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Challenges of Habitat Restoration in a Heavily Urbanized Estuary: Evaluating the Investment

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ABSTRACT

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Wetland restoration in urban estuaries involves unique challenges, risks, and uncertainties that often cause both the proponents and the public to question their investment. In certain cases, recovery of damaged natural resources or other legal obligations (*e.g.,* Native American treaty rights) mandate urban restoration, but non-regulatory restoration in urban settings may often be viewed as particularly counterproductive. Limited opportunities for siting, size, and design options often result in less than optimum restoration of habitat functions within the urban landscape. In addition, persistent sources of contaminants and invasive species may threaten the sustainability of a restoring site's performance. This may be especially true when fish and wildlife resources are drawn to a restoration site that has evolved into an attractive nuisance. Conversely, strategic restoration in urban estuaries can easily offset many of these constraints, when rare, quality patches in the disturbed landscape (a) contribute high ecological function in proportion to their size or complexity, (b) remove blockages for mobile or migratory fish and wildlife, (c) provide public exposure and appreciation for the value of restoration and protection, and (d) enhance the quality of the urban landscape. We examine a decade of estuarine intertidal restoration in the Duwamish River estuary, one of the Pacific Northwest's most heavily industrialized, to illustrate the "value-added" contribution that may be attainable within such challenging settings. Despite intense port and other commercial development, and a long history of watershed and estuarine modification and contamination, completion of eleven restoration sites and plans for two more in the near future has enhanced the ecological and societal values of this estuary. We illustrate this both by evidence of fish and wildlife utilization and by public involvement and investment in a broad spectrum of restoration initiatives above and beyond regulatory mandates. The potential contribution of restoration to the recovery of threatened/endangered Pacific salmon (*Oncorhynchus* spp.) is of particular interest. Our observations suggest that acceptable performance depends on strategic planning at the landscape scale, unusual institutional commitment, and acknowledgement that rehabilitation must often be the acceptable substitute for restoration.

ADDITIONAL INDEX WORDS: *Sustainability, strategic planning, landscape, salmon recovery,* Oncorhynchus.

INTRODUCTION

Over a decade ago, a synthesis of restoration science and policy in the United States (THAYER, 1992) included optimistic perspectives on ecosystem restoration in urbanized estuaries (HAWKINS *et al.,* 1992; SIMENSTAD and THOM, 1992) that described pragmatic approaches to the challenges of instilling "restoration" in extensively modified ecosystems. Such approaches exemplified the constraints and prospects of achieving functional "restoration" in highly compromised estuaries that are

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more likely to produce modified ecosystems or entirely new ecosystems or uses, instead of pre-existing natural conditions (ARONSON and LE FLOC'H, 1996; ZEDLER and CALLAWAY, 1999). Despite increasing restoration efforts in degraded estuaries over the last decade, the recovery of estuarine ecosystem functions in urban/industrial settings remains uncertain (KENNISH, 1999) and long-term sustainability is an increasingly decisive issue from any cost-benefit perspective.

Urbanized estuaries have been historically altered, and often completely, in both ecosystem structure and the underlying processes that sustain that structure and related functions and services. As a result, opportunities and long-term prospects for rehabilitation, much less restoration, are limited. Available public property is often restricted to established parks and recreational facilities, and commercial shoreline property is highly valued, such that derelict properties comprise the only site opportunities. Unfortunately, the derelict properties are often occupied by abandoned structures and are frequently contaminated with chemicals. Thus, many of the available sites are not conducive to conversion back to aquatic environments, or the related costs of restoration are prohibitive. If rehabilitation or restoration actions are feasible, the long-term prospects for acceptable performance are also in question; urban/industrialized estuary settings pose multiple stressors and disturbances, such as persistent contaminant sources, light and noise, and invasive species. In addition, lack of natural plant and animal propagules and organic matter may prolong or inhibit development of natural communities and food webs at the few feasible restoration sites. Watersheds of highly developed estuaries are also likely to be increasingly modified, further jeopardizing the long-term sustainability of processes required to sustain estuarine ecosystems. Given these compounded constraints, it is often difficult to attract and accumulate the extensive funding and other public resources required to address urban estuary restoration, although there have been some notable successes in obtaining public investment (*e.g.,* in San Francisco Bay through California Bay-Delta Authority [CALFED] restoration; see http://calwater.ca.gov/Programs/EcosystemRestoration/Ecosystem.shtml).

While public and institutional investment is only one aspect of estuarine restoration, it is important to recognize that most restoration actions in urban estuaries have originated from mitigation or contaminant clean-up and have benefited from the funding and other mandated resources available for regulated actions. Non-regulatory restoration in urbanized estuaries, especially at the ecosystem scale, represents a more daunting challenge given the usual small scale of community initiatives and a general lack of coordinated action. Challenges to voluntary restoration are compounded when specific opportunities are compared on a cost basis to similar projects in less disturbed estuaries.

Perhaps the most difficult obstacle is the concept itself of restoration in highly urbanized estuaries. The futility of restoration to re-establish the aboriginal state (STANFORD *et al.,* 1996) in highly developed estuaries is self-evident, but not necessarily precluded in some stakeholders' expectations. The sometimes phenomenal "build it and they will come" performance of restoration in less-impacted estuaries, which can rapidly achieve equivalency and sustainability under the right conditions (for example, see multiple papers in dedicated issue on dike/levee breach restoration of coastal marshes, *Restoration Ecology,* 10, 2002), is a seductive paradigm for even the most experienced restoration practitioners. However, in industrialized estuaries it is challenge enough to return a system to "a condition similar to the one that existed before it was altered, along with its predisturbance functions and related physical, chemical, and biological characteristics" by attempting to "establish a site that is self-regulating and integrated within its landscape, rather than to re-establish an aboriginal condition. . . ." (MIDDLETON, 1999). In contrast to restoration, rehabilitation or enhancement is often the best that can be expected, recognizing that impaired ecosystems will always require active, long-term management to reallocate processes and resources to the new ecosystems, support native species, and at least emulate\a naturally functioning system (ARONSON and LE FLOC'H, 1996; NATIONAL RESEARCH COUNCIL [NRC], 1992). Public values and expectations can completely redefine urban restoration, where it is often valued more for its passive recreational uses than the less-defined concept of ecosystem function (CASAGRANDE, 1996). Furthermore, ARONSON and LE FLOC'H (2000) warn us that if estuaries in other regions of the world are to avoid even greater restoration and rehabilitation costs in the future, the more humanistic, community-oriented, and recreational aspects of restoration in North America will need to be complemented by economic arguments based on natural capital and ecological services recovered by restoration.

Re-examining the issues of feasibility and expectation of restoration in existing restoration projects located within urbanized/industrialized estuaries may help remove the ambiguity surrounding such major investments. In this paper, we take a retrospective look at restoration in the Duwamish River estuary as a case study in technical strategies, practical constraints, and policy debates about restoration in industrialized landscapes. The Duwamish River estuary represents extreme restoration challenges because of the magnitude of historic development, the legacy of persistent and multiple stressors, and the value of public resources at risk. Among several examples of restoration attempts in heavily urbanized estuaries, SIMENSTAD and THOM (1992) described early habitat rehabilitation efforts in the form of littoral flat terraces constructed within segments of the extensively developed shorelines of the Duwamish River estuary. These were intended merely to imitate “elements” of the historic ecosystem, rather than the ecosystems themselves. Since that publication, the Duwamish River estuary has undergone numerous restoration actions that provide a provocative test of the potential for estuarine restoration in such settings. We address the omnipresent conundrum: “Given the constraints on the potential long-term function of restoration in highly urbanized/industrialized estuaries, is it worth it to restore such a dismembered ecosystem?” And, if found worthwhile for ecological, socioeconomic, and/or cultural reasons, how might we approach estuarine restoration in such a setting? More specifically, how must we modify our expectations, strategic planning, and performance measures to realistically fit the situations found in urbanized/industrialized estuaries?

