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# Potential use of phreatophytes for passive management of groundwater seepage at landfill sites

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## Abstract

Land-based phytoremediation using phreatophytes (e.g., willow) is a "passive" green technology that has potential to control offsite migration of contaminants in groundwater from landfill sites. In this approach, seepage of leachate from landfill sites would be captured or reduced by phreatophyte transpiration, a form of solar pumping. The phreatophytes would uptake excess nutrients such as ammonia. A case study site is presented, an old landfill along the waterfront in Kingston Ontario, which has two main contaminants of concern: ammonia and iron. A review of relevant phytoremediation literature indicated that if achievable, hydraulic capture of contaminants by phreatophytes at landfill sites might only be effective during the growing season. To determine whether the hydraulic control approach would be feasible, uncertainties in components of the hydrologic budgets must be addressed. These uncertainties can be reduced by detailed investigation of the hydraulic properties of subsurface materials at landfills, of tree characteristics and site conditions, and collection of hydrologic data including transpiration rates by phreatophytes growing at the landfills.

# Introduction

This review provides an assessment of the potential use of land-based phytoremediation to mitigate the seepage of leachate from landfills. Phytoremediation refers to a range of emerging biotechnologies in which green plants are used to remediate contaminated soil, sediments and/or water. Many of these biotechnologies have been introduced in the last decade and are still in the stage of development and/or demonstration. Phytoremediation approaches may provide cost-effective, "green" alternatives to expensive, energy-consumptive and disruptive conventional remediation technologies.

The specific phytoremediation approach that is examined in detail in this review is the potential use of phreatophytes to mitigate the impact of landfill leachate via a process referred to as "hydraulic control." Phreatophytes are terrestrial plant species that thrive under shallow water table conditions by extending their roots to the phreatic (saturated) zone and transpiring groundwater. In the hydraulic control or hydraulic containment approach, phreatophytes are used to uptake and transpire groundwater, thus controlling the migration of contaminants in the groundwater. This has sometimes been portrayed as a "solar pumping" approach, given that solar energy drives the transpiration process.

As a case study, this report provides a consideration of the closed waterfront Belle Park Landfill in Kingston, followed by a literature review of relevant studies of phreatophyte-based phytoremediation, together with a general assessment of the applicability this approach at the Belle Park site.

## Case Study: Belle Park Landfill, Kingston, Ontario

Belle Park is a 44 ha site along the west shore of the Inner Harbour of the City of Kingston (Figure 1). From 1952 to 1974, this waterfront site was operated as the Belle Park municipal landfill. A steeply sloped, mounded waste area that was created in the northwest portion of the site is known as the ski hill area. A Federal Dredged Sediment Disposal Site was constructed along the margin of the landfill in the early 1970s (CH2M Hill Engineering Ltd. 1994). After landfill closure in 1974, this municipally owned site has been operated as a multiple use recreational facility, including a golf course, a driving range, tennis courts, cross-country skiing and walking trails.

A hydrogeological investigation by Malroz Engineering Inc. (1999) indicated that the Belle Park site is generally underlain by the following sequence of deposits, from ground surface downward: a) silty top soil and surface cover (< 1 m); b) municipal wastes mixed with soil and fill (≤ 20 m); c) peat (0.1-2 m); d) clayey silt (≥ 6 m); e) limestone bedrock. The water table generally occurs between 0.5 and 2 m below ground within the buried wastes (Malroz Engineering Inc. 1999). Modeling by Malroz Engineering Inc. (1999) suggests that more than 97 % of the water that infiltrates the site flows laterally in the wastes in a radial pattern outward toward the margins of the site and to the Inner Harbour.

The mean hydraulic conductivity of the wastes is $\sim 1.5 \cdot 10^{-2}$ cm/s, and the average rate of groundwater flow in the wastes toward the shores of the Park is 40 to 70 m/year (CH2M Hill Engineering Ltd. 1994; Malroz Engineering Inc. 1999). Lateral groundwater flow is greatest in late spring, when infiltration from snowmelt occurs, and in late autumn, after leaf-fall, when infiltration is more important and harbour water levels are relatively low (Malroz Engineering Inc. 1999). The estimated steady-state daily volume of groundwater seeping laterally from the site to the Inner Harbour is 200 to 300 $m^3$(CH2M Hill Engineering Ltd. 1994; Malroz Engineering Inc. 1999). This is equivalent to 75,000 to 110,000 $m^3$ per year. The groundwater discharge appears to be focused in four shoreline seepage areas of concern, referred to as the North Shore, South Shore, East Shore and west stream zones (Fig. 1).

The average annual precipitation at Kingston is 0.79 m (Environment Canada: Canadian Climate Normals 1971-2000). Based on the annual average groundwater discharge to the Inner Harbour at the margins of the site indicated by Malroz Engineering Inc. (1999), the annual average net infiltration (precipitation minus evapotranspiration and runoff) is 22 % of precipitation.

**Contaminants of Concern**

The groundwater that occurs within the landfill waste at this site has elevated levels of chloride, ammonia and iron, as well as detectable concentrations of some organic contaminants (CH2M Hill Engineering Ltd. 1994; Malroz Engineering Inc. 1999; Bickerton and Van Stempvoort 2005). Similar to other landfills (e.g., Clements et al. 2000), ammonia is the main contaminant of concern, because of its potential impact on the adjacent surface water. In 1997-1999, the typical concentrations of total ammonia in groundwater at Belle Park ranged between 50 to 150 mg/L, with concentrations up to 330 mg/L in the waste beneath the ski hill (Malroz Engineering Inc. 1999). Groundwater discharge produces measurable ammonia concentrations in surface water along the shoreline (Malroz Engineering Inc. 1999).

