PERSPECTIVE

Urban Lake Shoreland Restoration: Landform, Vegetation, and Management Assessment 20 Years Later

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ABSTRACT

Residential development and recreation cause lake shoreland degradation, triggering vegetation loss and soil erosion. Shoreland restorations have been attempted for > 30 yrs but practices have received minimal evaluation and outcomes are unpredictable. Using comprehensive project records (13–20 yrs) and ecosystem response metrics (shoreline stability and vegetation), we assessed nine urban shoreland restoration sites, each making up part of a single large initiative on Lake Phalen, Minnesota, to ascertain guiding principles. Restoration scope included littoral wetlands, wet meadows, and upland prairie/savanna. All sites received attention to altered landforms, soil erosion, and active revegetation. In general, these restored shorelands are well-vegetated with native plant species, have low abundance of introduced and invasive species, and are, with some exceptions, very stable. Bank erosion was observed on four sites: high slope areas without full riprap berms. Informal footpath formation generated bare soil and required regular monitoring and response. Post-restoration management to control introduced species and encourage native vegetation establishment never exceeded 5% of individual project costs (per year). Although the number of introduced species/site ranged from 12–39 (in 2021), most sites (8) have 0–2 species with > 1% cover and none > 5%, suggesting that management was effective. Recovery lags of native vegetation were most evident at locations prone to stressors that favored introduced and invasive species over native species, particularly those with high recreational (pedestrian) traffic, high muskrat activity, and near large, unmanaged stands of invasive plants. Shoreland vegetation management overwhelmingly required fine-scale, inherently labor-intensive control approaches, which necessitated regular surveillance and rapid response.

Keywords: cost estimation, invasive species management, soil erosion control, littoral wetlands, Minnesota

Residential development and recreation cause widespread lake shoreland degradation and littoral wetland loss, triggering wave-generated soil erosion and diminished ecosystem function (Crowder et al. 1996, Radomski 2006, Haskell et al. 2017). When intact, lakeshore ecosystems support carbon subsidies to deeper water zones, littoral macrophyte plant communities, and high secondary productivity (i.e., fish and aquatic invertebrates) (e.g., Hershey et al. 2006, Francis and Schindler 2009). In the United States, approximately 1.8M km of lakeshore perimeter is associated with 5.8M inland lakes (Winslow et al. 2014). Reversing lakeshore degradation is a priority in the north-central US, where lake abundance is high. For example, shoreland restoration has been pursued for over 30 years in Minnesota (Vanderbosch and Galatowitsch 2011), which has the highest lake area in the US (11,200 km², nearly 5% of its total land area, Winslow et al. 2014). However, compared to their adjacent aquatic and terrestrial ecosystems, restoration practices of lakeshores have received minimal assessment and outcomes are generally considered to be unpredictable.

Shoreland restoration typically begins with bank stabilization to counteract slope instability and wave-triggered erosion exacerbated by vegetation clearing to improve views and recreational access. Revegetation of the terrestrial-aquatic transition generally requires planting assemblages of species suited to upland, wet meadow, and littoral conditions in narrow bands (i.e., often less than 2–3 m wide) corresponding to elevational changes of high-relief landforms (Vanderbosch and Galatowitsch 2010).

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Restoration Recap

- Lake Phalen restorations are among the earliest documented efforts to reverse shoreland degradation. An analysis of project records offers guidance for stabilization methods, species selection and post-restoration management requirements.
- The level of intervention needed to achieve desired shoreland vegetation outcomes is a function of pre-restoration conditions and landscape context.
- Plant materials were the costliest part of budgets; active revegetation enhanced native plant diversity and establishment of all shoreland zones.
- Analysis of costs and outcomes of reusing riprap for offshore wave break berms (a new practice), supports further application. Vegetation established and spread between the offshore wave breaks and toe slopes; emergent macrophytes colonized berms; cut-banks were not evident.
- Ongoing management is a sound return on investment. Annual management costs steadily declined and were generally 2–3% of initial project costs ten years post-restoration. Invasive species spread, unintended footpath formation and subsequent soil erosion were likely unavoidable without management.

Historically, bank stabilization practices have depended, at least to some extent, on installation of large rock or other hardscape materials to prevent land loss despite their poor suitability to support vegetation establishment (Gabriel and Bodensteiner 2012). Revegetation is also limited by poor matching of species to environmental conditions (especially in the wet meadow zone), lack of protection from herbivory and wave impacts (littoral zone), and competition from invasive species (all zones) (Vanderbosch and Galatowitsch 2010). However, shoreland restoration outcomes (landform or revegetation) are seldom monitored or reported, especially after initial establishment. Consequently, shoreland restoration practices have become standards with little evaluation of their efficacy.

The extent of post-installation management and corrective action likely has high potential to affect shoreland restoration outcomes, but norms have not been established for this aspect of practice either. Lakeshores are environments of high-frequency, high energy disturbances from wave impact and surface water runoff, which elevates risks of failure for newly constructed landforms or recent plantings. Like many kinds of ecological restoration, lakeshore projects are pursued with short-term (i.e., several years) grant funds, which limits ongoing monitoring and management (Galatowitsch and Bohnen 2020). Information on the return on investment for post-installation management is needed to improve project planning for lakeshore restorations.

In 2000, the Ramsey-Washington Metro Watershed District (RWMWD) began an initiative to restore 2.7 km (60%) of the shoreline of Lake Phalen in an urbanized area of Saint Paul, Minnesota, USA. Between 2001–08, nine shore segments ranging from 107 to 564 m were restored on an annual basis (Figure 1). These lakeshores have received ongoing management since installation, providing an opportunity to evaluate restoration practices and forward guiding principles for future projects and funding programs. Using detailed records of initial actions, long-term management (13–20 yrs), and ecosystem response metrics (shoreline stability and vegetation), we conducted a retrospective assessment of these restorations to determine the efficacy of shoreline stabilization and revegetation practices and to estimate costs associated with these practices. In 2021, we comprehensively surveyed landform attributes and vegetation composition to understand changes over time with respect to initial site conditions, installation practices, management practices and costs. Long-term monitoring of restoration practices in the context of actual projects has potential to elucidate worthwhile insights (i.e., "tacit knowledge" or learning by doing) that differ in comparison to those advanced through hypothesis-driven research (i.e., "explicit knowledge") (Hulme 2014).

