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FOCUS ARTICLE

Reintegrating the North American beaver (*Castor canadensis*) in the urban landscape

David R. Bailey[1,2] | Benjamin J. Dittbrenner[1] | Ken P. Yocom[3]

[1]School of Environmental and Forest Sciences, University of Washington, Seattle, Washington

[2]Natural Resources Department, The Tulalip Tribes, Tulalip, Washington

[3]Department of Landscape Architecture, University of Washington, Seattle, Washington

Correspondence
David R. Bailey, Natural Resources Department, The Tulalip Tribes, 6406 Marine Dr. Tulalip, WA 98271.
Email: dbailey1@uw.edu

In recent decades, ecological restoration and landscape architecture have focused on reintegrating ecological processes in the urban environment to support greater habitat complexity and increase biodiversity. As these values are more broadly recognized, new approaches are being investigated to increase ecosystem services and ecological benefits in urban areas. Ecosystem engineers, such as the North American beaver (*Castor canadensis*), can create complex habitat and influence ecological processes in natural environments. Through dam building and wetland formation, beaver can create fish habitat, diversify vegetation in riparian zones, and aggrade sediment to increase stream productivity. As beaver populations have increased in urban areas across North America, their presence presents challenges and opportunities. Beaver can be integrated into the design of new and established urban green spaces to improve ecosystem functions. If managed properly, the conflicts that beaver sometimes create can be minimized. In this paper, we examine how landscape architects and restoration ecologists are anticipating the geomorphic and hydrological implications of beaver reintroduction in the design of wetlands and urban natural areas at regional and site levels. We present an urban beaver map and three case studies in Seattle, WA, USA, to identify various approaches, successes, and management strategies for integrating the actions of beaver into project designs. We make recommendations for how designers can capitalize on the benefits of beaver by identifying sites with increased likelihood of colonization, leveraging ecosystem engineers in design conception, designing site features to reduce constraints for the reintroduction and establishment of beaver, and anticipating and managing impacts.

This article is categorized under:
Water and Life > Conservation, Management, and Awareness
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KEYWORDS

beaver, biodiversity, *Castor canadensis*, ecological design, ecological restoration, ecosystem engineers, ecosystem services

1 | INTRODUCTION

The North American beaver (*Castor canadensis*) is an important and controversial species known for dam building and the creation of large wetland complexes. Prior to European colonization beaver populations were estimated to number 60–400 million in North America (Naiman, Johnston, & Kelley, 1988). Beaver were intensively trapped for their pelts through the 1800s and eradicated from developed areas where they were often considered a nuisance. Beaver populations became isolated, and their numbers were dramatically reduced in urban and rural areas, with only about 10% of historical populations remaining (Wilson & Reeder, 2005). Yet, some landscape designers, ecologists, and land managers have begun to recognize the ecological benefits and services that active beaver populations can provide and are now considering ways in which the reintroduction of beaver may improve upon the existing urban landscape and the ecological functioning of urban green spaces.

In rural and urban environments, the action of beaver can improve degraded hydrologic regimes and geomorphology while enhancing habitat for native plant and animal communities. These actions also provide vital ecosystem services for developing and developed areas (Table 1). Beaver dams impound and reduce stream velocity during storm events, retaining flow to reduce storm-water run-off and increasing water retention (Bergstrom, 1985; Grasse & Putnam, 1950; Johnston & Naiman, 1987; Parker, 1986). Beaver ponds and wetlands also recharge groundwater through infiltration, elevating the water table and extending the area of riparian habitat and inundation (Bergstrom, 1985; Johnston & Naiman, 1987). This can be particularly beneficial in urban areas where the capacity for infiltration is severely diminished due to the extensive use of impervious surfaces such as roadways, buildings, and the compaction of soils (Chithra et al., 2015). Through the building of dam structures, beaver alter geomorphology by slowing and widening streams, resulting in the creation of step-pool sequences that reduce erosion potential and induce sediment collection (Butler & Malanson, 1995; Pollock et al., 2014). Aggradation of sediment behind beaver dams promotes channel building and floodplain reconnection, which further augments subsurface flow for riparian vegetation (Butler & Malanson, 1995; Butler & Malanson, 2005; Demmer & Beschta, 2008; Janzen & Westbrook, 2011). Together, these benefits reduce summer stream temperatures and increase available stream nutrients (Lowry, 1993; Rosell et al., 2005), often addressing planned climate change adaptation and carbon and water storage goals within local catchments (Bird et al., 2011; Cramer, 2012; Fouty, 2008; Hood & Bayley, 2008).

By raising water levels and spreading water laterally, beaver damming frequently drives the formation of wetland plant communities. Beaver can create and modify wetlands by capturing organically rich sediment, which can increase plant richness in the riparian zone by up to 25% (Polvi & Wohl, 2012; Wright et al., 2002). Beaver are selective in the harvest of woody vegetation, subsequently encouraging the growth of preferred forage food and prolonging the availability of a localized food source (Bailey et al., 2004; McGinley & Whitham, 1985). Plant communities and above-ground biomass may be affected by this foraging, creating an environment suitable for disturbance-tolerant woody vegetation, such as willows and alders (Polvi & Wohl, 2012; Wright et al., 2002). These fast-growing species facilitate pollution filtration and nutrient sequestration, and result

TABLE 1 Distinguishing the key system components and processes that drive ecosystems are important to understand how urban beaver can provide ecosystem benefits to their environment and ecosystem services to humans

Components and processes	Ecosystem benefit of beaver	Ecosystem services of beaver
Wetland and floodplain connectivity	Reestablish historical floodplains[1,2] and increase wetland habitat area[3]	Slow urban runoff[4,5]
Water storage	Ponds and side channels increase catchment storage[6,7,8,9]	Reduce flooding events[10,11,12]
Nutrient cycling	Created ponds increase nitrogen, phosphate, carbon, and other micronutrient availability[8,13,14,15]	Increasing mineral and carbon cycles that facilitate pollutant break-down[16]
Sediment transport	Increased sediment accumulation behind dams can improve high sediment systems and improve subsurface flow[6,17,18,19]	Provide bank erosion and downstream infrastructure protection[9,20]
Water quality	Decreasing water temperatures and higher dissolved oxygen improve outflowing water for fish and micro invertebrates[19,21,22]	Created ponds improve water quality by decreasing water temperatures and increasing pollutant filtration and sequestration[23,24]
Stream complexity	Create step-pool sequences and habitat diversity that increase hydrological pathways[18,19]	Decrease channelization by encouraging stream meandering[25,26]
Climate change and droughts	Increased water storage and carbon collection, address catchment climate change adaptation goals[27,28,29,30]	Urban landscapes become more adaptive to droughts, floods, and extreme weather events[31,32,33]
Riparian vegetation structure and buffer zones	Maintained groundwater levels allow for increased, dense, and complex vegetative patches[20,22,34]	Increased riparian vegetation buffer zones in high urban development areas[20,35]
Vegetation ground cover	Environment suitable for disturbance-tolerant and fast growing trees and shrubs such as willow and alder[20,34]	Increased regionally-appropriate species for pollution filtration[8,36]
Species diversity	Increased habitat for insects, amphibians, birds, mammals, fish, bio-indicator, and riparian-dependent species[26,37,38]	Increase bio-indicator and freshwater invertebrate species important to assessing stream and habitat health as well as wildlife viewing opportunities[39,40,41,42]
Species migration patterns	Increased natural passageways for urban wildlife and greater genetic diversity[37,46]	High quality foraging and rearing habitat for culturally significant species such as salmonids, ungulates, and predator species[18,22,43,44,45]

