A riverbank erosion control method with environmental value

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\textbf{ABSTRACT}

Between 1992 and 1998, 55 km of riverbank on the Ottawa River was protected from erosion using rounded granular material of glaciofluvial origin from local gravel pits. The method did not require slope reprofiling or the installation of a key or geotextile. It allows for the slopes of the structure and the banks to reach an equilibrium state and relies on natural vegetation regrowth on the banks and embankments rather than bioengineering revegetation techniques. A follow-up was done in 2011 to assess its effectiveness. After fifteen years, the structures have halted erosion, blended into the local landscape and created a riparian ecotone. They quickly acquired a natural, gently sloping profile and recreated a sinuous shoreline dotted with sandy beaches. The follow-up also shows that the banks and structures are 80–90% covered by indigenous vegetation. Furthermore, this vegetation is as diverse as the natural vegetation seen on the unstabilized sections of riverbank. The work minimized damage to the riverbanks as it was done in winter so that shore ice could be used for access. This approach helped avoid interventions on the banks themselves and protected the existing vegetation. The availability of granular sources near the work site was a key criterion. Riverbank protection work of this scale is uncommon. This article discusses the effectiveness of the protection method and its environmental advantages and limitations. This method could prove to be an alternative to traditional rock-fill methods or bioengineering techniques, which are often quite complex and costly.

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1. Introduction

Bank stabilization methods designed to fit all field conditions can sometimes lead to overdesigned structures that are poorly suited to the local environment (Kondolf et al., 2001). Some stabilization concepts use synthetic or manufactured materials such as walls, mattresses, interlocking blocks and hexagonal structures and often involve multiple interventions on the riverbanks (Abbe et al., 2011; Hare, 2008; Tilton, 2003). Traditional riprap is mostly used where infrastructures (roads, bridges and buildings) need to be protected or on sites where work space is limited (Water and Rivers Commission, 2000). It is a time-tested technique, highly durable and fairly easy to construct. However, laying steeply sloping fill composed of shot rock can artificialise banks, significantly reducing the potential for vegetation regrowth and limiting access to water for both animals and humans (FEMA, 2008). Several years after being put down, riprap let alone typically shows very little plant cover if no revegetation effort has been made. The technique has proved to be effective but is expensive and has limited environmental benefits (Hoitsma, 1999).

Bioengineering methods have been developed and their use has increased considerably in recent decades. In some cases, these methods can be limited to flattening the slope and planting vegetation. Plants can be attached to the substrate with various devices to resist erosion (Goupil, 1999; Hoitsma, 1999; Holanda and Rocha, 2011; Lachat, 1994; Lee et al., 1997). Piling and imbricating large woody debris or logs at the toe of the banks can also be effective (Larson et al., 2001; Lester and Boulton, 2008).

However, on treed clay or silt banks, vegetation sometimes fails to halt erosion. Repeated wave action or currents at the toe of the slope carry away the fine material, which cannot be maintained by plant roots alone. Bioengineering may then require hard structures (rocks or solid material) at the foot of the bank as well as major bank reshaping, removing the existing vegetation and planting selected...
species (Hare, 2008; Hoitsma, 1999). This can reduce plant diversity as compared to natural conditions (Bérubé et al., 1996). In addition, such methods also require monitoring and maintenance in the early years (Lachat, 1994).

Although bioengineering methods are generally considered to improve bank stabilization significantly, their large-scale use can be difficult due to high cost and sometimes complicated construction. In this paper, we introduce an approach based on geomorphology that uses natural granular material, no key or membrane and involves no planting of vegetation. The principle is to imitate naturally stable banks by providing the right material for local erosion conditions, avoiding overdesign and letting the vegetation grow naturally. The approach was developed for a very large project on the Ottawa River involving a variety of erosion conditions. In 2011, more than 15 years after the project was completed, a follow-up was done on the protected riverbanks and structures. The objectives were to see if the structures were stable, if erosion had stopped and if the established vegetation was as diverse as in the natural surroundings.