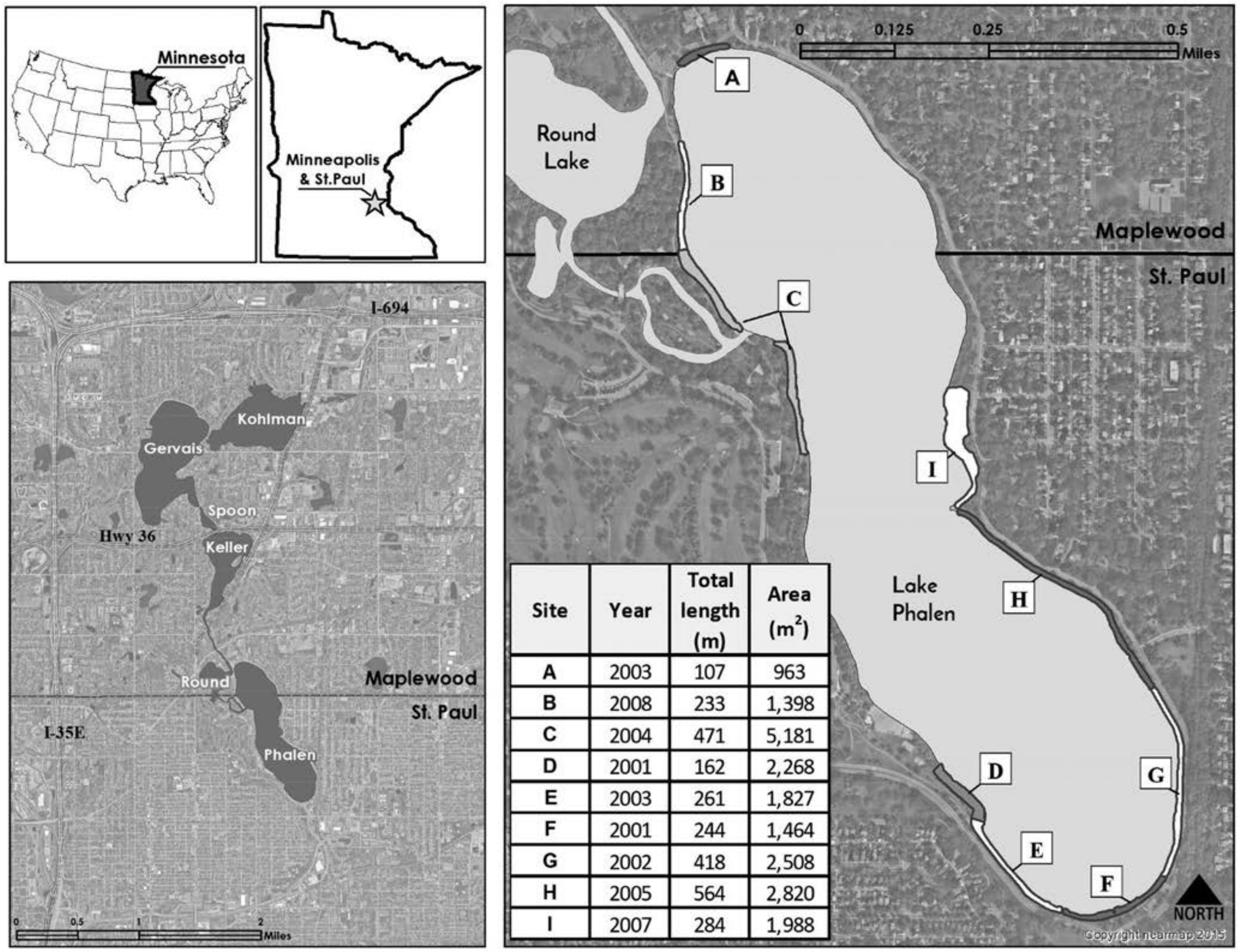
Methods

Pre-restoration Conditions and Restoration Scope

Located in a fully developed urban-residential watershed (6,068 ha), Phalen (81 ha) is the last lake in the Phalen Chain of Lakes and is fed primarily by surface water runoff. It is classified as a mesotrophic lake, having a maximum depth of 30 m and a mean depth of 7 m. Phalen Regional Park, owned by the City of Saint Paul, encircles the lake, which draws close to a million visitors annually (Figure 1). Fishing, swimming, rowing, sailing, wildlife viewing, and walking and biking around shoreland pathways are common recreational activities. None of the shoreline is residential or commercial.

Soils on the slopes adjacent to the lake are primarily Chetek sandy loam, with a lesser extent of DeMontreville loamy fine sands (USDA 2023). Chetek soils are sandy loams (to a depth of 40 cm) and gravelly loam sand (40–50 cm) overlying stratified sands and coarse sands. DeMontreville soils are loamy sands (to 60 cm) overlying sandy loams. Saturated soils of the lakeshores are classified generally as wet udorthents and not further distinguished to series.

Alteration to Lake Phalen's 4.5 km shoreline has been substantial and ongoing, beginning soon after park acquisition (1899). To create lawn areas adjacent to the lake, a steam-driven bucket dredge was used to excavate lake sediments and fill wet meadow areas along the shore. Initially, the shoreland lawns were maintained by grazing



Site	Year	Total length (m)	Area (m²)
A	2003	107	963
B	2008	233	1,398
C	2004	471	5,181
D	2001	162	2,268
E	2003	261	1,827
F	2001	244	1,464
G	2002	418	2,508
H	2005	564	2,820
I	2007	284	1,988

Figure 1. Nine project sites (A–I) comprised the initiative to restore a large portion of Lake Phalen's degraded shorelands. Lake Phalen is the central feature of an urban park within the Minneapolis-Saint Paul, Minnesota metropolitan area.

sheep, contributing to severe shoreline erosion. Within 20 years (1920s), severely eroding shoreline areas were treated with riprap. By the late 1990s, over 50% of the Lake Phalen shoreline had been modified, yet shoreline erosion worsened as popular access points resulted in gully formation and poorly designed erosion treatments failed (Elvecrog and Bartodziej 2008).