Aqueous ammonia exists as two species, ammonium ion ($NH_4^+$) and un-ionized ammonia ($NH_3$). $NH_4^+$ is relatively harmless, whereas $NH_3$ is toxic to aquatic organisms. Under near neutral pH conditions, most of the dissolved ammonia is present in the $NH_4^+$ form. Surface water monitoring along the shoreline of the Park by Malroz Engineering Inc. (1999) indicated a small minority of samples had un-ionized ammonia concentrations that exceeded the Provincial Water Quality Objective (PWQO) of 0.02 mg/L. These were samples collected in summer, when both pH and temperatures were elevated.

The groundwater has high dissolved iron concentrations, generally > 20 mg/L, up to 55 mg/L) (Frape 1979; Creasy 1981; Malroz Engineering Inc. 1999). Groundwater discharge has resulted in elevated iron concentrations in the surface water along the shore of Belle Park, sometimes exceeding the provincial water quality objective (PWQO) for iron (Malroz Engineering Inc. 1999).

Inferred trends in leachate chemistry since the 1970s for Belle Park are similar to trends observed at other landfills (Van Stempvoort and Bickerton 2005). For example, the leachates of older landfills often have high ammonia concentrations (Dedhar and Mavinic 1985; Chu et al. 1994; Clements et al. 2000). In some cases ammonia concentrations remain elevated more than 50 years after landfill closure (Chu et al. 1994).

## Current Management of Groundwater Seepage at Belle Park

Pumping wells were installed in the four areas of concern along the shorelines of Belle Park between 1997 and 1999 to manage offsite seepage of groundwater. Extracted groundwater is pumped to a municipal sanitary sewer. Prior to installation of this pump and treat system, total groundwater discharge from the four areas of concern was estimated to be 26,000 $m^3$/year (Malroz Engineering Inc. 1999). In contrast, current annual withdrawal of groundwater by pumping is ~150,000 $m^3$ (1999-2000 data). This comparison suggests that the high pumping rate is required to offset drawdown-induced increases in groundwater flow. Some of the pumped water may be inadvertently captured from the adjacent harbour, in response to drawdown. This has been addressed to some extent by adjusting pumps seasonally to match levels of the river (Malroz Engineering Inc. 2004).

Giving that the current pump and treat system is expensive, The City of Kingston is conducting feasibility studies of alternative remediation and treatment technologies. This includes a phytoremediation demonstration by Malroz Engineering Inc. that includes plantations of willow and poplar trees, and a constructed wetland component. In addition, Environment Canada (Bickerton and Van Stempvoort 2005) is conducting a study of transpiration by mature black willows (*Salix nigra*) at a location along the shoreline of the site (Fig. 1), to get a better understanding of the potential for the 'hydraulic control' phytoremediation approach.

## Potential Use of Phreatophytes for Phytoremediation of Landfill Leachate

Recent overviews of phytoremediation are available (Suthersan 1999; Pivetz 2001; van der Lelie et al. 2001; Schnoor 2002; McCutcheon and Schnoor 2003; Tsao 2003). In recent years, there have been hundreds of full scale demonstrations and applications of phytoremediation, particularly in the United States and Europe. There are now a number of firms that are dedicated specifically to phytoremediation applications (Masrmiroli and McCutcheon 2003). Phreatophytes are generally the preferred choice for phytoremediation applications in which groundwater contamination is being addressed.

In this review, two different phytoremediation approaches with phreatophytes are discussed with respect to landfill applications, with reference made to the Belle Park case study site: (1) potential use of phreatophytes for hydraulic control of the contaminated groundwater, and (2) potential use of phreatophytes for uptake of contaminants of concern from the groundwater, including the "phytoirrigation" approach.

## Potential for Hydraulic Control of Groundwater Seepage by Phreatophytes

In the hydraulic control or hydraulic containment approach, phreatophytes are used to uptake and transpire groundwater, thus controlling the migration of contaminants in aquifers. In some cases this approach is intended to offset or take the place of conventional pump and treat systems (Al-Yousfi et al. 2000; Pivetz 2001; Schnoor 2002; Sorel et al. 2002; Ferro et al. 2003). The phreatophytes are intended to perform as a solar-driven pump and treat system (Schnoor 2002). This approach is sometimes used with other remediation technologies, such as installation of barrier walls (Sorel et al. 2002; Ferro et al. 2003). Several years ago Rivetz (2001) reported that at least five U.S.

companies were actively installing phytoremediation systems that incorporated hydraulic control.

Willows, poplars, cottonwoods and other phreatophytes that have roots that extend to the water table have been considered for field applications of hydraulic control of groundwater (Schnoor 2002). The objective is that the phreatophytes will withdraw much or most of the water for their transpiration process from the saturated ("phreatic") zone. In some applications (e.g., Gatliff 1994; Al-Yousfi et al. 2000; Negri et al. 2003), phreatophyte trees are planted within casings to force the roots to develop within the phreatic zone, rather than the shallow subsurface. In the last decade, several companies in the United States have developed commercial applications of phytoremediation using the hydraulic control approach; in some cases the root systems of trees planted in wells reach as deep as 10 m below ground surface to the water table (Schnoor 2002; Negri et al. 2003).

### Hydrologic budget considerations

For each application of hydraulic control, it is important to obtain quantitative information on the transpiration of groundwater by phreatophytes. The most direct way to examine the ability of phreatophytes to transpire groundwater is to undertake a field investigation of water levels in monitoring wells in the vicinity of the phreatophytes (e.g., Rosenberry and Winter 1997; Eberts et al. 2003, Hays 2003). The diurnal fluctuations in wells can be used to infer the transient rate at which groundwater is being "pumped" by the phreatophytes.

The water level data can be compared to data collected by sap flow meters. Sap flow meters can be used to measure transpiration rates of individual trees, which can be extrapolated to larger stands (Vose et al. 2000; 2003). A comparison of these data provides a better indication of how much of the total transpiration flux is uptake of groundwater, evidenced by the drawdown of the water table, and how much is infiltrated precipitation that never reaches the saturated zone. The importance of these fluxes may vary over the growing season, related to precipitation events and periods of drought.