2. Methodology

In 1959, Hydro-Québec, a government-owned corporation that oversees the generation, production and distribution of electricity in the Province of Québec, Canada, was authorized to develop the hydraulic power of the Ottawa River (Fig. 1). Dam construction was completed in 1963, leading to the creation of a reservoir that raised the water level to an average of 1.4 m. Water regulation minimized the effects of floods and reduced the water level fluctuations compared to natural conditions. Raising the water level also flooded the vast flats bordering the main channel, allowing the waves to reach banks that previously had only occasionally been in contact with water. These new conditions exacerbated riverbank erosion. Bank recession was fairly gradual at first, but eventually led to caving (and even landslides; Fig. 2) when the water reached higher terraces. In 1992, Hydro-Québec began taking steps to set up an extensive riverbank stabilization program. An impact assessment (Hydro-Québec, 1994) was filed with the provincial government’s environmental department in 1994, and the Stabilization Program was approved and set in motion in 1996. More than 1200 riverside property owners were affected by the program.

2.1. Study area

The Ottawa River is one of Québec’s major waterways. It stretches over 1000 km and its watershed covers a vast territory (145,000 km²). The section concerned by the project was restricted to a stretch of about 110 km of the lower reach of the river (Fig. 1). The land along this segment is occupied by agriculture, nature reserves (wetlands and forest) and, to a lesser extent, urban areas (Bérubé et al., 1996).

The study area is part of the St. Lawrence Lowlands which are characterized by low, flat topography. Local outcrops of bedrock are usually overlain by marine or alluvial fine sediments (clay, silt or fine sand). After the retreat of the Champlain Sea some 10,000 years ago, the river gradually cut into the plain, carved terraces and built long alluvial levees along its course.

Prior to the creation of the reservoir in 1963, the riverbed was more or less confined to a central channel, 10–25 m deep and 300–600 m wide. The water levels used to vary considerably, flooding the broad flats and occasionally reaching the foot of the lower terraces. At that time, erosion affected 13% (42 km) of the land along the actual riverbanks (Poly-Géo Inc., 1990; Tanguay, 1964). Within a few decades of the commissioning of the powerhouse, erosion conditions changed and the stability of the new riverbanks became a concern, especially in inhabited areas. In 1990, a study estimated the proportion of active shoreline on the Quebec side of the reservoir to be 31% (about 100 km); many kilometers were apt to be affected by serious erosion in the short to medium term (Poly-Géo Inc., 1990).

2.2. Stabilization approach

The protection method consists of rounded granular fill material and is based on riverbanks that develop naturally in coarse glaciofluvial deposits. This material was the most appealing primarily because of its abundance in the area where the work was to be done, but also because it lends a natural quality to the riverbank.
The method allows for the use of different sizes of material depending on the erosion conditions encountered (large fetch, erosion by high flow velocity, steep embankment, etc.). The material ranges in size from sand (0.08–5 mm) to cobbles (80–300 mm) and boulders (>300 mm). Materials are screened so that at least 50% are larger than 10 cm in diameter to assure stability of the structure. Screening also had to allow a 10–20% sand fraction to support vegetation regrowth and fill the spaces between the cobbles and boulders, minimizing sediment suspension and the resulting turbidity.

Since the role of currents was greatly reduced after the reservoir was created, the optimal material size was determined according to effective wave energy on the shore rather than shear stress. The wave energy was calculated for 5 sites in the study area (Hydro-Québec, 1994; Roy, 1995), taking into account wind direction and speed, fetch, bank angle, water depth and the slope of the foreshore. Given that the slope is rarely steeper than 10% and that the water is very shallow on the foreshore, waves have lost much of their energy by the time they reach the riverbanks. That explains why the maximum material size, in most cases, is no more than 20 cm in diameter. For more severe erosion conditions or steeper slopes, the proportion of coarser material (up to 30 cm or even 45 cm in certain cases) is increased while the proportion of sand and gravel is decreased.