RWMWD sought to restore 60% of the Phalen shoreline length (2.7 km; Figure 1) with key objectives of stabilizing the shore (i.e., lake edge, bank, and slope) and revegetating native plant communities. Sites with substantial erosion that posed safety hazards (i.e., bank erosion within 1 m of walking paths) were given the highest priority. Legacy shoreland practices, altered hydrological conditions from the urbanized watershed, and heavy foot traffic caused bank erosion and gully formation. Prior to restoration, invasive plants and turf grass dominated shorelands. As part of the restoration process, all sites received attention to altered landforms (riprap removal, regraded gullies, fill soil removal), soil erosion (wave breaks, coir logs, slope protection), active revegetation, and invasive species management.

Initial Restoration Actions

Seven of the nine restorations were on slopes with riprap cover (0.3–1.0 m diameter); one (Figure 1, site A) was severely eroded but had not been armored with riprap and another (Site D) was an infilled wet meadow (Table 1). For sites with riprap (Figure 2), the general approach to restore landform was removal of excess rock from the shore slopes with a mid-sized (model 320 type) Caterpillar excavator and relocation of this material 1–2 m offshore This relocated rock formed a berm, 0.5 m above the Ordinary High Water (OHW) elevation to reduce wave impacts during normal lake level conditions. After the excess rock removal from slopes, soil (15–30 cm layer) was placed on top of the remaining rock and smoothed with the excavator bucket. Gullies and eroded banks were filled with soil and graded. Coir logs were installed immediately behind the rock berms to further dissipate wave energy and shield

Table 1. Summary of practices, relative costs, and general outcomes for each restoration site. All parameters related to vegetation are based ranks or categories of numbers of species (see Table 5 for details).

	Sites								
Practices	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Landform modification	none	Full offshore berm	Partial offshore berm	Wetland fill removal	Full offshore berm	Full offshore berm	Full offshore berm	Full offshore berm	none
Soil erosion control	PCR + blanket	PCR + blanket	PCR + blanket	blanket	PCR + blanket	Pre-veg mats + container stock	Pre-veg mats + container stock	PCR + blanket	PCR + blanket
Littoral revegetation	PCR +container stock, protective fencing	PCR +container stock	PCR +container stock, protective fencing	PCR +container stock, protective fencing	PCR +container stock	PCR +container stock	PCR +container stock	PCR +container stock	PCR +container stock, protective fencing
Upland & wetland revegetation	Seeding + seedlings	Seeding + seedlings	Seeding + seedlings	Seeding + seedlings	Seeding + seedlings	Seeding + seedlings	Seeding + seedlings	Seeding + seedlings	Seeding + seedlings
Native species planted-rank (1=high)	9	6	2	7	8	4	1	5	3
Costs									
Total installation costs per area (rank) (1=high)	7	3	8	9	1	5	2	4	6
Total management costs per area (rank) (1=high)	6	5	1	8	4	2	3	7	9
Outcomes									
Bank erosion	Minor	Minor	Moderate	Minor	Minor	Minor	Minor	Minor	Minor
Path formation	One-few	Many	Many	One-few	One-few	One-few	Many	Many	One-few
Native species present-rank (1=high)	9	2	1	6	8	6	5	4	3
Native species-spread (High=20+, Low=1)	Low	Medium	Medium	High	High	Medium	Medium	Medium	Medium
Introduced/invasive species present-rank (1=high)	5	1	2	8	9	5	3	3	5
Introduced/invasive species spread High=5+, Low=1	Medium	Low	0	0	Medium	High	Low	Medium	Low

Figure 2. Pre-restoration, construction, and post-installation (6 yrs) comparison of Site H. A) Pre-restoration image shows the steep riprapped slope with an informal path (foreground) from a walking path to the water. A portion of the riprap was re-used to make an offshore wave-break. B) A biolog providing secondary wave protection. The bank was regraded, seeded and protected with North American Green S-75BN (upland) and C-350 (toe of the slope) erosion control blankets. Emergent, wet meadow and upland prairie zones established by the sixth year (post-construction). C) Emergent vegetation (primarily *Schoenoplectus tabernaemontani*; softstem bulrush) colonized and spread between the offshore rock berm and the OHW elevation.

young plantings at the base of the shore slopes. At site D, 300 m^3 of fill material was removed to "daylight" wet meadow peat soils. Coir logs were not needed on this low-relief site. Required permits were secured for all movement of rock and soil, as well as for emergent species planting and cattail control.

On average, revegetation extended from 1–2 m lakeward of the OHW elevation to 8 m inland. Paved walking paths created the inland boundary for most of the restorations. Three vegetation zones were re-established in the restoration areas: 1) littoral wetlands, frequently inundated areas, 2) wet meadows, seasonally inundated areas, and 3) upland prairies/savanna openings. Surveys determined that there were no native remnant patches of vegetation to preserve in the restoration areas. As part of site preparation, turf grass in the upland, and introduced/invasive weed species in all zones were treated with glyphosate. After removing dead thatch, plants and seeds were installed by hand between May and July using a combination of staff and volunteer labor. Seed and plant mixes used were generally based on published native plant community descriptions for shorelands in this region (MN DNR 2005). Stock was selected from commercially available native species from local nurseries (Supplementary Material, Table S1, S2).

Because soil erosion control was a primary concern for all shoreland restoration areas, planting was combined with erosion control blanket installation (Table 1). On site D, in the wet meadow zone, we installed SC-150BN erosion control blanket (North American Green, Evansville, IN). In 2001–02, on sites with steeper shoreland slopes (Sites F and G), in the wet meadow zones we used pre-vegetated mats (North American Green C-350, Evansville IN) with 5 cm container stock plants at 10 cm spacing. High plant mortality occurred in the pre-vegetated mats soon after installation at these two sites. In response, we supplemented planting on those sites with pre-vegetated coir fabric (25 × 50 cm) rectangles (henceforth, PCRs), using strongly rhizomatous native species to combat erosion. From 2003–08 (i.e., on all other remaining sites), we hand broadcast a wet meadow seed mix, harrowed with rakes, and covered the area with North American Green C-350 erosion control blanket. We anchored PCRs on top of the blanket at approximately 60 cm spacing.