It has been reported that a single mature willow tree may transpire up to 19 $m^3$ of water on a hot summer day (Hinchman et al. 1998). Others have reported more moderate maximum transpiration rates: 1.6 to 1.8 $m^3$ per day per tree (Gatliff 1994, Pivetz 2001). The reported range is consistent with preliminary results of our field investigation at the case study site (Belle Park, Kingston) which indicates estimated transpiration rates ranging from 1.2 to 23 $m^3$ per day during the growing season by a mature black willow, based on sap flow metering and modeling of diurnal fluctuations in wells (Bickerton and Van Stempvoort 2005). For stands of phreatophytes, transpiration rates typically range between 1,500 and 7,500 $m^3$/ha per year, depending on the vegetation and other site conditions (Vose et al. 2003).

Numerical models used by hydrologists and hydrogeologists to determine soil, catchment or aquifer budgets generally consider evapotranspiration rather than transpiration. This is because the available hydrologic data typically cannot distinguish transpiration and evaporation components (Vose et al. 2000; Wilson et al. 2001). Evapotranspiration is the sum of transpiration plus evaporation, where evaporation includes the fraction of precipitation that has been intercepted by canopy and ground cover vegetation, plus soil surface evaporation (Vose et al. 2003). In mature stands of trees, evaporation of plant-intercepted precipitation is ~10 to 50 % of total precipitation, depending on rainfall intensity and plant surface characteristics (Vose et al. 2003). Evaporation from soil surfaces is minimal when canopy closure is complete (Vose et al. 2003).

Potential evapotranspiration is limited by solar radiation (Vose et al. 2000; Schnoor 2002), and by the humidity of the air. Actual evapotranspiration depends also on precipitation rates, species and ages of vegetation, the hydraulic properties of the subsurface and other site specific factors. Typical rates of evapotranspiration for mature stands of pheatophytes, such as willows or poplars, rooted in the groundwater table, are on the order of 4,000 to 9,000 $m^3$ per hectare per year (Schnoor 2002).

As shown in Equation 1, evapotranspiration is closely linked to other components of the hydrologic budget:

$$P = Ro + \Delta Su + \Delta Ss + ET \qquad (1)$$

where P is precipitation, Ro is the surface runoff, $\Delta Su$ and $\Delta Ss$ are the changes in water storage within the unsaturated and saturated zones respectively, and ET is evapotranspiration. For annual-average hydrologic budgets, the unsaturated storage ($\Delta Su$) term is assumed to be zero. For upland sites, the $\Delta Ss$ term indicates the rate of recharge to the saturated zone, which is precipitation less runoff and evapotranspiration. If phreatophytes are present, with roots that draw moisture from the saturated zone, then $\Delta Ss$ typically switches from a positive to a negative term, at least temporarily, between precipitation events, as transpiration releases water from storage. In such cases, diurnal cycles in the water table will be detectable, related to diurnal fluctuations in solar radiation and transpiration. In groundwater discharge areas, the annual-average value of ΔSs is a negative term, associated with net runoff and/or evapotranspiration in excess of precipitation.

In the hydraulic control approach, the goal is to use phreatophytes to maximize transpiration so that locally there net discharge of groundwater during the growing season (i.e., value of ΔSs is negative), and groundwater flow is induced toward the phreatophytes. If this occurs, for example on a daily or seasonal basis, then there is a net drawdown of the water table in the vicinity of the phreatophytes, analogous to drawdown observed during pumping from a well.

Water transpired by phreatophytes includes precipitation that infiltrates episodically, and a more steady uptake of groundwater from the saturated zone. Distinction of these two sources is not straightforward: some water taken up from the capillary/saturated zone by phreatophytes is probably infiltrated precipitation that moved quickly through the unsaturated zone to the saturated zone. To maintain a high efficiency of groundwater capture on a plantation-wide scale, the rate of transpiration by phreatophytes has to be significantly greater than the rate of infiltration of precipitation into the soil, at least during the growing season.

Recent overviews of theoretical considerations for numerical modeling in support of the hydraulic control approach have been provided (Tsao 2003; Ferro et al. 2003).

**Key advantages and disadvantages of hydraulic control approach**

One of the key advantages of the hydraulic capture approach is that the solar pumping of groundwater by phreatophytes is an inexpensive natural process, which does not require installation and maintenance of mechanical pumping systems, or the consumption of electrical power, and the potential for mechanical failure is eliminated. Another advantage is that this process can be more dispersed than the point withdrawals by pumping wells. Compared to active pumping approach, the use of phreatophytes might have less potential for localized or temporary, excessive drawdown of the water table at landfill sites, which could result in capture of some adjacent surface water (e.g. Belle Park case study), with attendant higher cost for water treatment.

A key limitation of the use of phreatophytes to capture contaminated groundwater is the seasonal nature of the transpiration process. Another disadvantage of the hydraulic control approach is that the efficiency of this process is limited by the ongoing infiltration of precipitation during the growing season, which reduces the capture and transpiration of groundwater by phreatophytes.

**Previous studies on phreatophytes for hydraulic control of groundwater**

Relatively well documented field demonstrations in the United States are ongoing at sites near Fort Worth, Texas (Eberts et al. 2000, 2003), Houston, Texas (Hong et al. 2001), Ogden, Utah (Ferro et al. 2001), San Francisco, California (Sorel et al. 2002), the Aberdeen Proving Grounds, Maryland (Schneider et al. 2002; Hirsh et al. 2003), and the Argonne National Laboratory near Chicago, Illinois (Quinn et al. 2001; Negri et al. 2003).

