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Landscape reclamation at a central Florida phosphate mine

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ABSTRACT

A 13-ha parcel of phosphate-mined land at the Gardinier Mine near Ft. Meade, Florida, USA, was reclaimed to test several design principles, establish planting and seed-dispersal trails, and monitor groundwater and surface water. The site was designed as a complete hydrologic unit with perched, basin, and lake-fringe wetland communities in upland communities. The design and placement of ecological communities resulted from the reclaimed topography and site hydrology. The percent growth for 11 wetland and mesic tree species averaged 127% (weighted average) in 3 years; some species averaged more than 160%. Percent survival ranged from 0% (*Cephalanthus occidentalis*) to 100% for several mesic forest tree species (*Fraxinus pennsylvanica*, *Liquidambar styraciflua*, *Magnolia grandiflora*). The percent survival of wetland species (weighted average) was 94.6%. An adjacent forested, floodplain wetland was evaluated as a source of windblown and bird-dispersed seeds to the site. Windblown seeds decreased in densities as distance from forest edge increased. Densities were from $125/m^2$ to $380/m^2$ within the forest, $50/m^2$ to $120/m^2$ at the forest edge and decreased exponentially as distance increased. Bird-dispersed seed densities at the base of constructed perches and tree "snags" ranged from $100/m^2$ to more than $300/m^2$. Rainfall and surface-water inflow along the edge of the site were the largest inputs to the reclaimed landscape's hydrologic budget. Groundwater flow and seepage were more important to growth and survival of planted species because of the maintenance of higher soil moisture during periods of drought.

INTRODUCTION

Reclamation of phosphate-mined lands in Florida, USA, has been mandatory since 1975 with enactment of laws that established a regulatory

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framework and criteria (Florida Statutes, Chapter 378). Pit mining of phosphate in central Florida had drastically altered more than 66 000 ha (165 000 acres) prior to 1986 (Marion, 1986) that resulted in three basic land forms: clay settling ponds, areas of mine cuts and overburden, and smaller areas of sand tailings. Once reclamation was required by law, industry and the State of Florida began funding research into reclamation techniques, enhancing succession on phosphate-mined lands, and studies of wildlife use [see Robertson's (1985) review of wetlands reclamation, and Marion's (1986) industry-wide analysis of reclamation].

Reclamation of drastically altered lands like those that result from phosphate mining is ecological engineering since it involves the recontouring of lands into usable forms, reestablishment of surface and groundwater hydrology, and revegetation (enhancing ecological succession). The degree to which the land is ecologically engineered or to which it is left to natural processes of erosion and revegetation ultimately relates to the length of time required for reestablishment of a functional landscape of ecological communities. Earlier research by Kangas (1981), Best et al. (1988) and Odum et al. (1983, 1990) suggested that successional processes as long as 75 years were required to establish some early successional communities when seeds were available, but that much of the phosphate-mined landscape would remain in arrested succession because of a lack of seed sources resulting from the scale of present-day mining. Doherty (1990, 1991) found that remnant forest islands in the mined landscape are extremely rare, small in size, and are primarily forested wetland communities. Few upland forested communities remain within the mined landscape, although there are still forested tracts around the periphery.

One of the most important factors affecting reclamation success is site hydrology. Both surface-water flows and groundwater elevations are significant driving forces that will dictate floral composition of ecological communities (Clewell, 1983; Brown et al., 1985; Rushton, 1988; Miller, 1990; Riekerk et al., 1990) and long-term landscape organization. Period and depth of inundation in wetland communities is a primary factor affecting species composition (Mitsch and Gosselink, 1986; Brinson, 1988), and soil moisture in upland communities is just as important (Laessle, 1958; Monk 1965, 1966, 1968; Veno, 1976). Best et al. (1990) showed strong correlations between species composition and soil moisture in both wetland and upland communities in north central Florida, USA.

Soil composition is also an important factor (Coultas and Calhoun, 1976; Wallace and Best, 1983a; Brown et al., 1985). Soils that result from phosphate mining do not resemble native Florida soils because the strip mining, in essence, turns the soil profile upside down to depths varying from 10–20 m, depending upon depth to the phosphate matrix (Wallace and Best, 1983b). Best et al. (1988) tested differing soil mixtures and inoculation with mycorrhizae on survival and growth of planted trees. A technique of spreading topsoil obtained from native communities (mulching) tested in earlier reclamation efforts (Brown et al., 1985) seemed to enhance revegetation, especially of herbaceous and shrub species. Clewell (1990 [unpublished results]) demonstrated success in establishing xeric communities using mulch from existing sand pine and scrub oak communities.

In all, the reclamation of phosphate-mined lands presents a most interesting dilemma in the combination of their structural features, hydrology and soil properties. Landforms that result from mining do not resemble native Florida landforms (Kangas, 1981); their surface drainage and subsurface hydrology are often significantly different from pre-mined conditions (Riekerk et al., 1991), and their soil properties differ markedly from native soils (Davis et al., 1991; Wallace, 1988). Successful reclamation and revegetation depends on how well these three factors are taken into account during design, site engineering, and revegetation. While there have been many studies of planting success and evaluations of developing community structure, there have been few "whole system" studies evaluating the long-term success of reclamation from a landscape perspective.

In this paper we give the details of a series of studies that were done on a relatively small parcel of phosphate-mined land in central Florida, USA. Overall, the parcel was reclaimed as a means of testing several design principles, and was the site of numerous planting and seed dispersal trials as well as extensive groundwater and surface-water monitoring. This paper contains details of the reclamation design, the results of vegetation studies and seed dispersal patterns, and a summary of the site's hydrology.

METHODS

Site description

The site, located at the Gardinier Mine near Ft. Meade, Florida, USA (Fig. 1), was bordered on the south and east by a clay settling pond (Fig. 2). The pond was last used for disposal of clay wastes in 1968 and had been inactive for 14 years at the start of this project. Several years before beginning this project, the settling pond dikes were pushed into the pond, in effect "capping" the outer two-thirds of the clays leaving two low, marshy areas in the very center. These low marshy areas were connected to two dewatering stations (each centered in the dikes on the east and south sides of the reclamation site) via interior channels. Two 1.23-m culverts (DS1 and DS2) drained the settling pond onto the site.

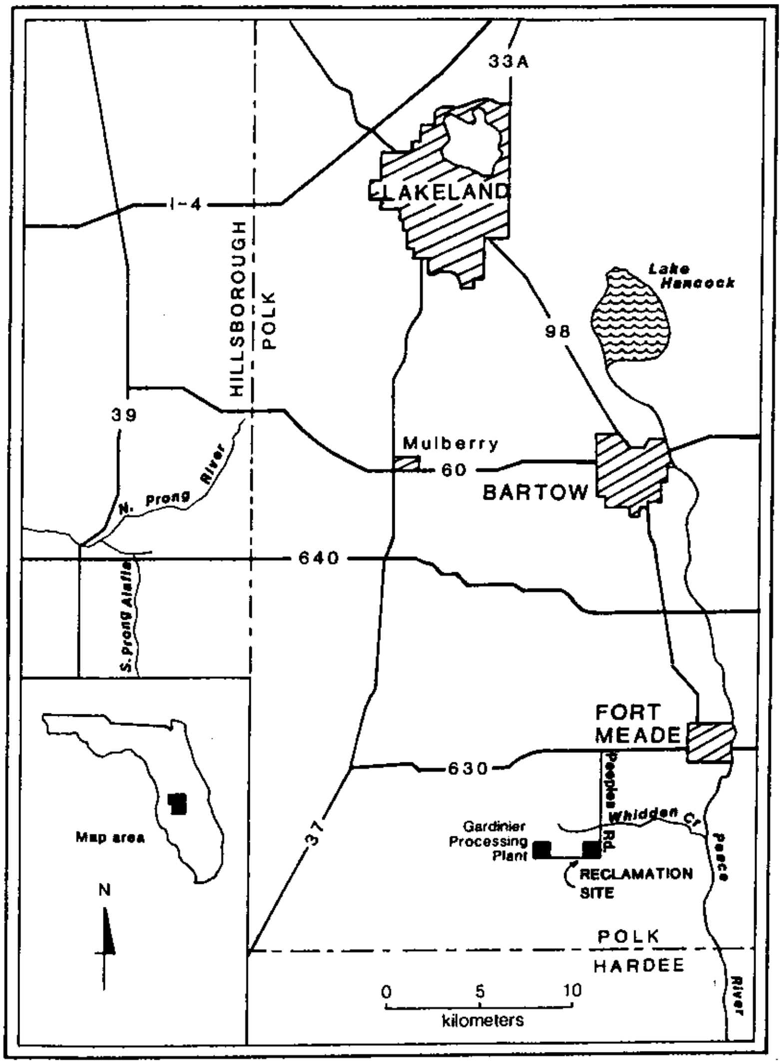

Fig. 1. General site location of the Gardinier reclamation site in central Florida, USA.

