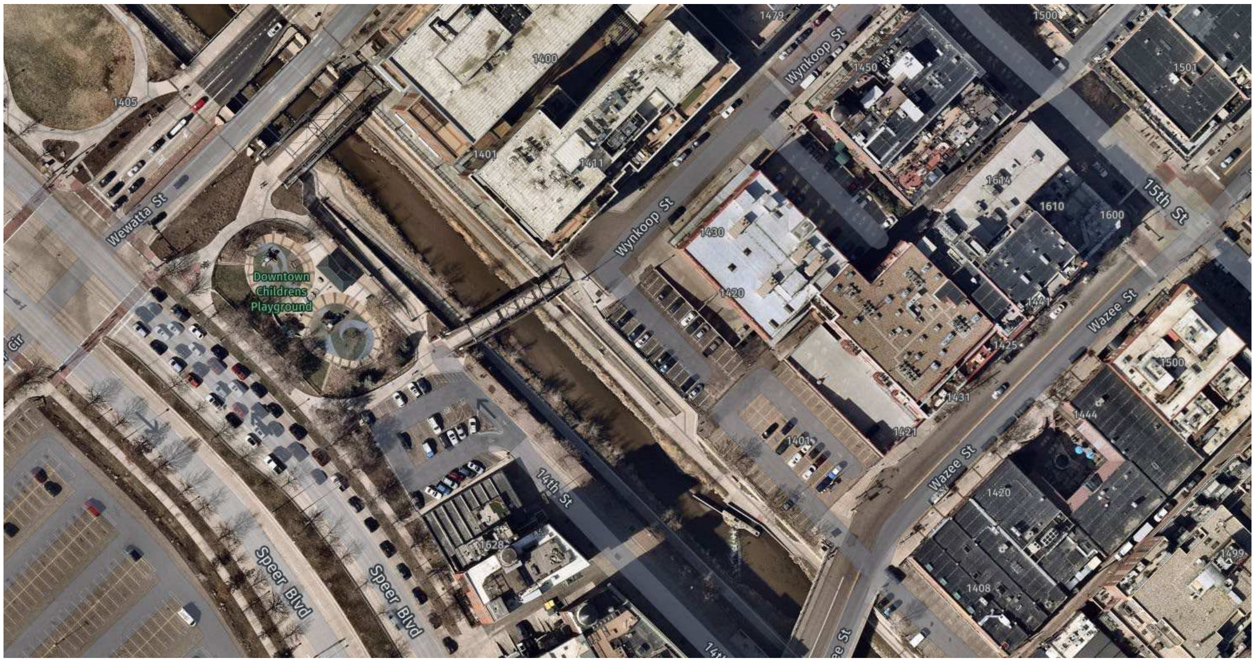
Stream behavior

Low flow stage: The perennial flow regime is a result of constant discharge from the Cherry Creek reservoir. At low flows, the discharge is contained in a single-thread channel, and the banks do not erode due to boulder edging.

Bankfull stag**e**: higher flows are capable of reaching narrow floodplain along the recreational corridor. The floodplain lacks floodplain geomorphic units and migration of the channel does not occur due to the bank revetment.

Overbank Stage: the constrained nature of the channel and its narrow floodplain promotes high stream power that conveys water and sediment above erosion thresholds.

Photos



Downtown
Childrens
Playground
Wewatta St
Wynkoop St
Wynkoop St
15th St
Wazee St
Wazee St
14th St
Speer Blvd
Speer Blvd
1405
1400
1401
1411
1450
1501
1614
1610
1600
1430
1420
1425
1431
1421
1401
1500
1444
1420
1408
1499

PROFORMA – STRAIGHT ANTHROPOGENIC-CONFINED SAND BED CHANNELIZED REACH TYPE (CONFINED)

The straight anthropogenic-confined sand bed channelized reach type occurs on the Cherry Creek mainstem within the lower sub-watershed. The single thread moderate to low slope (< 2%) reach type is found in artificially confined valley settings with minimal floodplain space outside of a larger flood control channel. The bed substrate is generally sand mixed with occasional gravels and cobbles. No floodplain geomorphic units are apparent due to concrete banks. The planform is strongly controlled by the rectangular channel section and transportation infrastructure. Instream geomorphic units are mostly runs and with occasional point bars. The floodplain is narrow and has changed substantially due to channelization, urbanization, and hydromodification.

<u>Sub-watersheds where this reach style is observed</u>

HUC 8: St. Middle South Platte-Cheery Creek (10190003)

HUC 10: Cherry Creek (1019000303)

<u>Details of analysis</u>

Representative reach: Cherry Creek mainstem between Wazee Street and Wewatta

Map sheets and air photographs used: Google Earth imagery from 1985-2021

<u>Stream character</u>

Valley setting: partly confined

Channel planform: low to moderate sinuosity (< 1.3)

Channel slope: Typically less than 0.01 ft/ft

Bed material texture: predominantly sand with pockets of fine deposits

Channel geometry: Continuous single thread trapezoidal channel generally 80 to 100 feet wide. Channel bed is composed of sand with banks composed of concrete.

<u>Instream geomorphic units</u>

Sculpted runs: The base flows create sculpted runs with little heterogenous geomorphic units with occasional bars.

Structural elements: reaches of this type include minimal structural elements due to the lack of adjacent willows and cottonwoods.

Floodplain geomorphic units

Narrow floodplain with uniform width

Vegetation Associations

Instream: vegetated by willow along channel margins with pockets of aquatic plants in shallow, slow water areas.

Floodplain: overgrown with willows and occasional deciduous trees.

Anthropogenic features and stressors

The reach includes recreational trails that parallel the creek and a pedestrian bridge. Road crossings, diversion structures, grade control structures, and multiple stormwater outfalls are also found in the reach.

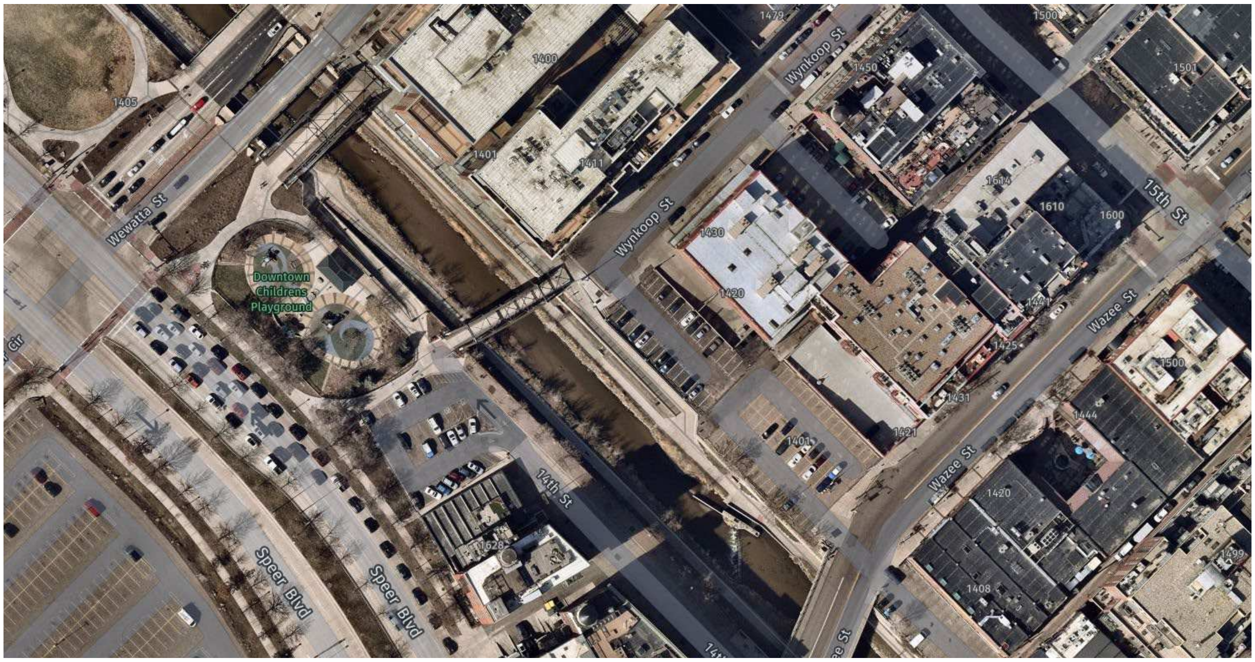
Stream behavior

Low flow stage: The perennial flow regime is a result of constant discharge from the Cherry Creek reservoir. At low flows, the discharge is contained in a single-thread channel, and the banks do not erode due to boulder edging.