[1]Naiman et al., 1988; [2]Pollock, Beechie, & Jordan, 2007; [3]McCall, Hodgman, Diefenbach, & Owen, 1996; [4]Hey & Philippi, 1995; [5]Faram, Osei, & Andoh, 2010; [6]Janzen & Westbrook, 2011; [7]Westbrook, Cooper, & Baker, 2006; [8]Naiman & Décamps, 1997; [9]DeBano & Heede, 1987; [10]Grasse & Putnam, 1950; [11]Parker, 1986; [12]Collen & Gibson, 2000; [13]Correll, Jordan, & Weller, 2000; [14]Perkins, 2000; [15]Leary, 2012; [16]Cirmo & Driscoll, 1993; [17]Butler & Malanson, 1995; [18]Pollock et al., 2014; [19]Demmer & Beschta, 2008; [20]Polvi & Wohl, 2012; [21]Lowry, 1993; [22]Rosell, Bozser, Collen, & Parker, 2005; [23]Johnston & Naiman, 1987; [24]Bergstrom, 1985; [25]Pollock et al., 2007; [26]Nagle, 2007; [27]Hood & Bayley, 2008; [28]Bird, O'Brien, & Petersen, 2011; [29]Fouty, 2008; [30]Cramer, 2012; [31]Chithra, Nair, Amarnath, & Anjana, 2015; [32]Chow, 2017; [33]Booth et al., 2004; [34]Wright, Jones, & Flecker, 2002; [35]May, Horner, Karr, Mat, & Welch, 1997; [36]Aronsson & Perttu, 2001; [37]Brown, Hubert, & Anderson, 1996; [38]Cunningham, Calhoun, & Glanz, 2007; [39]McCabe & Gotelli, 2003; [40]Brooks, Snyder, & Brinson, 2013; [41]Nummi, 1992; [42]Nummi & Holopainen, 2014; [43]Bouwes et al., 2016; [44]Ray, Ray, & Rebertus, 2004; [45]Rupp, 1955; [46]Oertli, Céréghino, Hull, & Miracle, 2009.

in more diverse, complex, and resilient wetland habitats over time (Aronsson & Perttu, 2001; Flanagan & Van Cleve, 1983: Naiman & Décamps, 1997; Rosell et al., 2005).

Aquatic invertebrate diversity and abundance is often increased through the creation of complex habitat and greater levels of micronutrient availability in beaver created ponds (McCabe & Gotelli, 2003). These diverse and abundant benthic invertebrates form the base of the food web for many aquatic organisms and are a key determinant in assessing stream health (McDowell & Naiman, 1986; Morley & Karr, 2002; Pollock et al., 1995). Through the process of dispersal, beaver frequently colonize marginal habitat and transform it into wetland systems through dam building. While this ecosystem engineering results in more preferable beaver habitat, it also provides suitable habitat for a diverse assemblage of animals, including birds, amphibians, reptiles, and mammals (Hood & Bayley, 2008). Beaver ponds are also effective at reducing silt loads within streams to improve spawning grounds, maintaining water temperatures for spawning, and creating new high quality rearing and foraging habitat for fish including cutthroat trout, coho and sockeye salmon (Pollock et al., 2014; Rosell et al., 2005) and steelhead (Bouwes et al., 2016).

Beaver populations in many urban areas are steadily rebounding with currently an estimated 6–12 million in North America (Naiman et al., 1988). Despite increasing human populations and habitat conversion from urban development (Dittbrenner et al., 2018; Faulkner, 2004), beaver have returned to high density areas, such as in New York City where the first beaver in over 200 years was identified in 2007 (O'Connor, 2007). As beaver continue to recolonize urban and suburban areas, their activities have the potential to cause conflicts with existing land use through their removal of trees and ability to flood property and infrastructure. While trapping has been traditionally utilized to decrease populations and remove nuisance beaver, increasing public reluctance towards trapping is allowing populations to thrive (Oogjes, 1997). In these areas where trapping is only occasionally or periodically implemented, adjacent beaver colonies can quickly recolonize historically inhabited streams and wetlands. Yet, the actions of beaver can pose long-term, cost-prohibitive management implications; therefore, site design considerations and management strategies to mitigate these conflicts need to be better understood. As the understanding of beaver ecology grows, designers and restoration ecologists have the opportunity to use beaver as an ecological design tool to benefit urban habitat systems and landscapes.

In this study, we provide an overview of the current state of knowledge on urban beaver benefits and services and how increasing urban beaver populations can be addressed and leveraged in urban landscape design. We review and evaluate site designs for intended beaver colonization to inform researchers and designers of potential beaver management strategies and design considerations.

2 | ECOLOGICAL DESIGN

The allied ecological design fields of landscape architecture and ecological restoration continue to expand in scope and purview within the built environment, evolving to reflect shifting societal values and priorities. Throughout its history as a professional field and academic discipline, landscape architecture has served to improve upon a wide variety of urban open space functions. Previously, landscape architecture primarily focused on design elements aimed at providing experiential and aesthetic opportunities, but often with limited local ecosystem function and services (Hunt, 1994). Today, as our understanding of ecological systems has evolved, so has the incorporation of this information into design practices in efforts to incorporate ecosystem functions into urban green spaces such as providing habitat corridors, improving water quality (R. R. Horner, personal communication, May 15, 2014; May et al., 1997), and reducing heat island effects within urban catchments (Getter & Rowe, 2006). While landscape architecture has begun to identify some of these complexities, the proportion of ecologically functional urban green spaces in metropolitan areas has not kept pace with urban expansion over the last century (Hunt, 1994). Moreover, while landscape architecture aims to incorporate ecological principles and benefits, some ecological and hydrologic processes cannot be reproduced solely by intentional design actions (Bains, 2013), but are reliant upon inherent natural ecosystem processes and drivers at each site.