The site's northern border was the floodplain forest of Whidden Creek, a tributary of the Peace River (Fig. 2). The site was within the drainage basin of Whidden Creek, with a general surface-water flow pattern from east to west. Once reclaimed, the site would once again contribute surface flows to the creek. The site was bordered on the west by a water control ditch and land uses associated with the production plant.

Substantial surface-water flow had been discharging onto the site through the two dewatering stations from the higher, clay settling pond, carving erosion channels between the outlets and Whidden Creek. These site

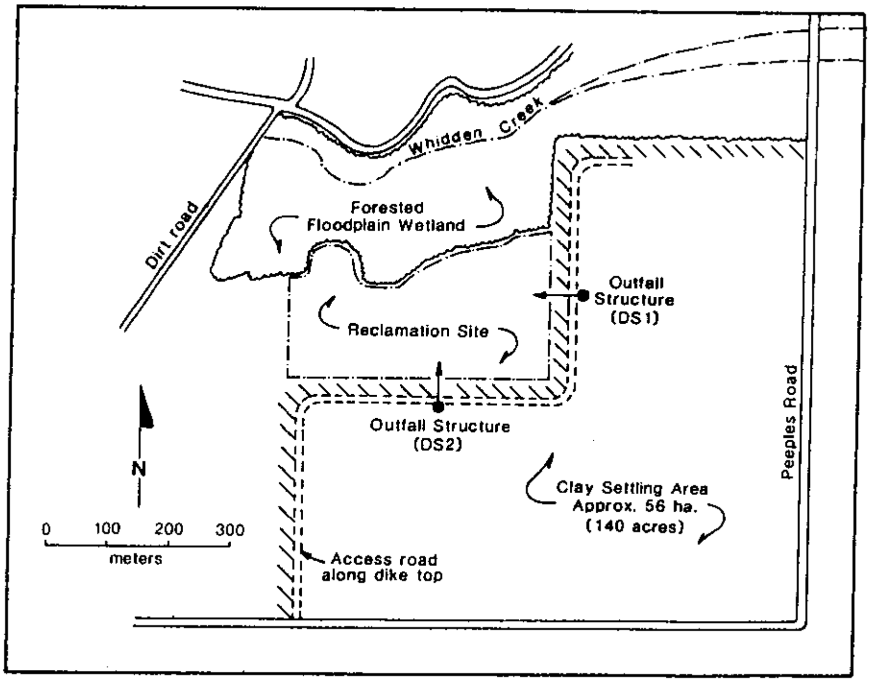

Fig. 2. Gardinier reclamation site, showing surrounding land uses. The clay settling area to the southeast drained through the site into Whidden Creek.

conditions suggested the possibility of designing an integrated system of wetlands, uplands, and aquatic habitats. With the runoff from this larger drainage area (56 ha), it was possible to design an array of wetland types whose areal extent was greater than that which could be hydrologically supported by the reclamation site alone. However, soon after completion of recontouring and revegetation, flow from the clay settling area ceased as a result of the combined effects of lower than normal rainfall and internal settling and desiccation of the clays. This development seriously altered anticipated site hydrology.

Site design

Reclamation of the site was conceived and designed as a surface-water system that would receive surface drainage from the clay settling area to the south and east, attenuate its pulses, and discharge to Whidden Creek to the north of the site (Fig. 3). The difference in elevation between the clay-settling-pond outfall structures and Whidden Creek presented a complicating factor because of the relatively short distance over which waters

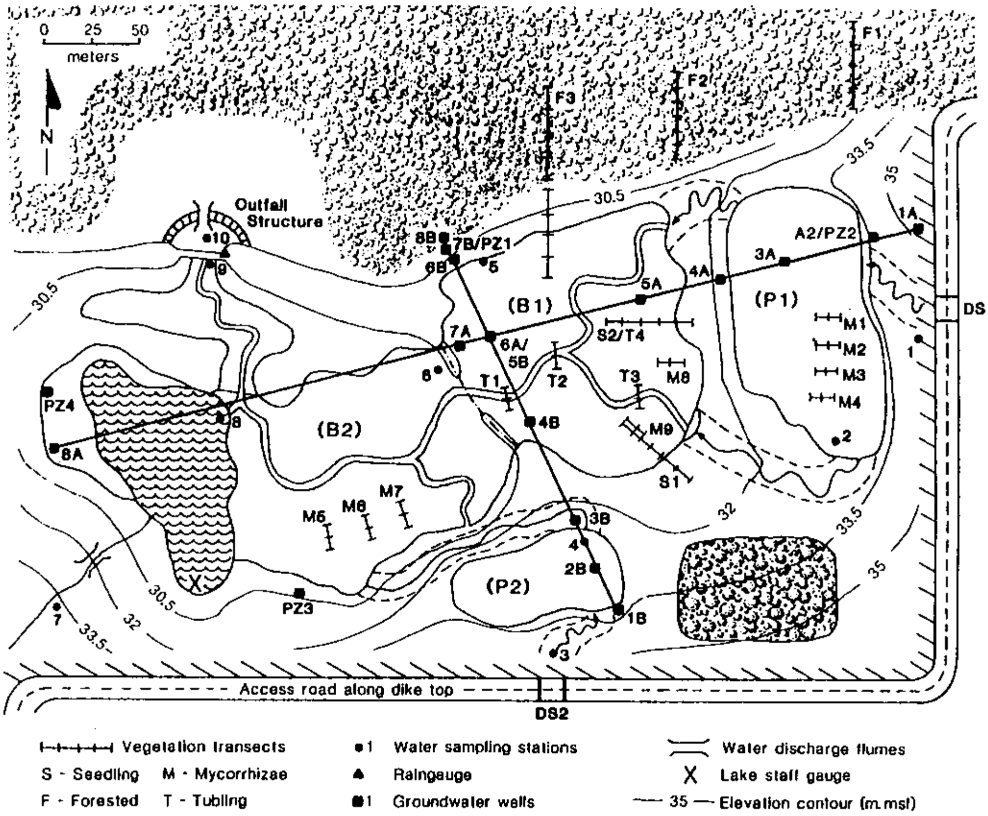

Fig. 3. Hydrologic and vegetation monitoring networks at Gardinier site. Shown are the various wetland community types that were created, including two perched wetlands (P1, P2), lake border wetland (LB1), and an herbaceous wetland (H1). Solid lines are approximate locations of vegetation and hydrology transects (GDN1, GDN2).

traveled before exiting the site. A series of wetlands and sinuous stream channels were designed to minimize slope and avoid turbulent flow in surface waters. Figure 4 contains cross-sections through the site showing the elevational relationships between the various wetlands, lake and outfall. Table 1 lists the area within each of the wetlands and lake.

Plan of study

There were several objectives within this project. First and foremost was the design of a reclamation scheme that incorporated several previously untested landscape components (perched wetlands, intermittent stream channels, and seepage and basin wetlands). Other objectives were the testing of several techniques of revegetation, including: direct planting,