Our exposure to and involvement in restoration in the Duwamish River estuary is multifaceted, from long-term research and restoration management to stakeholder/public involvement, with different perspectives of investment and benefit. We describe below the bases of our guardedly optimistic opinion that although rehabilitation must often be the acceptable substitute for restoration, there is much to gain by investing in restorative actions in urbanized estuaries.

DUWAMISH RIVER ESTUARY AS CASE STUDY

Historic Degradation

The Duwamish River estuary and adjoining Elliott Bay (Figure 1) were extensively developed over the last 150 years as Seattle became a densely populated urban center and active seaport (BLOMBERG *et al.,* 1988; TANNER and CLARK, 1999), and they illustrate the rapid changes common to large Puget Sound estuarine deltas (BORTLESON *et al.,* 1980). In addition to virtually complete loss of productive estuarine ecosystems, the estuary became highly contaminated from industrial pollutants in the estuary and urban contaminants from the surrounding city, and the watershed was virtually “re-plumbed”. The pre-existing estuarine mosaic of almost 500 ha of tidal forest, 515 ha of estuarine marsh, and 587 ha of unvegetated tidal flats was reduced by between 17% (marshes) and 52% (swamps) between the mid-Nineteenth century and the beginning of the Twentieth century. The industrial waterway was completed in 1917, with a resulting expansion by almost 100 ha of deep water habitat at the cost of 88% loss in shallows and flats, which were either dredged or filled with the dredged material (BLOMBERG *et al.,* 1988). By 1936–1940, tidal swamps were completely eliminated and tidal marshes had been diminished to 8% of the virgin marsh area. Only 2% of the historic estuarine delta wetlands remained by 1986, replaced by over 2,100 ha of developed shorelines and floodplain (*ibid*). In the navigable, lower ~10 km of the riverine portion of the estuary, about 15% of the shoreline is covered by over-water structures (King County Department of Natural Resources [KCDNR], 2001).

In addition to being progressively blanketed by the largest urban population and industrial center in the region, the Duwamish watershed was also reduced significantly, with commensurate diminution of freshwater inflow, sediment flux, large wood, anadromous fish migrations, and the natural disturbance regimes associated with dynamic river flows (BLOMBERG *et al.,* 1988). At one time, the estuary received the combined flows of three major watersheds covering almost 4,250 km^2—White River, Green River, and Lake Sammamish/Lake Washington/Black River—that annually contributed between 71 and 255 m^3s^{-1} freshwater flow. From 1906–1915, the White River (25.2% of historic watershed) was permanently diverted to the Puyallup River drainage, and by 1916 the entire Lake Sammamish, Lake Washington, and Cedar River drainages (40.6%) were rerouted through the construction of the Lake Washington Ship Canal, resulting in the disappearance of the Black River (Figure 2). The end result is an estuary that has lost 70%-75% of its historic freshwa-

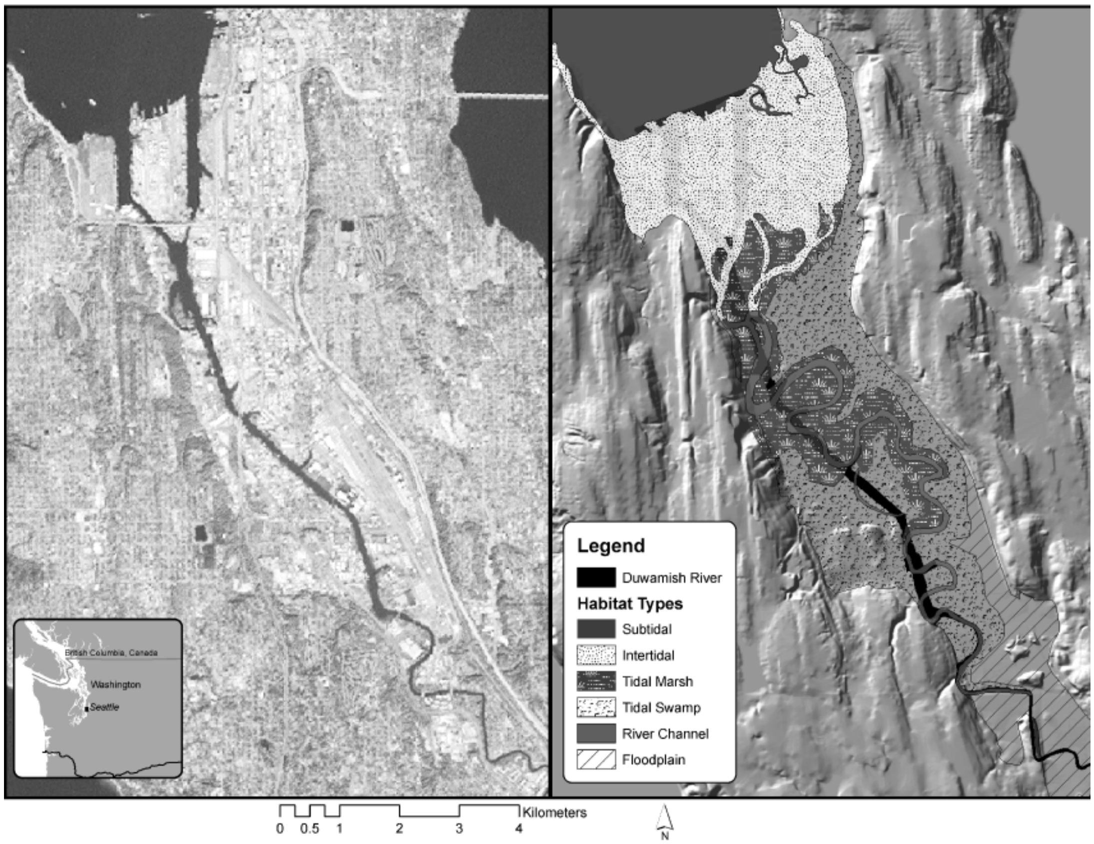

Figure 1. Modern and historic images of Duwamish River estuary and Elliott Bay on Puget Sound, within the urban setting of Seattle, Washington USA. Right panel shows outline of historic river channel and shallow water wetlands with modern, maintained navigational channel shaded in black.

ter inflow. While reduced freshwater inflow to estuaries around the world has been shown to dramatically alter their functions at multiple ecosystem scales (ROZENGURT and HAYDOCK, 1981; ROZENGURT and HEDGEPETH, 1989; CLOERN *et al.,* 1983; BEAMISH, *et al.,* 1994; STANLEY and WARNE, 1993; JAY and SIMENSTAD, 1996; LIVINGSTON, 1997), to our knowledge no scientific investigations have examined the responses of such an extreme change on estuarine circulation, geochemical processes, or biological resources such as those which have occurred within the Duwamish River estuary.

Contamination of the Duwamish River estuary changed from urban and resource-based industrial contaminants (*e.g.,* organic wastes) at the turn of the century to more complex and toxic contaminant discharges during World War II (BLOMBERG *et al.,* 1988). By 1936–1940, eight direct sewer outfalls and four combined sewer overflows discharged into the estuary and twelve documented industrial effluents were building a legacy of metal (chromium, cadmium, copper, lead, zinc), pentachlorphenol (PCP), polychlorinated biphenyl (PCB), polycyclic aromatic hydrocarboms (PAH), and halogenated hydrocarbon contamination. Since the 1950s, water pollution control regulations and toxic contaminant remediation efforts have significantly reduced raw waste discharges. In addition, decreases in sewage releases to the estuary that occur through combined sewer outfalls (CSOs) under extreme storm events, and land runoff from impervious surfaces (~50% of those surrounding the estuary) is concentrated and to some degree treated through the City of Seattle's storm drain system. Such extreme water quality problems as describing the Duwamish running ". . . red with