Emergent plant species (Supplementary Material Tables S1, S2) were planted via PCR mats and 3.8 l containers installed at 1 m spacing in the littoral zone. Offshore rock berms were not planted. The littoral zone of Site C experienced near total mortality from muskrat herbivory and was replanted in 2005–06. Installation usually took place during summer when water levels were low (i.e., saturated to 10 cm depth). We installed protective fencing (wood lath or wire fences and brush bundles) to surround the littoral zones of Sites A, C, D and I (shore segments without rock berms) to combat herbivory from muskrat and geese, and to reduce wave action (Table 1).

In upland zones, we broadcast prairie and savanna seed mixes, harrowed, and covered with North American Green S75-BN blankets (Table 1). We installed additional prairie seedlings (5 cm container stock) at 60 cm spacing through openings in the erosion control blankets. We watered newly installed vegetation during dry periods of the first growing season after planting. A Honda 25cc water pump was used to extract water from the lake and irrigate the restoration areas during dry periods (i.e., > 7 days without precipitation). RWMWD staff watered (2–3 cm in depth) the newly planted areas with a garden hose sprayer setup. Vinyl coated metal fencing (1.5 m height) was installed near pathways to reduce foot traffic. Signage was posted along the perimeter of each site to inform visitors of the restoration project underway and to warn them to stay off the site.

Ongoing Management

Since the initial installations, staff from both RWMWD and St. Paul has managed the sites. Staff visit each site at least monthly to evaluate soundness of erosion control installations, scout for invasive species, and identify other problems (e.g., failed plantings, vandalism, mower encroachment). Based on this routine surveillance, RWMWD staff undertakes necessary site management (invasive species control, replanting, reseeding, prescribed burns). Field notes included staff hours, methods of control and species targeted for control. City of St. Paul staff conducted prescribed burns, as needed, to promote establishment and spread of prairie vegetation by reducing weed abundance (i.e., annuals and woody plants). RWMWD maintained detailed records of all management activities on the restoration sites, including person-hours for specific practices.

Invasive species control techniques were chosen to maximize treatment efficacy of target species and to minimize non-target impacts. The perennial invasive species *Cirsium arvense* (Canada thistle), *Phalaris arundinacea* (reed canary grass), *Rhamnus* spp. (buckthorns) and *Urtica dioica* (stinging nettle) were most frequently targeted for control. Large stands of non-native annual and biennial species were also regularly treated prior to flowering to prevent seed production. Depending on target patch size, proximity of non-target species, and target species growth form (i.e., woody or herbaceous), herbicides were applied with backpack sprayers, by hand wicking individual plants, or as cut-stump treatments. All herbicides were used at standard rates, following label instructions. An aquatic formulation of glyphosate (1.5%) was used to treat *P. arundinacea*, *Typha* × *glauca* (hybrid cattail) and *U. dioica*. A clopyralid-based herbicide was applied to *C. arvense*, *Lotus corniculatus* (bird's-foot trefoil), *Securigera varia* (crownvetch), *Arctium minus* (lesser burdock), *Solidago canadensis* (Canada goldenrod), and *Sonchus arvensis* (field sowthistle). A concentrated formulation of glyphosate (20%) was used for cut-stump treatments of woody invasive species (e.g., *Rhamnus* spp.). Non-chemical treatments including string trimming and hand pulling were also commonly used for invasive species control. Methods were selected depending on characteristics of the invasive species, abundance, and distribution.

Project Costs

We estimated project costs for each site based on records compiled during the restoration, converting expenditures to 2023 USD. These cost estimates included supplies and materials, contracted excavation services, labor for installation, and management. We itemized supplies such as plants, seed, erosion control blanket, fencing, and soil to compute a total material cost for each site. Contracting costs for excavation used to move riprap, soil, and to create rock berms were totaled for each site. Because volunteers and inmate crews installed most of the plant and erosion control materials, direct costs and work hours logged were not a good representation of the typical labor needed for project installation. Instead, we estimated labor hours and costs required to conduct installation activities from industry contracting standards (Natural Shore, pers. comm.) for the Minneapolis-St Paul metropolitan area. We also used this approach for estimated annual management costs from RWMWD records.

Assessment of Long-term Restoration Outcomes

To evaluate Lake Phalen restoration outcomes, we surveyed the vegetation and physical conditions at each site in 2021 (July–September). We assessed shoreline stabilization using four metrics: 1) effects of bank erosion on buffer width, 2) bare soil area in 2021, 3) changes in riprap berm elevation, and 4) vegetation colonization of berms. To determine if bank erosion was diminishing buffer width, we compared buffer widths at installation (high-resolution orthoimagery in ArcMap) to 2021 buffer widths determined from ground surveys. Three components were used to calculate slopes: 1) OHW, 2) buffer width, and 3) and pathway elevation determined by high-resolution orthogonal and oblique images and digital elevation models supplied by EagleView Technologies (2022–23). We mapped and measured (using GPS) all eroded banks > 0.15 m, bare soil areas > 1 m^2 and worn footpaths with exposed soil > 0.5 m in width. To assess changes to berm elevations, we used field surveys (direct leveling) to determine 2021 berm elevations and compared these data to as-built elevations. We recorded colonization of vegetation during surveys of the littoral zones in 2021 (described below).

Plant community establishment considered three components: 1) the composition of seeded and planted species, 2) the colonization of unplanted species, and 3) effects of vegetation management on introduced/invasive species prevalence. We gathered these data using timed meander surveys, adapted from Bohnen and Galatowitsch (2016). We surveyed vegetation twice, in July and September 2021, facilitating identification of nearly all species encountered. We chose the timed meander sampling technique, a plotless assessment method, because it allowed for comprehensive coverage of sites and was adaptable to the linear configuration of shorelines. At each of the nine sites, we surveyed vegetation along three separate meander routes for the littoral, wet meadow and upland shoreland areas. During the survey of the littoral zone, we also recorded the total aerial cover of rooted emergent species observed on riprap berms installed as offshore wave breaks. We recorded all the species, both native and introduced (i.e. non-native), encountered during the meander (i.e., those visible from the route, to approximately 3.5 m either side of the observer) and estimated aerial cover using a 6-class cover scale (Galatowitsch and Bohnen 2020, adapted from Mueller-Dumbois and Ellenberg 1974). Each site was fully surveyed in 90 minutes or less (not including time needed to resolve plant identification uncertainties). Taxonomy follows NRCS (2022) and Kartesz (1994).