Bankfull stage: higher flows are capable of reaching narrow floodplain along the recreational corridor. The floodplain lacks floodplain geomorphic units and migration of the channel does not occur due to the bank revetment.

Overbank Stage: the constrained nature of the channel and its narrow floodplain promotes high stream power that conveys water and sediment above erosion thresholds.

Photos



PROFORMA – LOW-MODERATE SINUOSITY ANTHROPOGENIC-CONTROLLED SAND BED CHANNELIZED REACH TYPE (PARTLY CONFINED)

The low-moderate sinuosity anthropogenic-controlled sand bed partially-channelized reach type occurs on the Cherry Creek mainstem within the lower sub-watershed. The single thread moderate to low slope (< 2%) reach type is found in partly confined valley settings with minimal floodplain space outside of a larger flood control channel. The substrate is generally sand mixed with occasional gravels and cobbles. No floodplain geomorphic units are apparent. The planform is strongly controlled bank revetments and transportation infrastructure. Instream geomorphic units are mostly runs and point bars. The floodplain is narrow and has changed due to channelization, urbanization, and hydromodification.

Sub-watersheds where this reach style is observed

HUC 8: St. Middle South Platte-Cheery Creek (10190003)

HUC 10: Cherry Creek (1019000303)

Details of analysis

Representative reach: Piney Creek near Tower Road

Map sheets and air photographs used: Google Earth imagery from 1985-2021

Coordinates: upstream: 39°36'14.32"N 104°46'32.01"W

Stream character

Valley setting: partly confined

Channel planform: low to moderate sinuosity (< 1.3)

Channel slope: Typically less than 0.02 ft/ft

Bed material texture: predominantly sand with pockets of fine deposits

Channel geometry: Continuous single thread "U-shaped" channel generally 20 to 40 feet wide. Channel bed is composed of sand with banks composed of riprap and fine-grained deposits.

Instream geomorphic units

Runs and glides: The flows create runs and glides with little heterogenous geomorphic units, including pools or bars. Overland flows tend to scour the channel and cause wide, shallow sheetflow. These form the continuous channels that occasionally actives the narrow floodplain.

Structural elements: reaches of this type include some structural elements due to the perennial flows supporting willows and cottonwoods.

Floodplain geomorphic units

Narrow floodplain with uniform width

Vegetation Associations

Instream: vegetated by willow along channel margins with pockets of aquatic plants in shallow, slow water areas.

Floodplain: overgrown with willows and occasional deciduous trees.

Anthropogenic features and stressors

The reach includes recreational trails that parallel the creek and a pedestrian bridge. Road crossings, diversion structures, grade control structures, and multiple stormwater outfalls are also found in the reach.

Stream behavior

Low flow stage: The perennial flow regime is a result of a large upstream drainage area and urban runoff. At low flows, the discharge is contained in a single-thread channel, and the banks show some lateral bank erosion.

Bankfull stag**e**: higher flows are capable of reaching the overgrown vegetated narrow floodplain. The floodplain lacks floodplain geomorphic units and migration of the channel does not occur due to the bank revetment and adjacent transportation infrastructure.

Overbank Stage: High flows driven by thunderstorms occur rapidly for short durations, and capable of mobilizing the sediment found on channel beds. In addition, the bed of the channel may be scoured, and vegetation (including willows and small trees) which colonize the channel and banks may be torn out at these stages. The constrained nature of the channel and its narrow floodplain promotes high stream power that conveys water and sediment above erosion thresholds.

Photos

E Maplewood Ave
S Ventura Ct
E Maplewood Dr
E Oakwood Pl
S Tower Rd
S Tower Rd
S Walden Way
E Caley Cir
S Walden Ct
E Weaver Av
S Walden Way
S Zeno Ct
S Andes Pl
Piney Creek Hollow Park
S Cathay Ct
nearmap
Thu Mar 24 2022
200 ft
Imagery © 2022 Nearmap, HERE

6321
6332
nearmap
Sun Sep 5 2021
50 ft
Imagery © 2022 Nearmap, HERE

PROFORMA – LOW-MODERATE SINUOSITY PLANFORM CONTROLLED SAND BED ADJUSTING REACH TYPE (PARTLY CONFINED)

The low-moderate sinuosity planform-controlled sand bed adjusting reach type occurs in intermittent streams tributary to Cherry Creek within the middle sub-watershed. The moderate to low slope (< 4%) reach type is found in partly confined valley settings with modest floodplain space for accumulation of stream bed materials, primarily sands and gravels. The channel planform is low sinuosity, planform-controlled single thread. The substrate is generally sand mixed with occasional gravels and cobbles. Floodplain geomorphic units are homogenous alluvial flats with occasional ridges. The planform is controlled by hillslope terraces and anthropogenic features. Instream geomorphic units are mostly absent due to the episodic flow regime and lack of large wood along the stream banks. The floodplain topography may have been influenced by ranching and farming.

Sub-watersheds where this reach style is observed

HUC 8: St. Middle South Platte-Cheery Creek (10190003)

HUC 10: Headwaters Cherry Creek (1019000301)

Details of analysis

Representative reach: Oak Gulch

Map sheets and air photographs used: Google Earth imagery from 1937-2021

Coordinates: upstream: 39°29'28.54"N 104°47'54.73"W

Stream character

Valley setting: partly unconfined

Channel planform: low to moderate sinuosity (< 1.3)

Channel slope: Typically less than 0.04 ft/ft

Bed material texture: predominantly sand with pockets of fine deposits

Channel geometry: Continuous single thread "U-shaped" channel generally 10 to 20 feet wide. Channel bed is composed of sand with banks composed of finer deposits composing the contemporary floodplain.

Instream geomorphic units

Runs and occasional riffles and pools: The fine-grained material and intermittent flows create sculpted runs with occasional riffles and pools at meander bends. Overland flows tend to scour the channel and cause the continuous channels that occasionally actives the narrow floodplain.

Structural elements: reaches of this type include minimal structural elements due to the lack of adjacent willows and cottonwoods.

Anthropogenic features: relatively few road crossings, diversion structures, or grade control structures.

Floodplain geomorphic units

Relatively narrow floodplain with occasional floodplain pockets

Vegetation Associations

Instream: little to no riparian vegetation along the channel margins, although grasses and small shrubs are common near the channel and uplands indicating limited connection to the groundwater table and no active subsurface flow except following snowmelt or a storm event.