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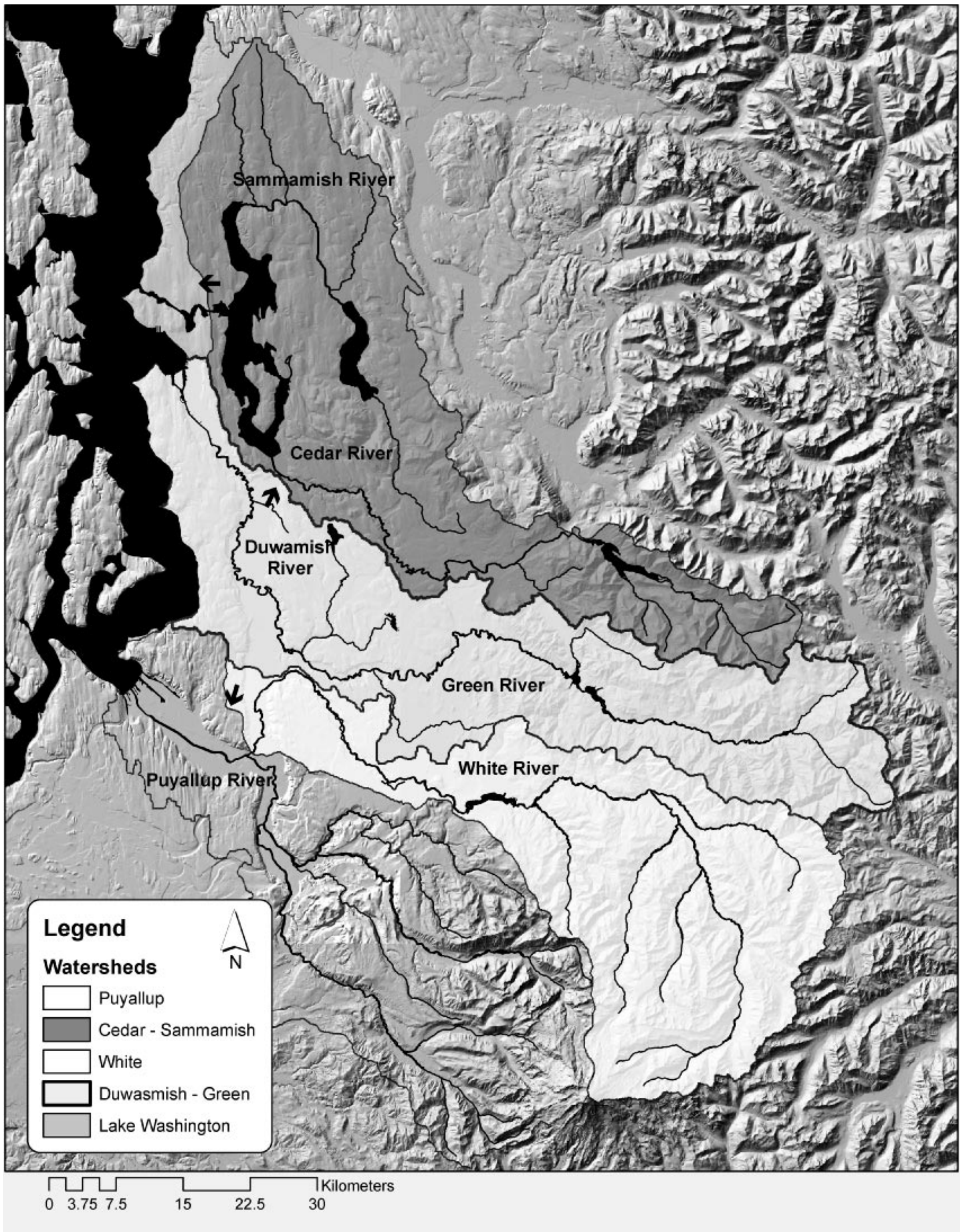

Figure 2. Reorganization of Duwamish River watershed between 1912 and 1916, involving diversions (arrows) of the White River into the Puyallup River and the Lake Sammamish/Lake Washington and Cedar River drainages to the Lake Washington Ship Canal.

waste from meat packing plants. . . .” and summer month “. . . dissolved oxygen concentrations occasionally drop(ping) to 1 ppm . . .” (METRO, 1985) are now comparatively rare or non-existent as a result of better water pollution control and regulation. Diversion of treatment plant effluents from the river to Puget Sound, and increased (managed) summer river flows from Howard Hanson Dam on the Green River, have also enhanced freshwater outflow.

However, the legacy of contamination has not disappeared from the Duwamish River estuary. It is a major Superfund (Comprehensive Environmental Response, Compensation, and Liability Act [CERCLA]) site, and although some settlement with potentially responsible parties (PRP) has occurred, overall settlement and clean-up has not been achieved. For example, sediments in the commercial waterway and along the shoreline have concentrations of carcinogenic PAH exceeding 800 $\mu g\ kg^{-1}$ dry weight, 65 $mg\ kg^{-1}$ organic content PCB (20 times the PCB Clean-up Screening Level [CSL]), and 200 $\mu g\ kg^{-1}$ dry weight tributyltin. Based on the levels of PCB contamination alone, the Washington State Department of Health has recommended that consumption of any combination of resident fishes (perch [Embiotocidae], flounder [Pleuronectidae], and English sole [*Pleuronectes vetulus*] caught in the lower Duwamish River as well as rockfish [Scorpaenidae] caught in Elliott Bay close to the mouth of the Duwamish River) be limited to one meal per month (WASHINGTON STATE DEPARTMENT OF HEALTH, 2002).

The condition of the Duwamish River estuary is not necessarily controlled by problems that originate within the estuary itself. Recent documentation has suggested that small urban drainages to the estuary are so contaminated that salmon die before they are able to spawn. For instance, adult coho salmon (*Oncorhynchus kisutch*) that migrated through the estuary into Longfellow Creek (a model for stream rehabilitation in the region) in fall 2001 showed behavioral symptoms indicating underlying neurological or respiratory disorders, which led to death of 90% of the pre-spawning fish. Preliminary evidence suggests that this pre-spawn mortality may be related to PAH residues from roadway contaminants flushed into Longfellow Creek with the first rainfall of the season (NW FISHLETTER, 2002).

On the surface, this litany of persistent stressors in the Duwamish River estuary could imply that restoration or even rehabilitation may not be achievable or justifiable. Nevertheless, restoration of natural shoreline ecosystems in the Duwamish River estuary has become a high priority for trustees of the damaged public resources under CERCLA actions, resource agencies, non-governmental organizations, and unaffiliated citizenry who believe in the feasibility of returning some natural functions to the Duwamish estuary. The human and financial investment has been exhaustive, and the existing natural environment equity of still viable habitat from which to build on is miniscule (Figure 3). Much of the most intensive restoration effort has been driven by the regulatory mandate of mitigation, either through individual actions dictated by federal (*e.g.,* Clean Water Act [CWA] Section 404) or local requirements for compensation arising from continued development pressures, or through the comprehensive actions negotiated in the Superfund settlement. The larger, higher profile mitigation and damage recovery actions have been rapidly followed by intensified grassroots, non-regulatory restoration. For most of the parties active in restoration of the system, the fact that the estuary still supports resources such as a nesting population of great blue herons and viable salmon populations that transit the estuary to and from spawning habitats has prompted expectations that some productive rehabilitation can be realized.