Some consider the potential for successful hydraulic containment to be enhanced at arid sites, given that P is low, and ET is enhanced under low humidity conditions (per

Equation 1). The Texas demonstration sites are relatively arid. However, it was not feasible to fully contain contaminated groundwater at the Fort Worth site (i.e., reduce the offsite migration/seepage of groundwater to negligible levels), because the drawdown induced by solar pumping resulted in an increased hydraulic gradient, and a corresponding increase in the velocity of the groundwater (Eberts et al., 2003). Modeling suggests that future transpiration rates will likely result in maximum capture of 30 % of contaminated groundwater.

Hong et al. (2001) reported preliminary results for a demonstration of hydraulic containment of a MTBE plume in a shallow confined aquifer in Houston, Texas. Their modeling indicated that the plume could be contained by deep-rooted phreatophyte plantation (hybrid poplars).

Sorel et al. (2002) are investigating hydraulic control of an arsenic plume in a shallow silty-sand aquifer at an industrial site near San Francisco, California. Over 600 trees were planted in 1997-98, and a bentonite slurry wall was installed.

Ferro et al. (2001) reported the results of a phytoremediation study in Utah, in which a plantation of poplars was rooted in a hydrocarbon-contaminated shallow aquifer. Although a substantial amount of groundwater was transpired in 1999, equivalent to a 10 ft. thickness of the saturated zone, there was no evident depression of the water table.

The hydraulic control approach has been applied at some temperate climate sites. For example, Schneider, Hirsh and coworkers (Schneider et al. 2002; Hirsch et al. 2003) reported the seasonal capture (partial) of TCE-contaminated groundwater at a coastal site at the Aberdeen Proving Ground, Maryland, USA. The plume is in a slowly permeable surficial aquifer, seeping toward an adjacent marsh. Due to initial success with 170 hybrid poplar trees, 600 more trees were planted in the fall of 2001.

Quinn et al. (2001) and Negri et al. (2003) reported an ongoing demonstration at the Argonne National Laboratory near Chicago, Illinois, where a confined aquifer is contaminated by volatile organic compounds and tritium. 450 poplars were planted in large diameter boreholes drilled through 10 m of drift, with aeration tubes to enhance the growth. Predictive modeling (Quinn et al., 2001) indicated strong seasonal drawdown, and a large degree of hydraulic containment.

Negri et al. (2003) reported an ongoing full scale demonstration of hydraulic control at a coastal landfill on Staten Island, New York. Analogous to the Belle Park case study, the objective is to control migration of the leachate, which is laden with ammonia and heavy metals and has impacted two shallow aquifers. Following the plantation of over 500 trees in 1998, strong diurnal fluctuations in the monitoring wells suggested that hydraulic control may be a useful strategy.

For most if not all applications of hydraulic containment, the plantations of phreatophytes have not yet reached maturity. Accordingly, the evaluations of performance are still in progress. In such cases, hydrologic modeling can be used to infer future trends in water balance (e.g., Rog and Isebrands 2000; Hong et al. 2001; Sorel et al. 2002; Quinn 2002; Eberts et al. 2003; Hirsh et al. 2003). Some of the predictions have been optimistic. For example, in predictive modeling of hydraulic containment for a landfill site in Wisconsin, Rog and Isebrands (2000) inferred that evapotranspiration rates by phreatophytes may exceed annual recharge rates by 10 to 40 times, and that the pheatophytes would cause aquifer drawdown during growing seasons, resulting in residual ground water capture during "leaf off" periods.

In his recent review, Schnoor (2002) observed that the concept that "deep-rooted trees can create a cone of depression and totally capture a plume is still not proven in the field." Schnoor cited the recent field demonstrations at Forth Worth and at the Argonne National Laboratory, where total captures of contaminant plumes were not achieved. On a more positive note, Schnoor pointed out that pump and treat systems were also employed at these locations, which had increased the hydraulic gradients and made plume capture by the trees more difficult. Schnoor observed that some applications for uptake and capture of plumes containing chlorinated solvents have been "quite successful," citing the Forth Worth and Houston studies.

**Potential for hydraulic control at the Belle Park case study site**

If the hydraulic control approach was efficient during the growing season at Belle Park, then it could potentially offset the current conventional pump and treat approach for 4 to 5 months each year. The growing season may be the most critical time to intercept ammonia-laden seepage. During monitoring, the concentrations of un-ionized ammonia in surface water along the shoreline of the site exceeded the PWQO in summer events only (Malroz Engineering Inc., 1999). However, the rate of groundwater discharge along the shorelines is greatest during spring snow melt, and in autumn after leaf-fall (Malroz Engineering Inc. 1999). At these times, transpiration by phreatophytes is negligible.

The average total precipitation during the growing season at Kingston (May through September) is 0.4 m ((Environment Canada: Canadian Climate Normals 1971-2000).

Approximately 0.05 to 0.2 m of this growing season precipitation would be intercepted and evaporated on the surfaces of vegetation or at the soil surface (Vose et al. 2003). A conservative assumption that runoff in phreatophyte plantations at the Park would be negligible during the growing season indicates an average infiltration of 0.2 to 0.35 m would occur during this season. Based on field studies conducted elsewhere, plantations of phreatophytes that are functioning well typically have transpiration rates up to 0.75 m (7,500 $m^3$/ha) through the growing season. Under optimal conditions, we might expect mature phreatophyte plantations at Belle Park to transpire 5,000 to 7,500 $m^3$ of water per hectare each growing season. Under typical climate conditions for the site, this would result in net solar pumping of 1,500 to 5,500 $m^3$ groundwater per ha from the saturated zone each growing season (in excess of infiltration).