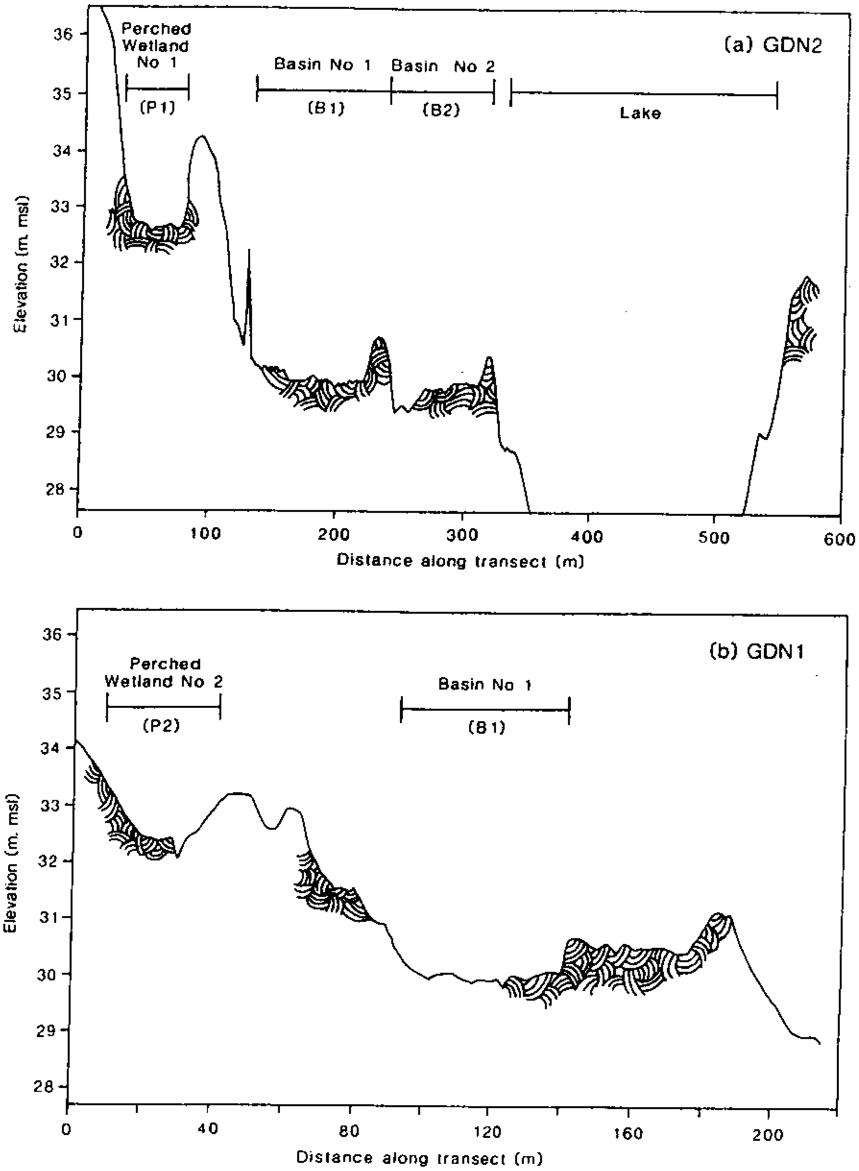

Fig. 4. Elevation profiles across Gardinier site, along north–south (GDN1) and east–west (GDN2) transects shown in Fig. 3.

mulching, and natural seeding by wind and wildlife. Finally, a main objective was the monitoring of site hydrology including groundwater to evaluate the changes that occur as a reclamation site matures. In essence, the Gardinier site became an outdoor laboratory where numerous, smaller-scale

TABLE 1

Area of wetlands and uplands in the reclaimed landscape at the Gardinier reclamation site. Abbreviations refer to sites in Fig. 3

Wetland	Area (ha)
Forested basin wetland (B1)	1.25
Forested basin wetland (B2)	1.17
Perched wetland (P1)	0.73
Perched wetland (P2)	0.28
Herbaceous wetland (H1)	0.28
Lake border swamp (LB1)	0.24
Lake	0.99
Total wetlands and lake	~ 5.0
Total uplands	~ 8.0

studies of revegetation and hydrology of reclaimed landscapes were carried out.

Vegetation

Tree seedlings of varying sizes and species were planted throughout the site. Mesic species were planted around the perimeter of each of the wetland systems — pines and oaks in the uplands, and wetland species within the wetland areas. Several seedling experiments were established where various treatments were laid out in randomized block designs, and growth and survival were monitored for a year or more.

Vegetation transects

Quantitative measurements of tree species that might contribute to the natural revegetation of the site were conducted using three transects through the Whidden Creek Floodplain Forest. Three belted transects (10 m × 50 m) were laid out south to north from the edge of the forest adjoining the reclamation site to the creek (transects F1, F2, and F3 in Fig. 3). All trees in mature and shrub/sapling size classes in 10-m-long increments (quadrats) along each transect were identified and DBH was measured. Relative frequency, relative density, relative dominance, and importance value were calculated (Smith, 1980).

Both containerized and bare-root seedlings were planted throughout the site for revegetation and as experimental designs for testing various techniques and treatments. General revegetation plantings were installed in a "random" fashion where trees were randomly planted in zones without documentation of locations. Later, belted transects were established to measure a subsample of these trees. In September 1986, two 10-m-wide belted transects totaling more than 500 m in length were established across the site. The first ran east–west from the middle of the eastern levee to the west side of the lake, and the second ran south–north from the middle of the southern levee to the floodplain forest (see Fig. 3). Seedlings from the previous plantings that occurred within the transects were recorded by species, height, and crown size (approximate areal coverage of the branches of the seedling). In December 1987, seedlings in these transects were remeasured for growth. Figure 3 shows the locations of the various vegetation studies.

Seed dispersal

The presence of the adjacent floodplain forest of Whidden Creek provided the opportunity to measure seed dispersal onto the site from a variety of pathways including wildlife, wind, and gravity. Additionally, seed dispersal by water in Whidden Creek was also measured as a means of estimating the importance of this potential source of seeds.

Dispersal of seeds onto the site from the Whidden Creek Floodplain Forest was measured using seed trap transects set perpendicular to the forest edge (McClanahan, 1984; Wolfe, 1987). The traps were set out in a 6 × 6 array. The traps were checked biweekly and seeds collected from the traps were identified and counted.

To measure the dispersal of seeds by birds, artificial perches were established throughout the site. Two separate types of perches were utilized — "planted" dead trees (snags) and constructed perches. The first perch experiment involved the use of snags that were placed throughout the site. Eight snags ranging in height from 7 to 20 m tall were "planted" in the site, at random locations. McClanahan (1984) placed seed traps at 1, 2, and 3 m from the base of three of these snags. Wolfe (1987) later studied all eight snags with the same arrangement of traps, including a control trap placed 10 m from each snag. Traps were checked monthly from September to December 1983 (McClanahan, 1984) and, in a follow-up study, Wolfe (1987) checked monthly from May 1984 to February 1986.

To determine both the long-term and short-term fate of seeds dispersed beneath the snags, seed bank and germination studies were undertaken in 1989 and 1990. Analysis of the seed bank was done by taking soil samples from the snag locations (8 cm diameter and 10 cm deep) and germinating seedlings under controlled conditions in a greenhouse. A second set of soil samples ($0.25 \text{ m}^2 \times 2$ cm deep) were sieved out and the organic matter was floated off. The organic matter was then dried and sorted, and seeds were identified and counted. Long-term survival studies consisted of determining species and their densities in 1 m^2 quadrats below snags in September 1989, 7 years after the snags were initially established on the site.

In the second perch experiment, perches were constructed of 2.5 cm × 5 cm furring strips 2.4 m long with 1.2-m-long crossbars and placed throughout the site. Each perch was driven into the ground, with the crossbars standing approximately 1.8 m above ground. Seed collection trays were placed beneath each perch. Initially, three rows of four perches at 30-m intervals were placed randomly throughout the site. These were checked monthly from September to December 1983 (McClanahan, 1984). In a follow-up study, four rows were placed systematically in the site, perpendicular to the floodplain forest beginning 30 m from the edge and extending to a distance of 150 m, at 30-m intervals. A fifth row of seed traps without perches was also set up as a control. Traps were checked monthly from May 1984 to February 1986 (Wolfe, 1987). Species and abundance of seeds were measured.

To determine natural germination of seeds dispersed from the floodplain forest and the snag perches, three 50-m-long transects were established in April 1984 (S1, S2, and S3 in Fig. 3). On each transect, seedlings were identified and counted in a 3-m-wide band, in increments 1.0, 2.5, or 5.0 m long, depending on the density of seedlings encountered. Transect S1 was established to measure seedling germination from bird dispersal, and was placed at the base of a snag farthest from the floodplain forest. Transect S2 was located halfway between S1 and the forest edge. No snags or perches were near this transect. The final transect (S3) was located to measure dispersal germination away from the floodplain forest. It began at the forest edge and ran southerly into basin 1.

Wolfe (1987) studied the dispersal of seeds in flowing water in Whidden Creek, at three locations downstream from the reclamation site. Three seed traps, supported by styrofoam floats and constructed of fiberglass screen in the shape of a funnel 60 cm long with a 15.5-cm-diameter mouth, were suspended equally spaced across the channel. Approximately 10 to 15% of the trap opening was above the surface of the water. At each of the three sampling stations the traps were left in the water for 48-h each month from July 1984 to February 1986. Seeds were collected, dried, and identified. Seeds/day were determined using seeds/trap, trap diameter, and river cross-section. Flow rates in the creek were approximated to determine seed dispersal as seeds per cubic meter per day.

Hydrology

Both groundwater and surface-water hydrology were monitored for more than 4 years with an extensive network of surface-water flumes, water-level recorders, rain gauges, and groundwater wells (Fig. 3). A temporary stilling dam was constructed at the outfall to aid in accurately measuring outflow from the site. A water budget was calculated from measurements of rainfall, surface inflow and outflow, groundwater inflow and outflow, and evapotranspiration.