The protection structures consist of a flat bench, 1–3 m wide, bordered by a slope that extends several meters onto the foreshore (Fig. 3). The total width of the structure ranges from 3 to 7 m. Wider structures are allowed at the toe of the highest active banks in order to catch material that falls from the upper part of the bank, which over the medium term will reach an equilibrium slope. The structures have an initial slope of 33% (3H:1V). The elevation of the structures, generally 42.2 m, is based on the mean high-water level, plus a 30-cm freeboard to account for the effect of waves and tributary inflow. Upstream, the structures can reach an elevation of 42.8 m, but the overall height of the structure is generally never more than 1 m. Just over 90% of the structures were built using the standard fill shown in Fig. 3. For the rest of the stabilized banks, the fill consisted of larger material (up to 45 cm in diameter) and slopes were steeper. The heavier structures were installed on banks subject to more severe erosion conditions or were used to repair existing protection structures.

The construction requires very little intervention on the riverbank, and does not involve any keys, geotextile or slope reprofiling. The structures were built in winter: the ice at the site was excavated following the natural shoreline contour, the material was deposited and shaped into a specified profile. Shore ice anchored to the shallows can be used as a roadway for equipment, thus sparing riverside property by minimizing the number of times access is required. Once the work is finished, the structures built using this method are expected to evolve naturally, so that their profiles shift in the first few years.

2.3. Program scope

The program initially provided for the stabilization of just over 71 km of riverbank. In the end, the work was done on a total of 55 km, including 22 km of riverbank affected by high to medium erosion, 25 km by limited erosion and 8 km where the existing structures needed repair. During the project, the stakeholders made a joint decision to exclude about 16 km of lightly eroded

Fig. 2. Petite Presqu’ile, before stabilization (1991). Locally, erosion became threatening for roads, especially in Plaisance Wildlife Reserve.

Fig. 3. Typical section of the planned protection structures.
riverbanks because of the limited benefits anticipated compared to the extent of the work that had to be done.

Most of the work (47 km) was done during the winters of 1996, 1997 and 1998. However, some emergency work had to be done between 1992 and 1995 at sites where erosion had become too significant and threatened infrastructures (Fig. 2). In addition, a number of test banks of the protection method were built in 1992 to refine design and assess impact.

2.4. Site selection for the follow-up

A general survey of the riverbanks was done by motorboat to assess the overall condition of the shoreline and to select sampling sites in the study area (Fig. 1). Eighteen (18) sites were selected to be representative of the study area in terms of geomorphology and the various erosion conditions to which the riverbanks were subjected to (Table 1). Thirteen (13) of the sites were typical of the riverbank protected. In composition and size, the structures built at these sites correspond to more than 75% of the structures installed. Furthermore, the selected sites cover most of the biophysical conditions in the study area. None of the bank at the selected sites appears to have undergone anything but natural changes (flooding, windstorms, landslides) since the structures were installed. Two of the sites were test banks built in 1992.

Five (5) sites outside the program were also selected in order to document plant diversity on riverbanks that had not been worked on. Two of these five sites had little or very little erosion and the others were naturally stable. The current erosion conditions at these sites were therefore not representative of those in the active sections prior to stabilization. No unstabilized sites undergoing heavy or moderate erosion could be selected, as all the heavily eroded sections of riverbank were stabilized during the program.

2.5. Field surveys

To assess bank evolution, a survey was done of the structure profiles and composition, the embankments they protect and the natural banks in the vicinity of the structures at the 18 selected sites. The way local residents had adapted and used the new riverbanks was also noted. Bank and structure profiles were surveyed in accordance with the method used throughout the program (baseline conditions, preparation of plans and specifications, and record of work), using a surveying chain and a clinometer. Elevation measurements were taken using a hand level from the level of the river. The substrate composition and particle size of the protection material were assessed visually on the surface of the structures and in the sides of shallow pits made with a hand shovel.