Restoration Incentives and Actions

Recovery of some of the natural estuarine functions in the Duwamish River estuary began in 1988, with progressive actions designed as compensatory mitigation for development and historic damage (Table 1). Slightly more than a decade of concerted efforts has resulted in ~6 ha of rehabilitated habitat. What were initially single-authority projects have gradually evolved into broader partnerships, where one restoration authority has been able to expand on emerging restoration sites through “value-added” unions of a variety of governmental and non-governmental entities committed to restoration in the estuary. A restoration constituency has evolved among the local and regional community, which views restoration actions as more than just compensation for past damages to the Duwamish River estuary, but also as investments in building valued assets in the estuary. These include recovering fish and wildlife, reducing human health risks, recreational opportunities, and education and outreach about the history,

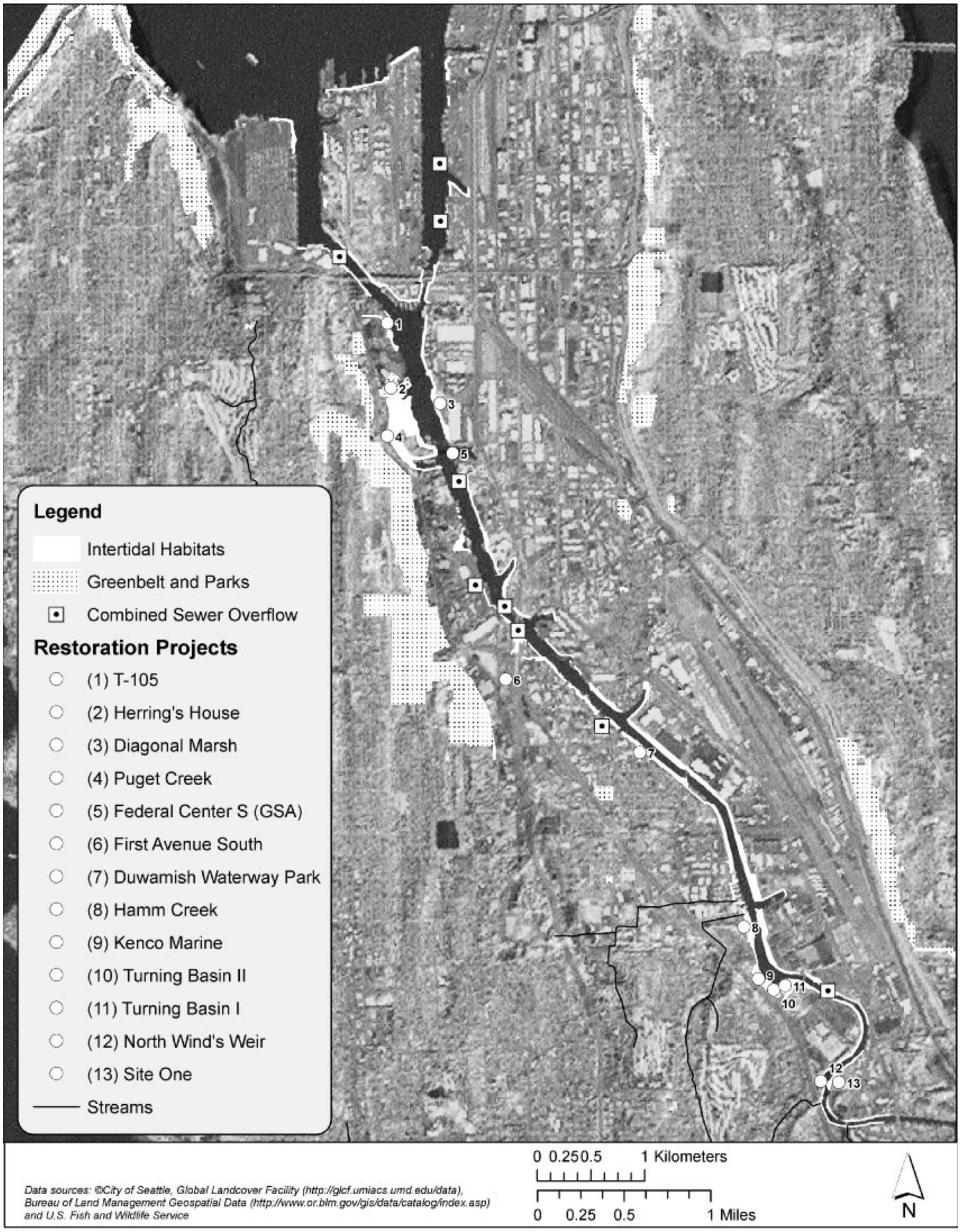

Figure 3. Existing intertidal habitats, streams, restoration sites and combined sewar outfall (CSO) locations in the Duwamish River esturary; see Table 1 for additional restoration site information.

Table 1. *Major restoration projects in Duwamish River estuary completed or initiated since 1988; CERCLA = Superfund, CA = Coastal America, WSDOT = Washington State Department of Transportation, POS = Port of Seattle, and USACE = US Army Corps of Engineers.*

Restoration Site	Authority	Completion Date	Intertidal Area (ha)
Diagonal Marsh	POS	February 1988	0.16
Federal Center S (GSA)	CA	February 1993	0.10
Turning Basin I	CA	May 1994	0.16
T-105	CA	April 1996	0.23
Duwamish Waterway Park	community	June 1996	<0.01
First Avenue South	WSDOT	January 1997	0.84
Turning Basin II	POS	February 1999	0.53
Puget Creek	POS	July 1999	0.07
Herring's House	CERCLA	March 2000	0.85
Hamm Creek	CERCLA	June 2000	0.32
North Wind's Weir	CERCLA	February 2003	0.42
Kenco Marine	CERCLA	October 2004	0.30
Site One	USACE	September 2006	1.01

culture, and social role of the estuary. The concept of a sustainable coexistence between an urbanized, industrial economy and some elements of a naturally functioning estuarine ecosystem has become a feasible goal for a broad collaboration of societal sectors.

Early "habitat projects" in the estuary originated with CWA and regional mitigation requirements for Port of Seattle and other shoreline or in-water development, including dredging of the waterway. Most of these projects involved creation or enhancement to increase natural shallow-water habitats supporting important fish and wildlife, particularly juvenile Pacific salmon (*Oncorhynchus* spp.) migrating through or rearing in the estuary. As a consequence, mitigation projects have tended to focus, often exclusively, on habitat attributes intended to provide for juvenile salmon three things: refuge from predation, food, and brackish waters for physiological adaptation. Despite associations of juvenile salmon with distinctive positions along the estuarine gradient, depending on the ontogenetic and physiological phase of their migration (SIMENSTAD *et al.,* 2000), location of most mitigation sites were typically based on opportunistic criteria (property availability and cost) rather than ecological context.

Created habitat features included mounds in open water that rise into intertidal or shallow subtidal elevations, terraces of fine sediments within high-gradient armored shorelines, removal of shoreline armoring to increase middle and upper intertidal elevations, and planting of riparian vegetation (SIMENSTAD and THOM, 1992). Diagonal Marsh, a 0.16-ha embayment excavated in the armored shoreline of the lower river/estuary, and Turning Basin II, a 0.53-ha excavation and conversion into intertidal habitat, are examples of the more recent, and more ecologically complex, mitigation projects (Table 1).

Between 1992 and 1996, the Federal Coastal America Program (CA) prompted the first non-regulatory restoration actions in the estuary. Under the coordination of the U.S. Fish and Wildlife Service (FWS) and multiple federal (U.S. National Oceanographic and Atmospheric Administration-National Marine Fisheries Service [NOAA-NMFS], Environmental Protection Agency [EPA], Army Corps of Engineers-Seattle District [ACE-SD], General Services Administration [GSA]) and local (Port of Seattle [POS]) sponsors, three projects were chosen to remove shoreline debris, regrade the shoreline to restore intertidal elevations suitable for mudflat and marsh development, and re-establish riparian vegetation buffers. Although these sites were chosen primarily because of their availability and suitability for restoration, and only accounted for 0.5 ha, they provided the foundation for two distinct clusters of restoration sites that have emerged in the estuary (Figure 3). As with the mitigation projects, the Coastal America projects were created around a definition of fish and wildlife habitat rehabilitation or creation because the historical habitat template and processes could not be restored *per se.* The T-105 project employed an additional strategy of excavating a tidal channel away from the shoreline and tapping into a small drainage area. This strategy was also utilized by the Washington Department of Transportation (WSDOT) in their mitigation action at the First Avenue South site, where WSDOT staff uncovered a stream that previously ran through a culvert between a setback marsh and the estuary, restoring full tidal action to the historic marsh (Table 1).

By the mid-1990s, expanded, community-based partnerships began to emerge for non-regulatory restoration, exemplified by the Duwamish Waterway Park project and several of the Port of Seattle projects, which merged diverse funding sources, resources and responsibilities, and local stewards. These were typically limited to small shoreline projects 0.1 ha or less, but often took advantage of and built on prior projects (*e.g.,* Turning Basin II (Table 1 and Figure 4), where a basin was excavated from historic fill and connected to existing upland drainage) or focused on particularly key landscape features, such as the relict mouth of a former stream, as in the case of the Puget Creek restoration (also involving fill excavation).