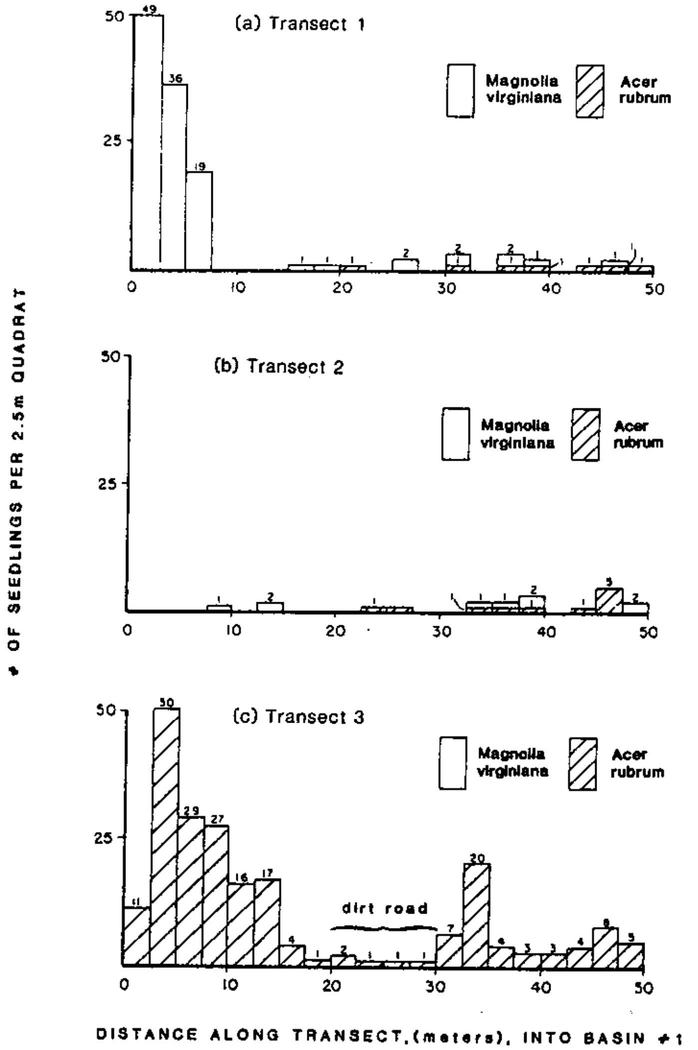

Fig. 5. Germinated seedlings from windblown *A. rubrum* and bird-dispersed *M. virginiana* sources along transects S1–S3 (see Fig. 3). Transect S1 begins at the base of a tree snag. Transect S2 represents average seed rain across the landscape. Transect S3 shows windblown seeds from the edge of Whidden Creek.

Site hydrology

In May 1985, surface monitoring was initiated. A 1 m, 1.4 m^3/s (50 ft^3/s) capacity flume with a water-level recorder was installed at the outflow and continuous measurement initiated. A continuous-recording rain gauge was also installed at this location (Fig. 3). The primary source of surface inflow was from a small channel located along the base of the western edge of the settling pond (see Fig. 3). This channel contributed roadside drainage and some processing plant outflow to the site. Another flume and water level recorder were installed within the channel, a short distance upstream from its discharge into the lake (Fig. 5).

To understand the interaction of the water table with the vegetation and to analyze the groundwater contribution of the adjoining settling area, a network of shallow groundwater wells was installed. Each well was constructed of 6.25 cm diameter PVC pipe of sufficient length to penetrate the groundwater lense. The bottom 50 cm of each well was slotted at approximately 1 cm intervals. By April 1984, 10 wells had been installed along two transects approximately N–S and E–W across the site (Fig. 3). In September 1986, in conjunction with vegetation transects described earlier, four more wells were installed. Together with a staff gauge installed in the southern portion of the lake, and four more piezometers placed independent of the transects (Fig. 3), the network allowed a detailed description of the surficial groundwater system underlying the site. Depth to the water table was measured monthly using a weighted, chalked tape measure.

Surface water quality

On a monthly basis from September 1983 to April 1984, water samples were collected from 10 locations throughout the site (see Fig. 3) to evaluate the ability of vegetation to stabilize erosion from the site over time, and as a means of evaluating the spatial differences in suspended solids that resulted from the various site treatments. These samples were analyzed for turbidity using a nephelometer and standard methods. Data were expressed as nephelometric turbidity units (NTU).

RESULTS

Vegetation

Whidden Creek Floodplain

Table 2 lists several related parameters measuring frequency, density, dominance, and importance of tree-sized (> 5 cm DBH) and

TABLE 2

Abundance characteristics of trees (> 5 cm DBH) in the Whidden Creek Floodplain Swamp

Species	Frequence Relative (%)	Density		Dominance		Importance value [a]
		Stems/ha	Relative (%)	Basal area	Relative (%)	
Tree size class						
Acer rubrum	23.0	193	25.3	2.81	26.8	25.0
Liquidambar styraciflua	18.0	119	15.6	2.32	22.1	18.6
Dead	11.0	99	13.0	1.14	10.9	11.6
Carpinus caroliniana	11.0	104	13.6	0.82	7.8	10.8
Magnolia virginiana	11.0	79	10.4	0.65	6.2	9.2
Quercus virginiana	5.0	30	3.9	1.33	12.7	7.2
Nyssa sylvatica	7.0	40	5.2	0.28	2.7	5.0
Total		664				
Sapling/shub size class						
Magnolia virginiana	11.0	652	16.0	0.54	22.3	16.4
Nyssa sylvatica	7.0	454	11.2	0.62	25.6	14.6
Carpinus caroliniana	12.0	395	9.7	0.20	8.3	10.0
Sambucus canadensis	9.0	632	15.5	0.13	5.4	10.0
Acer rubrum	9.0	336	8.3	0.18	7.4	8.2
Cornus spp.	9.0	277	6.8	0.15	6.2	7.3
Cephalanthus occidentalis	7.0	257	6.3	0.12	5.0	6.1
Total		3003				

[a] Importance value = (relative frequency + relative density + relative dominance)/3.

sapling/shrub-sized (< 5 cm DBH) plant species in the Whidden Creek Floodplain Swamp. The dominant canopy species (in accordance with all parameters) was *Acer rubrum* followed by *Liquidambar styraciflua*. *Magnolia virginiana* and *Nyssa sylvatica* were the two dominant subcanopy trees in the sapling-sized class. Total stems per hectare in the canopy and subcanopy were 664 and 3003, respectively. Canopy stem density was low compared with mean stem density in floodplain forests of central Florida (Brown and Tighe, 1991), where the mean was 1290 stems per hectare. Stem density in the subcanopy, on the other hand, was quite high in the Whidden Creek Swamp (3003 stems/ha), while subcanopy densities measured in other floodplain swamps were about 1000 stems per hectare (Brown and Tighe, 1991). The small number of species (six trees and three shrub species) was low compared with mean species richness for central Florida floodplain swamps (Brown and Tighe, 1991). The mean species richness in comparable floodplain swamps was 13.5, although there was wide variation (standard deviation was 6.5).

Planted seedlings

A summary of growth and survival (in the third and fourth year after planting) of tree species planted at the Gardinier site is given in Table 3. These data were taken from two transects: GDN1 (north–south) and GDN2 (east–west). Eleven species were identified within these belted transects. Species with high relative densities were *A. rubrum* and *Taxodium distichum* followed by *Fraxinus pennsylvanica* and *L. styraciflua*.

Using the total area of both transects (5080 m^2) and the total number of live trees (201) the average density of planted trees on the site as a whole was one tree per 25.4 m^2 or 394 trees/ha. Density of planted trees in wetland areas (where most tree planting was concentrated) was one tree per 19.1 m^2 or 521 trees/ha.

Overall survival of seedlings from the first year of measurements to the second was about 91%. The majority of the trees within these transects were 4-l containerized seedlings. Of the nonsurviving trees (19 out of 220) two were containerized seedlings (their heights were greater than 1 m) while the remaining 17 were probably bare-root seedlings (all less than 1 m in height). Trees with greatest mortality were *Cephalanthus occidentalis* with 0% survival and *Catalpa bignonioides* with 50% survival. *M. virginiana* had a survival of only 67% in transect GDN1 and 75% in transect GDN2. All other species had greater than 80% survival.