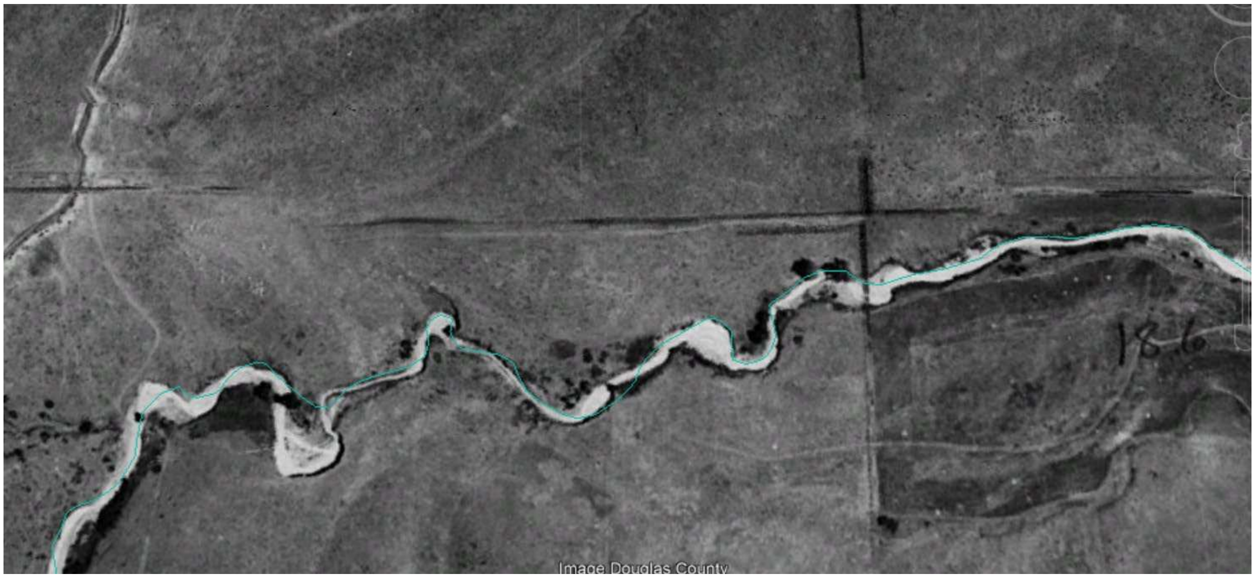
Floodplain: generally covered in grasses, active channel bounded by small shrubs and occasional deciduous trees.

Stream behavior

No and low flow stage: The intermittent flow regime is a result of short-duration and high-intensity runoff events such as spring snowmelt and summer thunderstorms. As such, the term 'no flow' applies here to the majority of the year, when the channel is dry. At low flows, the channel is contained in a single-thread flow path, and the banks are show some lateral bank erosion.

High flow stage: These channels flow infrequently, and thus there is no 'bankfull' discharge. High flows driven by snowmelt or thunderstorms occur rapidly for short durations, and capable of mobilizing the sediment found on channel beds. In addition, the bed and banks of the channel may be scoured, and vegetation (including shrubs and small trees) which colonize the channel and local hillslopes during periods of no flow may be torn out at these stages. The undercutting of banks may oversteepen the adjacent hillslopes, leading to mass wasting. Channel slope is typically less than 0.04 ft/ft in these small drainages. At this stage, the valley floor may be completely inundated, given its narrow width, and some degree of bank scour may occur, with recent evidence of lateral migration and bank erosion. The lack of established riparian and upland vegetation implies that overbank stages are rarely reached but for a very limited amount of time during spring and summer thunderstorms.

<u>Photos</u>




S Fire
S Jordan Rd
Hess Rd
Hess Rd
Rd
nearmap
Tue Mar 31 2020
100 ft
Imagery © 2022 Nearmap, HERE

PROFORMA – LOW-MODERATE SINUOSITY PLANFORM CONTROLLED SAND BED NEAR NATRUAL REACH TYPE (PARTLY CONFINED)

The low-moderate sinuosity planform-controlled sand bed near natural reach type occurs in intermittent streams tributary to Cherry Creek within the middle sub-watershed. The moderate to low slope (< 4%) reach type is found in partly confined valley settings with floodplain space for accumulation of stream bed materials, primarily sands and gravels. The channel planform is low sinuosity, planform-controlled single thread. The substrate is generally sand mixed with occasional gravels and cobbles. Floodplain geomorphic units are homogenous alluvial flats with occasional ridges. The planform is strongly controlled by alluvial deposits and hillslope terraces. Instream geomorphic units are mostly absent due to the episodic flow regime and lack of large wood along the stream banks. The floodplain topography may have been influenced by ranching and farming.

Sub-watersheds where this reach style is observed

HUC 8: St. Middle South Platte-Cheery Creek (10190003)

HUC 10: Headwaters Cherry Creek (1019000301)

Details of analysis

Representative reach: Kinney Creek near Betts Ranch Road

Map sheets and air photographs used: Google Earth imagery from 1937-2021

Coordinates: upstream: 39°27'54.84"N 104°43'14.66"W

Stream character

Valley setting: partly unconfined

Channel planform: low to moderate sinuosity (< 1.3)

Channel slope: Typically less than 0.04 ft/ft

Bed material texture: predominantly sand with pockets of fine deposits

Channel geometry: Continuous single thread “U-shaped” channel generally 10 to 20 feet wide. Channel bed is composed of sand with banks composed of finer deposits composing the contemporary floodplain.

Instream geomorphic units

Runs: The fine-grained material and intermittent flows create sculpted runs with little heterogenous geomorphic units, including pools or bars. Overland flows tend to scour the channel and cause wide, shallow sheetflow. These form the continuous channels that occasionally actives the narrow floodplain.

Structural elements: reaches of this type include minimal structural elements due to the lack of adjacent willows and cottonwoods.

Anthropogenic features: relatively few road crossings, diversion structures, or grade control structures.

Floodplain geomorphic units

Relatively narrow floodplain with occasional floodplain pockets

Vegetation Associations

Instream: little to no riparian vegetation along the channel margins, although grasses and small shrubs are common near the channel and uplands indicating limited connection to the groundwater table and no active subsurface flow except following snowmelt or a storm event.

Floodplain: generally covered in grasses, active channel bounded by small shrubs and occasional deciduous trees.

Stream behavior

No and low flow stage: The intermittent flow regime is a result of short-duration and high-intensity runoff events such as spring snowmelt and summer thunderstorms. As such, the term 'no flow' applies here to the majority of the year, when the channel is dry. At low flows, the channel is contained in a single-thread flow path, and the banks are show some lateral bank erosion.

High flow stage: These channels flow infrequently, and thus there is no 'bankfull' discharge. High flows driven by snowmelt or thunderstorms occur rapidly for short durations, and capable of mobilizing the sediment found on channel beds. In addition, the bed and banks of the channel may be scoured, and vegetation (including shrubs and small trees) which colonize the channel and local hillslopes during periods of no flow may be torn out at these stages. The undercutting of banks may oversteepen the adjacent hillslopes, leading to mass wasting. Channel slope is typically less than 0.04 ft/ft in these small drainages. At this stage, the valley floor may be completely inundated, given its narrow width, and some degree of bank scour may occur, with recent evidence of lateral migration and bank erosion. The lack of established riparian and upland vegetation implies that overbank stages are rarely reached but for a very limited amount of time during spring and summer thunderstorms.

<u>Photos</u>

PROFORMA – MEANDERING PLANFORM-CONTROLLED SAND BED ADJUSTING REACH TYPE (PARTLY CONFINED)

The meandering planform-controlled sand bed reach type occurs in intermittent streams tributary to Cherry Creek within the middle sub-watershed. The moderate to low slope (< 2%) reach type is found in partly confined valley settings with floodplain space for accumulation of stream bed materials, primarily sands and gravels. The channel planform is sinuous meandering, planform-controlled single thread. The substrate is generally sand mixed with occasional gravels and cobbles. Floodplain geomorphic units vary with occasional floodplain pockets and topographic ridges. The planform is strongly controlled by alluvial deposits and hillslope terraces. Instream geomorphic units are mostly absent due to the episodic flow regime and lack of large wood along the stream banks. The floodplain topography may have been influenced by ranching and farming.

Sub-watersheds where this reach style is observed

HUC 8: St. Middle South Platte-Cheery Creek (10190003)

HUC 10: Headwaters Cherry Creek (1019000301)

Details of analysis

Representative reach: South Newlin Gulch

Map sheets and air photographs used: Google Earth imagery from 1937-2021

Coordinates: upstream: 39°26'31.53"N 104°51'22.64"W

Stream character

Valley setting: partly unconfined

Channel planform: sinuous (> 1.3)

Channel slope: Typically greater than 0.01 ft/ft

Bed material texture: predominantly sand with pockets of fine deposits

Channel geometry: Continuous single thread "U-shaped" channel generally 10 to 20 feet wide. Channel bed is composed of sand with banks composed of finer deposits composing the contemporary floodplain.