At each of the 18 sites, vegetation was sampled along a transect perpendicular to the river. A record was made of each plant community present on the transect, from the top of the bank down to the water, including identification of the vascular species and assessment of its recovery, expressed as the Braun-Blanquet coefficient of abundance (Gouyou, 1969). The results were used to calculate absolute and relative recoveries and frequencies to determine the importance value of each species identified at the sites. Vegetation surveys were also grouped by site to compare species diversity on the stabilized and natural banks using the Simpson diversity index (D) (Legendre and Legendre, 1984; Scherrer, 1984).

3. Results

3.1. Structures (profile and stability)

The follow-up showed that the various types of structures installed during the program were stable and in good condition. Overall, the profile of the few steeply sloping structures built of very coarse material seems to have changed little in 15 years. As anticipated, the structure built on 90% of the stabilized banks had changed shape. Wave action and flooding of the structures during high water events dislodged the surficial sand, leaving a pavement of coarser material on the surface of the structure. The force of the waves reshaped the initial 3H:1V (33%) gradient to 25% reducing gradually to 10% toward the river (Fig. 4). Regardless of the size of the structure and the erosion conditions to which it was subjected (fetch, exposure, etc.), the profile systematically shows the same sequence from bank to river.
Section A corresponds to part of the structure’s original flat bench, which is relatively undisturbed. It shows a gently sloping section of variable width (depending on the initial size of the structure) where the original protection material is recognizable but whose surficial fine fraction has been slightly washed away. Section A lies above the two-year flood-event level and was therefore reached only periodically (frequency of 2% of the time over 20 years; Fig. 4). Wave action at this level only changed the slope of the flat part of the structure very slightly and failed to wash away the surficial sand fraction.

Section B is a concentration of cobbles, usually accompanied by boulders or gravel. The slope formed by these materials is fairly constant (20–25%). This area would have developed as the original material was washed away by wave action. Section B was reached regularly during high-water periods (30% of the time over 20 years; Fig. 4), mainly between November and May. In the ice-free seasons, wave attack carried away part of the sand fraction, leaving only the coarsest protection materials.

Section C forms a cobble pavement sloping 10–20% on most sites. The interstitial spaces are often filled with sand and gravel, probably from the top layer washed away by the waves. Most of the original matrix of protection material, namely medium to coarse sand, gravel and cobbles, can still be found under the coarse pavement.

Section D (usually immersed in summer) constitutes a foreshore with a gentler slope (less than 10% at most sites), composed mainly of sand and gravel or gravel with scattered cobbles. Outside of the high-water period (May–November), the waves reach only the lower part of the structures (sections C and D). These conditions occurred 70% of the time over 20 years (Fig. 4). Over the years, repeated wave action in this part of the structures washed away the surficial sand fraction, and then caused the formation of a gently-sloping pavement composed mainly of cobbles and gravel capped with sand in places.

Thus reshaped, the new profile of the structures was effective in stopping erosion by intercepting the waves and protecting the base of the banks. Part of the sand fraction that was washed away appears to have accumulated at the toe of the structures or drifted sideways into small coves that formed locally.

3.2. Riverbanks (profile and stability)

Installation of the structures did not involve any interventions on the upper part of the embankments. On high riverbanks (>5 m), slopes that were initially unstable readjusted naturally and have now reached an equilibrium state (Figs. 5a and 6). The banks that were initially affected by erosion and largely bare (four of 13 sites studied, Table 1) have evolved toward a new equilibrium slope (66%). Particles detached from the upper part of the slope (due to freeze–thaw action and/or runoff) and were then carried by gravity to the toe of the bank, covering part of the structure (section E, Fig. 5a). Although these banks appear to have reached an equilibrium state, their upper part remains bare in some places (Fig. 6b). The profile of the high banks that were already covered by vegetation prior to the project (3 of 13 sites) seems to have changed little. Only the base of such banks, once subjected to erosion, appears to have softened and is now covered by recent vegetation. The profile of the stabilized low riverbanks (<2 m high, six of 13 sites) has changed little, as they are largely protected by the structure.

