Hydrologic Management of Contaminated Sites Using Vegetation

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INTRODUCTION

Near-constant growth of the world economy has been accompanied by a corresponding increase in contaminated sites and degraded lands. In North America and Western Europe alone, there are over 300,000 and 400,000 contaminated sites, respectively.[1] The range of contaminants polluting these sites is broad and consists of both organic and inorganic compounds, many of which are mobile within the soil profile and thus pose a threat to underlying groundwater and to surrounding environments. The negative effects these sites have on agricultural production and human health results in lowered economic growth and reduced quality of life. Mitigation of these negative effects is therefore imperative.

Traditional cap-and-contain technology may be used at sites leaching contaminants to ground or surface waters; however, such caps are generally costly to install and may not retain their integrity long-term. Moreover, sealing the site in this manner does not result in contaminant degradation; thus, the initial problem may reappear if the cap degrades.

In some instances a vegetative cap may offer a sound alternative to traditional caps while allowing work toward future remediation of the site via phytostimulation and/or phytoextraction.[2] Here, we investigate the principles behind the hydrologic sealing of contaminated sites and discuss the application of vegetative caps. A case study is presented that outlines the establishment of a vegetation cap on a disused sawdust pile contaminated with boron, arsenic, copper, chromium, and pentachlorophenol (PCP).

PLANTS AS BIOPUMPS

Roots have been described as ''the big movers of water and chemicals in soil.''[3] Indeed, of the global average of 720 mm of rainfall per annum, some 410 mm are transpired from the earth surface by plants.[3] Plants require water for growth and regulation. Upward of 95% of water taken up by plants is returned to the atmosphere via evapotranspiration. This both cools the plant and translocates many essential, and nonessential, elements to the aboveground portions.

Solar radiation is the primary driver of plant growth and water use, and climatic conditions set an upper limit on evapotranspiration. Biological variables determine the actual evapotranspiration of various vegetation types, which may be much less than the theoretical upper limit. In many climates, annual evapotranspiration is much greater from fast-growing deep-rooted trees than from shallow rooted herbs or grasses.[4] During periods of drought, deep-rooted species have greater access to water and continue to transpire long after shallow-rooted species have gone dormant. Tree canopies act as umbrellas where at least 15% of rainfall may be evaporated before it reaches the ground.[5] Some species have sunken stomata, and hairy or waxy leaves that can greatly reduce actual transpiration.[6] By closing stomata, many plants conserve water in conditions that would otherwise result in excessive water loss. Some species such as kiwifruit sometimes transpire at night.[7] Evapotranspiration is dependent on the developmental stage of the plants, primarily through the development or senescence in leaf area or leaf function.

These biological parameters should be carefully considered when choosing a vegetative cap for landfills. Species should be chosen that tolerate the range of local climatic and edaphic conditions. Shallow-rooted turf species do control surface erosion and dust from a contaminated site; however, turf does not give the same level of water removal from deep within the profile as tree species may. The shallow-rooted nature of many turf species means contaminant leaching is generally greater under a grass cover when compared to trees.[4]

Vegetative caps using several species or varieties overcome the risk of all plants being destroyed by pests or environmental conditions. If the substrate to be vegetated is not soil, trials may be needed to determine the optimal species for the vegetative cap. Fig. 1 demonstrates the effect of genetic differences among poplar clones grown on a contaminated sawdust pile.

Low-growing species may be combined with deciduous tree species to provide a transpiring green surface

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Fig. 1 Variation in growth of poplar clones growing on a contaminated sawdust pile. *(Go to www.dekker.com to view this figure in color.)*

during the winter months. Legumes can be used to fix nitrogen in low-fertility substrates such as mine tailings or sawdust piles (Fig. 2).

Before planting, contaminated sites may be capped with soil to provide a fertile substrate for plant growth and a buffer zone that captures and stores rainfall. Although more expensive, such ''sponge and pump'' systems reduce leaching by providing the vegetation with a longer period to transpire infiltrated water. This is due to the retention of water within the soil buffer zone and subsequent uptake by the plants. The soil cap thickness may be critical to the success of the vegetative cap, and must be balanced with the costs of earthmoving.

Modeling the performance of the vegetative cap can provide information on project viability and optimal site management, such as the thickness (if any) of the soil cap, species selection, fertilization, and required irrigation.

Plant water use can be calculated using a modified Penman–Monteith equation[8] that integrates environmental factors, including net solar radiation, ambient air temperature, and vapor pressure deficit between air and plant leaves, and that includes stomatal conductance and tree leaf area data. Whole-system models can calculate water and contaminant movement in the substrate–plant–atmosphere continuum and may predict the vegetative caps performance for mitigating environmental effects.