2.1 | Design principles

As the understanding of ecosystem and habitat dynamics continues to grow, designers and managers have attempted to incorporate these ideas and concepts into urban open spaces (Musacchio, 2009). For example, early designer, Frederick Olmsted, in 1878 proposed a unique plan in the Boston Fens, MA, USA, which leveraged sanitary engineering techniques with the ecosystem functions and aesthetic attractiveness of tidal marshes (Egan, 1990). More recently, in 2010, the design firm Turenscape incorporated aesthetics and ecological function at Shanghai Houtan Park, Shanghai China, resulting in flood protection and habitat production on a former industrial river site (Rottle & Yocom, 2010). Presently, landscape architecture focuses on design that serves to emulate ecological processes, patterns, and ecological quality found in highly functioning reference systems (Nassauer, 1995; Rottle & Yocom, 2010). These concepts are often applied across spatial scales, from green roofs and gardens to regional and catchment open space planning (Beatley & Newman, 2013; Freeman, 2011). To effectively mimic reference systems, however, designers use key design principles that work across temporal scales to frame the potential site evolution over time (Musacchio, 2009; Rottle & Yocom, 2010).

Using ecological design principles, relatively large-scale and dynamic site design projects, such as the case studies that we examine in this paper, tend to address three primary design goals. The first is human recreational use or therapeutic design, which focuses on creating diverse and useable spaces that attract people to the place (Jackson & Sinclair, 2012). The second is to provide ecosystem services for urban environments. To date, many ecologically-based urban designs are primarily related to modifying streamflow and hydrology with the common goal of improving water quality by strategies that retain and infiltrate water with designed vegetative and green open space systems (Jackson & Sinclair, 2012). The third goal is to create and enhance urban habitat through conservation and restoration design, building from landscape ecology principles to facilitate increased connectivity and genetic diversity (Boswell, Britton, & Franks, 1998; Jackson & Sinclair, 2012).

2.2 | Recent trends

Recent trends in urban ecological design and restoration focus on developing and implementing a functionally oriented approach to optimize water-related ecosystem services and ecological benefits throughout stages of the design and the project implementation process. For example, constructed wetlands are often designed to collect a portion of their hydrology from stormwater to create vernal pools with varying microtopography that mimic natural surface and groundwater conditions (Beck, 2013). This contrasts with more traditionally designed artificial ponds that require a constant supply of water and filtration to remain functional (Beck, 2013). Similar to the Boston Fens example above, the contemporary use of constructed wetlands utilizes hydrologic and geomorphic knowledge to inform a design approach that can achieve a higher level of ecosystem function than if a traditional artificial pond were created (Beck, 2013).

Ensuring greater ecosystem function using an ecological design approach, however, often requires articulating long-term management objectives and incorporating an iterative design process. Project planning requires a diverse, interdisciplinary team of scientists, planners, and designers to effectively work together to ensure primary project design goals and ecological targets are met (Palazzo & Steiner, 2012). Capitalizing on natural processes through an interdisciplinary approach to ecological design has the potential to allow diverse design teams to leverage specific expertise and identify strategies to lower long-term site costs and minimize site design changes (Van der Ryn & Cowan, 1996). To achieve these goals, design teams should consider the initial level of effort and resources needed to meet the functional goals of a project (Figure 1). Mimicking and recreating the processes prevalent in natural systems using physical design elements, such as berms, weirs, depressions, or the selection of specific plant species can serve to meet a variety of design goals ranging from functional system needs to aesthetics and access. A collaborative and multi-functional approach to design may serve to decrease initial costs for the project and proactively engage opportunities for long-term success.

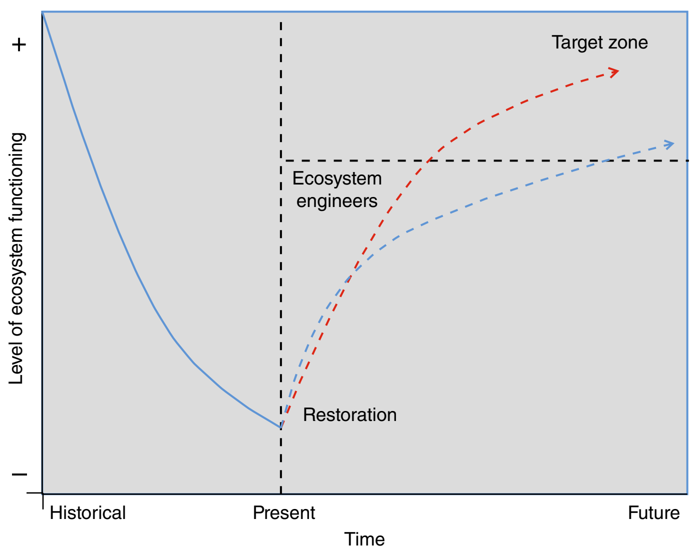

FIGURE 1 The understanding and use of ecosystem engineers in restoration and design projects (solid blue line) can facilitate a greater level of ecosystem function. The dashed blue line represents a restoration project's level of success as it develops through time. By taking an interdisciplinary approach, design teams have the opportunity to consider and leverage ecosystem engineers (red line) as a restoration agent in restoration design to achieve the targeted level of success sooner. (Adapted with permission from Rottle and Yocom (2010))

The integration of keystone species and ecosystem engineers into ecological design practices is emerging as a way to increase the level of ecosystem function (Beck, 2013). Keystone species are organisms that have a disproportionate effect on their habitat and ecological community despite their relative abundance (Mills & Doak, 1993), while ecosystem engineers are organisms that actively modify the natural environment to create and maintain their preferred niche or habitat (Jones, Lawton, & Shachak, 1994). Beaver are both ecosystem engineers and keystone species; they are proficient at creating and maintaining wetland systems and offer a unique opportunity to be used in designs to create dynamic natural systems in urban environments. However, beaver have not been traditionally considered or utilized in the design of constructed or enhanced wetlands, riverine areas, and green spaces since they have been historically considered nuisance animals. We propose that as landscape architecture and the allied environmental design fields place greater value on systems design and habitat formulation, the incorporation of ecosystem engineers, such as beaver, is required to better mimic natural systems. Anticipating the impacts of ecosystem engineers to modify and enhance ecosystem services and benefits within site design practices is a step towards advancing ecologically based landscape design and restoration (Figure 1).