3.3. Vegetation

3.3.1. Recovery and composition – structure and foreshore

By the time the Stabilization Program was completed in 1998, the effects of erosion on the banks had been substantially mitigated. Prior to the survey, vegetation had already begun colonizing the first structures built (Bérubé et al., 1996).

The 2011 follow-up showed that vegetation colonized the flat bench of the structure (sections A and B, Fig. 5a and b) soon after the stabilization work was completed. Average vegetation recovery on the test banks built in the winter of 1992 was noted to be 11% in the first year, 43% in the second year and over 50% after five years (Hydro-Québec, 1994; Bérubé, 1999, in: Poly-Géo Inc, 1999). This vegetation consisted of tree and shrub seedlings, as well as herbaceous species. In 2011, mean vegetation recovery on this same portion of the structures was estimated at 92%. This vegetation forms a shrubby riparian ecotone (Fig. 7c) consisting mainly of facultative wetland species including speckled alder (Alnus incana ssp. rugosa), red ash (Fraxinus pennsylvanica) and red-osié dogwood (Cornus sericea). Some paper birch (Betula papyrifera) is also found. Trees, however, are short and are generally part of the shrub layer.

On banks with high fetch exposure, the tall shrubs have been replaced by a riparian ecotone of low shrubs, principally composed of riverbank grape (Vitis riparia) or herbaceous plants such as common silverweed (Argentina anserina) and wild strawberry (Fragaria virginiana). On banks well sheltered from wind and waves, the riparian ecotone is edged by a narrow high marsh of reed canary grass (Phalaris arundinacea).

There is still a section devoid of vegetation in the lower part of the structure (sections C and D, Fig. 5a and b). This part of the structures, very often swept by the waves, has only very sparse vegetation cover (5% recovery). A low marsh consisting mainly of broad-fruited burreed (Sparganium eurycarpum) and hard-stemmed bulrush (Schoenoplectus acutus) sometimes occupies the lower end of the structure in areas where low marsh existed prior to the project. This marsh generally extends into the shallow water to the end of the structures or further, onto the foreshore. American eelgrass (Vallisneria americana), accompanied by pondweed (Potamogeton spp.) or tuberous white water-lily
Fig. 5. Comparative typical profiles for (a) high banks and (b) low banks.

[Diagram showing comparative profiles for high and low banks]

(Nymphaea odorata ssp. tuberosa), is always present on the fore-
shore; it starts at a water depth of around 0.4 m and extends to an
average depth of 1.6 m.

3.3.2. Recovery and composition – embankments

The embankments are generally well vegetated, with an esti-
mated mean recovery of 82% in 2011 (Fig. 6b). However, the plant
species present vary, mainly depending on the site. The banks ini-
tially vegetated are now covered by deciduous woodland. Slopes
that were completely or partially bare prior to the project are now
covered with variable herbaceous communities, tall shrubland of
staghorn sumac (Rhus hirta) or young trees and even young decid-
uous forests. It seems that plant colonization of the banks depends
mainly on the surrounding vegetation and seed sources. It could
be mosses and field horsetail (Equisetum arvense) or wild straw-
berry and heart-leaved aster (Symphoyotrichum cordifolium) that
colonize the embankment, or staghorn sumac, paper birch (Betula
papyrifera), eastern white pine (Pinus strobus) or eastern white
cedar (Thuja occidentalis) that take the opportunity to become
established.