We compared the lists of seeded and planted species for each site to 2021 occurrence data. To identify species that were most and least likely to persist over time, we calculated the frequency of establishment across all sites. We also used this comparison to evaluate the relative importance of natural colonization (i.e., passive revegetation) to active revegetation (i.e., seeding and planting). We tabulated and ranked the frequency of all species observed that had not been seeded or planted. Patterns of establishment considered species lifespan, growth form, and origin. Species were classified into six life forms (guilds) based on Galatowitsch and van der Valk (1994), Galatowitsch et al. (2000), and life history and wetland indicator status (NRCS 2022): AN—Annual and biennial forbs and grasses, WO—Trees, shrubs, subshrubs, woody vines, GR—Perennial grasses, sedges, rushes, PF—Perennial forbs, EM—Emergent macrophytes, and AQ—Submersed and floating aquatics. Each was also identified as native or introduced/invasive to the region based on NRCS (2022). Introduced/invasive species include those that are non-native to the region (i.e., introduced) and species with uncertain origin that are considered highly invasive.

To assess the effectiveness of vegetation management in limiting the abundance of introduced and invasive species, we compared occurrence data from each site to records of management effort. Management records compiled for these restorations also indicated which species were targeted for control.

Results

Installation and Managements Costs

Initial shoreland restoration costs ranged from \$563/linear m to \$790/linear m, with an average of \$619 m^{-1} (Table 1, 2). Generally, sites with wider upland buffer

Table 2. Installation costs and management labor for each restoration site. Planning and preparation include field surveys, restoration design, securing materials, scheduling contractors and other related project management activities. Landform and soil preparation include heavy equipment contractors, soil, delivery, and labor required to prepare soil for seeding and planting. Plant materials include plants, seeds, and prevegetated mats. Erosion control materials include erosion control blankets, coconut biologs, brush bundles, and temporary fencing. Management hours include site surveillance, management, irrigation, herbicide, and equipment rental necessary for treatments. Hours/area/year is adjusted for number of years post-restoration (see Figure 1). Linear and areal dimensions for each site are also presented in Figure 1.

	Sites								
	A	B	C	D	E	F	G	H	I
Total Cost (USD x 1000)	60.2	152.6	316.9	110.7	206.3	138.5	281.7	286.5	131.1
USD linear m^{-1}	563	655	672	683	790	567	673	507	461
USD m^{-2}	63	109	61	49	113	96	112	102	66
Installation Components (USD x 1000)									
Planning & preparation	7.7	15.4	16.5	10.8	17.5	17.3	20.1	23.3	17.0
Landform & soil preparation	12.3	46.5	61.1	28.9	39.4	37.6	68.7	82.4	30.8
Plant materials	33.1	44.2	200.7	57.8	96.5	27.4	96.2	70.7	43.5
Erosion control materials	7.2	46.4	38.6	13.2	52.9	55.9	96.8	110.2	39.9
Management—Total hours	343	549	1438	551	783	639	1022	825	405
Hours m^{-2}	0.36	0.39	2.85	0.24	0.42	1.17	0.40	0.27	0.06
Hours m^{-2} yr^{-1}	0.02	0.03	0.17	0.01	0.02	0.06	0.02	0.02	<0.01

areas had a lower restoration cost unit area. Plants and seed (40%), erosion control materials (27%), excavation and labor (24%), and restoration planning and preparation (9%) comprised most of the project expenditures. PCR mats ($0.27 cm^{-2}) were the costliest means by which to revegetate native plants, even compared to C-350 mats ($0.04 cm^{-2}) with seeding or planting.

Over 13 years post-restoration (2008–20), 5,830 field labor hours (total) were employed to manage the nine restoration sites (20,417 m^2). Management effort peaked one year after project installation at 4.41 hrs/100 m^2, 5% of total project costs, and then steadily declined to 1.01 hrs/100 m^2 in year 13 (Figures 3 and 4). Primary management methods employed were hand weeding (43%), prescribed burns (22%), chemical treatment of herbaceous weeds (15%), string trimming (13%), and chemical stump treatment of weedy woody vegetation (7%). Hand weeding and string trimming declined six-fold during this period (Figure 3), from a year-1 peak of 711 hrs to 111 hrs in year 13. Chemical treatments of both woody and herbaceous vegetation and prescribed burns remained relatively constant over time.

Shoreline Stabilization

A comparison of the as-built rock berm elevations to the existing berm elevations revealed no change, suggesting that wave and ice action did not cause appreciable rock movement (Table 3). Bank erosion of the restored shorelines of 20–40 cm (bank drop to the OHW) was observed on four of the restoration sites in 2021, generally in high slope areas without the full rock berms present at other sites that provide the main offshore wave protection (i.e., biologs were installed as secondary protection, Table 3, Figure 2). The total distance of bank erosion was 302 m (11% of total restored shoreline) with 60% of the bank erosion length occurring on one site (C, along an area of shore without berm protection). For all restoration sites, buffer width loss was equal to or less than 30 cm, which is within the error limits of the photo interpretation. Informal footpaths formed on all the restored shorelines and are responsible for all bare soil areas greater than 1 m^2. These paths were heavily used, had an average width of 50 cm and extended from paved park pathways to the water's edge. Forty-one of the 50 footpaths occurred on four sites (B, C, G, H).

Although seeding or planting did not take place in or immediately adjacent to the berms, nine rhizomatous wetland species did colonize amongst the rock (Table 3). We observed that vegetation colonized in microsites with leaf litter and masses of decomposing submersed vegetation lodged in rock crevices. Plant cover was generally < 25% of berm surfaces. The most common species were *Sparganium eurycarpum* (broadfruit bur-reed), *Schoenoplectus acutus* (hardstem bulrush), and *Typha* spp.