Instream geomorphic units

Sculpted runs and pools: The fine-grained material and intermittent flows create sculpted runs and pools with little heterogenous geomorphic units, including bars. Overland flows tend to scour the channel and cause wide, shallow sheetflow. These form the continuous channels that occasionally actives the floodplain.

Structural elements: reaches of this type include minimal structural elements due to the lack of adjacent willows and cottonwoods.

Anthropogenic features: relatively few road crossings, diversion structures, or grade control structures.

Floodplain geomorphic units

Relatively narrow floodplain with occasional floodplain pockets

Vegetation Associations

Instream: little to no riparian vegetation along the channel margins, although grasses and small shrubs are common near the channel and uplands indicating limited connection to the groundwater table and no active subsurface flow except following snowmelt or a storm event.

Floodplain: generally covered in grasses, active channel bounded by small shrubs and occasional deciduous trees.

Stream behavior

No and low flow stage: The intermittent flow regime is a result of short-duration and high-intensity runoff events such as spring snowmelt and summer thunderstorms. As such, the term 'no flow' applies here to the majority of the year, when the channel is dry. At low flows, the swale is contained in a single-thread flow path, and the banks are relatively stable.

High flow stage: These channels flow infrequently, and thus there is no 'bankfull' discharge. High flows driven by snowmelt or thunderstorms occur rapidly for short durations, and capable of mobilizing the sediment found on channel beds. In addition, the bed and banks of the channel may be scoured, and vegetation (including shrubs and small trees) which colonize the channel and local hillslopes during periods of no flow may be torn out at these stages. The undercutting of banks may oversteepen the adjacent hillslopes, leading to mass wasting. Channel slope is typically less than 0.02 ft/ft in these small drainages. At this stage, the valley floor may be completely inundated, given its narrow width, and some degree of bank scour may occur, with recent evidence of lateral migration and bank erosion, although occasional bedrock outcrops provide stability in these streams. The lack of established riparian and upland vegetation implies that overbank stages are rarely reached but for a very limited amount of time during spring and summer thunderstorms.

Photos

PROFORMA – LOW-MODERATE SINUOSITY SAND BED CHANNELIZED REACH TYPE (UNCONFINED)

The low-moderate sinuosity sand bed channelized reach type occurs in reaches of the Cherry Creek and tributaries within the middle sub-watershed. This reach type is found in laterally unconfined valley settings, where the channel is can adjust moderately across the floodplain within the constraints of anthropogenic features. The channel interacts with foothills or anthropogenic features (i.e., transportation infrastructure) less than 10% along its length. The floodplain is composed of vertically accreted, fine-grained material deposited by successive overbank floods. The channel is primarily single thread. The banks are stable and steep-sided, with a moderate width to depth ratio.

The bed is underlain by sand and occasional gravels and cobbles; instream geomorphic units include runs and glides in straight sections, and short pool-riffle sequences developed at meander bends or at grade control locations. Bars are uncommon.

Sub-watersheds where this reach style is observed

HUC 8: St. Middle South Platte-Cheery Creek (10190003)

HUC 10: Headwaters Cherry Creek (1019000301)

Details of analysis

Representative reach: Piney Creek near Joplin Way

Map sheets and air photographs used: Google Earth imagery from 1937-2021

Coordinates: 39°36'36.65"N 104°48'04.18"W

Stream character

Valley setting: laterally unconfined

Channel planform: low to moderate sinuosity (< 1.3)

Channel slope: Typically less than 0.01 ft/ft

Bed material texture: predominantly sand with pockets of gravel and occasionally cobbles

Channel geometry: Continuous single thread “U-shaped” channel generally 20 to 40 feet wide. Cross section contains coarser (gravel/cobble) sheets overlain by finer sand and gravel deposits composing contemporary floodplain.

Instream geomorphic units

Bars: absent

Islands: none present

Runs and riffles: Runs are the most common instream geomorphic unit, often connecting long distances between riffle crests with occasional pools.

Structural elements: reaches of this type, including the proforma site, include some instream large wood sourced from adjacent willows and occasional cottonwoods.

Anthropogenic features: grade control structures and adjacent stormwater and transportation infrastructure.

Floodplain geomorphic units

Narrow floodplain with side channels, ridge and swale topography, occasional secondary channels

Vegetation associations

Instream: vegetated by willow along channel margins with pockets of aquatic plants in shallow, slow water areas.

Floodplain: generally covered in grasses, active channel bounded by small willows and larger deciduous cottonwood trees. Noticeable vegetation density increases around side channels and small wetland complexes, indicative of shallow groundwater and overbank flow paths.

Anthropogenic features and stressors

The reach includes multiple grade control structures Multiple stormwater outfalls are apparent. The reach is adjusting to encroachment, hydromodification, and sediment regime changes.

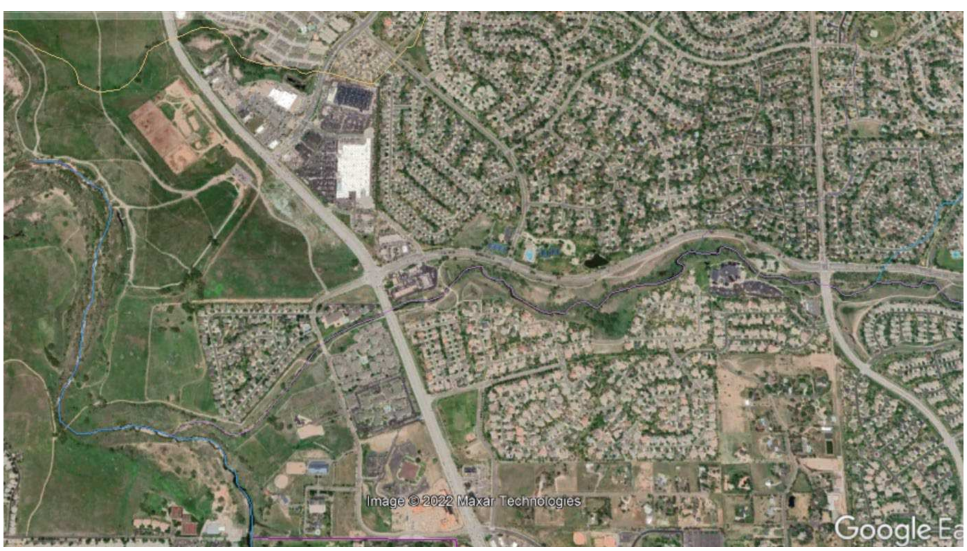
Stream behavior

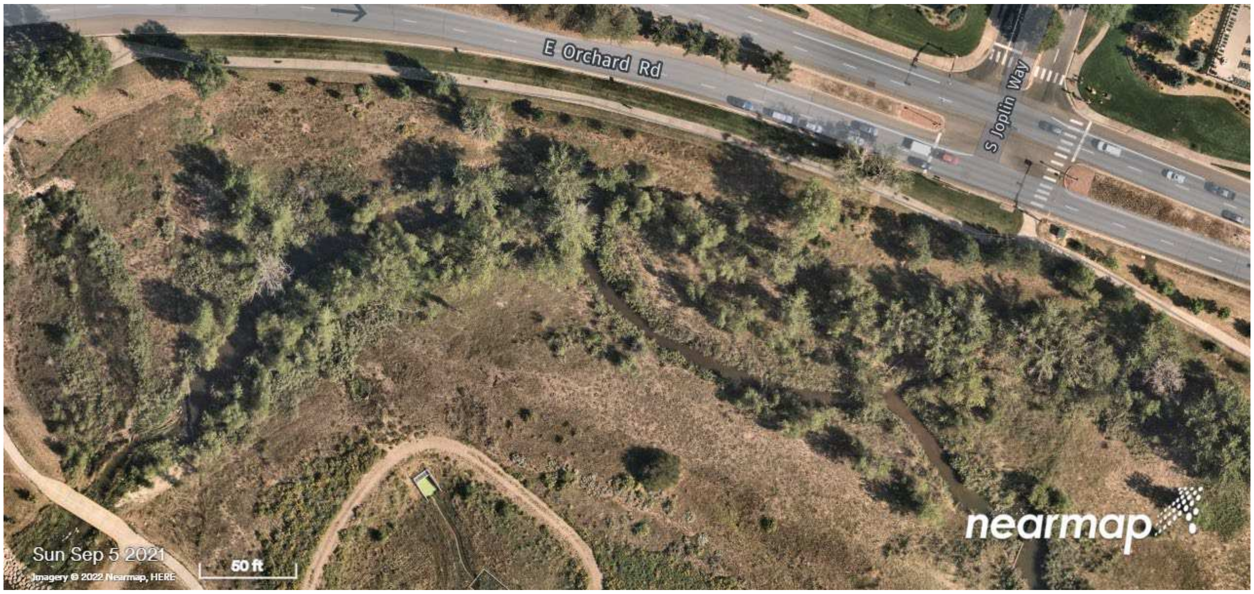
Low Flow Stage: At low flows, the channel is well contained in a single-thread channel, and the banks are generally stable. There appears to be minimal heterogeneity created by large wood or variation in channel-bed sediment size.