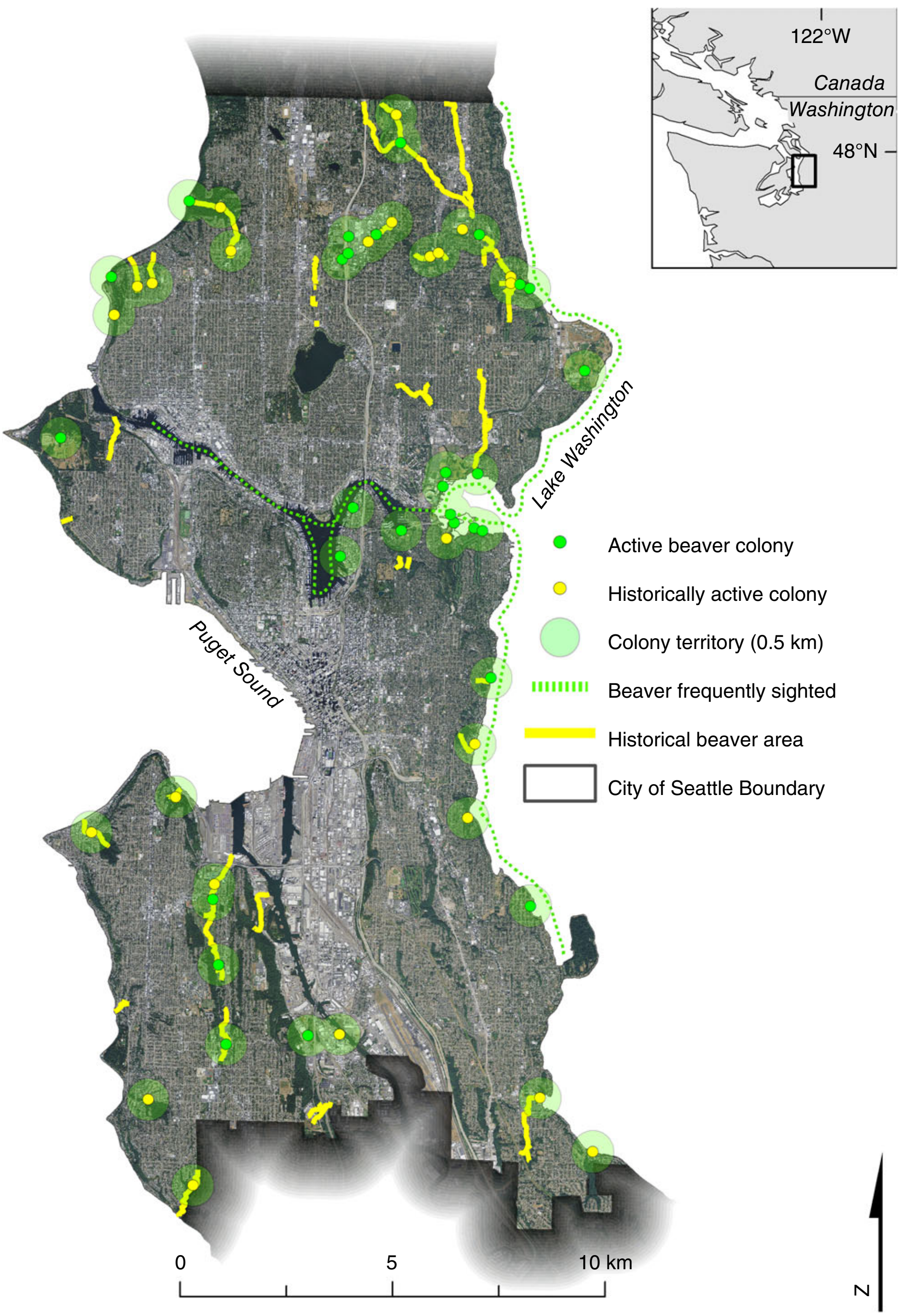

FIGURE 2 Surveys in 2015 identified active and recently active beaver colonies in most perennial natural streams in Seattle (WA, USA)

3 | CASE STUDIES

As designers seek to simulate ecological systems to improve urban spaces, beaver, along with many other adaptable species, are attracted to these areas of suitable habitat. Seattle, WA, USA, where our case studies are based, serves as a representative example of resurging beaver populations in urban areas. Changes to Washington State's beaver trapping laws in 2001 (RCW (Revised Code of Washington), 2001) resulted in reduced trapping efficiency and a drop in yearly trapping numbers from approximately 5,000 per year prior to 2001 to approximately 500 per year after 2001 (WDFW, 2000). The combination of limited trapping and low predation within urban areas has allowed beaver to thrive in even the most urban waterways of metropolitan Seattle.

In 2015, we conducted stream surveys and informally interviewed municipal agencies, nongovernmental organizations (NGOs), conservation groups, and other organizations in Seattle to identify the extent of beaver colonization within the city limits (Figure 2). We found that, of the more than 60 km of perennially flowing streams in Seattle, approximately 86% of suitable habitat is actively used by beaver or shows signs of recent activity, given an estimated colony density of approximately 1 colony per 0.5 stream kilometer (Johnston & Naiman, 1987). Most of Seattle's suitable stream habitat is currently occupied (Figure 2). What remains is marginally suitable habitat that beaver are slowly colonizing and attempting to convert into higher quality habitat by damming and tree removal.

While many urban open spaces in Seattle were not initially designed with beaver colonization in mind, some designers have embraced and encouraged the return of beaver colonization to project sites. Here, we present three case studies identified by designers and land managers as recent public projects affected by beaver. These sites demonstrate how emerging design and management strategies are anticipating and utilizing beaver as part of the design process to improve the level of ecosystem function and services. Each case study identifies a distinct approach to beaver colonization, and examines the successes and challenges for incorporating beaver into urban open space design.

3.1 | Golden gardens park

Seattle's Golden Gardens Park is a popular 35.6-ha public park located on the shores of Puget Sound. In 1997, Seattle Parks and Recreation designed and constructed a coastal lagoon within the park by converting a parking area into a wetland complex and natural area (Figure 3). The goals were to restore a historical lagoon for waterfowl habitat, cap an area of contaminated