3.3.3. Comparison to natural riverbanks (not stabilized)

In natural (unstabilized) environments, there is sometimes a
wooded swamp populated by silver maple (Acer saccharinum), or
a narrow shrubland of red-osier dogwood and willows (Salix spp.)
while red ash and speckled alder are predominant on stabilized
banks (Table 2). Nearer the water, there is a wide beach or a series of
high and low marshes of highly variable composition. High marshes
were either made of purple loosestrife (*Lythrum salicaria*), American groundnut (*Apios americana*), or reed canary grass while low marshes consisted of broad-fruited burreed, common spikerush (*Eleocharis palustris*), rice cutgrass (*Leersia ozyoides*) or pickerelweed (*Pontederia cordata*) and a bed of American eelgrass. One site with limited erosion has a high bank with a bare upper portion and a lower portion colonized by field horsetail, spreading dogbane (*Apocynum androsaemifolium*) and smooth brome (*Bromus inermis*), followed by a beach with a narrow discontinuous low marsh of blunt spikerush (*Eleocharis obtusa*) and a bed of American eelgrass.

### 3.3.4. Plant diversity and ecological value

“Stabilized bank” sites generally have a shrubby riparian ecotone consisting of speckled alder, an ecotone not present in natural settings. The 2011 survey revealed the presence of 203 taxa at the 18 sites surveyed. Some species were found exclusively on stabilized or natural banks. The group of plants unique to stabilized banks consists mainly of species that colonized the banks or those associated with the riparian ecotone created. The plants unique to natural banks tend to be species associated with wetlands. The average number of plant species is estimated to be 49 on the stabilized banks and 37 on the natural banks. However, the Simpson diversity is the same for all sites. Species diversity is estimated to be 0.992 overall for all the sites, 0.992 for stabilized sites and 0.993 for sites not stabilized. Species diversity on the stabilized sections of riverbanks is similar to that of natural banks with little or no erosion and with more developed riparian and aquatic environments.

### 4. Discussion

Very few riverbank stabilization projects of such a scale (55 km of stabilized riverbanks) have been monitored over a significant number of years. Projects with follow-up studies have experimented with several stabilization techniques (soft and hard structures) on river segments ranging from 100 m to 2–3 km at most (*Batier, 2004; Brown, 2000; FEMA, 2008*). In most cases, durability and effectiveness of structures were assessed for periods ranging from 1 to 10 years (*Batier, 2004; Niezgoda and Johnson, 2012*).

Some 15 years after their construction, the structures of rounded granular material on the Ottawa River have halted erosion, blended into the local landscape and created a riparian ecotone. The vegetation that took root naturally on the stabilized riverbanks covers 80–90% of the banks and structures and its diversity is similar to the vegetation on natural banks. *Palmer et al. (2005)* have proposed a method for measuring the success of river restoration projects. According to the authors, a successful, effective project meets the following three objectives:
Table 2

<table>
<thead>
<tr>
<th>Species (common name)</th>
<th>Stabilized riverbanks</th>
<th>Unstabilized riverbanks</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Acer saccharinum</em> (sugar maple)</td>
<td>4.90</td>
<td>54.17</td>
</tr>
<tr>
<td><em>Ailus incana</em> spp. <em>rugosa</em> (speckled alder)</td>
<td>25.73</td>
<td>0.00</td>
</tr>
<tr>
<td><em>Betula papyrifera</em> (paper birch)</td>
<td>7.76</td>
<td>12.50</td>
</tr>
<tr>
<td><em>Carya cordiformis</em> (bitternut hickory)</td>
<td>19.60</td>
<td>0.00</td>
</tr>
<tr>
<td><em>Fraxinus nigra</em> (black ash)</td>
<td>11.52</td>
<td>5.92</td>
</tr>
<tr>
<td><em>Fraxinus pennsylvanica</em> (red ash)</td>
<td>12.75</td>
<td>11.76</td>
</tr>
<tr>
<td><em>Populus alba</em> (white poplar)</td>
<td>11.04</td>
<td>11.26</td>
</tr>
<tr>
<td><em>Populus tremuloides</em> (trembling aspen)</td>
<td>11.12</td>
<td>7.84</td>
</tr>
<tr>
<td><em>Quercus rubra</em> (black willow)</td>
<td>11.12</td>
<td>8.49</td>
</tr>
<tr>
<td><em>Ulmus rubra</em> (slippery elm)</td>
<td>11.62</td>
<td>0.00</td>
</tr>
</tbody>
</table>