Bankfull stage: higher flows are capable of reaching the finer-grained floodplain deposits which compose the flat, broad floodplain. Small middle channel bars are largely unvegetated and can be reworked at bankfull flows. Migration of the channel may be promoted along meander bends with sparse vegetation.

Overbank Stage: the planform is prone to floodplain accretion due to the connectivity between the floodplain and the channel.

<u>Photos</u>




E Orchard Rd
S Joplin Way
nearmap
Sun Sep 5 2021
50 ft
Imagery © 2022 Nearmap, HERE

PROFORMA – LOW-MODERATE SINUOSITY SAND BED ADJUSTING REACH TYPE (UNCONFINED)

The low-moderate sinuosity sand bed reach type occurs in reaches of the Cherry Creek within the middle sub-watershed where valley expansion or floodplain preservation has created lateral space and a wide, uniform floodplain (Figure 1). This reach type is found in laterally unconfined valley settings, where the channel is free to adjust across the floodplain unimpeded and is laterally unstable unless constrained by anthropogenic features. The channel interacts with foothills or low relief alluvial fans less than 10% of the time along its length. The floodplain is composed of vertically accreted, fine-grained clay silt and fine sand deposited by successive overbank floods. The channel is primarily single thread with occasional side channels. The banks are stable and steep-sided, with a moderate width to depth ratio.

The bed is underlain by sand and occasional gravels and cobbles; instream geomorphic units include runs and glides in straight sections, and short pool-riffle sequences developed at meander bends or at grade control locations. Point bars are common, with occasional diagonal and lateral bars present. Multiple “restoration” projects have addressed incision and bank instabilities at the proforma site.

<u>Sub-watersheds where this reach style is observed</u>

HUC 8: St. Middle South Platte-Cheery Creek (10190003)

HUC 10: Headwaters Cherry Creek (1019000301)

<u>Details of analysis</u>

Representative reach: Cherry Creek mainstem downstream of Broncos Parkway

Map sheets and air photographs used: Google Earth imagery from 1937-2021

Coordinates: upstream: 39°34'45.21"N 104°48'04.18"W; ***downstream***: 39°34'52.69"N 104°48'06.18"W

<u>Stream character</u>

Valley setting: laterally unconfined

Channel planform: low to moderate sinuosity (< 1.3)

Channel slope: Typically less than 0.01 ft/ft

Bed material texture: predominantly sand with pockets of gravel and occasionally cobbles

Channel geometry: Continuous single thread "U-shaped" channel generally 20 to 40 feet wide. Cross section contains coarser (gravel/cobble) sheets overlain by finer sand and gravel deposits composing contemporary floodplain.

Instream geomorphic units

Bars: lateral, mid channel, and point bars present.

Islands: none present

Runs and riffles: Runs are the most common instream geomorphic unit, often connecting long distances between riffle crests with occasional pools. Riffles tend to occur at flow constriction points formed by bars or islands and are much less common.

Structural elements: reaches of this type, including the proforma site, include some instream large wood sourced from adjacent willows and occasional cottonwoods.

Anthropogenic features: Bridge crossings and diversion structures, and instream riffle grade control structures.

Floodplain geomorphic units

Broad floodplain with side channels, ridge and swale topography, occasional meander and secondary channels

Vegetation associations

Instream: vegetated by willow along channel margins with pockets of aquatic plants in shallow, slow water areas.

Floodplain: generally covered in grasses, active channel bounded by small willows and larger deciduous cottonwood trees. Noticeable vegetation density increases around side channels and small wetland complexes, indicative of shallow groundwater and overbank flow paths.

Anthropogenic features and stressors

The reach includes multiple grade control structures and recreational trails parallel the creek. A pedestrian bridge crosses midway and the Broncos Parkway bridge is immediately upstream. No stormwater outfalls are apparent. The reach is adjusting to encroachment, hydromodification, and sediment regime changes.

Stream behavior

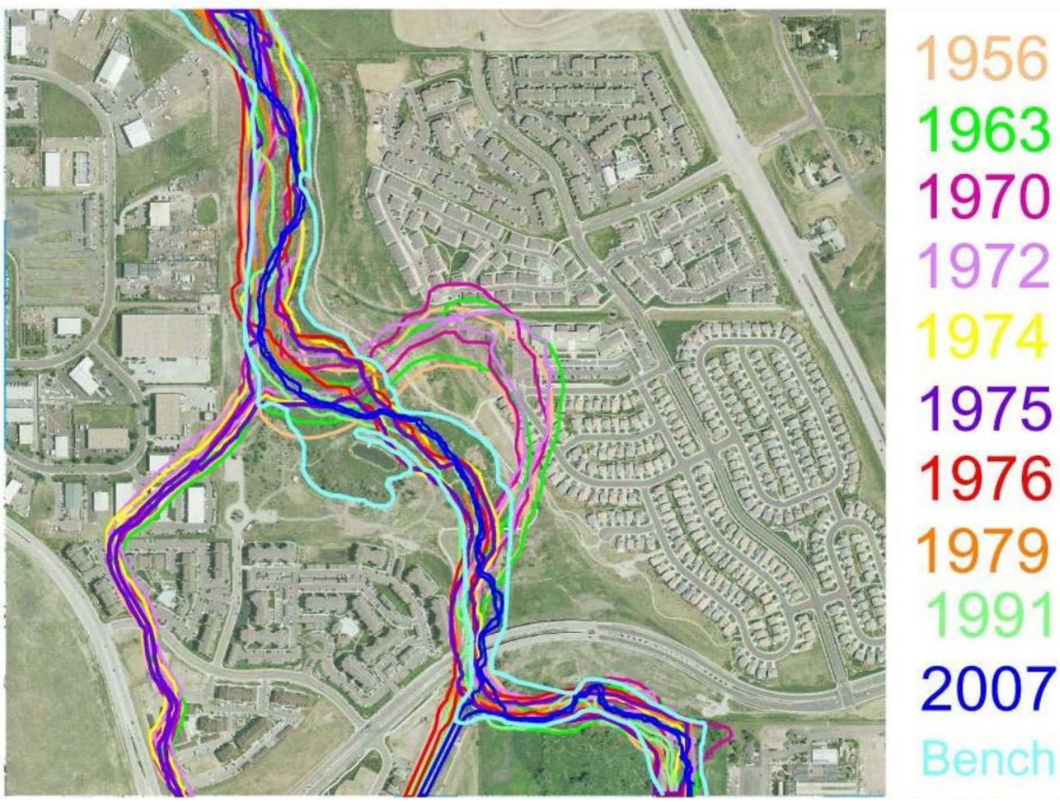
Low Flow Stage: this reach type is the product of valley widening and the associated deposition and storage of sediment delivered from upstream and by tributaries that source material to the valley floor via local and general sediment transport. At low flows, the channel is well contained in a single-thread channel, and the banks are generally stable. There appears to be minimal heterogeneity created by large wood or variation in channel-bed sediment size.

Bankfull stage: higher flows are capable of reaching the finer-grained floodplain deposits which compose the flat, broad floodplain. Small middle channel bars are largely unvegetated and can be reworked at bankfull flows. Migration of the channel may be promoted along meander bends with sparse vegetation.