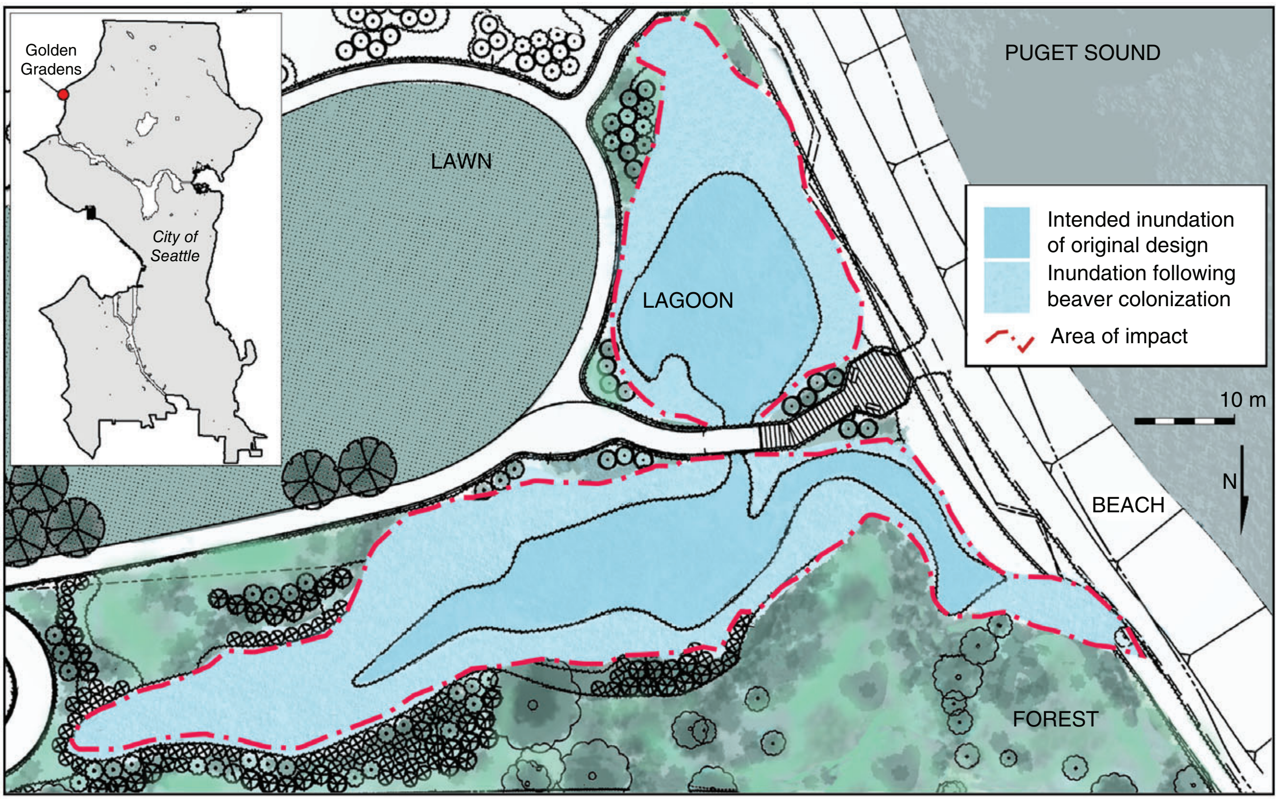

FIGURE 3 Adaptation of the 1997 design plan for the creation of a lagoon at Golden Gardens Park, Seattle, WA, used in a restoration design. Beaver colonized the site in 2014, building a lodge and dam, increasing the lagoon height, surface water storage, and ecological function. Original design plan, adapted from Bruce Dees Associates (Tacoma, WA, USA)

soil, and provide handicap and recreational access to the beach. The design team intended to create pond habitat by impounding surface and groundwater runoff from an adjacent hillside by installing a weir at the outlet of the system.

In 2014, beaver colonized the site, began felling large trees densely planted around the lagoon, and constructed a dam at the outlet to the beach, which increased the elevation of inundation and altered the vegetative structure within the site. The assumption of beaver colonization was not included in the initial project design, since the site is constrained by exposed coastline beach topography, adjacent to a nearby bluff. As the designed lagoon levels have continued to rise behind the newly constructed beaver dam, site managers are concerned about threatened public access over a boardwalk through the site. Some members of the public have also voiced concern over the loss of large alder trees surrounding the lagoon, which the beaver are harvesting. Given the site's topographic constraints, long-term management strategies such as installing a pond-leveling device (Taylor & Singleton, 2014), which is a perforated pipe that maintains water levels, as well as wrapping larger vulnerable trees with wired fencing to discourage beaver felling, are being implemented to address potential flooding issues and ensure continued use of the boardwalks.

Despite affecting the intended experience and aesthetics of the original design, the flooding impact from beaver was minimal due to a lack of nearby infrastructure and the design team and site managers' ability to adapt to physical changes that did not adversely affect initial design goals. Site managers are working to retain beaver on-site, increase public education to users through signage, and realize further benefits for wildlife habitat from the increased surface water area. While the site originally consisted of a relatively simple habitat intended to filter stormwater generated from a nearby parking lot, beaver have increased site complexity and augmented design goals by expanding wetted edge and water storage capacity, while enhancing aquatic and avian habitat.

3.2 | Magnuson park constructed wetland system

Located on the shore of Lake Washington in Seattle, Magnusson Park is a 142-ha public park that provides active and passive recreational opportunities (Figure 4). The design team, consisting of hydrologists, ecologists, and architects, created a 4.9-ha wetland complex on the site of a decommissioned military airfield to provide wildlife habitat and support passive recreational opportunities. The original project design intent was to capture and filter stormwater runoff from the surrounding neighborhood and nearby government facilities. The design incorporated two distinct elements to create amphibian and bird habitat. First, an upland component of the project intercepts seasonal rainfall and was designed to mimic vernal pools that dry up every summer, providing seasonal amphibian habitat. Second, downstream, a lowland component features two larger ponds and an engineered channel that directs outflow into nearby Lake Washington. This intensively engineered system, leveraged by a management plan that prioritizes enhancing the ecological integrity of the site, allows for adaptive low cost changes to occur.

FIGURE 4 Design plan for the Magnuson Park wetland complex, Seattle, WA. Completed in 2012, it includes a variety of water features including large ponds, wetland, and nonperennial vernal pools. Beaver colonized in 2014 and created additional ponding area within the areas originally designed to be wet meadows and vernal pools. Original design plans, adapted from the Berger Partnership (Seattle, WA, USA)

Prior to construction, the designers suspected that beaver would eventually colonize the site since it provided ideal deep-water habitat, abundant food, and beaver colonies were known to exist in nearby Lake Washington. The designers displayed flexibility in their design by reducing site constraints, such as minimizing hydrological pinch points and pathways near potential flooded areas. They also used design elements to anticipate colonization by creating a series of broad berm-style weirs to function like beaver dams to achieve ecosystem function before colonization (Sheldon & Gresham, 2007).

Beaver colonized the site in 2014, building a lodge in the lower pond, and constructing two large dams increasing the size of both ponds. These actions increased surface water storage by 30%, backing up water into the upstream vernal pools, converting some them to permanently saturated depressions (G. Michaelson, personal communication, February 26, 2015). While the initial vernal pool design was ideal for birds and amphibians it was less desirable mammal habitat due to the lack of permanently flowing water, lack of woody vegetation for beaver, no likelihood of fish presence, and lack of banks for denning (Sheldon & Gresham, 2007). Despite an increase in the water table, which altered the intended design goals by flooding some walking trails and vegetation, the public and the designers have perceived the beaver presence within the site as positive. Site managers and the design team recognize the beaver have diversified the wetland edge with an increase in shrub groundcover resulting from higher soil moisture around the pond edges. Despite losing some vernal pool qualities, an increase in amphibian and avian numbers has been documented throughout the site (G. Michaelson, personal communication, February 26, 2015). Recognizing their benefit, the designers have used beaver management approaches to allow beaver to remain on-site by reengineering a pivotal pinch-point and using three pond-leveling devices to control pond levels for reduced flooding (G. Michaelson, personal communication, February 26, 2015). Even when anticipating colonization and employing initial design interventions, it is important to note that the managers had to adopt flexible management strategies, make site modifications to accommodate beaver activity, and even revise certain ecological goals to allow beaver to improve the ecological function and habitat diversity of the site overall without disrupting the project goals.