Mean percent growth between measurements is given in the sixth column for each species. The majority of species exhibited large increases in height; most growing more than 100% in the year and three months between measurements. The only species with less than 100% growth,

TABLE 3

Tree seedlings found along transects of Gardinier reclamation site. Transect locations are shown in Fig. 3

Species	Mean height (cm)					
	Number	Relative density	September 1986	December 1987	Percent growth	Percent survival
GDN1 transect (north–south)						
Acer rubrum	22	0.40	0.43	0.72	167	86
Fraxinus pennsylvanica	5	0.09	1.52	1.7	112	100
Liquidambar styraciflua	4	0.07	1.34	1.63	122	100
Magnolia grandiflora	1	0.02	0.33	0.59	179	100
Magnolia virginiana	3	0.05	0.51	0.80	157	67
Taxodium distichum	20	0.36	1.61	1.88	117	95
GDN2 transect (east–west)						
Acer rubrum	18	0.22	0.62	1.01	166	94
Carya aquatica	11	0.07	0.84	1.15	136	80
Catalpa bignonioides	4	0.02	0.73	1.10	151	50
Cephanlanthus occidentalis	5	0.03	0.86	NA	0	0
Fraxinus pennsylvanica	28	0.17	1.79	2.09	117	93
Gordonia lasianthus	9	0.05	0.78	0.80	103	89
Liquidambar styraciflua	15	0.09	1.42	1.93	136	100
Magnolia grandiflora	2	0.01	0.72	0.93	129	100
Magnolia virginiana	4	0.02	0.67	0.50	75	75
Nyssa sylvatica var. *biflora*	10	0.06	0.96	1.41	147	90
Taxodium distichum	59	0.36	1.35	1.69	125	98

other than *C. occidentalis*, was *M. virginiana* (the four on transect GDN2 exhibited only a 75% increase in height).

Seed dispersal

Table 4 summarizes the number of seeds found in various sites. Seeds dispersed from snags and perches revealed the highest densities found, probably resulting from the concentrating effect of the perches. The lowest seed densities occurred in regional, mined landscapes (51 seeds m^{-2} year^{-1}). This density represented the average seed rain over a mined landscape. By comparison the average seed rain over the landscape as a whole was about three times that of the mined landscape or about 140 seeds m^{-2} year^{-1}.

Figure 5 shows the number of germinated seeds found along three transects at the Gardinier site. The transect placed beneath a large snag

TABLE 4

Components of seed dispersal in disturbed landscapes in central Florida, USA

Mechanism	No. seeds (m^{-2} $year^{-1}$)	Source
Wind (regional landscape)	140 [a]	Wolfe, 1987
Wind (mined landscape)	51 [a]	Wolfe, 1987
Wind (adjacent to forest)	20 [b]	This study
Wind (average mined landscape)	0.4 [a]	This study
Gravity (Whidden Creek Floodplain Forest)	360 [a]	Wolfe, 1987
Gravity (composite of three forested wetlands)	563 [a]	Wolfe, 1987
Birds (snags)	8– 20 [b]	This study
Birds (perches)	230–2100 [a]	Wolfe, 1987
Birds (snags)	1500– 496 [a]	Wolfe, 1987
Mulch	38– 143 [b]	Brown et al., 1985
Mulch	33000–1877 [c]	Dunn and Best, 1983

[a] Measured yearly input of seeds.

[b] Measured by germinated seedlings in field.

[c] Measured by germinated seedlings in greenhouse.

(S1) had many seedlings within the first 7 or 8 m from the perch and few farther away (Fig. 5a). All 104 of the sprouted seeds in the first 10 m were *M. virginiana*, which is primarily an animal-dispersed seed. Of the 18 seedlings counted in the remainder of the transect, 11 were *M. virginiana* and seven were *A. rubrum*. The transect in the middle of the basin (S2), which was distant from both the floodplain forest and snags (Fig. 5b), had only 20 seedlings along its entire 50 m length. The abundance and species composition of seedlings found were compatible to that found in the last 40 m of transect S1, with 11 *A. rubrum* and nine *M. virginiana* spread throughout the length of the transect. Seedling composition in the third transect (S3), placed near the floodplain forest, consisted entirely of *A. rubrum* (Fig. 5c). While abundance decreases with distance from source, the decrease is not as sharp as that found in transect S1, which was dependent on bird droppings as a primary seed source.

Wind dispersal

Figure 6 shows wind dispersal of seeds within and away from the Whidden Creek Floodplain Forest from Wolfe (1987) and McClanahan (1984). The upper graph shows seeds per square metre for 1 year at 15-m intervals. The data show the expected exponential decay of numbers as the distance from the forest edge increases. Within the canopy (−15 m) the number of seeds per year was about $370/m^2$, at the forest edge about $120/m^2$ and at 15 m from the edge, about $20/m^2$.

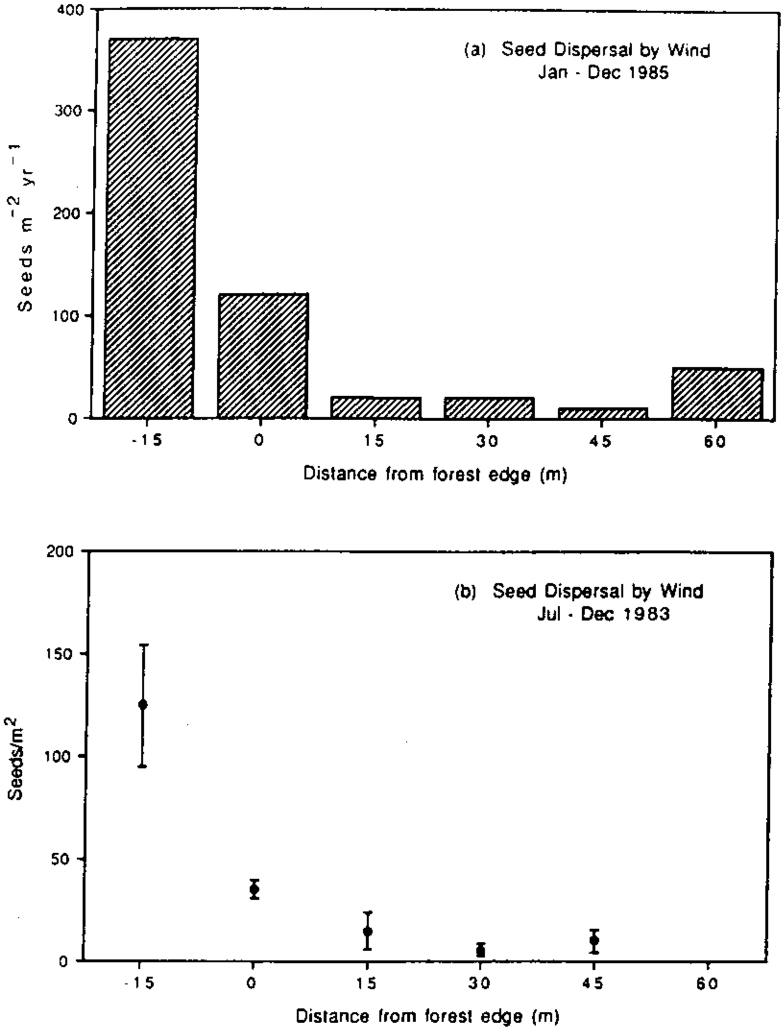

Fig. 6. Wind dispersal of seeds from Whidden Creek Floodplain Forest onto the Gardinier site, (a) January–December 1985 and (b) July–December 1983 (data from Wolfe, 1987; McClanahan, 1984).

McClanahan's (1984) data for a 4-month period from July 28 to December 4, 1983, show mean seed densities within the forest of 129/m^2, at the forest edge about 31/m^2, and 14/m^2, 4/m^2, and 10/m^2 at 15, 30, and 45 m, respectively. Wolfe's data show an increased number of seeds at 60 m and McClanahan's also shows an increased number, but at 45 m.

Tables 5 and 6 summarize the species composition of wind-dispersed seeds from the Wolfe and McClanahan studies. Wolfe found that the most common species were *A. rubrum*, *Ulmus americana*, and *Carpinus carolini-*

TABLE 5

Seed production (No. seeds m^{-2} $month^{-1}$) and percent composition of seeds dispersed from the Whidden Creek forest edge. Data are for May 1984 to February 1986 (from Wolfe, 1987)

Species	Distance to forest edge (m)						
	−15[a]	0	15	30	45	60	%
Acer rubrum	17.1	28.8	40.0	40.5	45.8	21.6	24.8
Ulmus americana	64.9	54.5	59.3	59.2	45.8	78.4	60.1
Carpinus caroliniana	10.5	3.2	0	0	0	0	6.3
Phytolacca americana	0.1	0.8	0.1	0	7.1	0	0.5
Callicarpa americana	0	0.2	0	0	0	0	0.1
Celtis occidentalis	1.8	0.7	0	0	0	0	1.1
Myrica cerifera	0.6	1.0	0	0	0	0	0.6
Smilax spp.	0	1.0	0	0	0	0	0.4
Cornus foemina	0.1	0.1	0	0	0	0	0.1
Lantana camara	< 0.1	0	0	0	0	0	< 0.1
Pinus spp.	< 0.1	0	0	0	0	0	< 0.1
Magnolia virginiana	0.3	0.8	0	0	1.2	0	0.5
Toxicodendron radicans	< 0.1	0	0	0	0	0	< 0.1
Liquidambar styraciflua	0.7	0.8	0.5	0.3	0	0	0.7
Vitacea[b]	0.9	2.9	0	0	0	0	1.5
Quercus spp.	1.4	0.6	0	0	0	0	0.3
Taxodium distichum	0.4	0.2	0	0	0	0	0.3
Fraxinus caroliniana	0.9	4.2	0.1	0	0	0	2.0
Unknown	< 0.1	0.1	0	0	0	0	< 0.1
% composition	48.8	36.4	8.8	3.7	1.9	0.4	100.0

[a] Distance of −15 m indicates samples from 15 m within the forest.