Vegetation Response

A total of 320 plant species were observed across all sites in 2021; of these, 232 are native to the region. About one-third (109) of species observed in 2021 had been planted in at least one site; emergent macrophytes (72.7%), graminoids (56.8%), and perennial forbs (47%) had the greatest proportion of planted species (Table 4). On average, 94 species were planted at each site (range= 42–157), 177

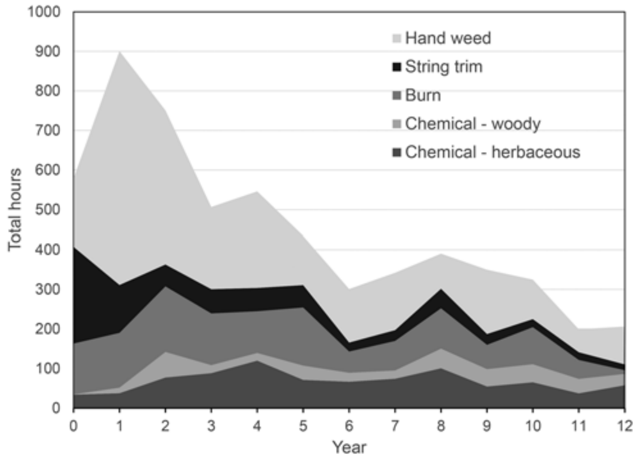


Figure 3. Post-restoration changes in the effort (person-hours per year) over time for different types of vegetation management. Year 0 effort consists of actions taken immediately after installation of soil erosion control materials and planting.

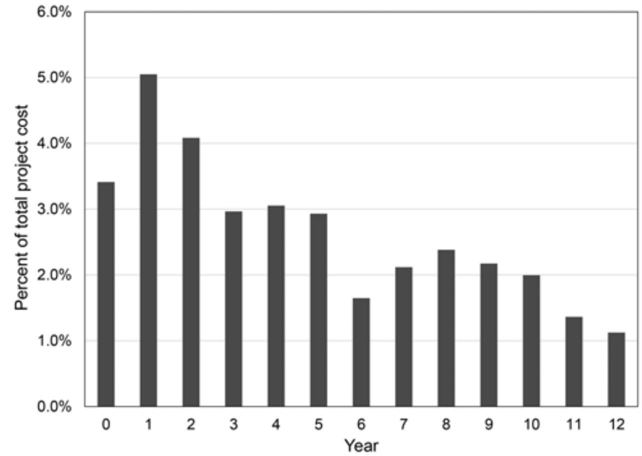


Figure 4. Change over time in the relative cost of annual management post-restoration (% of total project costs). Year 0 annual management costs are for actions taken immediately after installation of soil erosion control materials and planting.

total across all sites. Sixty-five planted species were not observed on any restoration site in 2021 (Supplementary Material, Table S2). About half of those (33) were planted on only one or two sites; however, 12 were planted on 6–9 sites, including *Lupinus perennis* (sundial lupine, 9), *Carex comosa* (longhair sedge, 8), *Liatris pycnostachya* (prairie blazing star, 8), and *Sporobolus heterolepis* (prairie dropseed, 8).

Of the planted species that did establish, three graminoids, *Calamagrostis canadensis* (Canada bluejoint, 8 sites), *Carex lacustris* (hairy sedge, 7 sites), and *Spartina pectinata* (prairie cordgrass, 3 sites), most commonly became a dominant component of the vegetation (i.e., > 5% cover in a zone) (Supplementary Material, Table S1). Four planted emergent species had a cover > 5% on at least one site: *Acorus americanus* (sweetflag), *S. acutus*, *Schoenoplectus pungens* (common threesquare), and *S. eurycarpum*, as did five perennial forbs, *Iris versicolor* (harlequin blueflag), *Monarda fistulosa* (wild bergamot), *Pycnanthemum virginianum* (Virginia mountainmint), *Solidago speciosa* (showy goldenrod), and *Tradescantia occidentalis* (prairie spiderwort).

Table 3. Attributes used to assess shoreland landform restoration and stabilization at each site. Slope (%) was measured from paved pathways to OHW elevation. The berms of five sites (B, E, F, G, H) extend the full shoreline length. The C site berm provides partial protection. Three sites (A, D, I) do not have riprap berms. Note that there was no buffer width lost on any site, no patches of bare soil > 0.1 m^2 other than those associated with paths, and no change to riprap berm elevation.

	Sites								
Metrics	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
Slope (%)	22	31	18	7	22	25	27	30	18
Cut-bank drop (cm)	20	0	40	0	0	0	20	0	20
Cut-bank length (m) (% of total)	9 (8.4)	0 (0)	179 (38)	0 (0)	0 (0)	0 (0)	30 (7.2)	0 (0)	93 (32.7)
No. paths with bare soil	1	9	13	2	3	2	10	9	1
Vegetation cover class-berms	N/A	1–5%	5–25%	N/A	25–50%	50–75%	1–5%	5–25%	N/A
No. species colonizing berms	N/A	1	4	N/A	5	6	6	6	N/A
Acorus calamus	—	—	—	—	X	—	—	—	—
Bolboschoenus fluviatilis	—	—	X	—	X	X	X	—	—
Carex lacustris	—	—	—	—	X	X	—	X	—
Schoenoplectus acutus	—	X	X	—	—	X	X	X	—
Sparganium eurycarpum	—	—	X	—	X	X	X	X	—
Schoenoplectus pungens	—	—	X	—	X	—	X	X	—
Schoenoplectus tabernaemontani	—	—	—	—	—	X	X	X	—
Typha spp. *(T. x glauca, T. angustifolia)*	—	—	—	—	—	X	X	X	—

Table 4. The plant composition of restored shorelands by life forms (guilds). Approximately one-third of observed species had been planted or seeded; one-fifth of all species were widespread (i.e., occurring on 7–9 sites). Less than 15% of all species (i.e., planted and unplanted) had spread to have more than 5% cover in a zone (littoral, wet meadow, upland prairie/savanna) on any site.