- *Acer saccharinum* (sugar maple)
- *Ailus incana* spp. *rugosa* (speckled alder)
- *Betula papyrifera* (paper birch)
- *Carya cordiformis* (bitternut hickory)
- *Fraxinus nigra* (black ash)
- *Fraxinus pennsylvanica* (red ash)
- *Populus alba* (white poplar)
- *Populus tremuloides* (trembling aspen)
- *Quercus rubra* (black willow)
- *Ulmus rubra* (slippery elm)

It fulfills the expectations of the proponent and local stakeholders.

It enhances river ecology.

Project information is made available for future applications.

We think the stabilization program meets Palmer’s objectives. The structures have completely halted riverbank erosion and succeeded in protecting the roads, houses and farm buildings likely to be affected by erosion. Also, the simplicity of the method and the availability of local manpower and materials helped control costs and maximize local economic benefits. The work caused minimal damage because it was done in winter, thus avoiding disturbances for wildlife and vegetation, as well as recreational users. Bank interventions were also minimal due to the construction method used, which involved access and work from the river side rather than from the top of the banks. No changes were made to bank slopes, and no clearing was done. In 2011, the granular embankments installed in natural areas were mostly covered with vegetation. Furthermore, active banks that were initially bare over several meters and littered with fallen trees had been replaced by banks largely covered in vegetation (Fig. 7). In inhabited settings, riverbank stabilization provided better access to the river for local residents compared to riprap. A riparian ecotone with plant diversity equivalent to that of the natural environment was created. Riparian ecotones are known to be habitats for birds, amphibians, reptiles and semiaquatic mammals, while grass beds and marshes provide feeding, shelter, nursery and spawning areas for fish. Some stabilized sites also contain threatened or vulnerable plants, such as butternut (*Juglans cinerea*), common hackberry (*Celtis occidentalis*), flatsedge (*Cyperus odoratus*).

The design of the method also took environmental dynamics into account. The causes of erosion in various contexts were analyzed to develop a specific response to erosion problems and avoid over-design. The most suitable particle size for the erosive forces was determined based on a specific study of the effects of waves and currents (*Roy, 1995*). The structures have not required any maintenance since their installation and they evolve naturally toward an equilibrium profile. Structure and bank stability may increase with the vegetation root system. The presence of a riparian ecotone on the structures enhances stability (*Abbe et al., 2011; Abernethy and Rutherford, 2000; Briggs et al., 2008; Evette et al., 2009; Hubble et al., 2010*). The root system holds the soil and increases its cohesion. Shrubs are probably even more effective in this regard as they produce a denser root system (*Xu et al., 2010*). Finally, project information was made available to the public. An Environmental Impact Assessment was carried out between 1992 and 1994 and two follow-up studies were done, one in 1998, just a few years after the work, and another 15–20 years after in 2011.

The Ottawa River Stabilization Program may thus be qualified as an ecologically successful project. The method used was effective to halt erosion but also provided a high environmental added value as it created a natural riparian ecotone. This approach could be used along the banks of lakes, reservoirs and large rivers where erosion is caused more by wave action than currents. It can be adapted to suit other contexts by varying certain parameters, including material size and structure gradient. In 2008, installation of granular fill was selected for a program to protect the banks of a section of the La Grande River in northern Québec (*Vinet and Levesque, 2010*). This is a high-energy setting where waves, tides and currents are the main agents of erosion. The solution selected to reduce erosion was a fill composed of granular material like that used for the Ottawa River, but placed with a sufficient total height to intercept waves during even the highest tides. These structures are only a few years old but have so far proven to be efficient.

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