Based on Malroz Engineering Inc. (1999), prior to installation of the active pump and treat system, the total volume of groundwater seepage from the Park to the Inner Harbour during each growing season was 30,000 to 40,000 $m^3$. It would take 6 to 25 hectares of willow trees or other phreatyophytes planted near or along the shoreline margins to transpire the same volume of groundwater, assuming the above range in potential rates of solar pumping of groundwater by phreatophytes at Belle Park (1,500 to 5,500 $m^3$/ha each growing season). Setting aside localized changes in groundwater flow in response to solar pumping (e.g., Eberts et al. 2003), the above calculations suggest that 6 to 25 hectares of phreatophytes would intercept much of the groundwater seepage from the Park to the harbour during the growing season. This simple calculation suggests that a large portion (approx. 10 to 60 %) of the Park would have to be planted with phreatophytes in order to intercept a substantial amount of the total groundwater seepage to the harbour during the growing season.

Dedicating up to 60 % of the area of Belle Park to phreatophyte plantations is likely not a feasible option given the current recreational land use of the Park by the City of Kingston (e.g., golf course). However, similar to the current pump and treat approach, solar pumping by phreatophytes could perhaps be used to curtail seepage in the four areas of concern. Elsewhere the groundwater seepage is inferred to leave the site as diffuse discharge to the nearshore harbour sediments (Malroz Engineering Inc. 1999).

Malroz Engineering Inc. (1999) estimated that, before their installation of the mechanical pump and treat system, the total groundwater discharge from the four seepage areas of concern was ~71 $m^3$ per day, which is ~11,000 $m^3$ during the growing season. Assuming that this seepage could be minimized by solar pumping of groundwater by phreatophytes of the same magnitude (10,000 – 20,000 $m^3$) and that this solar pumping could be maintained at between 1,500 to 5,500 $m^3$/ha each growing season (see above), then 2 to 20 hectares of phreatophytes could potentially take the place of the mechanical pump and treat process during the growing season.

At this stage, it is unknown whether seasonal capture of groundwater seepage along the margins of the Belle Park site is possible, analogous to the capture obtained at a coastal site in Maryland by Hirsh et al. (2003), or whether plantations of phreatophytes would intercept/contain less than half of the seasonal flux of contaminated groundwater, analogous to the findings at Fort Worth, Texas (Eberts et al. 2003) and Ogden, Utah (Ferro et al. 2001). Causes for differences in capture success at various demonstration sites are unknown, but may be primarily related to differences in the hydraulic properties of the geologic or fill materials within the saturated zones.

Annual changes in the hydraulic gradient along the shorelines of the park affect the amount of groundwater seepage. The water level of the Inner Harbour fluctuates in response to the regulated rise and fall of the level of Lake Ontario (Malroz Engineering Inc. 1999). Consequently, there appears to be an annual reversal of flow, with temporary influx of water from the Inner Harbour to the saturated wastes in the subsurface along the shorelines of the park. This apparently occurs in spring/early summer when Harbour water levels are highest (e.g., Malroz Engineering Inc. 2004).

As an alternative or supplement to shoreline placements, phreatophyte plantations could perhaps be placed in interior locations at Belle Park. Based on the schematic cross sections provided by Malroz Engineering Inc. (1999), the water table at interior locations within the Park is typically less than 2 m below ground. If transpiration by phreatophytes in interior areas resulted in a significant reduction in net recharge (the $\Delta Ss$ flux of Equation 1) compared to current conditions, this would potentially decrease the hydraulic gradients across the site, resulting in a reduced rate of lateral seepage of groundwater toward the Inner Harbour.

There are large uncertainties in the hydrologic budget for Belle Park, both for current conditions and for conditions modified by the plantation of phreatophytes. For current conditions, the key uncertainties appear to be the rate of net infiltration (in excess of evaporation and runoff) in both nearshore and interior areas, and the seepage flux of groundwater to the harbour along various portions of the shoreline, including the areas of concern. Another key uncertainty is the transpiration rate achievable by plantations of willow or other phreatophytes.

Uncertainty ranges in the estimated solar pumping rates provided in this preliminary evaluation are large, resulting in an order of magnitude uncertainty in the size of plantations required for hydraulic control. Subject to field testing, this review suggests that solar pumping by several hectares of phreatophytes might drastically reduce requirements for active mechanical pumping of groundwater during the growing season. This would potentially result in a substantial cost-saving to the City of Kingston.

**Potential Uptake of Ammonia by Phreatophytes (Phytoextraction)**

In addition to their potential use to control or capture contaminant plumes, phreatophytes can uptake dissolved contaminant species, thus reducing their concentrations in groundwater. For example, uptake of nitrate by riparian vegetation is well documented (Corell, 1997). According to Pivetz (2001), the uptake of excessive nutrients from groundwater is one of the most promising applications of phytoremediation.

Contaminant uptake (phytoextraction) by phreatophytes can be designed as a "passive" technology: relying on the plants themselves to uptake the contaminants from soil or groundwater via their root systems. Alternatively, "active" approaches are sometimes used to facilitate the uptake of contaminants by terrestrial plants. For example, in an approach referred to as "phytoirrigation or "pump and tree" (Jordahl et al.

2003), contaminated groundwater or wastewater is pumped mechanically and applied by irrigation to plots of phreatophytes, such as poplars or willow.

This section considers the evidence that phreatophytes have potential to uptake ammonia, which is often a contaminant of concern at landfills (e.g., Belle Park case study). In contrast, the literature does not indicate a strong potential for plants to effectively remove iron from landfill leachate (Van Stempvoort and Bickerton, 2005).

Ammonium is readily taken up by trees and other plants as a nutrient. Under some laboratory conditions, various tree species may uptake ammonium more readily than nitrate for their source of N (Desrochers et al. 2003). There is considerable information on uptake rates of N by plants, including natural forest ecosystems, managed forests and agricultural crops. Relatively high uptake rates of N as biomass have been reported: for example, between 200 and 300 kg/ha per year by 17 year old plantations of pine in Louisiana (Dicus and Dean 2002), and similar rates by crops in Europe (Bumb and Baanante 1996). Typical rates of N uptake by natural forests are apparently between 10 to 100 kg/ha per year (e.g., Schlesinger 1991; Beier et al. 2001).