The Elliott Bay/Duwamish River CERCLA actions began appearing by 2000 and expanded the dimension and distribution of restoration sites throughout the estuary (Table 1). Given the Superfund resources available, these actions were larger and more complex than previous efforts (*e.g.,* Herring's House, Table 1) and included the complete reconnection of a significant stream watershed (Hamm Creek, Table 1 and Figure 4). Partnerships and citizen stewardship became the rule, rather than the exception, even though these were regulatory actions. For example, the Hamm Creek project both figuratively and literally reconnected a community's watershed to the estuary. This project linked a coalition of citizens and local governments (I.M.A.P.A.L. Foundation, Duwamish Tribe, King County Department of Natural Resources, Institute for Washington's Future, People for Puget Sound) actively working on restoration of the creek with CERCLA action on the estuary sponsored by King County and the ACE-SD. The project recreated 0.32 ha of intertidal estuarine marsh habitat from upland fill along the estuarine shoreline, created 0.85 ha of freshwater marsh, recreated 580 m of new productive riparian stream bed, and planted the created intertidal and riparian habitats with native vegetation.

Recently, the scope of restoration in the Duwamish River estuary has expanded even further by the inclusion of the Green/Duwamish Ecosystem Restoration Project (ERP), which is coordinated by ACE-SD with multiple partners (King County; the cities of Tukwila, Kent, Auburn, Seattle, Tacoma, and Renton; the Muckleshoot and Suquamish Tribes; agencies; and local interests). The ERP includes the 1-ha Site One, with restoration funds provided by extensively leveraged funding from the ERP partners and a significant award from the Washington State Salmon Recovery Funding Board (SRFB). The North Wind's Weir and Site One projects are particularly significant from an ecological perspective because they extend further up-estuary, into the tidal freshwater region, a different habitat from the original cluster of restoration sites in the brackish part of upper estuary. As a result, this restoration directly addresses the important physiological transition zone for juvenile salmon entering the estuary on their seaward migration.

Constraints and Opportunities

The expansion of restoration in the Duwamish River estuary, while not at the ecosystem scale, has been impressive in distribution, diversity of approaches, and partnerships. However, the cost is equally impressive. The projects for which the total costs are known or can be reliably estimated (Table 2) indicate that, on average, completed cost of restoration within the estuary is $\sim\$3.0 \times 10^6$ ha^{-1} when the value of the commercial land is included, or $\$2.6 \times 10^6$ ha^{-1} when not accounting for the real estate value. Costs are not available for the smaller community-based and other non-regulatory projects, such as the Duwamish Waterway Park and Puget Creek, which are likely to cost less because of volunteer and in-kind contributions. These costs reflect a number of unique circumstances in heavily urbanized/industrialized estuaries, in addition to the value of the property: (1) construction costs involved in fill removal and regrading (as compared to the relatively simple technique of dike breaching and tidegate removal in more rural settings), (2) handling of contaminated sediments, and (3) more elaborate construction techniques to deal with the constraints of boat wakes and other disturbance factors.

The disturbance history and regime of urbanized estuaries necessitates some unaesthetic and ecologically unnatural approaches to restoration. The assertion "build it and they will come" does not necessarily work for target plant and animal species in urbanized/industrialized estuaries. However, in the case of exotic and nuisance species, it may indeed be the rule. For example, perhaps one of the more important constraints on restoration

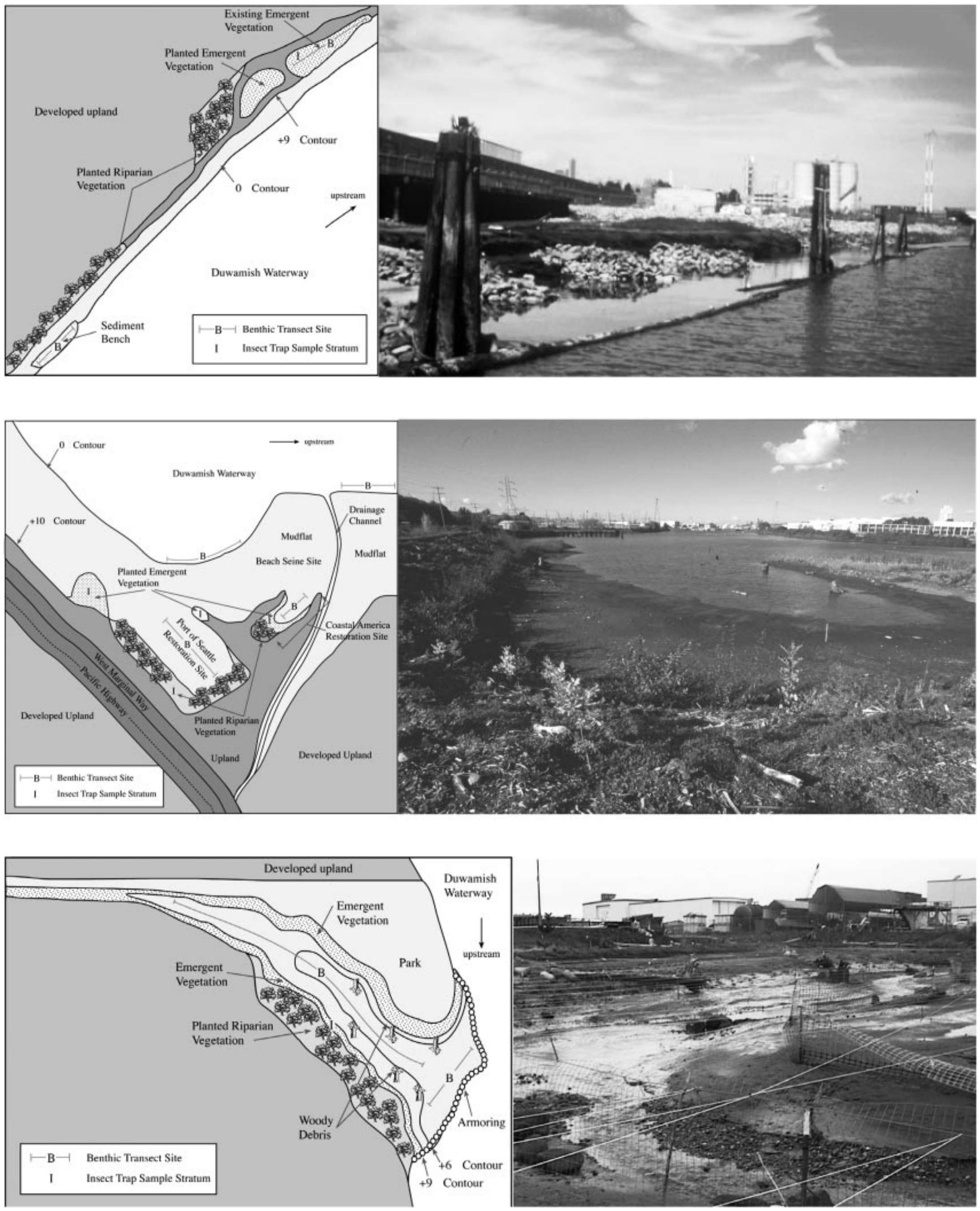

Figure 4. Diagrams and post-construction photographs of four representative restoration projects, Duwamish River estuary, Washington USA; top, GSA; middle, Turning Basin; bottom, Hamm Creek; see Table 1 and Figure 3.