3.3 | Thornton Creek Confluence and Meadowbrook Pond

Located at the confluence of the North and South branches of Thornton Creek, within Seattle's largest catchment, the Thornton Creek Confluence project is a 2.4-ha riparian improvement project surrounded by single-family residential properties (Figure 5). The project site is located immediately above a reach of Thornton Creek that provides the highest quality habitat for Chinook salmon spawning of any stream in the city (Hall et al., 2007).

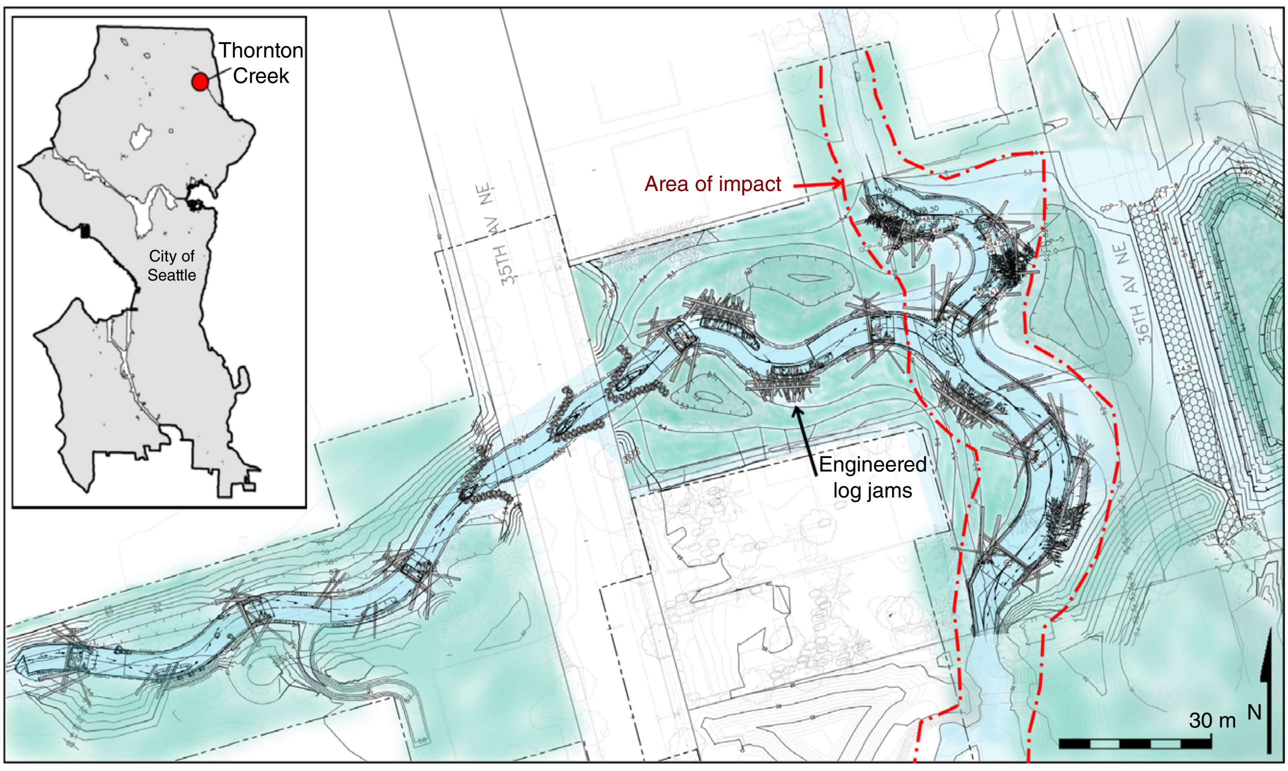

FIGURE 5 Design plan for the creation of the Thornton Creek Confluence restoration project. The project was completed in 2014 as a floodplain reconnection and habitat creation project within the City of Seattle's largest urban catchment. Permanent beaver colonization has yet to occur; however, early signs of beaver activity have been identified (shown in red). The many woody instream structures (engineered log jams) and wide flood plain increase the ability for beaver to colonize and increase the future success of ecological function at the site. Adapted from Natural Systems Design (Seattle, WA, USA)

Constructed in 2014, the intent of the design was to maximize water retention to reduce localized flooding, improve water quality, and improve sediment and debris transport. The design team addressed these goals by creating 0.8-ha of connected floodplain, improved stream meandering, enhanced stream structure, and improved aquatic and wildlife habitat. Aesthetically, passive recreational opportunities for the public include fish and wildlife viewing along boardwalks and trails strategically located throughout the site, away from the floodplain.

The project's site management plan anticipates the likely colonization of beaver because of known populations in the directly-adjacent Meadowbrook Pond, and utilizes their anticipated dam building and pond creation as a project element. Minimizing site constraints in project design, such as maximizing floodable area and avoiding low-lying pathways or channel spanning infrastructure, will allow for beaver occupancy with reduced conflict. For example, a portion of the project reconnected the large floodplain to the upper stream channel, and replaced a culvert under an adjacent arterial road with a floodplain spanning bridge. The design team planted native plants, created pools and installed instream woody structures as habitat for fish and other aquatic organisms. These elements are all ideal for future dam structures and important design elements beaver can leverage. The greatest concern remains the extensive plantings installed to achieve reduced stream temperature goals at risk of beaver herbivory. The designers hope to address the goals of the site by establishing the baseline habitat and then leverage potential beaver colonization to increase the future habitat complexity. However, if beaver colonize the site too early, food availability may be low and beaver may degrade the intended design. With site goals in mind, managers will be required to monitor and adaptively manage the site as beaver colonize and vegetation and hydrology evolve.

These case studies highlight the potential and detail the challenges of beaver colonization in urban areas. It is important to note that these examples are located on publicly owned lands. The design goals and subsequent management decisions reflect an approach that would likely unfold much differently if these sites were located on private property and managed as nuisance situations. While nearby landowners and green space users have a voice, the land managers can choose to educate the public, as in the case of the Golden Gardens example, or designers can minimize potential resident conflict by establishing deep-water habitat capable of water increase, or provide a wide floodplain for pond creation as in the case of Thornton Creek. The following section provides a set of design and management strategies, based on the findings from these case studies and other surveyed sites, for enabling the recolonization of beaver in urban areas of the Pacific Northwest of the U.S. and abroad to areas that could utilize beaver recolonization in design.

4 | DEVELOPING URBAN BEAVER MANAGEMENT STRATEGIES

4.1 | Design and beaver management

As urban beaver populations increase, expansion of beaver into designed public spaces that contain perennial surface water and food is likely to increase. In Seattle, Washington, as beaver colonization increases, we have observed that the original project elements of designed spaces are often affected in substantial ways. Physical constraints and human perception of the effect beaver have on the site most commonly influence whether the outcome of these impacts has negative, neutral, or positive effects on the site's ecologic trajectory and design goals. In some cases, colonization cannot be tolerated. In others, however, beaver can enhance site functions in novel ways. Based on the three case studies identified, Figure 6 describes possible pathways in which beaver can be integrated into urban landscapes through explicit design and management strategies.