Overbank Stage: the planform is prone to floodplain accretion due to the connectivity between the floodplain and the channel and side channels will activate, as these areas are generally located 5 feet or less above the active channel (see photos below). The wide nature of the channel and its broad floodplain promotes water and sediment activating the floodplain, resulting in deposits of finer mud, sand, gravel, and detritus (sticks, leaves, etc.) across the valley bottom.

Photos

Figure 1: Comparison of a section of Cherry Creek showing channel planform and geometry evolution between 1955 and 2019.



PROFORMA – MEANDERING SAND BED CHANNELIZED REACH TYPE (UNCONFINED)

The meandering sand bed channelized reach type occurs in reaches of Cherry Creek main stem within the middle sub-watershed where valley expansion and floodplain management has created lateral space and a uniform floodplain (see image below). This reach type is found in laterally unconfined valley settings, where the channel can adjust across the floodplain. The low flow channel has been stabilized so it is stable and moderately constrained by anthropogenic features. The active floodplain interacts with foothills or anthropogenic feature less than 10% along its length. The floodplain is composed of vertically accreted, fine-grained materials deposited by overbank floods. The channel is primarily single thread with occasional secondary channels at meander bends. The banks are stable and steep-sided, with a moderate width to depth ratio.

The bed is underlain by sands and gravels with occasional cobbles; instream geomorphic units include runs in straight sections, and pool-riffle-pool sequences developed at meander bends. Point bars are common, with occasional diagonal and lateral bars present.

Sub-watersheds where this reach style is observed

HUC 8: St. Middle South Platte-Cheery Creek (10190003)

HUC 10: Headwaters Cherry Creek (1019000301)

Details of analysis

Representative reach: Cherry Creek mainstem upstream of Broncos Parkway

Map sheets and air photographs used: Google Earth imagery from 1937-2021

Coordinates: 39°34'43.30"N 104°48'05.218"W

Stream character

Valley setting: laterally unconfined

Channel planform: sinuous (> 1.3)

Channel slope: Typically less than 0.01 ft/ft

Bed material texture: predominantly sand with pockets of gravel and occasionally cobbles

Channel geometry: Continuous single thread "U-shaped" channel generally 10 to 30 feet wide. Cross section contains coarser (gravel/cobble) sheets overlain by finer sand and gravel deposits composing contemporary floodplain.

Instream geomorphic units

Bars: lateral, mid channel, point, and compound bars present.

Islands: none present

Runs and riffles: Runs are the most common instream geomorphic unit, often connecting long distances between riffle crests with occasional pools. Riffles tend to occur at flow constriction points formed by bars or islands and are much less common. Constructed (artificial) riffles are also present.

Structural elements: reaches of this type, including the proforma site, include some instream large wood sourced from adjacent willows and occasional cottonwoods.

Anthropogenic features: Grade control structures, recreational trail on river left and river right, social trails down to the channel. Channel was channelized to arrest degradation and bank erosion.

Floodplain geomorphic units

Broad floodplain with side channels, ridge and swale topography, occasional meander and side channels

Vegetation Associations

Instream: vegetated by willow along channel margins with pockets of aquatic plants in shallow, slow water areas. Side channels are heavily vegetated by grasses, reeds, and other aquatic species, often having a marsh-like appearance.

Floodplain: generally covered in grasses, active channel bounded by small willows and larger deciduous cottonwood trees. Noticeable vegetation density increases around side channels and small wetland complexes, indicative of shallow groundwater and overbank flow paths.

Stream behavior

Low Flow Stage: At low flows, the channel is well contained in a single-thread channel, and the banks are generally stable. There appears to be minimal heterogeneity created by large wood or variation in channel-bed sediment size. Vegetation flanks the channel and it influence the channel morphology at this stage.

***Bankfull stag*e**: higher flows are capable of reaching the finer-grained floodplain deposits which compose the flat, broad floodplain. Small middle channel bars are largely unvegetated and can be reworked at bankfull flows. Migration of the channel may be promoted along meander bends with sparse vegetation. A rise in the groundwater table during wet periods may result in these low areas being filled with water and acting as temporary side channels.

Overbank Stage: the side channels along the valley floor will be activated, as these areas are generally located 5 feet or less above the active channel (see image below). At this stages, the planform is prone to floodplain accretion due to the connectivity between the floodplain and the channel. The wide nature of the channel and its broad floodplain promotes water and sediment activating the floodplain, resulting in deposits of finer mud, sand, gravel, and detritus (sticks, leaves, etc.) across the valley bottom.


E Broncos
Cherry Creek
Valley
Ecological Park
S Lewiston St
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7493
7495
7499
E Broncos Pkwy
16400
E Broncos
nearmap
Sun Sep 13 2020
100 ft
Imagery © 2022 Nearmap, HERE


Cherry Creek
Valley
Ecological Park
16400
nearmap
Thu Mar 24 2022
50 ft
Imagery © 2022 Nearmap, HERE

PROFORMA – MEANDERING SAND BED ADJUSTING REACH TYPE (UNCONFINED)

The meandering sand bed adjusting reach type occurs in reaches of Cherry Creek main stem within the middle sub-watershed where valley expansion or floodplain preservation has created lateral space and a wide, uniform floodplain (see image below). This reach type is found in laterally unconfined valley settings, where the channel is free to adjust across the floodplain unimpeded and is laterally unstable unless constrained by anthropogenic features. The channel interacts with foothills or low relief alluvial fans less than 10% of the time along its length. The floodplain is composed of vertically accreted, fine-grained clay silt and fine sand deposited by successive overbank floods. The channel is primarily single thread with occasional chute cutoffs at meander bends. The banks are stable and steep-sided, with a moderate width to depth ratio.

The bed is underlain by sands and gravels with occasional cobbles; instream geomorphic units include runs in straight sections, and pool-riffle-pool sequences developed at meander bends. Point bars are common, with occasional diagonal and lateral bars present.

Sub-watersheds where this reach style is observed

HUC 8: St. Middle South Platte-Cheery Creek (10190003)

HUC 10: Headwaters Cherry Creek (1019000301)

Details of analysis

Representative reach: Cherry Creek mainstem between E470 and Cottonwood Drive

Map sheets and air photographs used: Google Earth imagery from 1937-2021

Coordinates: upstream: 39°33'00.78"N 104°46'48.29"W; ***downstream***: 39°29'33.22"N 104°47'06.02"W

Stream character

Valley setting: laterally unconfined

Channel planform: sinuous (> 1.3)

Channel slope: Typically less than 0.01 ft/ft

Bed material texture: predominantly sand with pockets of gravel and occasionally cobbles

Channel geometry: Continuous single thread "U-shaped" channel generally 10 to 20 feet wide. Cross section contains coarser (gravel/cobble) sheets overlain by finer sand and gravel deposits composing contemporary floodplain.

<u>Instream geomorphic units</u>

Bars: lateral, mid channel, point, and compound bars present.

Islands: none present

Runs and riffles: Runs are the most common instream geomorphic unit, often connecting long distances between riffle crests with occasional pools. Riffles tend to occur at flow constriction points formed by bars or islands and are much less common.

Structural elements: reaches of this type, including the proforma site, include some instream large wood sourced from adjacent willows and occasional cottonwoods.

Anthropogenic features: Minimal, recreational trail on river left and social trails down to the channel. Channel is adjusting to encroachment, hydromodification, and sediment regime changes.

<u>Floodplain geomorphic units</u>

Broad floodplain with side channels, ridge and swale topography, occasional meander and side channels

<u>Vegetation Associations</u>

Instream: vegetated by willow along channel margins with pockets of aquatic plants in shallow, slow water areas. Side channels are heavily vegetated by grasses, reeds, and other aquatic species, often having a marsh-like appearance.