Table 2. *Cost of restoration projects in Duwamish River estuary; * denotes estimated real estate costs based on general price for undeveloped industrial shoreline in the Duwamish Waterway.*

Project	Cost ha^{-1} Including Real Estate	Cost ha^{-1} Without Real Estate
Federal Center S (GSA)	$1,328,000	
Turning Basin I	$8,376,774*	$804,233
T-105	$1,287,968*	$1,029,630
Turning Basin II	$1,034,457*	$6,363,514
Herring's House	$4,649,030	
Hamm Creek	$3,322,000	
North Wind's Weir	$1,432,317*	$2,395,856
Site One	$4,356,436	$2,475,247

of native vegetation in the Duwamish River estuary is the necessity of protecting planted and naturally recruiting intertidal emergent vegetation from grazing by the urbanized, non-migratory Canada goose (*Branta canadensis*). As global goose populations increase, the highly urbanized Duwamish River estuary has experienced increased herbivore pressure that has resulted in the failure of some re-vegetation efforts and probably in the decline of existing stands of *Carex lyngbyei* (*Lyngbye's sedge*; Cyperaceae). *C. lyngbyei* dominates low marsh vegetation in brackish reaches of most Pacific Northwest estuaries and is considered a particularly important habitat attribute for migrating juvenile salmon (SIMENSTAD and CORDELL, 2000; SIMENSTAD *et al.,* 2000; HOOD, 2002).

To evaluate the effect of grazing by Canada geese on the fitness of *C. lyngbyei* plants on restoration sites, experimental exclosures (1-m tall chicken wire fences crisscrossed on top with nylon line; Figure 5, top) were installed at an intertidal restoration site in the Duwamish River (CRANDELL, *personal communication*). Geese were observed to consume all plants that were not protected during the first growing season. Based on scanning and sequential observation techniques, grazing pressure during daylight hours at this site was quantified as 0.000576 $\pm$ 0.00256 goose day^{-1} m^{-2} of available *C. lyngbyei,* or 330–450 goose-days ha^{-1} of available *C. lyngbyei.* During the second growing season, grazing of plants that had been protected for one year resulted in significant decreases in aboveground (AG) and belowground (BG) plant metrics. There was no significant effect on dead BG biomass or on total nonstructural carbohydrates (TNC). Grazed plants were less developed above and below ground at the end of the second

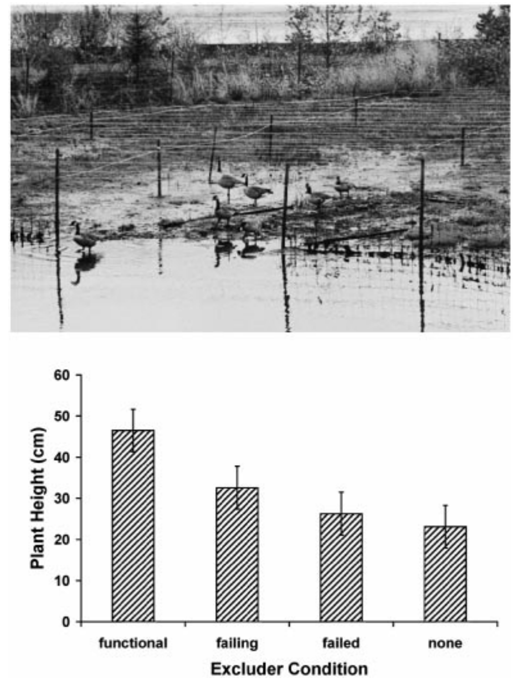

Figure 5. Canada goose and goose excluder devices at the intertidal restoration site in the Duwamish River estuary (top) and the height of intertidal vegetation shoots within exclusion areas where excluder devices were functional, failing, failed, or not present (bottom); error bars are 1 standard error of four means; source: People for Puget Sound.

growing season than they were at the end of the first growing season, during which they were protected. In other words, one-year-old plants had regressed in fitness after exposure to grazing. Although TNC was of similar concentration in both protected and grazed plants, larger plants have more total energy reserve and, presumably, are more capable of over-wintering and eventually withstanding some level of grazing than are smaller plants. Plants protected for two years at the restoration site developed between 58% and 80% of the fitness of the reference stands, as measured by BG biomass and indicators of vegetative reproduction (Figure 6). Planted *C. lyngbyei* would be expected to approach the level of fitness of reference stands if protected for at least three years. In reference plots, grazing resulted in a biologically meaningful (but not statistically significant) difference between protected and grazed plants with respect to live BG biomass. Trends were otherwise consistent with the experimental plots at the res-

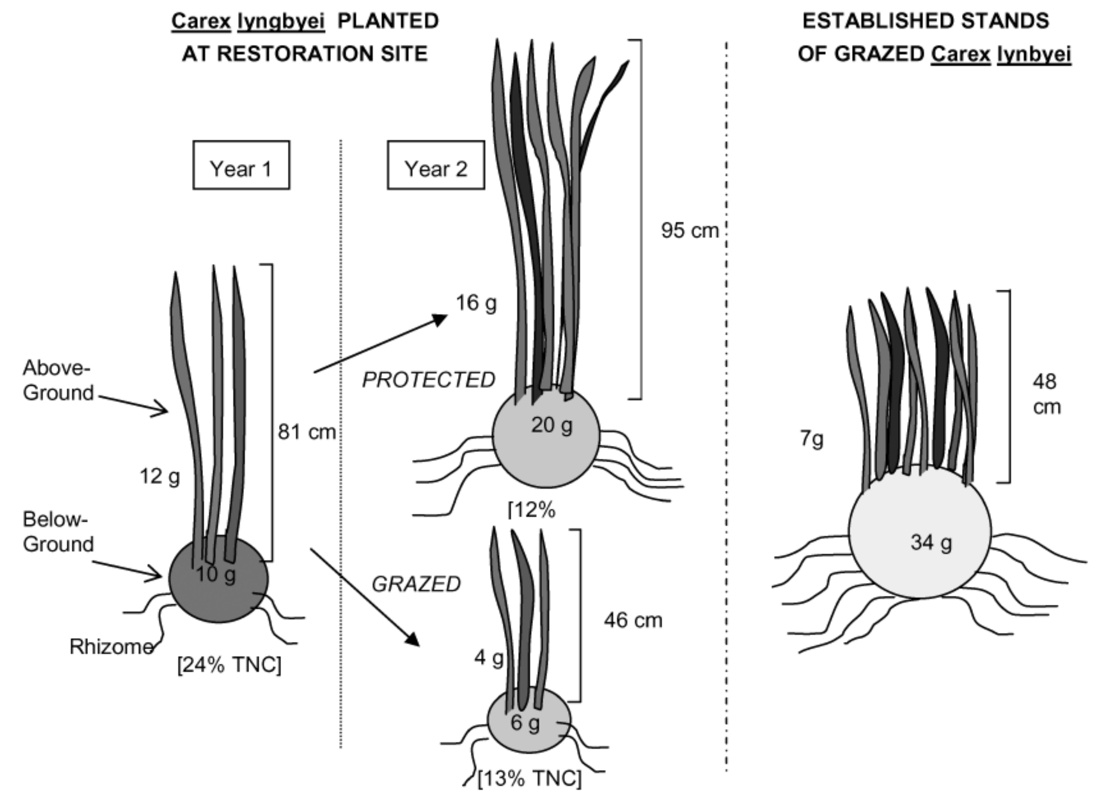

Figure 6. Response of *Carex lyngbyei* to grazing by Canada goose (*Branta canadensis*) at a restoration site in the Duwamish River estuary, Seattle, Washington. Reference stands (i.e., established grazed stands) are provided for purposes of comparison. Values are means rounded to the nearest whole number. Numbers of shoots and rhizomes are reduced for the sake of simplicity and are proportional to each other. TNC = total nonstructural carbohydrates; source CRANDELL, 2000.

toration, with the exception of stem height (which was equal in grazed and protected plots), and TNC (which was not measured at reference sites).

Unanticipated responses to this exclusion experiment were almost as enlightening as the hypothesized response. Not only did the *C. lyngbyei* grow within the experimental exclosures once herbivore pressure was removed, but previously unsuccessful plantings and other previously absent volunteer species also grew within the exclosures. *Scirpus acutus* had been planted the year before the experiment but had not produced any visible shoots; following removal of herbivore pressure, *S. acutus* reached heights of 200 cm. Volunteering within the exclosures were 29 other pioneer species from the following families: Apiaceae, Asteraceae, Brassicaceae, Caryophyllaceae, Chenopodiaceae, Cyperaceae, Fabaceae, Juncaceae, Lythraceae, Plantaginaceae, Poaceae, Polygonaceae, Ranunculaceae, and Solanaceae. More non-target species volunteered in the plots with smaller (less fit) *C. lyngbyei* plants than volunteered in the plots with larger (more fit) plants. These results suggest that, without some concerted management efforts, urbanized geese populations in settings such as the Duwamish River estuary may constrain the development of naturally complex vegetation assemblages on restoration sites.