Life Form	No. observed	%, (no.) observed species-planted	% widespread	% spread
Perennial forbs	147	47.0 (69)	23.0 (34)	6.1 (9)
Woody plants	57	10.5 (6)	17.5 (10)	7.0 (4)
Annuals/Biennials	49	2.0 (1)	18.4 (9)	4.1 (2)
Perennial graminoids	44	56.8 (25)	18.2 (8)	6.8 (3)
Emergent macrophytes	11	72.7 (8)	27.3 (3)	36.6 (4)
Aquatic & Floating	5	0.0	20.0 (1)	20.0 (1)
ALL	320	109	20.3 (65)	6.9 (22)

Eleven unplanted native species had a cover of > 1% on at least one site, including four woody plants, four perennial forbs, two annuals, and one aquatic species (Supplementary Material, Table S3). By 2021, most sites had at least four native species (planted or unplanted) with > 5% cover, except for sites B (2), C (2), and H (3). However, the numbers of planted species observed on these sites were similar to those at other sites (Table 5). Sites D and E had markedly greater native vegetation development, with 21 and 27 species, respectively, with covers > 1%.

Post-restoration, Sites B and C also had the greatest number of introduced/invasive species (31 and 29, respectively), while sites D and E had the fewest introduced/invasive species (14 and 13, respectively; Table 5). Immediately west of sites B and C was an unmanaged 4 ha parcel of parkland with an abundance of invasive species, notably *Bromus inermis* (smooth brome), *C. arvense*, *S. arvensis*, and *S. varia*. This unmanaged parcel was a source of invasive weed seed.

Only one site (F) had more than two introduced/invasive species with cover > 1% in 2021. Six introduced/invasive species were widely distributed (7–9 sites) in the 2021 vegetation survey: *B. inermis, P. arundinacea, C. arvense, Rumex crispus* (curly dock)*, Solanum dulcamara* (climbing nightshade), and *S. arvensis* (Supplementary Material, Table S3). In 2021, no introduced or invasive species had a cover of > 5% on any site.

Discussion

The restorations of Lake Phalen shorelands were among the earliest lake-wide efforts to reverse degradation of these transitional ecosystems. Methods used to stabilize high wave impact areas were novel, including the installation of offshore berms; other methods for vegetating slopes and littoral zones (i.e., pre-vegetated mats) were previously largely untested. Nonetheless, our findings indicate that these restored shorelands are well-vegetated with native plant species, have low abundance of introduced and invasive species, and are, with few exceptions, very stable. Because these restorations received ongoing surveillance and management and complete records were kept of these efforts, we can offer guidance to improve future shoreland projects pertaining to slope and bank stabilization methods, species selection and post-restoration management requirements.

The Lake Phalen initiative demonstrates that keeping complete records is essential for offering guidance for future lakeshore restorations, including: 1) budgeting, 2) evaluating the efficacy of new practices, and 3) avoiding use of less effective practices. By consistently recording labor and materials, we were able to establish that costs for initial shoreland restoration, encompassing many of the conditions typical of inland lakes in the region, was not highly variable, ranging from \$461–791 linear m^{-1}. Post-restoration management was more variable, ranging from 0.06 to 2.85 hrs m^{-2}, reflecting the differential pressures of

Table 5. Species planted and colonized that were observed on shoreland restoration sites. Colonized species are those that were observed in 2021 vegetation site surveys but had not been planted. Species with more than 1% cover are those that had spread to this extent over at least one zone (littoral, wet meadow, upland prairie/savanna) of a site.

	Sites								
Numbers of Species	A	B	C	D	E	F	G	H	I
Total observed	108	173	191	138	112	142	149	165	148
Total planted	42	93	112	87	82	104	121	97	105
Planted species observed	25	72	88	63	55	69	81	72	69
Native species colonized observed	65	70	74	61	44	55	47	62	71
Native species >1% cover	10	12	14	21	27	14	14	13	14
Introduced species colonized observed	18	31	29	14	13	18	21	21	18
Introduced species >1% cover	2	1	0	0	2	5	1	2	1

recreational use, herbivory, and invasive species on native plant community development (e.g., Cavaillé et al. 2015, Liu et al. 2020, Zingraff-Hamed et al. 2022).

Reducing wave impacts during re-establishment of littoral and meadow zones has been problematic region-wide, with few options for inland lakes (McComas 2003, Vanderbosch and Galatowitsch 2010, Vanderbosch and Galatowitsch 2011). Our analysis of costs and outcomes of re-using riprap for offshore wave breaks (a new practice), supports further application. We observed vegetation establishment and spread, including emergent macrophytes and perennial graminoids, between the offshore berm (wave break) and toe slopes (e.g., Figure 2), as well as colonization of emergent plants (not planted) on the berms. Most critically, there was a lack of measurable bank erosion along a majority of the shoreline with wave-breaking berms. Compared to traditional slope stabilization (i.e., riprap on slopes and banks) (Tisserant et al. 2021), offshore berms do not constrain native perennial vegetation and are potentially a much more effective restoration practice for moderate to low energy lakeshores.

For these lakeshore restorations, plants and seeds were the costliest part of the initial budgets (40% of the total), as is likely typical across the region. Active revegetation is widely considered essential for lakeshore restoration: lakeshores are erosion-prone settings and, in public and residential settings, need to be aesthetically pleasing. Our findings suggest that active revegetation did enhance the diversity and establishment of three key components of shoreland vegetation: emergent macrophytes, perennial graminoids, and perennial forbs, doubling the species richness of these groups compared to colonizing species only. Importantly, many of the unplanted species that colonized were, not surprisingly, ruderals (annuals, biennials, woody species), and introduced/invasive species. This assessment offers guidance for species selection to improve cost-effectiveness. Of the 177 species planted, approximately one-third did not establish, including 32 planted on more than a few sites. Choosing species that have a high probability of succeeding in the conditions present at the onset of lakeshore restoration and planting them in sufficient quantities is likely to be more efficacious than maximizing the numbers of species in vegetation mixes (Vanderbosch and Galatowitsch 2010). For example, our study identified *C. canadensis, C. lacustris*, and *S. pectinata* as reliable graminoids for wet meadow revegetation and *A. americanus, S. acutus, S. pungens*, and *S. eurycarpum* for littoral zones (see Supplementary Material, Table S1 for full list of planted species that consistently established), which aligns with reliable species identified by Vanderbosch and Galatowitsch (2010).