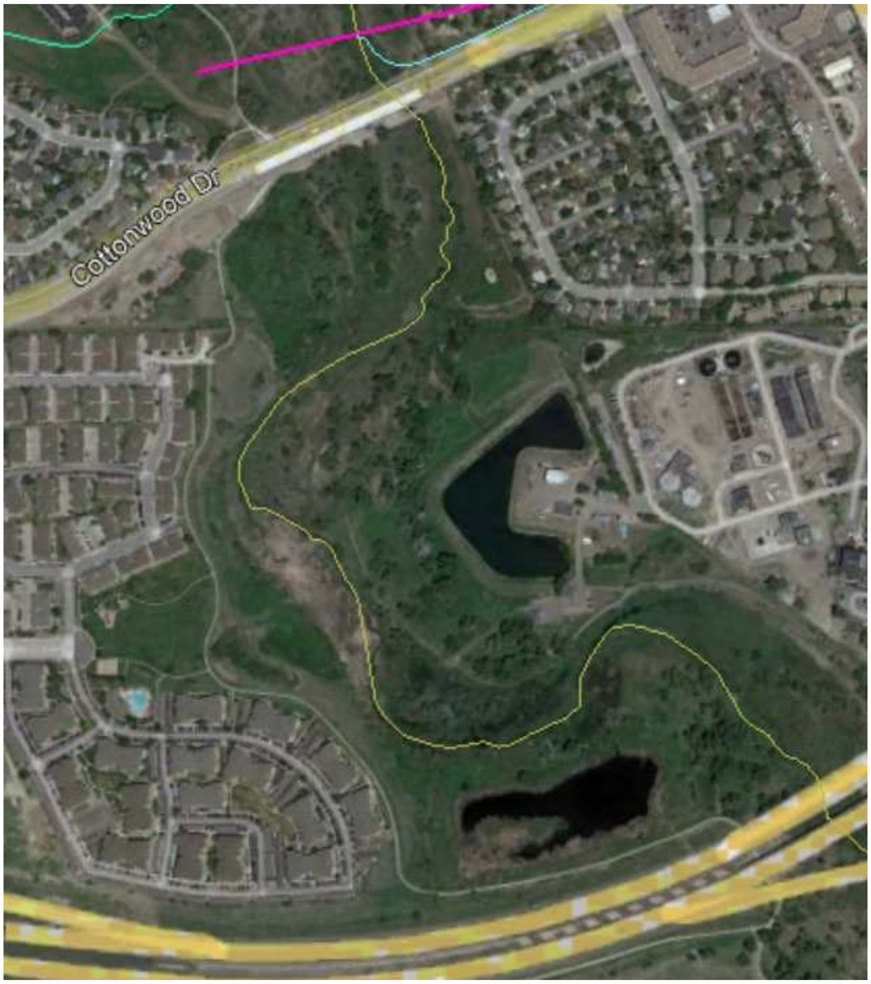
Floodplain: generally covered in grasses, active channel bounded by small willows and larger deciduous cottonwood trees. Noticeable vegetation density increases around side channels and small wetland complexes, indicative of shallow groundwater and overbank flow paths.

<u>Stream behavior</u>

Low Flow Stage: this reach type is the product of valley widening and the associated deposition and storage of sediment delivered from upstream and by tributaries that source material to the valley floor via local and general sediment transport. At low flows, the channel is well contained in a single-thread channel, and the banks are generally stable. There appears to be minimal heterogeneity created by large wood or variation in channel-bed sediment size. Vegetation flanks the channel and it influence the channel morphology at this stage.

***Bankfull stag*e**: higher flows are capable of reaching the finer-grained floodplain deposits which compose the flat, broad floodplain. Small middle channel bars are largely unvegetated and can be reworked at bankfull flows. Migration of the channel may be promoted along meander bends with sparse vegetation. A rise in the groundwater table during wet periods may result in these low areas being filled with water and acting as temporary side channels.

Overbank Stage: the side channels along the valley floor will be activated, as these areas are generally located 5 feet or less above the active channel (see image below). At this stages, the planform is prone to floodplain accretion due to the connectivity between the floodplain and the channel. The wide nature of the channel and its broad floodplain promotes water and sediment activating the floodplain, resulting in deposits of finer mud, sand, gravel, and detritus (sticks, leaves, etc.) across the valley bottom.


Cottonwood Dr

APPENDIX C

EXAMPLE REACH-SCALE METRICS FOR EACH FACET

Human connections and values reach-scale metrics

Indicator: Access to Nature

Metrics	Analysis type	Data source
Natural space opportunities	Quantity and Quality of/ Enhancements to Trail(s), walks, or Access points (i.e. trailheads, intersections, rest/amenity areas, ramps, etc.) Observations of social trails, unoffical dog park, access down to creek as opposed to trails along the reach	Field observations
Gaps in natural space	Identification and measurement of gaps using a demographic profile with the most urgent need for public parkland and natural space opportunities based on land use and cover characteristics, schools, community gardens, etc.	DRCOG 2022, TPL 2017
Universal access	Identification and measurement of universal access points (quantitative) using equity map, neighborhood trail connections, and recommended trail connections	Field observations

Indicator: Vitality

Metrics	Analysis type	Data source
Safety and security	Traffic Accident and Crime Data (adjacent) Physical Conditions (i.e. visual barriers, safety hazards, access hinderances, ADA, etc.). Desirable(or non) human activity (i.e. encampments)	Field observations, DRCOG 2022, TPL 2017
User experience	Positive Aesthetic/Experiential Character - i.e. Landscape and Architectural Forms, Materials, etc.	Field observations
	Zoning/land uses (immediately adjacent) and presence of desirable amenities/services, location of stormwater outfalls, sightlines	Field observations

Indicator: Economics

Metrics	Analysis type	Data source
Maintenance costs	Infrastructure Condition Assessment (Immediately Adjacent)	Field observations
Community development	Equity mapping along the corridor based on equity index and demographics.	DRCOG 2022, TPL 2017
	City long range development plans, future redevelopment, economic development and strategtic plans, HUD, greenfields/brownfield plans	Community planning and development departments

Indicator: Stewardship

Metrics	Analysis type	Data source
Political/Community Activism	Evidence of stewardship by community - i.e. community led projects, plans, etc. Community reports, planning efforts, etc.	Field observations
Conservation/ preservation of natural resources	Monitoring/Reporting for distribution of green/pervious vs non, water usage/conservation, vegetation types (i.e. predominant turf vs balanced), circulation patterns, Heat island/shade, water and air quality,	Field observations

Hydrologic processes and hydraulic characteristics reach-scale metrics

Indicator: Flow regime

Metrics	Analysis type	Data source and period of record if applicable	Finest scale of resolution for data collection or curation	Ranges of application
Magnitude	Evaluation of flow rate and magnitude between historical, existing, and future conditions (quantitative). Master Plan Data and/or Hydrograph flow-routing for existing and future land use from hydrologic model; stream gage analysis for historical and existing conditions, if gage data is available	Hydrologic data (gage or model)	Reach	All flow regime types
Volume	Analysis of total volume between historical, existing, and future conditions (quantitative).	Hydrologic data (gage or model)	Reach	All flow regime types
Frequency	Analysis of flood frequency between historical (baseline), existing, and future conditions (quantitative).	Hydrologic data (gage or model)	Reach	All flow regime types
Rate of change	Analysis of departure between historical (baseline), existing, and future conditions (quantitative).	Hydrologic data (gage or model)	Reach	Perennial streams
Timing	Analysis of departure between historical (baseline), existing, and future conditions (quantitative).	Hydrologic data (gage or model)	Reach	Perennial streams

Indicator: Flood and fluvial hazards

Metrics	Analysis type	Data source and period of record if applicable	Finest scale of resolution for data collection or curation	Ranges of application
Structures in the regulatory floodplain	Measurement of depth and associated hazard of structures within FEMA SFHA floodplain (quantitative)	Modeling data	Reach	All stream types
Structures in the FHZ	Measurement of number of structures in FHZ (quantitative); identification of FHZ and encroachment (quantitative)	Modeling data	Reach	All stream types