Designed spaces that were originally constructed without consideration of the potential for beaver colonization and have aquatic features surrounded by flat topography (Figure 6a) are often at greatest risk for infrastructure conflict. Beaver-caused flooding in these sites can dramatically reduce the intended functions of the designed site. Removal of the colony may offer a temporary solution if the public is initially tolerant of trapping. If there is sufficient beaver population in the surrounding area, however, it is likely that the site will become repeatedly recolonized. In cases where the public is not tolerant of lethal trapping or has encountered trapping fatigue through repetitive annual trapping, elements of the site will need to be redesigned or modified to accommodate beaver. In some cases, these modifications may restore some level of ecosystem service provisioning. The combination of continued trapping, management, and modification of the site will result in high management costs in these areas. At sites like the Golden Gardens Park case study, small elevation changes can cause widespread flooding of unintended areas including public boardwalks. While beaver can be managed here, site constraints may require that design goals be modified. The need for public education on ecosystem engineers and their benefits may also be necessary.

Sites that have been designed with the assumption that beaver could colonize the site after a period of time (Figure 6b), or those that have sufficient topographic variability to allow moderate levels of beaver dam building and wetland creation can accommodate beaver colonization with fewer conflicts. At these sites, such as the Magnuson Park case study, where the site's design element mimics step-pool systems using weirs, beaver will augment riverine areas and wetland infrastructure to retain or increase ecological functions and services. While their presence can be tolerated and is largely beneficial, they need to be

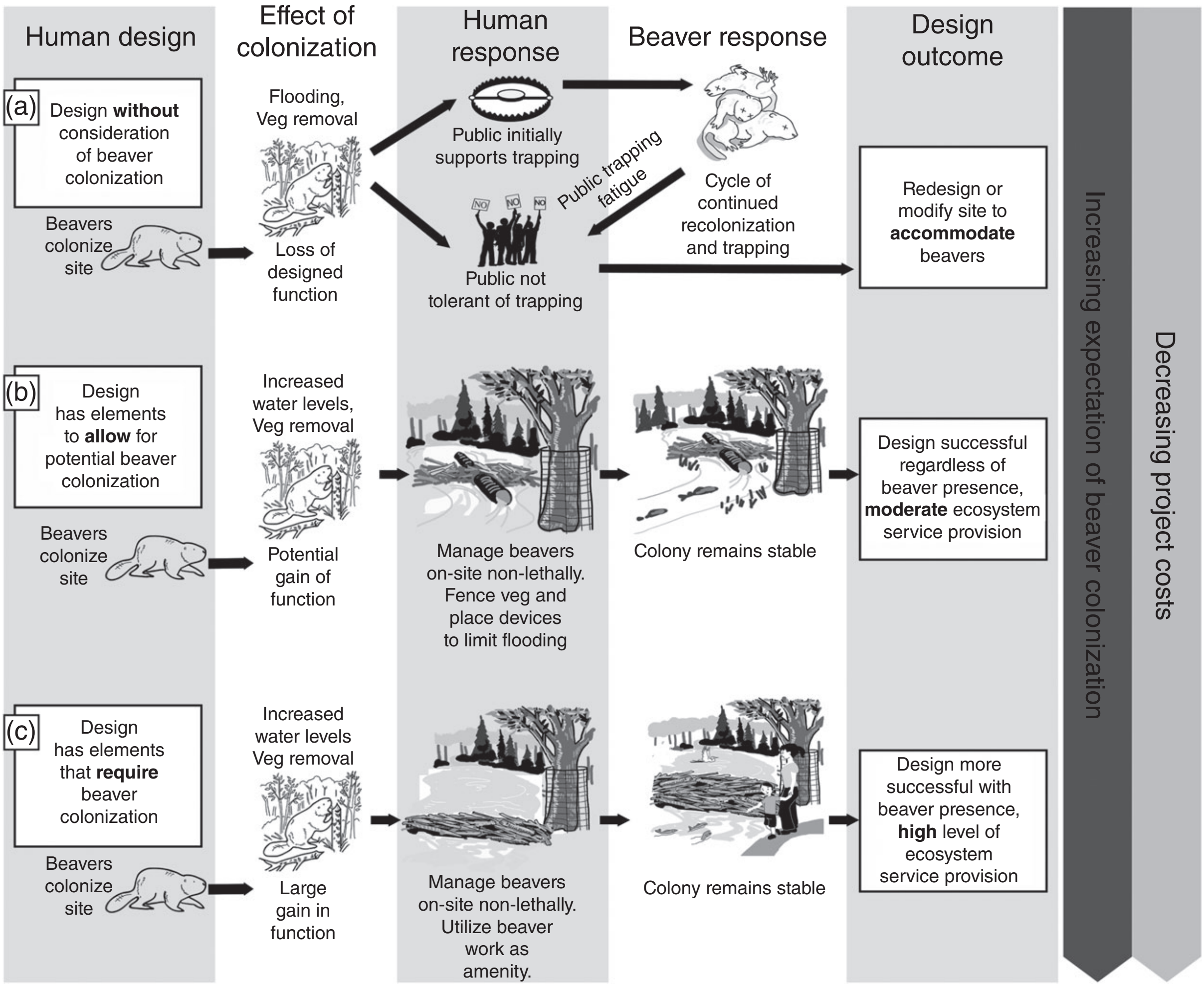

FIGURE 6 Pathways for integrating beaver into urban landscapes. Designed spaces where beaver colonization was not anticipated (a) incur high long-term costs with little benefit when responding to subsequent colonization. Designed spaces that had either included design elements that allow potential colonization (b), or had incorporated elements that require colonization to function fully (c) are less costly over the long-term and have greater levels of ecosystem services and ecological benefits

actively managed so that excessive pond building and vegetation removal do not conflict with the stated goals of the site. Active beaver management in these areas consists of fencing vegetation and placing beaver flow control devices (Taylor & Singleton, 2014), such as pond-levelers or exclusion fencing at dams and culverts to reduce or stabilize pond levels. With these management approaches and an iterative and adaptive management approach, the colony can remain in place and pond levels can remain stable indefinitely. In these cases, while beaver may or may not have been included in the initial design, their presence may lead to an increase in ecosystem services and ecological functions.