[b] Seeds identified only to family Vitaceae. May include *Parthenicissus quinquefolia, Ampelopsis arborea*, and *Vitis* spp.

ana (Table 5). McClanahan, on the other hand, found *C. caroliniana*, *Parthenocissus quinquefolia*, and *M. virginiana* to be the most common species, with no *A. rubrum* or *V. americana* (Table 6).

Bird dispersal

Figure 7 shows Wolfe's data for the number of seeds per month of shrub and tree species dispersed from snags on the reclamation site. There was a break in monitoring for forested seeds from February to July of 1985. Shrub seeds far outnumbered tree seeds. Shrub seeds averaged about 15 seeds m^{-2} $month^{-1}$ (with a high of 90 in March of 1985), while monthly tree seeds averaged about eight seeds per month (with greatest number in any month of 20 seeds/m^2).

TABLE 6

Rain adjacent to the Whidden Creek floodplain from July 28 to December 4, 1983 (from McClanahan, 1984)

Distance (m)	Genera	Seeds/trap	Total seeds/trap	Seeds/m^2 ave. ± SD
−15 [a]	*Magnolia*	6		
	Carpinus	77		
	Phytolacca	5		
	Parthenocissus	12		
	Unknown	2		
	Liquidambar	1		
	Vitis	2		
	Total		105	129.4 ± 94.7
0	*Magnolia*	1		
	Carpinus	4		
	Phytolacca	1		
	Parthenocissus	13		
	Unknown	2		
	Callicarpa	2		
	Persea	2		
	Total		20	30.8 ± 18.6
15	*Parthenocissus*	9		
	Unknown	1		
	Unknown	1		
	Total		11	13.6 ± 24.0
30	*Magnolia*	1		
	Phytolacca	1		
	Unknown	1		
	Total		3	3.7 ± 6.2
45	*Magnolia*	1		
	Phytolacca	1		
	Parthenocissus	3		
	Callicarpa	1		
	Unknown	2		
	Total		8	9.9 ± 11.1
Total seeds collected			147	

[a] Distance of −15 m indicates samples from 15 m within the forest.

Figure 8 shows McClanahan's data for bird dispersal from snags. Distance from the forest edge seemed to increase the number of seeds dispersed to snags (Fig. 8a). However, when stem branching was taken into account (Fig. 8b), the increased density of seeds with distance may have resulted from increased number of branches on snags that were further

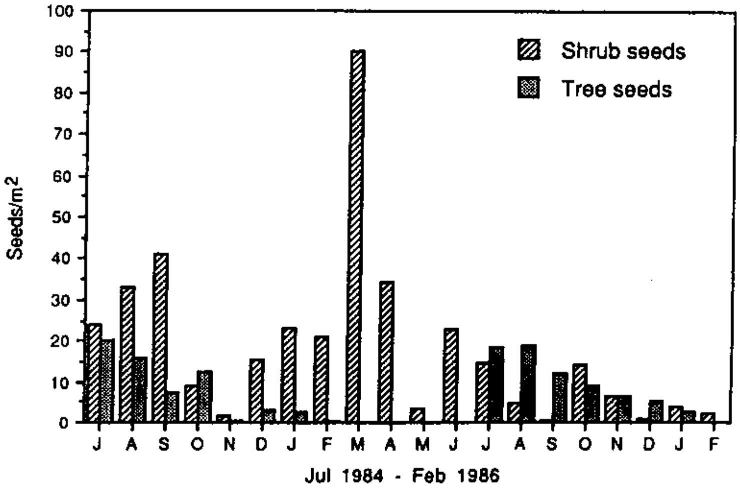

Fig. 7. Monthly seed dispersal of shrub and tree species from snags for the period July 1984 to February 1986 (data from Wolfe, 1987).

away from the forest edge. Figure 8c shows the effect of distance from snags on the density of seeds; even at 30 m from the snags, the density of seeds was high when compared with background or wind dispersal.

Constructed bird perches caused birds to concentrate into a tighter area than with the snags and therefore the density of seeds under them was quite high. Figure 9 shows the density of seeds found in 1 year under constructed perches on the Gardinier site. Shrub seeds have densities from 2100 seeds m^{-2} $year^{-1}$ to a low of about 100 seeds m^{-2} $year^{-1}$ (Fig. 9a). The greatest number were found at intermediate distances from the forest edge. Unlike the shrub seeds, more tree seeds were found at 30-m and at 90-m perches than at the 60-m perches (Fig. 9b). The largest number of tree seeds was found at the 30-m perch (mean about 82 seeds m^{-2} $year^{-1}$), while the lowest number was found at 60 m (mean about 18 seeds m^{-2} $year^{-1}$).

To determine the overall long-term consequences of seed dispersal by birds on the vegetative structure of a reclaimed site, studies of the seed bank and vegetation under snags were undertaken 7 years after they were installed. Figure 10 summarizes several consequences of that study. Figure 10a gives number of seeds by species that were caught in seed traps under snags from July to December of 1983. The seed bank in soil samples taken 7 years after the initial seed rain studies was analyzed; the resulting species composition and numbers are given in Figure 10b. Soil samples germinated under favorable conditions in the greenhouse revealed the species composition and numbers shown in Figure 10c. Finally, species and numbers of

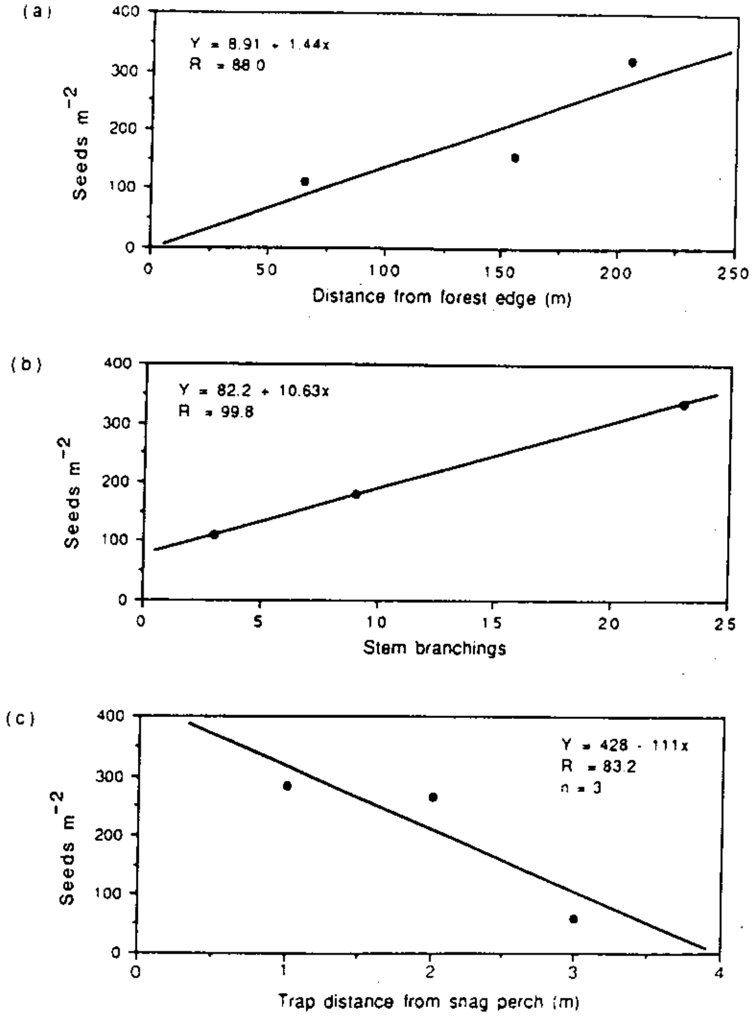

Fig. 8. Bird dispersal of total seeds from snags. (a) Versus distance from forest edge; (b) versus number of branches on snags; (c) versus distance from snags (data from McClanahan, 1984).

individual plants that had germinated and survived 7 years later were surveyed beneath snags; the resulting species composition is shown in Fig. 10d.