There are some reports of passive use of phreatophytes to extract ammonia and/or other nutrients from groundwater. For example, a study in New Jersey (Gatliff 1994; Nyer and Gatliff 1996) indicated uptake of both nitrate and ammonia by poplars, with an estimated annual removal of N from the groundwater equivalent to 45 to 90 kg/ha, and inferred a potential of more than 300 kg/ha per year as the phreatophytes matured. These authors reported a shrinkage of the ammonia plume in the groundwater. Other applications of passive phytoremediation to uptake excessive concentrations of ammonia in soil and/or groundwater have been implemented (e.g., Schnoor 1997; Suthersan 1999;

TreeTec Environmental Corp. 2000), but apparently there are few cases for which details have been published. Some phytoremediation studies have emphasized N uptake rather than ammonia/ammonium uptake specifically (e.g., European Commission 2003).

It appears that the most common approach for nutrient uptake by terrestrial plants is the method referred to as "phytoirrigation or "pump and tree" (Jordahl et al. 2003). There are quite a few applications of phytoirrigation at landfills, where nutrient-laden leachate (largely ammonia) is often applied to plantations of willow or hybrid poplars. Jordahl et al. (2003) have provided a useful overview of this approach, citing, for example, application of phytoirrigation at the Riverbend Landfill near McMinnville, Oregon since 1992. Similar to the Belle Park case study, the primary contaminant in the Riverbend landfill leachate is ammonia (approx. 100 mg/L as N). At Riverbend, a lagoon is used to store landfill leachate pumped from the subsurface. The leachate is applied via irrigation to a 6.9 ha plot of hybrid poplars. Between 1994 and 1999 the irrigation rate ranged between 0.42 and 0.81 m per year, and total N applied was 273 to 522 kg/ha per year. By 1995 the concentration of N in soil water below the effective root zone was reduced to less than 10 mg/L, the US drinking water standard. Thus the fraction of irrigated water that passes through the rooting zone is not considered to be a concern. In this way the nutrient contaminant is largely removed by the trees, rather than relying on hydraulic containment of the contaminated groundwater.

Aronsson and Perttu (2001) reviewed studies on use of short-rotation willow "vegetation filters" to treat landfill leachate and other contaminated waters, with a focus on work in Sweden. According to these authors there are more than 30 facilities in Sweden that use willow vegetative filters for treatment of landfill leachate. In the typical applications, the willow are grown as short rotation coppice, irrigated with landfill leachate using drip or sprinkler systems, and harvested every few years. Generally the leachate is stored in constructed ponds during the no-growth winter season. The willow plantations uptake excess N including ammonium, and decrease the net discharge of leachate from the landfills to the adjacent subsurface. Once the willow plantations are established, typical biomass plus soil retention of the N is on the order of 100 to 200 kg/ha per year, with "substantial" additional losses as $N_2$ due to denitrification (Aronsson and Perttu 2001).

A recent report on short-rotation willow plantations at field sites in Sweden, France, Northern Ireland and Greece (European Commission 2003) found moderate rates of uptake of N to willow stems (18-73 kg/ha per year). In spite of the fact that N loading sometimes exceeded rates of N uptake by plants, the impact of excess N on the underlying soil and groundwater was generally small, suggesting that denitrification and volatilization as $N_2$ or $N_2O$ and $NH_3$ were important processes.

Compared to passive techniques, a disadvantage of the "phytoirrigation" approaches is that costly active pumping has to be maintained. According to a review by Suthersan (1999), extremely high levels of ammonia are toxic to poplars, though no details were provided. Based on the successful results of applications such as the Riverbend Landfill in Oregon (total N in leachate approx 100 mg/L: Jordahl et al. 2003), toxicity of ammonia for phreatophytes is probably not a problem at most landfills.

A preliminary estimate of the potential uptake of ammonia by phreatophyte tree species at landfill sites is suggested by combining typical annual phreatophyte evapotranspiration rates (4,000 to 9,000 $m^3$/ha: Schnoor 2002), and annual rates of N uptake (up to 200 to 300 kg/ha N). If such N uptake rates could be maintained by phreatophytes under typical evapotranspiration conditions, this would be equivalent to an uptake of 0.02 to 0.03 kg of ammonia per each $m^3$ of water transpired, or 20 to 30 mg/L ammonia in the water that is transpired. This range (20 to 30 mg/L) might be considered an approximate target range for the potential quantitative uptake of ammonia by phreatophytes at landfill sites, with conversion of ammonia-N to biomass N.

Although the concentrations of ammonia in the groundwater at some landfill sites exceeds the above 20-30 mg/L range (e.g., typically 50 to 100 mg/L at the Belle Park Case Study site), any excess ammonia that would be taken up by the phreatophytes and not incorporated as biomass-N would apparently be excreted by leaves during transpiration. Such excreted ammonia would likely be either volatilized or converted to nitrate under aerobic conditions (surfaces of leaves or stems, soil) and leached back to the groundwater environment as nitrate. Given the reducing conditions in the subsurface at many landfills, this would likely result in subsequent denitrification and release of N to the atmosphere as $N_2$ and $N_2O$.

## Other Remediation Options for Landfill Leachate

The phreatophyte-based phytoremediation approaches that are discussed in this review comprise one range of options within the context of a larger array of remediation options that could be considered for application at landfills. Van Stempvoort and Bickerton (2005) have provided a brief outline of other remediation approaches, together with references and information on some of their advantages and disadvantages. For example, other non-conventional remediation options that could be considered include alternative phytoremediation approaches, such as the use of an evapotranspiration landfill cap, or constructed wetlands. Examples of in-situ bioremediation approaches that could be considered include various bioreactor technologies that incorporate leachate recirculation: anaerobic or aerobic, sometimes with a nitrification step. Another in-situ approach would be the use of biosparging.