Response of citizens and local regulators to restoration opportunities has been equally encompassing. The opportunity for citizen and community stewardship of restoration sites has expanded and become formalized even in the case of the regulation-mandated projects. In more than one case, a grassroots community initiative for restoration provided the impetus or at least collaboration for implementation of a major restoration project. Citizen monitoring has been instituted for both regulatory restoration (*e.g.,* CERCLA) as well as community-based projects. For instance, as a part of their Sound Stewardship Program, the regional, non-profit citizens group People for Puget Sound has developed a partnership with the CERCLA trustees, the Port of Seattle, FWS, and other restoration partners in the Duwamish River estuary to involve citizens in technical monitoring of six of the major restoration sites in the estuary. While citizen monitoring cannot cover the full spectrum of technical monitoring tasks required for regulatory compliance (*e.g.,* mitigation and CERCLA sites), there are many monitoring protocols that are feasible for enthusiastic, diligent citizen monitoring groups. For example, citizens involved in the Sound Stewardship Program have provided data on the effects of goose grazing and effectiveness of goose exclusion cages (Figure 5, bottom) and vegetation shoot density that has demonstrated the performance of restoration sites in the estuary. Perhaps the most valuable role of citizen involvement has been to identify problems at the restoration sites including invasive species, upland plant desiccation, and vandalism, and to direct site managers to organize stewardship efforts to effectively address these problems. This program has expanded both in partnerships (*e.g.,* including the National Partnership between NOAA-NMFS Community-Based Restoration Program and Restore America's Estuaries) and volunteer participants as more restoration sites have become available for stewardship and monitoring.

The diverse regulatory and non-regulatory incentives for restoration in the Duwamish River estuary has not allowed planning, design, and implementation of restoration sites in a broader landscape perspective that would promote cumulative performance. However, it is worth repeating that restoration sites in the Duwamish River estuary are clustered in two ecologically-opportune regions of the estuary:first at the head of salt intrusion in the Turning Basin and the transition from the meandering channel with natural bathymetry to the dredged navigational channel, and second in the lower, more saline region near Kellogg Island, the largest remnant of historic estuarine wetland (Figure 3). Early restoration designs tended to be simple excavations of fill material or removal of shoreline structures, while more recent restoration designs have incorporated more landscape-based approaches, such as merging with existing restoration sites, linking to upland drainages, development of tidal channels and sloughs, and addition of natural estuarine wetland attributes, such as large woody debris. This new incorporation of a landscape context may be just as much recognition of the inadequacy of natural ecosystem building processes in the extensively developed Duwamish River estuary as a desire to exploit any of the limited opportunities that would advance and build on remediation, rehabilitation, and enhancement of ecosystem functions.

Response to Restoration

More than any other restoration situation, assessing the response to restoration in an urbanized/industrialized estuary such as the Duwamish River is difficult at any scale, but may be especially demanding given persistent, multiple stressors and disturbances, limited reference sites, and other constraints (TANNER and CLARK, 1999). Yet, remediation of contaminant sources and other stressors is progressing and natural resources continue to occupy the estuary. Although the spring run of Chinook salmon (*O. tshawytscha*) has become extinct in the Duwamish-Green Rivers watershed (NEILSEN *et al.,* 1999) and naturally spawned spring, summer/fall, and fall Chinook salmon runs from the Puget Sound Ecologically Significant Unit (ESU) are considered likely to become endangered in the foreseeable future (MYERS *et al.,* 1998), the summer/fall stock of Chinook in the watershed is considered healthy, with annual escapement levels of 4,000–10,000 spawners (WEITKAMP and RUGGERONE, 2000). Of the Chinook salmon in the estuary, the fall stock is the most likely to be impacted by limited estuarine habitat quantity and quality, because their residence time during their downstream migration through the estuary is comparatively long (HEALEY, 1991). The chum salmon stock in the watershed is similarly classified as healthy (JOHNSON *et al.,* 1991). Persistence of viable salmon populations using the estuary to any degree is heartening given their bioaccumulation of substantial levels of PCBs and other toxic contaminants (MCCAIN *et al.,* 1990) and evidence of concomitant dysfunctional immune responses (VARANSI *et al.,* 1993; ARKOOSH and COLLIER, 2002) during their passage through the estuary. Other fish and wildlife populations persist in their use of the estuary's intertidal shoreline, such as shorebirds and wading birds (CORDELL *et al.,* 2001).

By traditional restoration monitoring metrics such as emergent vegetation recruitment, cover, biomass, and height, most of these sites are progressively developing attributes comparable to adjacent, albeit disturbed, reference sites (CORDELL *et al.,* 2001). Even in heavily industrialized estuaries, vegetation can be a robust metric of restoration performance. However, given the potential injury and damage to aquatic resources in the Duwamish River estuary, monitoring of fish and wildlife response is important. Restoration in urban estuaries such as the Duwamish may need to address a somewhat higher order: If you build it, will they come and not suffer for it? Due to the emphasis on CERCLA injury compensation and Endangered Species Act (ESA) contribution to salmon recovery, particular attention has been focused on monitoring responses to restoration sites by juvenile salmon, their prey resources, and other habitat attributes. This can be particularly difficult when the particular attributes that link juvenile salmon habitat to their fitness and survival are unknown or purely inferential and appropriate reference conditions are lacking (SIMENSTAD and CORDELL, 2000). COrdell *et al.* (2001) document the dilemmas in trying to assess ecological function of restoration sites in the Duwamish River estuary, especially juvenile salmon habitat. Their approach has been to examine indicators of the capacity of the restoring habitats to support salmon (*e.g.,* abundance and distribution of potential prey organisms) and to identify the attributes (*e.g.,* vegetation, substrate) that account for that support, relative to the few relict patches of natural shoreline in the estuary (Figure 3). They noted that, in general, prey of juvenile salmon in the Duwamish River estuary is dominated more by a composition of insects (*e.g.,* collembolans, psyllids, ants, wasps) different from what is commonly documented in the diet of juvenile salmon (chironomid larvae, pupae, and emergent adults) in natural and restored habitats in other estuaries in the region. However, prey composition from fish occupying the T-105 restoration site was generally parallel with those captured at the nearby reference site (Kellogg Island), suggesting that this difference is occurring at the estuarine landscape scale and not at the site or habitat scale. CORDELL *et al.,* (2001) suggest that this effect may be attributable to the limited distribution of emergent vegetation in the estuary.

Monitoring of juvenile salmon prey resources provides another, perhaps more direct assessment of the performance of a restoring site (SIMENSTAD and CORDELL, 2000). Sampling for benthic infauna or insects indicated that the juvenile salmon prey taxa *Corophium* spp. amphipods and the larvae of ceratopogonid flies were equally or more dense at some restoration sites adjacent to reference sites, and comparatively more abundant than comparable natural habitats in the considerably less-disturbed, rural estuary of the Snohomish River (CORDELL *et al.,* 2001). Thus, although the diet of juvenile salmon migrating through the Duwamish River estuary includes prey that are not typical of less-altered estuaries, they are utilizing the types of organisms that colonize restoration sites. Other functions, such as refuge from predation provided for juvenile salmon by shallow-water habitat may be provided as soon as the restoration site is developed, although there has been no monitoring or studies to validate that decreased predation rates occur in restoration sites.