Seed-bank data show that very few seeds dispersed from snags are incorporated into the seed bank. Table 7 lists the number of seeds in the seed rain, in the seed bank, and standing vegetation (germinated). While fewer seeds actually germinated (Fig. 10 and Table 7), densities of bird-dispersed plants were at least 100 times more dense beneath snags than away

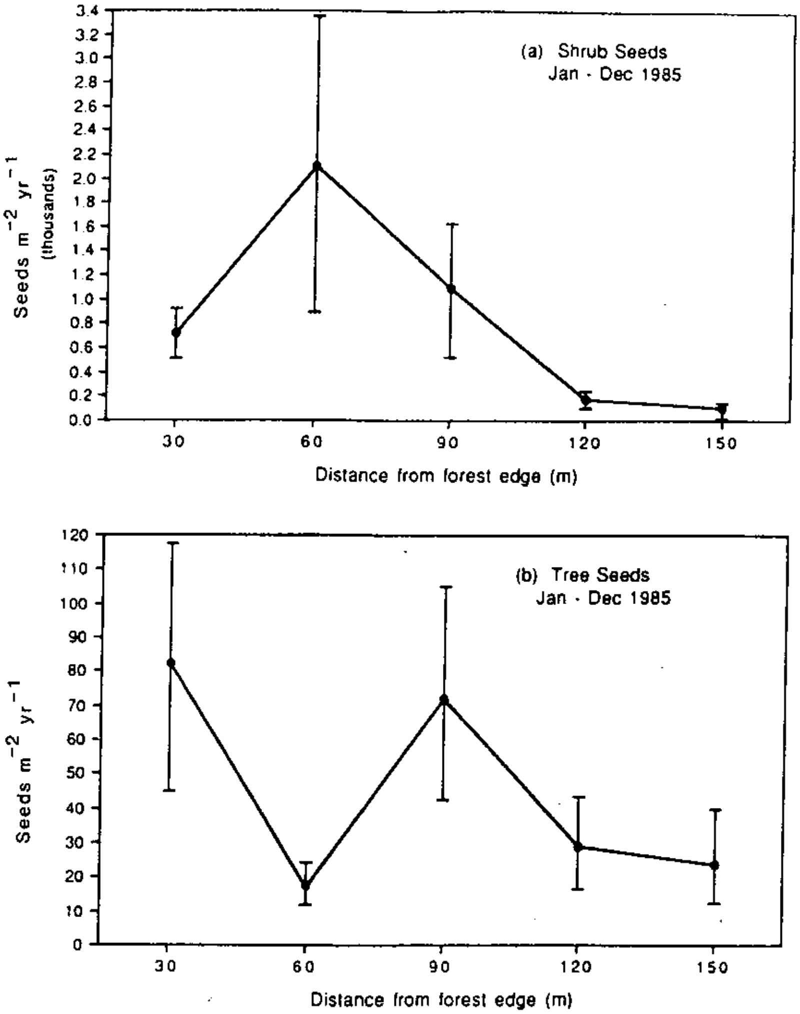

Fig. 9. Bird dispersal of seeds from constructed perches for (a) shrub seeds, and (b) tree seeds (data from Wolfe, 1987).

from snags. Nonetheless, as the third column in Table 7 indicates, plant diversity remained constant between seed rain, seed bank and germination.

Water dispersal

Wolfe's data for waterborne seeds in Whidden Creek at two different locations are given in Fig. 11. The lowest number of seeds per day over the entire year is associated with the upstream seed station where the creek flows out of an old mined area (dispersal ranging from 0 to 200 seeds per

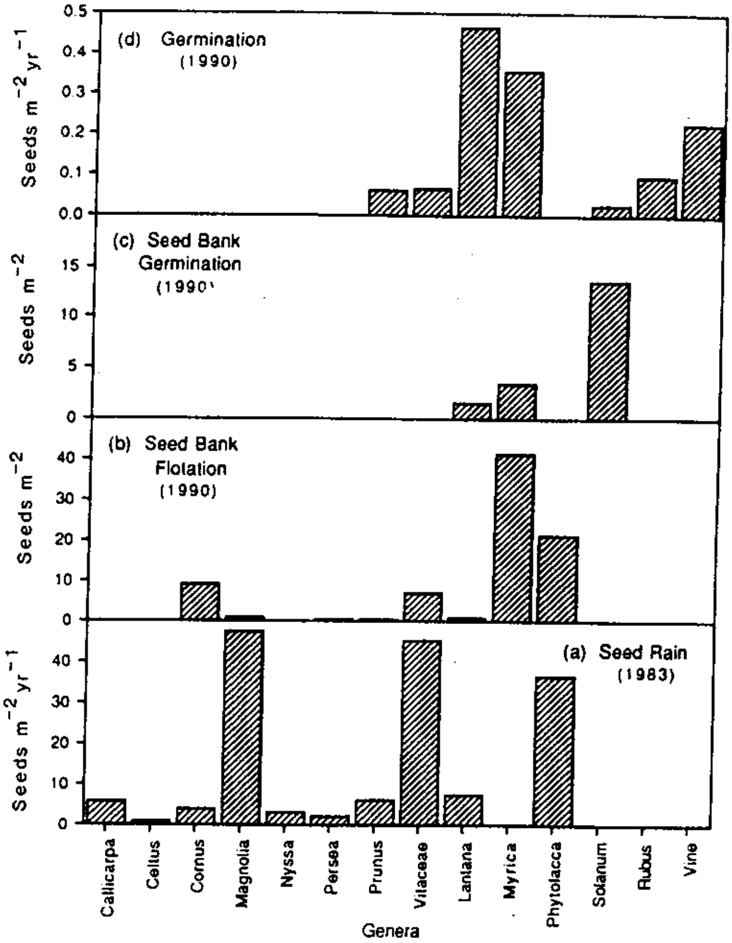

Fig. 10. (a) Seed rain at Gardinier reclamation site in 1983, compared to (b) seed bank in 1990 as measured by flotation of seeds from soil samples, (c) germination in a greenhouse (1990), and (d) natural regeneration on site (1990).

day). Highest dispersal rates were found downstream of the forested floodplain where the numbers were from 200 to 5000 seeds per day.

Hydrology

Surface water

Figure 12 presents the surface-water budget for the reclamation site. The most abundant source of water was surface water from the clay-settling pond dike at the western end of the site; however, owing to its

TABLE 7

Number of seeds and diversity in the initial (1983) and follow-up (1990) seed-bank analysis

Analysis	Number of seeds	Simpsons diversity (seeds/m^2)
Seed rain [a]	155	0.78
Seed bank [b]	85	0.67
Germinated [c]	16	0.37
Vegetation [d]	2	0.75

[a] Measured in 1983 using seed traps beneath snags.

[b] Measured in 1990 by flotation of seeds from soil samples.

[c] Germinated seedlings in 1990 from soil samples.

[d] Measured in the field below snags in 1990.

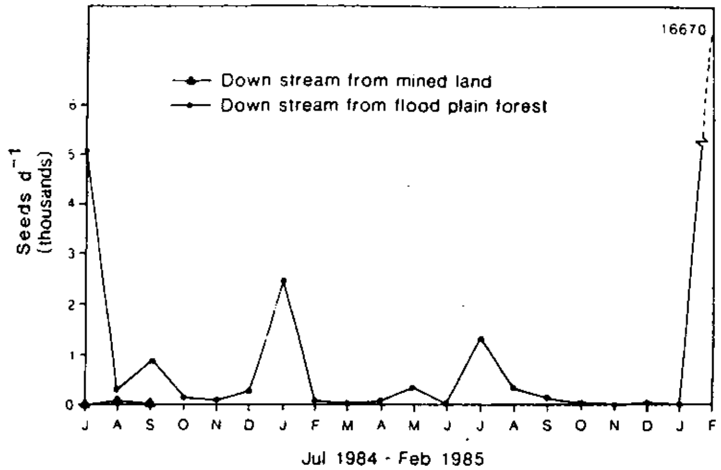

Fig. 11. Density of waterborne seeds downstream from mined land and the Whidden Creek Floodplain Forest (data from Wolfe, 1987).

peripheral location, this source was of little consequence to overall site hydro-dynamics.

The second most abundant source of surface water was rainfall, contributing less than half that from the surface source (Fig. 12). Groundwater seepage from the higher clay settling area made a significant impact on surface water (not so much in quantity) because it caused much of the site to remain wet throughout the year.