Vegetative caps are porous and leaching may occur in some climates. In systems where rainfall is greater than evapotranspiration, leaching can be managed by trapping the leachate leaving the site and circulating it back onto the vegetation.[9] In effect this can be done ad infinitum and with each pass through the root zone the leachate is further modified and more contaminants removed. An increase in the level of solutes including sodium and chloride within the leachate may be of concern if leachate is to be reapplied to the site. However, depending on the composition of the leachate, it may have beneficial effects on plant growth when compared to unirrigated vegetation.[9] If leachate is applied via overhead sprinklers, there may be a negative effect on plant foliage and growth; thus, application directly onto the substrate surface is recommended.[9]

Where rainfall is greater than evapotranspiration, there is no possibility of eliminating drainage. However, vegetative caps may be used to eliminate drainage during low-rainfall periods. Depending on the contaminants in the drainage, the small volumes leached during wet periods may be diluted in receiving waters to the point so that they do not pose an environmental risk.

Limitations of Vegetative Caps

Vegetative caps will not always provide a suitable solution for contaminated sites. Contaminant toxicity or extreme environmental conditions may prevent plant establishment and effective seal development. In high-rainfall

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Fig. 2 Clover planted between establishing poplars on a sawdust pile. *(Go to www.dekker.com to view this figure in color.)*

regions, plant transpiration will not be able to keep pace with drainage from the site, thus rendering the vegetative cap ineffective. If an instant solution is sought then a vegetative cap may not be appropriate. The time to establish a sound vegetative cap is dependent on the species of plant selected, but in general it will take 2–4 years with perennial tree species. Common choices include *Populus* sp., including cottonwood, and the *Salix* sp. These tree species are chosen because of their rapid establishment, high water-use characteristics, high tolerance of environmental and contaminant extremes, ease of establishment, and ability to take up some contaminants.[10] Drying the soil profile may create an aerobic environment where metal mobility is reduced.[2] Biological activity is enhanced under vegetation, which stimulates the decomposition of some organic compounds.[11]

Application

Long-term management of closed landfills has posed problems in the past. Generally, a clay cap is installed and turf is established. Because of the settling of waste under the cap with time, clay caps can lose integrity as they age. The establishment of a deep-rooted species on closed landfills can control leachate migration from the site and

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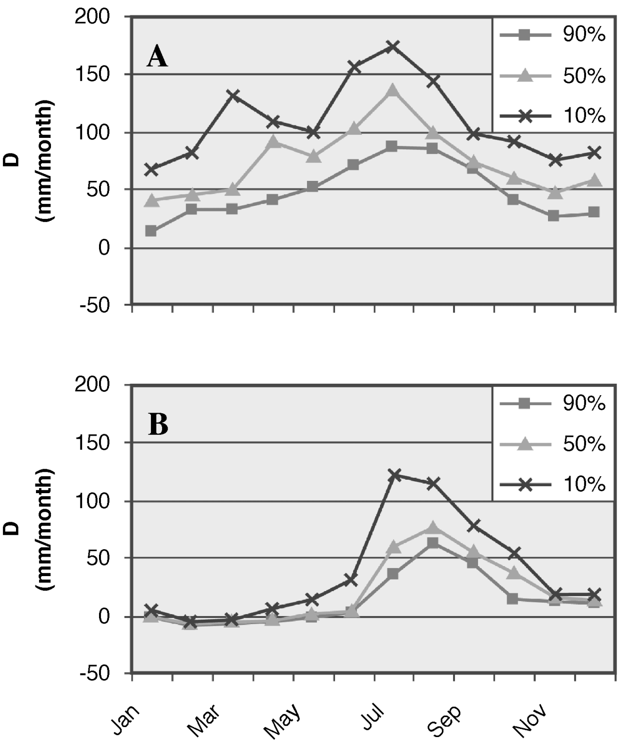

Fig. 3 Drainage probability modeled using SPASMO of bare Kopu sawdust pile (A) and planted with willow (B) at full canopy (unpublished). *(Go to www.dekker.com to view this figure in color.)*

allows circulation of leachate back onto the site, closing the hydrological system.

The establishment of vegetation directly on metalliferous mine tailings controls leaching and erosion and also wind-borne dust contamination of surrounding environments. Sites contaminated with organic compounds may be remediated through plants via phytostimulation of soil microflora and fauna, which degrade organic compounds to their primary products.[12]

Soluble fertilizers and nutrients, such as N and P, pose a serious pollution threat to ground and surface water bodies. Plants can be used to protect riparian areas from stock effluent and from applied fertilizers. Work currently progressing in New Zealand indicates that dairy shed effluent may be applied to poplar and willow species as an alternative to application directly onto pasture (data not currently published). This has advantages in that the water use of trees is greater than grass.[4] Trees therefore work more effectively as N sponges and require less area in systems where excess N tends to leach and become a contaminant. The biomass produced by palatable species may be fed to stock as fodder.