DISCUSSION

Restoration in the Duwamish River estuary has been driven by a number of regulatory/legal mandates and obligations above and beyond the fundamental desire to return portions of the system to some resemblance of its original function. Mitigation under the Clean Water Act, damage compensation and rehabilitation under CERCLA, and salmon habitat restoration under ESA all have provided impetus for the restoration actions completed to date. In addition to these mandates, native American treaty rights guaranteeing harvestable salmon and joint involvement in salmon management adds additional incentives and resources for aquatic habitat restoration in the estuary. Management of trust resources demand restoration as part of compensation. The fact that the Duwamish River estuary has the largest concentration of estuarine restoration sites in the Pacific Northwest region of the USA is unquestionably due to these regulatory mandates.

It might be argued that the impetus for restoration would not have reached the threshold that prompted non-regulatory actions if these regulatory actions had not occurred. Certainly, the ultimate performance of critical functions, such as providing habitat for recovering salmon stocks, will ultimately depend on the successful CERCLA remediation of toxic contamination, because this regulatory action will determine whether or not risks to juvenile salmon caused by recontamination of restored sites outweighs the benefits of the created habitat.

As in almost all restoration programs in urban, industrialized estuaries, sites and designs in the Duwamish River estuary are generally opportunistic. They are largely driven by the availability, location, cost, and other constraints of limited restoration sites. By design (KCDMS, 1994), the diverse restoration actions in the Duwamish River estuary over the past decade have in aggregate formed a landscape approach consisting of clusters of sites in strategic locations along the estuarine gradient that are perceived to be critical for migrating juvenile salmon. This "strategy" may not be as beneficial for other resources or functions, but likely serves the most prominent goal of restoration—salmon recovery—in this estuary. Some landscape connectivity in the system has also emerged, intentional or not. Cumulative restoration projects may provide habitat linkages that will create a landscape-scale habitat function for migrating salmon that exceeds site-specific levels. The linkages of Hamm and Puget Creeks to upland drainages provide peripheral freshwater input, drift organisms, detritus, and fish and wildlife corridors to park green spaces; in the case of Hamm Creek, salmon spawning habitat is connected to the estuarine restoration. Present urban runoff and stormwater management continues to constitute a potentially non-trivial source of contaminants from the large area of surrounding impervious surfaces. Obviously, one of the greater challenges to urban estuarine restoration is control of toxic contamination sources.

Other urban estuary factors, such as the impacts on planted and naturally recruiting vegetation by Canada goose grazing, constrain the natural development of estuarine emergent vegetation assemblages. However, research on the scale of this disturbance factor suggests that certain restoration design and management strategies can mitigate for this factor. To establish persistent marsh vegetation on restoration sites in the Duwamish, CRANDELL (2001) recommended the following practices:

1) Physically protect *C. lyngbyei* shoots in areas frequented by Canada goose to prevent total loss of plant material. Three-foot-high fencing should surround a planted area, with nylon (or other) line crisscrossing the top of the protected area.
2) Protect plants for at least three years and as many as five to prevent irreversible degradation following eventual exposure to grazing. The minimum size of a planted stand might be 30 m^2 in areas experiencing 330–450 goose-days ha^{-1} of available *C. lyngbyei*.
3) Install exclosures in native established stands of *C. lyngbyei* that are currently grazed by geese in order to provide a boost to the BG development and long-term fitness of the stands.
4) Plant *C. lyngbyei* in conditions for which it is well suited so that it can compete successfully with volunteering plant species that may also be able to grow once grazing pressure is removed.
5) Install exclosures in unvegetated areas at elevations that might be expected to support bona fide intertidal vegetation so that volunteering species can become established.

Perhaps one of the most significant functions of urban estuarine restoration observed in the Duwamish River estuary is not ecological or geochemical, but social: citizen support, investment, and direct involvement in estuarine restoration has flourished with the recognition by citizens that some degree of rehabilitation of damaged ecosystems in their "own backyard" is feasible, and that they can take some responsibility for it. Urban revitalization focused in derelict industrial areas would generate more estuarine backyards and, presumably, more incentive for restoration of a sustainable city environment. Such direct contact and involvement with urban restoration has many cultural benefits because it addresses the historical, social, political, aesthetic, and moral attributes, as well as the technical goals, of restoration. And, while restoration in rural and isolated estuarine settings may be self-sustaining, restoration in urban estuaries will not be sustainable without public commitment to long-term stewardship, well after entities such as the CERCLA trustee panel have dissolved.

The investment is large and the risk commensurate. However, small incremental improvements in such degraded landscapes may have disproportionately large impacts. Strategic restoration actions have the potential to produce a huge signal: noise response. As seen in the Duwamish River estuary, despite the small incremental steps taken, habitat area and quality has expanded from a minute and continually degrading base prior to the 1970s to a progressively broader distribution of rehabilitated patches clustered in ecologically meaningful regions of the estuary.

Evidence of the benefit to fish and wildlife from habitat restoration is still somewhat ambiguous.

It is uncertain whether or not growth and survival is increased due to their increased use of restoring habitats in the estuary. However, in the case of some resources, such as at-risk anadromous salmon, we must ensure that restoration and all other measures toward salmon recovery based in the watersheds are matched by equal efforts to rehabilitate salmon habitat in estuaries. By monitoring and study of key metrics linking the attributes of restoring sites to their function for aquatic resources such as juvenile salmon, we have isolated some relationships that may direct the increased scaling up of restoration approaches and locations. For instance, the association of preferred prey with emergent and riparian vegetation (CORDELL *et al.,* 2001) provides information for more strategic designs for future restoration.

CONCLUSIONS

In retrospect, any enthusiasm for the potential of restoration in urban, industrialized estuaries must confront the reality that "this is not your average restoration." In areas such as the industrialized Duwamish River estuary, true restoration is not possible; rather, it is expensive rehabilitation and enhancement at best. Exemplifying what WEINSTEIN and REED (*in press*) consider an *urban-industrial* estuary, the Duwamish provides the challenge of ecosystem rehabilitation in a landscape dominated by industrial development. Because of these obstacles it is easy to discount the potential return on the investment, however large and long-term. Urban estuarine restoration demands different approaches that address, and perhaps even take advantage of, the urban landscape:

- Acknowledge system constraints and understand and work with existing natural processes. Probably the biggest misconception is that urban/industrialized estuaries can be returned to predevelopment conditions. Understanding anthropogenic changes in key ecological processes, and how they limit the approaches, patterns, and rates of restoration, is essential to realizing the spectrum of possible responses. As with the fundamental understanding of any estuary, this requires knowledge of key processes that originate from the watershed and receiving coastal waters, as well as from within the estuary.
- Learn from what is already in place. Consider the experimental tableaux of the urban estuary as a testbed for landscape concepts, alternative restoration approaches, performance metrics, and monitoring in challenging systems. Understand how to use the landscape connectivity and other conservation biology concepts of landscape ecology, both proximally and at regional scale, as a way to maximize the constrained array of restoration options available. This includes the larger-scale contribution of the estuary to coastal receiving waters such as Puget Sound in the case of the Duwamish River estuary.
- Explore innovative and adaptive approaches. Treat restoration projects as adaptive management experiments and *intensively* monitor and experiment. In the best of cases, even in relatively undisturbed ecosystems, estuarine restoration is experimental. In the case of urbanized/industrialized estuaries such as the Duwamish, we cannot afford not to formalize adaptive management and adhere to its most rigorous concepts.
- Realize that the characteristics of placing relatively small restoration sites in a larger matrix of urban environments requires significant and ongoing stewardship, but also that human resources and institutions are available and ready to help.
- Expand social and cultural connections and institutional commitments. Ultimately, whether or not investment in restoration of urban estuaries will become accepted will depend upon public realization that the return on the investment is worthwhile.

If we can continue to document how and why estuarine ecosystem functions can persist in the face of sustained economic, social, and cultural pressures, we have the potential to change perceptions about whether or not it is worthwhile investing in restoring urbanized/industrialized estuaries. This requires a mechanistic understanding, demanding much more than a "build it and they will come" confidence in mimicking structural elements of estuarine shorelines, wetlands, and channels. It requires understanding, most importantly, the legacies and futures of the human imprint, but also the surrounding landscape and which ecosystem processes can persist and be recovered at the watershed scale. Ultimately, it requires realization that ecologically functioning estuaries are a social, economic, and cultural investment.

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