As has been reported for many kinds of restorations, lakeshore restoration outcomes reflect pre-restoration conditions and landscape context (e.g., NRC 1992). The level of intervention needed to achieve desired outcomes is also a function of these factors, as much as specific practices (Table 1). Two restoration sites with relatively greater spread of native shoreland species and fewer invasive species are on sites with richer soils and sediments (e.g., exposed peat from fill removal-D; wave-protected littoral zone-E; and a gradual slope-D). Site D required considerably less management effort (especially initially) to effectively promote native vegetation establishment. We see evidence that the efficacy of restoration actions and need for follow-up management reflect system stressors that cannot be addressed. Of the nine restorations at Lake Phalen, lags in recovery are most evident at locations prone to stressors that have favored introduced and invasive species over native species. Very high muskrat densities associated with inter-lake channels caused initial high mortality to littoral zone plantings, and close proximity to areas with extensive, uncontrolled populations of introduced species and very high recreational traffic (i.e., recurrent path formation) pose ongoing threats to restored lakeshore grasslands and meadows. In experiments conducted on establishment of emergent vegetation in shorelands, Vanderbosch and Galatowitsch (2011) also found muskrat herbivory to be a major determinant of planting survival. In contrast, the influences of these three stressors appear much lower at sites (i.e., D and E) with the greatest recovery of native plant communities (all zones). Even after 13–20 years of continued management, some restored lakeshores (i.e., Sites B and C) remain especially vulnerable to re-degradation, as has been previously reported for shoreland restoration (Wieher et al. 2003).

This study demonstrates that consistent long-term surveillance and management are essential for achieving the goals of both stabilization and native community revegetation. For example, despite the high visitor use of the lakeshore, informal footpaths are few (< 3) on most sites. Through regular (i.e., monthly) surveillance and response, crews detect footpaths with active erosion, install barrier fencing and revegetate before more extensive damage occurs. Early detection and rapid response for introduced/invasive plant species has also been critical: we observed that the establishment and spread of native graminoids is greater where introduced/invasive species are less prevalent. Perennial rhizomatous weed species have been kept at relatively low abundance primarily by strategic spot herbicide treatments with a backpack sprayer and hand wicking application. While the abundance of *B. inermis* and *U. dioica* slowly diminished over a period of years with regular treatments, species such as *C. arvense* and *P. arundinacea* have persisted but have not reached levels that require aggressive control measures (that also carry substantial non-target risks). Other introduced species (e.g., annuals, biennials) were effectively controlled with regular mechanical control measures, facilitating the spread of native perennials and reducing the need for management effort over time. Because of steep topographic gradients and corresponding high species turnover, management of shoreland restorations require fine-scale control approaches (i.e., hand weeding, spot-spraying to facilitate native vegetation recovery; Hess et al. 2019) that are only feasible with early detection.

The Lake Phalen assessment revealed that post-installation management can be a sound return on investment of the initial restoration actions. In the 10 years post-restoration, annual costs were generally between 2–3% of initial project costs, followed by a decline to approximately 1% (Table 3). Without these relatively modest investments in surveillance and management, it is unlikely that footpath-triggered soil erosion and the spread of introduced and invasive species could have been avoided. Both would have entailed costly actions to repair—significant setbacks that can be perceived as project failures and lead to abandonment (Galatowitsch and Bohnen 2020). The establishment of native perennial forbs and graminoids is necessary for long-term slope protection (as well as for habitat restoration), but requires recovery times of more than a few years (e.g., Aronson and Galatowitsch 2008). Moreover, public support for natural vegetation (vs. turfgrass) in urban park settings depends on aesthetic appeal and minimizing weed infestations (Gobster et al. 2007). An ongoing commitment to restoration (i.e., beyond grant funding) is uncommon, often due to barriers in organizational capacity (Galatowitsch 2023). For this restoration initiative, a partnership between the City of Saint Paul (CSP) and RWMWD, formalized during project planning, facilitated long-term management. RWMWD was responsible for surveillance and response to soil erosion control, species-specific plant management, as well as record-keeping; CSP conducted prescribed burns and handled disposal of weed material.

Several key needs for shoreland restoration practice, based on cost-effectiveness and predictability of outcomes, were identified from the assessment of these projects. Methods that soundly address both immediate site stabilization and native plant revegetation—a very common need—are lacking. For example, in wet meadows and littoral zones, we found that plant establishment using pre-vegetated mats was poor, while PCRs combined with seeding and planting achieved better outcomes but were relatively costly. Similarly, biologs used in combination with rock berms were effective at dissipating wave action when positioned at the OHW (e.g., Figure 2). Wetland and emergent plant material installed at the base of the shore slopes established quickly, with observable rhizomatous spread within two weeks post-installation. The major downside to using biologs was cost, which ranged from 20–25% of the total project budget. Formal trials are needed to advance these stabilization-revegetation methods but are beyond the scope of individual restoration projects and would be better pursued as research experiments. As has been reported previously (Vanderbosch and Galatowitsch 2011), the planting methods used at Lake Phalen are prone to failure because of muskrat herbivory and other factors, resulting in costly replanting attempts. Although muskrats were prevalent around the entire lake, we were unable to predict which areas would experience substantial feeding damage and impact plant establishment. Because of this uncertainty, we suggest planting emergent species (e.g., *S. eurycarpum*) that are more resistant to feeding damage when muskrats are prevalent (Bartodziej et al. 2008).

Demands for shoreland restoration are likely to grow in lake-rich regions, given the probable acceleration of degradation from climate change-induced stressors, high intensity storm events and invasive species spread, on top of increasing pressure from residential development and use of urban parks (Haskell et al. 2017, Huang et al. 2021). Despite the imperative, restoration will not be a logical investment without a commitment to surveillance and management beyond the grant-funded installation phase. The annual costs of these commitments are relatively economical and especially crucial for shorelands because early detection and rapid response minimizes damage to site stability and risks to non-target plants and animals at the terrestrial-aquatic interface. An expectation of ongoing management of restorations will challenge the capacity of organizations accustomed to short-term, grant-based involvement. Nonetheless, this is an issue that must be addressed for restorations to be successful not only for shorelands but in many other ecosystems worldwide (Galatowitsch 2023).

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