Van Stempvoort and Bickerton (2005) concluded that the use of phreatophyte tree species to control groundwater and contaminant fluxes at landfill sites would potentially be relatively passive and less expensive compared to most of the other remediation approaches. However, they also pointed out that phreatophyte-based phytoremediation might not function as a stand-alone remediation approach for a given landfill. Accordingly, it may prove useful to consider using phreatophyte-based phytoremediation in combination with one or more other remediation technologies.

## Conclusions

Conventional remediation technologies to address the offsite migration of leachate from landfill sites include the pump and treat approach. Alternative remediation approaches that are emerging over the past decade may be more effective and offer some cost savings, if used in combination with conventional approaches.

This review indicates there is some potential that a "passive" technology, land-based phytoremediation using phreatophytes (e.g., willow) could be used effectively at landfill sites, such as the Belle Park Landfill in Kingston, Ontario. In this approach the seepage of contaminants such as ammonia and iron in groundwater would be captured or reduced by phreatophyte transpiration, a form of solar pumping. Uptake of the nutrients including ammonia (as biomass-N) is also anticipated. If achievable, hydraulic capture by phreatophytes would potentially be only effective during the growing season. Uncertainties in the hydrologic budget at landfills can be reduced by detailed investigation of the hydraulic properties of the subsurface, tree characteristics and site conditions, and collection of data on transpiration rates by mature phreatophytes growing at the site. Other alternative remediation approaches could potentially be used in combination with phreatophyte-based phytoremediation at landfill sites.

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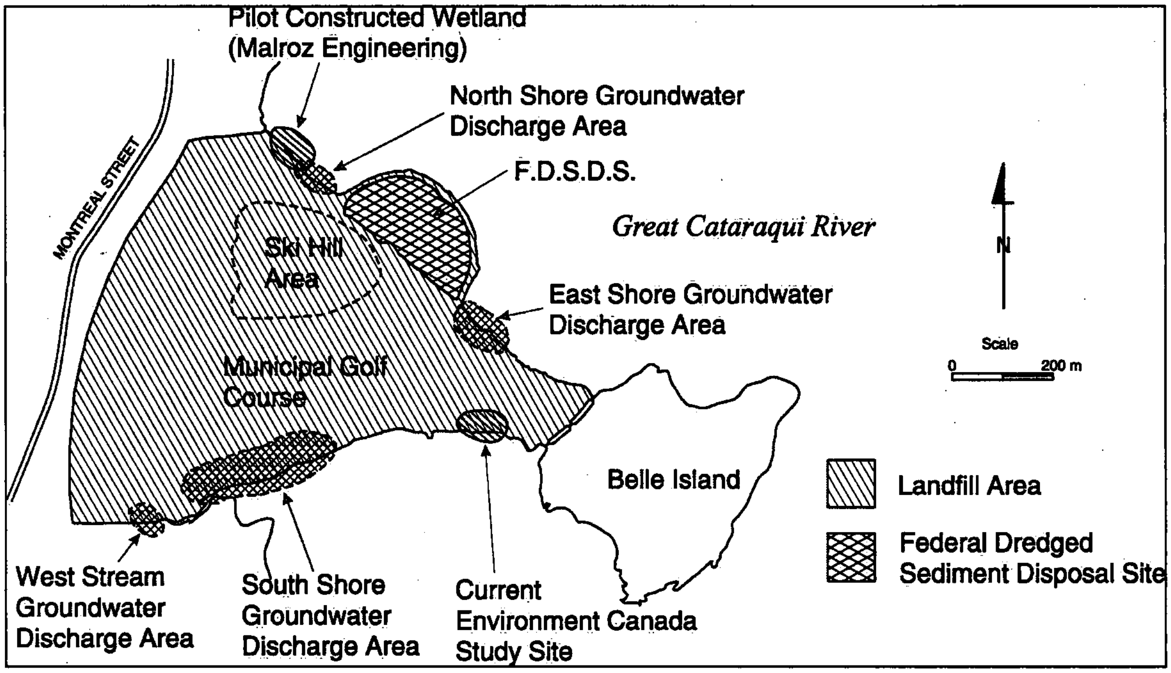


Figure 1. Plan view of the Belle Park site. The central land area was created as a landfill of a wetland area between Belle Island and the west shore of the Inner Harbour, at the mouth of the Great Cataraqui River. See text for further information on the subareas identified.

# Potential use of phreatophytes for passive management of groundwater seepage at landfill sites

Dale Van Stempvoort and Greg Bickerton

**Abstract**

Land-based phytoremediation using phreatophytes (e.g., willow) is a "passive" green technology that has potential to control offsite migration of contaminants in groundwater from landfill sites. In this approach, seepage of leachate from landfill sites would be captured or reduced by phreatophyte transpiration, a form of solar pumping. The phreatophytes would uptake excess nutrients such as ammonia. A case study site is presented, an old landfill along the waterfront in Kingston Ontario, which has two main contaminants of concern: ammonia and iron. A review of relevant phytoremediation literature indicated that if achievable, hydraulic capture of contaminants by phreatophytes at landfill sites might only be effective during the growing season. To determine whether the hydraulic control approach would be feasible, uncertainties in components of the hydrologic budgets must be addressed. These uncertainties can be reduced by detailed investigation of the hydraulic properties of subsurface materials at landfills, of tree characteristics and site conditions, and collection of hydrologic data including transpiration rates by phreatophytes growing at the landfills. Other non-conventional bioremediation approaches that could be investigated for control of leachate seepage at landfills include "phytoirrigation", evapotranspiration covers, various constructed wetland strategies, and in-situ bioreactors (anaerobic or aerobic).