Lastly, designs that incorporate and require beaver presence as a design element (Figure 6c) have potential for the greatest level of ecosystem service and function and lower levels of conflict. Beaver colonization, dam building, and wetland creation in these sites are an essential component of the project design intent; the project will not become fully functional until beaver have occupied and modified the site. While these sites also need to be actively managed so that beaver do not expand beyond the initial anticipated design or colonize a site too early, the design has sufficient flexibility to accommodate the inevitability of beaver colonizing the site, while minimizing potential conflict. The flexibility of the site design allows beaver to create necessary wetland complexes that introduce variable hydrologic regimes and geomorphic complexity to the site. Site designs such as the Thornton Creek Confluence case study are able to satisfy project goals, regardless of changing water levels caused by beaver damming, because designers recognize that colonization is likely and have planned for such an occurrence. The uncertainty of the final project state can be initially unnerving for designers and managers, but flexible and complex site designs allow for greater levels of habitat and species diversity, ecosystem service, and ecological function than constructed wetland complexes. The incorporation of beaver presence in design can also offer additional amenities such as a greater variety of wildlife viewing and aesthetics for some users. Cumulative maintenance costs of sites where beaver were included in the project design are comparatively lower than sites that did not anticipate colonization in their management plans (Boyles & Savitzky, 2008).

4.2 | Management strategies

We present criteria to evaluate whether beaver are appropriate for or likely to colonize an urban natural area based on case study observations, literature, interviews, and our experience mapping urban beaver sites (e.g., Figure 2). We also present guidelines for designers, land managers, and ecologists to consider when using beaver as a design tool (Table 2). Before beaver can be leveraged in design for their functional benefits, managers should identify whether their site is suitable for beaver and likely to be colonized. This can be done by evaluating the proximity of known beaver colonies and through evaluation of available beaver distribution maps. As seen in two of the case studies, there is a high likelihood that the site will eventually become colonized if colonies exist nearby and the site has a perennial water source and vegetation. If this is the case, designers should consider how to reduce site constraints during the design stage of the project. For example, Magnuson Park incorporated habitat features at varying elevations, which allowed colonizing beaver to activate these elements as water levels change. Land managers have found overplanting of vegetation, plant protection, and planting of variable and nonpreferred species will allow for some loss due to browse, but overall retention of riparian vegetation. The project design should avoid elements that will likely produce conflicts such as long, narrow water features as these could be easily dammed in multiple locations; use footbridges instead of culverts, wherever possible.

While the utilization of ecosystem engineers in project design may introduce a greater degree of uncertainty in the evolution of the site, the ecosystem services and benefits offered will likely offset these uncertainties. Allowing uncertainty and flexibility in the site design demands a system-based iterative approach, which will provide lower initial cost inputs and rely on beaver as an ecosystem engineer to drive ecosystem functions in the future to achieve site design goals (Figure 1). Magnuson Park designers recommend the benefit of multi-phase projects that offer multiple periods during which the site can be evaluated and adaptively managed to revise the trajectory of both benefits and impacts to the site following beaver colonization. We recommend site designs that can encourage beaver damming at preferred locations by creating natural pinch points, varying elevation features or through the construction of artificial, wood-based, instream structures known as Beaver Dam Analogues (Bouwes et al., 2016; Pollock, Lewallen, Woodruff, Jordan, & Castro, 2015). Beaver often focus work on existing structures or narrow areas, so installing these elements just upstream of potential conflict areas or in areas where there is a high potential benefit can yield dramatic results.

Once the site is constructed, or if responding to colonization at an existing site, managers can anticipate impacts and manage them in a number of ways. Fencing vegetation, creating vegetation enclosures, and using exclusion devices on high-risk culverts are low-cost, yet highly effective approaches to retaining vegetation and maintaining water levels. In some cases where ponding cannot be tolerated beyond a certain level, a pond-leveling device may be required to establish a maximum normal pond height. Beaver ponds slow water and allow sediment to aggrade above the dam. In systems with high sediment loads, the placement of access points to the pond can allow for periodic sediment removal if warranted.

TABLE 2 Beaver management and design considerations for designers, ecologists, and land managers. Through an iterative design approach there are opportunities to address specific site considerations and take design actions with beaver in mind, such as the likelihood of colonization, site constraints, design feature considerations, and long-term site management

Design actions	Evaluation criteria
Identify sites with increased likelihood of colonization	Does project site have perennial water and deciduous vegetation?
	Do established beaver colonies exist within close proximity to project?
Design site to reduce constraints	Increase topographic diversity to accommodate some variation in water level
	Overplant to accommodate some loss of vegetation and plant nonpreferred species
	Minimize long, narrow water features
	Utilize footbridges rather than culverts
Utilize ecosystem engineers for ecosystem services and habitat	Multi-phase projects allow for design adaptation as colonization occurs
	Create pinch-points in water-features where damming could be beneficial
	Create beaver dam analogs (artificial beaver dams) to encourage beaver damming in specific locations
	Create variable elevation terrain in riparian zones, later to be flooded to different depths, creating complex habitat
Anticipate and manage impacts	Implement adaptive, low cost solutions (e.g., place wire fencing around high value trees, exclusion devices around high risk culverts)
	Anticipate and plan for damming at culverts, pond outlets, similar areas
	Use nonlethal beaver devices to control pond height and flooding
	Anticipate where sediment will accumulate and incorporate hardened features that allow for removal

5 | CONCLUSIONS

Designing landscapes with the flexibility to accommodate beaver colonization leverages their ability to engineer ecosystems in ways not easily replicated by humans. It is challenging for designers to mimic the hydrologic benefits of beaver dams while simultaneously maintaining equivalent levels of permeability, seasonal fluctuation, and structural stability. Moreover, when present, beaver continue to maintain the site and repair it after disturbances occur, such as large storm events. As shown in our case studies, beaver can disrupt the intended goals and functionality of a designed landscape. If not planned for, beaver can alter hydrology and sediment transport at pivotal pinch-points, cut down excessive vegetation, flood pathways and boardwalks, or change the intended aesthetics of the design. An iterative and adaptive design and management approach can allow ecosystem engineers to drive successional patterns and create heterogeneous environments, while minimizing these unanticipated impacts.

To maintain resilience and long-term success, it is important that designers consider the impacts of beaver on urban landscapes, weigh their on-site costs and benefits, and include design elements that allow for a variety of system changes. Addressing urban beaver colonization in design and management can increase awareness of urban beaver distribution, broaden knowledge of their urban impacts and benefits, facilitate interdisciplinary trainings, and improve adaptive management strategies. Our case studies focused on how beaver affect designs found within the City of Seattle—a densely occupied, urban area with a mild, mesic climate generally flat topography, and abundant vegetation in riparian areas. Our management recommendations relate to similar urban areas with sufficient hydrology, vegetation, and urban green spaces likely to be colonized by surrounding beaver colonies as well as to cities with drier climate conditions where beaver colonization can be leveraged to improve urban hydrology. As beaver populations increase in urban natural spaces, designers, planners, and managers are presented with the opportunity to reintegrate and utilize these ecosystem engineers to increase ecosystem function and environmental services beyond current urban landscape design methods.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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