Case Study

A disused sawdust pile, 15 m deep and 5 ha in size, contaminated with As, B, Cu, and Cr was continuously leaching B, As, and tannins into local surface water bodies and into the nearby harbor. Under New Zealand's Resource Management Act (1991), the site owners were required to avoid, remedy, or mitigate any adverse effects of their activity on surrounding environs. A traditional clay cap was initially proposed for the site; however, the cost of cap installation was approximately $750,000. An alternative strategy proposed included the establishment of selected poplar species on the site and the installation of a dam to trap escaping leachate to recirculate it onto the sawdust pile. A risk assessment, using the soil plant atmosphere model (SPASMO) similar to that described in Ref. [13] demonstrated the change in site water balance with the establishment of vegetative cap (Fig. 3). Table 1 gives mean monthly precipitation, mean monthly potential evapotranspiration, and the mean monthly number of expected rainfall days for the site to aid interpretation of

Table 1 Mean precipitation (mm), mean potential evapotranspiration (mm), and the mean number of rain days per month for the Kopu field site

Month	Mean precipitation (mm)	Mean evapotranspiration (mm)	Mean number of rain days
Jan	65.14	129.02	7.2
Feb	63.87	112.51	5.2
March	98.65	100.69	7.7
April	95.58	72.66	9.0
May	85.12	56.63	10.3
June	121.69	44.97	11.5
July	141.85	48.70	13.0
Aug	121.48	54.96	13.5
Sept	111.00	65.56	12.4
Oct	81.45	86.89	10.2
Nov	79.08	102.30	9.3
Dec	80.62	121.10	8.3

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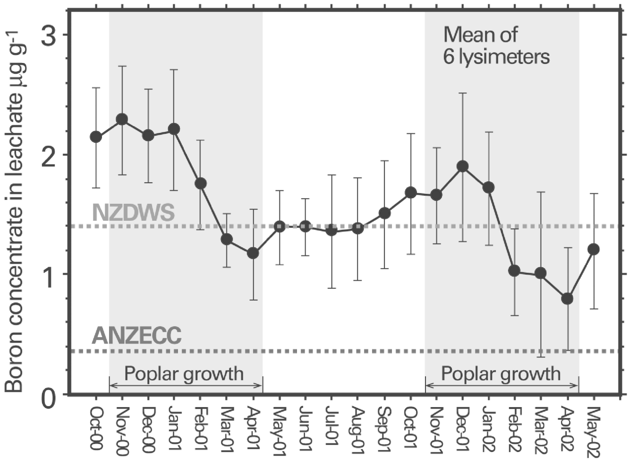

Fig. 4 Average concentration of B leaving the lysimeters in the leachate from 2000 to 2002. NZDWS represents the New Zealand Drinking Water Standard and ANZECC represents the Australian New Zealand Environment Conservation Council (unpublished). *(Go to www.dekker.com to view this figure in color.)*

Fig. 3. Parallel lysimeter studies were conducted in conjunction with plant establishment on the pile. SPASMO was parameterized for the poplar species grown at Kopu from data collected during the lysimeter study.[2] Full details for the lysimeter experiment are outlined in Ref. [14]. The lysimeter study demonstrated the efficacy of poplar to remove B from the exiting leachate (Fig. 4). Data from this study also show accumulation of B within poplar leaves of lysimeter grown trees to levels as high as 700 mgkg^{-1} dry mass.[2] Traces of Cu and Cr were also recorded in poplar leaves from the lysimeter study.[2] Boron removal coupled with the poplar trees capacity to dewater the site suggest poplars provide a suitable phytoremediation tool for B contaminated sawdust.[2] As the trees mature, hydrologic management of the field site will be further enhanced.

CONCLUSION

In contrast to the immediate solution provided by traditional containment technologies, living vegetative caps may take 4 to 5 years to become fully functional. However, in suitable circumstances living systems can offer better long-term solutions, which improve with time. This may provide a remediation solution rather than a solution that conceals the problem for others to confront later. Trees have aesthetic and ecological advantage. They enhance the environment and enjoy wide public acceptance. Hydrologic management of contaminated sites using vegetation will not always be a suitable solution; however, increasing public awareness and a demand to ''do something'' will ensure a steady increase in the use of plants, either alone or in conjunction with more traditional containment solutions.

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