# NWRI RESEARCH SUMMARY

## Plain language title

Review on use of willow trees and similar plants to intercept leachate at urban landfills

## What is the problem and what do scientists already know about it?

Many older landfills in Canada are located immediately adjacent to surface water bodies. Seepage of leachate from these landfills may contaminate the surface water and affect fish and other aquatic life. For example, leachate in the closed Belle Park landfill site along the waterfront at Kingston Ontario has high ammonia concentrations. Current approaches to prevent offsite migration of the leachate are expensive, so alternative methods are being considered. One of these alternatives is "phytoremediation": for example, planting of willow trees along the shoreline to remove the leachate by "solar pumping". This proposed method takes advantage of the fact that willow consume a lot of water during the growing season during transpiration, and also incorporate ammonia as a nutrient.

## Why did NWRI do this study?

Scientists at NWRI were interested in investigating the potential to apply this relatively new "passive", "green", biotechnology at urban sites in Canada. There was a need to study the technology under Canadian conditions, given that other similar phytoremediaton studies have generally been conducted at warmer and/or drier sites (e.g., United States).

## What were the results?

The review indicates that willow trees are effective solar pumps that can potentially be used to mitigate seepage of landfill leachate.

## How will these results be used?

Taking advantage of the positive results may lead to cost-savings at landfill sites. The results of this review are being applied to a field investigation of phytoremediation potential at Kingston, Ontario.

## Who were our main partners in the study?

Environmental Technology Advancement Directorate – Biotechnology of Environment Canada (Gatineau, Quebec); City of Kingston

**Utilisation potentielle des phréatophytes dans la gestion passive des eaux d'infiltration souterraines à des sites d'enfouissement**

Dale Van Stempvoort et Greg Bickerton

## Résumé

La phytorestauration par les phréatophytes (des saules, par exemple) est une technologie « passive » verte qui pourrait permettre d'intercepter et d'éliminer les contaminants en provenance des sites d'enfouissement, qui risquent de migrer dans les eaux souterraines. Grâce à cette méthode, les eaux de lixiviation des sites d'enfouissement seraient interceptées ou réduites par la transpiration des phréatophytes, une forme de pompage solaire. Les phréatophytes absorberaient également les nutriments excédentaires comme l'ammoniac. Un site d'étude de cas est présenté. Il s'agit d'un ancien site d'enfouissement en bordure du secteur riverain de Kingston, en Ontario, dont les eaux de lixiviation renferment deux principaux contaminants préoccupants : l'ammoniac et le fer. Une analyse documentaire pertinente sur la phytorestauration indique que, s'il s'avère réalisable, le captage hydraulique des contaminants par les phréatophytes des sites d'enfouissement ne serait efficace que pendant la saison de croissance. Pour déterminer la faisabilité du captage hydraulique, les incertitudes des bilans hydrologiques doivent être examinées. Il est possible d'atténuer ces incertitudes en procédant à une analyse plus exhaustive des propriétés hydrauliques du sous-sol des sites d'enfouissement, des caractéristiques des arbres et de l'état des sites, et en recueillant des données hydrographiques, notamment les taux de transpiration des phréatophytes qui poussent sur les sites. Il existe d'autres méthodes novatrices de biorestauration qui pourraient être envisagées pour assurer l'interception des contaminants contenus dans les eaux de lixiviation en provenance des sites d'enfouissement, par exemple, la « phytoirrigation », l'exploitation de l'évapotranspiration par l'aménagement de couverts végétaux, la construction de milieux humides et le recours à des bioréacteurs in situ (anaérobies ou aérobies).

# Sommaire des recherches de l'INRE

## Titre en langage clair

Étude sur l'utilisation des saules et autres végétaux similaires pour intercepter les eaux de lixiviation dans les sites d'enfouissement urbains.

## Quel est le problème et que savent les chercheurs à ce sujet?

De nombreux sites d'enfouissement aménagés il y a de nombreuses années jouxtent des plans d'eau de surface au Canada. Le lixiviat qui migre de ces sites peut contaminer les eaux de surface et nuire aux poissons et autres formes de vie aquatique. Par exemple, le lixiviat de l'ancien site d'enfouissement du parc Belle, situé le long du secteur riverain de Kingston, en Ontario, contient des concentrations élevées d'ammoniac. Les méthodes actuelles utilisées pour prévenir la migration du lixiviat en dehors du site étant coûteuses, d'autres méthodes sont à l'étude, notamment la « phytorestauration » qui consiste, par exemple, à planter des saules le long de la rive afin d'éliminer le lixiviat par « pompage solaire ». Cette méthode tirerait parti du fait que les saules consomment beaucoup d'eau durant la saison de croissance (via la transpiration) et absorbent l'ammoniac sous forme d'élément nutritif.

## Pourquoi l'INRE a-t-il effectué cette étude?

Les chercheurs de l'INRE désiraient évaluer le potentiel de cette biotechnologie « passive » « verte » et assez nouvelle dans des sites urbains au Canada. Il est nécessaire de mettre à l'essai cette technologie dans des conditions canadiennes, car les autres études portant sur la phytorestauration ont généralement été menées dans des sites plus secs ou plus chauds (p. ex. aux États-Unis).

## Quels sont les résultats?

L'étude montre que les saules constituent d'excellentes pompes solaires qui pourraient être utilisées pour atténuer la migration du lixiviat en provenance d'un site d'enfouissement.

## Comment ces résultats seront-ils utilisés?

Si les résultats sont positifs, des économies pourraient être réalisées dans les sites d'enfouissement. Les résultats de cette étude sont utilisés pour appuyer les recherches en cours sur les possibilités de phytorestauration, à Kingston, en Ontario.

## Quels étaient nos principaux partenaires dans cette étude?

Direction générale de l'avancement des technologies environnementales – Biotechnologie d'Environnement Canada (Gatineau, Québec); Ville de Kingston.

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