Indicator: Flow conveyance

Metrics	Analysis type	Data source and period of record if applicable	Finest scale of resolution for data collection or curation	Ranges of application
Riverscape (channel and floodplain) capacity	Evaluation of the capacity and space available for a riverscape (channel and floodplain) to convey the full spectrum of flows.	Modeling data	Reach	All stream types
Crossing structure capacity	Measurement of number of structures in FHZ (quantitative); identification of FHZ and encroachment (quantitative)	Modeling data	Reach	All stream types

Indicator: Floodplain connectivity

Metrics	Analysis type	Data source and period of record if applicable	Finest scale of resolution for data collection or curation	Ranges of application
Floodplain connectivity ratio	Measurement of width and longitudinal length (quantitative); identification/ checking of modern floodplain (qualitative)	Aerial imagery, GIS spatial data, and field observations	Reach	All stream types
Entrenchment ratio	Identification and measurement of bankfull stage and flood-prone width (quantitative)	GIS spatial data, field measurements	Reach	Perennial streams
Overbank return interval	Modeling bankfull stage and flood-prone width (quantitative)	Modeling data	Reach	All stream types

Geomorphic forms and processes reach-scale metrics

Indicator: Sediment regime

Metrics	Analysis type	Data source and period of record if applicable	Finest scale of resolution for data collection or curation	Recommended relative scoring contribution to indicator score
Channel sources	Qualitative: Visual assessment of disturbances and stressors. Quantitative: Identification and measurement of corridor sediment sources and stressors using DEMs of Difference.	LiDAR from DRCOG 2020 or multiple years from Colorado IT Office.	Reach	
Sediment continuity	Semi-quantitative: Identification and measurement of blocking structures; visual assessment of channel sediment transport patterns upstream and downstream of blocking structures.	Aerial imagery, GIS spatial data, and field observations	Sub-reach	
Sediment transport capacity	Quantitative: Determine if the channel is supply or capacity limited using capacity supply ratio (CSR)	HEC-RAS model, LiDAR or survey channel cross section data, and aerial imagery	Reach	

Indicator: Stability

Metrics	Analysis type	Data source	Finest scale of resolution for data collection or curation	Ranges of application or confinement
Stream power gradient	Quantitative: Specific stream power associated with channel forming flows such as 10% and 20% AEPs. Qualitative: identification and measurement of erosion or depositional areas.	Modeling, aerial imagery, GIS spatial data, and field observations	Corridor or reach	Partly unconfined, laterally unconfined
Lateral migration	Quantitative: Identification and measurement of historical range of meander bends, sinuosity, and average channel widths. Qualitative: identification of eroding banks.	Aerial imagery, GIS spatial data, and field observations	Reach	Partly unconfined, laterally unconfined
Channel stability index	Qualitative: Identification and measurement of bed material, bed/bank protection, degree of incision, degree of constriction, bank erosion, bank instability, bank accretion.	Field observations	Reach	Partly unconfined, laterally unconfined

<u>Indicator: Morphology</u>

Metrics	Analysis type	Data source	Finest scale of resolution for data collection or curation	Ranges of application or confinement
Geomorphic functionality – **profile**	Quantitative: identification and measurement of slope changes along corridor profile; Qualitative identification/checking of slope irregularities	Aerial imagery, GIS spatial data, hydraulic model, and field observations	Reach	All channel types
Geomorphic functionality – **continuity**	Qualitative: identification of crossing structures; visual assessment of partial or complete interception	Field observations	Reach	All channel types
Geomorphic functionality – **channel bed forms**	Quantitative: percentage of the reach length with alteration of the natural heterogeneity of forms expected for that stream type.	Aerial imagery, GIS spatial data, and field observations	Reach	All channel types
Geomorphic functionality – **geometry**	Quantitative: identification and measurement of length of altered portions	Aerial imagery, GIS spatial data, and field observations	Reach	All channel types
Artificiality – **bank protection**	Quantitative: length of bank stabilization measures	Aerial imagery, field observations	Reach	All channel types
Artificiality – **levees/ embankments**	Quantitative: length and distance of levee(s) and/or embankments	Aerial imagery, field observations	Reach	Partly unconfined, laterally unconfined
Channel adjustments – **pattern**	Quantitative: changes in channel pattern based on changes in sinuosity, braiding, and anastomosing indices	Aerial imagery, field observations	Reach	All types; evaluated only for perennial channels or channels > 10 ft wide
Channel adjustments – **width**	Quantitative: changes in channel width based on historical top width, bankfull and/or active channel widths	Aerial imagery, field observations	Reach	All types; evaluated only for perennial channels or channels > 10 ft wide
Channel adjustments – **bed-level**	Qualitative or quantitative: evidence of incision or aggradation	Aerial imagery, GIS spatial data, and field observations	Reach	All types; evaluated when field evidence or information is available
Channel adjustments – **SEM stage**	Qualitative: evidence of stream evolution stage	Aerial imagery, GIS spatial data, and field observations	Reach	Partly unconfined, laterally unconfined

Ecological reach-scale metrics

Indicator: Vegetation flow conveyance

Metrics	Analysis type	Data source	Finest scale of resolution for data collection or curation	Ranges of application
Riparian Zone Woody Cover	Quantitative: percent woody cover in the riparian zone	Aerial imagery or field observations	Watershed, Corridor, Reach	All channel types
Channel woody cover	Quantitative: percent woody cover within the riparian zone	Aerial imagery or field observations	Watershed, Corridor, Reach	All channel types
Clogging of crossing structures	Qualitative: clogging of channel spanning structures such as bridges and culverts via encroaching trees and shrubs.	Field observations	Corridor, Reach	All channel types
Floodplain Roughness value consistency	Quantitative/Qualitative: range of floodplain roughness values that do not result in rise in water surface. N values reported for floodplain vegetation.	Field observations	Reach	All channel types
Vegetation Cover in the Channel	Qualitative: composition, height, and cover of vegetation in the channel	Field observations	Reach	All channel types

Indicator: Dynamic Stability

Metrics	Analysis type	Data source	Finest scale of resolution for data collection or curation	Ranges of application
Riparian Vegetation Cover	Quantitative: percent vegetation cover within the riparian zone (watershed and corridor scale) or relative native plant cover (reach scale).	Aerial imagery or field observations	Watershed, Corridor, Reach	All channel types
Wetland Vegetation Cover	Quantitative: percent wetland community cover (watershed and corridor scale) or relative native cover in wetlands at reach scale.	Aerial imagery or field observations	Watershed, Corridor, Reach	All channel types
Vegetation Vigor	Quantitative: NDVI for riparian width at watershed scale; percent cover of plant senescence at reach scale	Field observations	Watershed, Corridor, Reach	All channel types
Bank Stability	Quantitative: bank stability index (Winward 2000) calculated based on dominate (> 20%) greenline species	Field observations	Corridor, Reach	All channel types
Streamside buffer width	Quantitative: width of riparian and wetland plant communities in valley bottom	Field observations	Corridor, Reach	All channel types
Valley bottom buffer width	Quantitative: width of wetland, riparian, and upland plant communities in valley bottom	Field observations	Corridor, Reach	All channel types

<u>Indicator: Resiliency</u>

Metrics	Analysis type	Data source	Finest scale of resolution for data collection or curation	Ranges of application
Hydrologic Alterations	Quantitative: number of impoundments/channel blocking structures (*what is size threshold for this?)* Qualitative: visual assessment to document disconnecting elements (including culverts, pipes, etc)—non-natural elements	Aerial imagery, GIS spatial data, and field observations	Watershed	All channel types
Riparian Zone Fragmentation	Quantitative: Mean proximity or mean nearest neighbor	Aerial imagery, GIS spatial data, and field observations	Watershed	All channel types
Noxious Weed Cover	Quantitative: absolute percent cover of noxious weeds within the riparian zone	Field observations	Reach	All channel types
Riparian functional traits	Quantitative: index value of hydric functional traits for dominant riparian and wetland species.	Field observations	Reach	All channel types
Riparian zone plant richness	Quantitative: number of unique plant species in upland, riparian, and wetland communities	Field observations	Reach	All channel types
Wetland plant richness	Quantitative: number of unique plant species in wetland community only	Field observations	Reach	All channel types