Water quality

Turbidity values are presented in Table 8 for the 10 sampling locations shown in Fig. 3. The first samples were taken within several weeks of

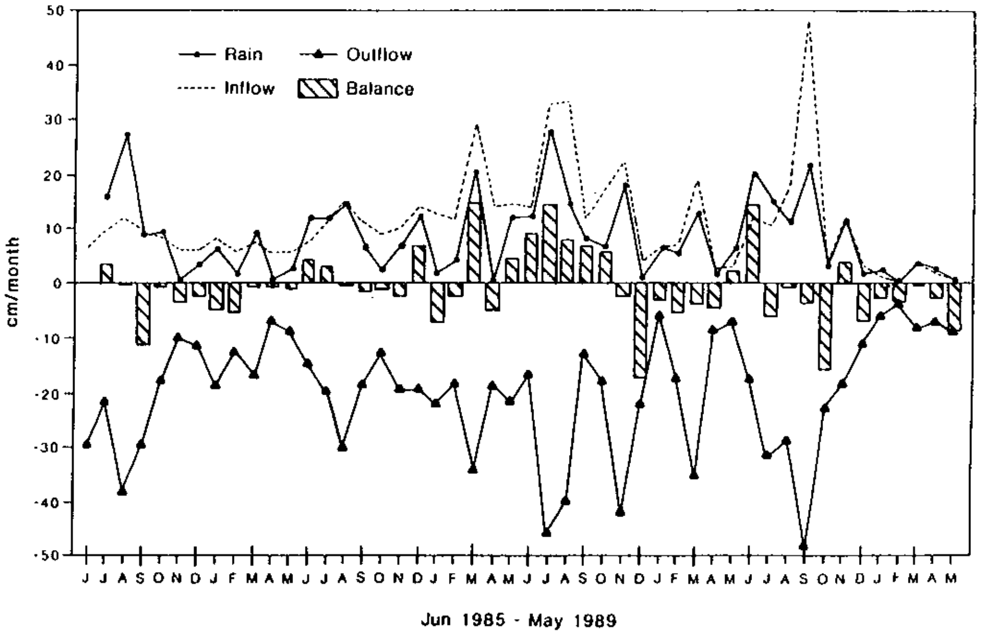

Fig. 12. Surface-water budget at Gardinier site, June 1985 to May 1989 (from Riekerk et al., 1990).

completion of site recontouring, thus the very high turbidities. The highest readings were associated with the most downstream sites (8, 9, and 10). Turbidity values generally declined during the 7 months of data collection, although turbidity exceeded 40 NTUs in several samples. As the site

TABLE 8

Turbidity at the Gardinier site. Sampling locations are shown in Fig. 3

Sampling station	Turbidity (NTU)				
	September 24 1983	October 23 1983	December 21 1983	March 1 1984	April 30 1984
1	5	8	4	5	*
2	110	*	41	28	*
3	6	*	*	*	*
4	42	9	78	5	11
5	110	78	42	35	40
6	125	17	52	17	9
7	*	8	*	7	5
8	145	45	56	16	11
9	145	40	53	12	9
10	145	53	68	14	21

* Sampling station was dry.

stabilized and vegetation helped to filter surface waters, the turbidity of water samples dropped off significantly (from 145 to 21 NTUs at the outfall).

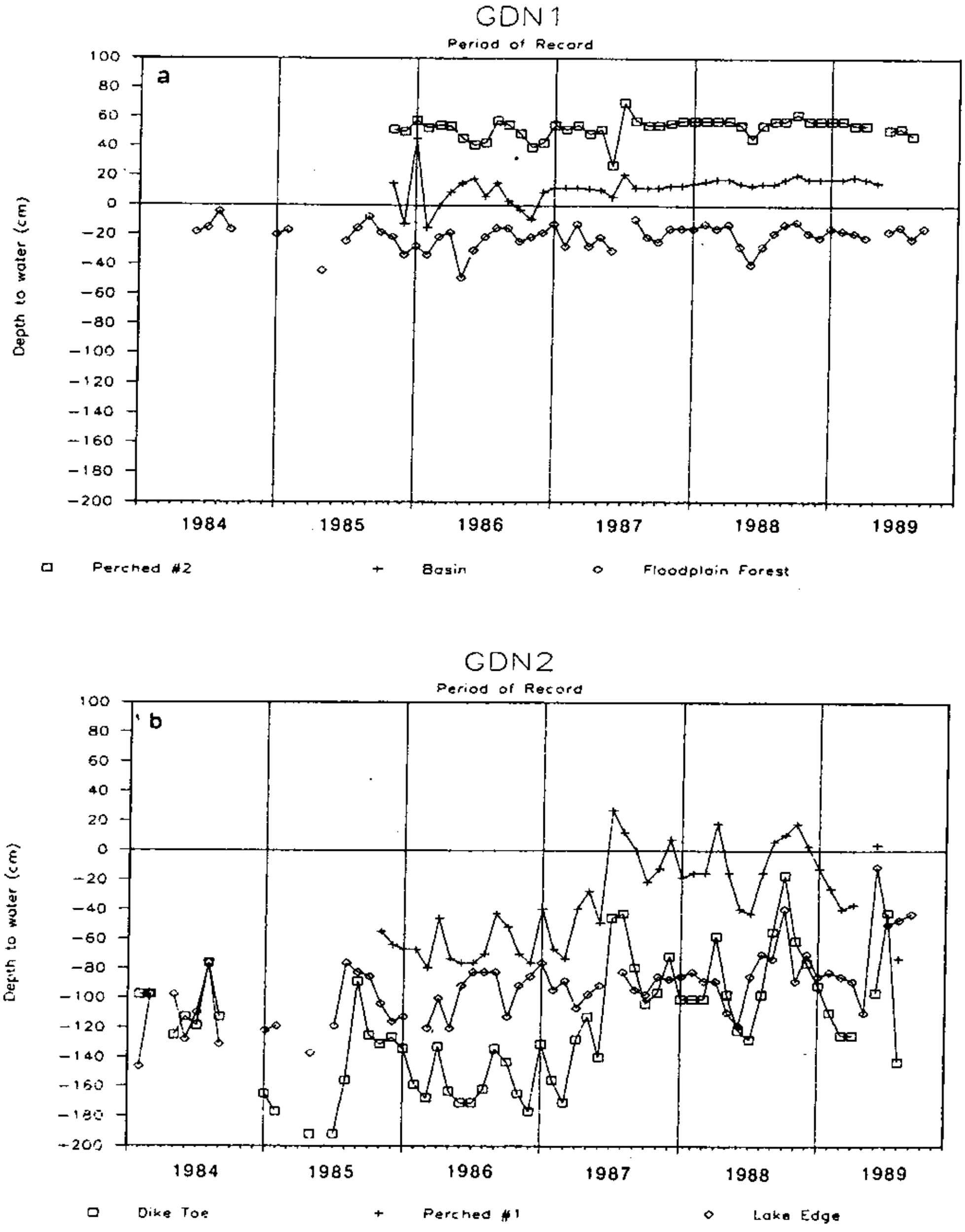

Fig. 13. Water levels in wells along the (a) N–S and (b) E–W transects at Gardinier site at locations shown in Fig. 3.

Groundwater

Figure 13a gives seasonal water levels in several wells along the north–south transect (GDN1, see Fig. 3), showing the effect of groundwater seepage in maintaining relatively high and stable water levels in perched wetland 2, minor depth, but relatively stable levels of surface water (< 10 cm) in the central basin, and high water table elevations next to the floodplain forest of Whidden Creek. Groundwater elevations were not as high in the east–west direction (GDN2, Fig. 3), as shown in Fig. 13b. Water elevations in perched wetland 1 were below ground surface for most of the period of record and showed greater range of fluctuation than perched wetland 2. Further downstream, water levels were much deeper.

DISCUSSION

Hydrology

Probably the single most important lesson learned from the overall planning and design of the reclamation site resulted from the change in surface-water characteristics of the adjacent clay settling area. For several years prior to commencement of reclamation, water had flowed from both dewatering stations onto the site. However, shortly after completion of recontouring on the site, flow from the clay settling areas ceased. Groundwater velocity and direction showed substantial flows through the dike into the site. In essence, the clay settling area switched from a surface water to a groundwater feature. The reclamation site became primarily a groundwater dominated system rather than the surface-water system it was designed to be.

Exactly what changes within the adjacent clay settling area had taken place to precipitate the eventual loss of surface-water discharge is unknown. There were no active measures taken by Gardinier, so we surmise that continued desiccation and settling of the clay caused elevations to recede sufficiently that surface storage within was large enough to accommodate most rainfall events. In addition, desiccation of the clays may have caused enough surface cracking that downward migration of surface waters was facilitated. Previous to this study, the general belief by industry and state regulatory agencies was that surface runoff would dominate the hydrology of clay settling areas and, therefore, regional surface runoff would increase after reclamation. An analysis of this and other reclamation areas (Riekerk et al., 1990) suggests that these elevated "catchment areas" will contribute more via groundwater seepage.

The seepage of groundwaters from south to north (Fig. 13) had a significant effect on the site. The southern half of the site remained sufficiently moist to promote vigorous vegetative growth. Seepage areas throughout the southern portions of the site developed small surface-water streams that contributed to soil moisture in the central basin. In all, while the surface-water budget was dominated (volumetrically) by surface inflow into the lake, it was the groundwater contribution from the clay settling area that dominated the site's ecological organization.

Vegetation

Whidden Creek Floodplain

Results of analysis of the vegetation structure of the Whidden Creek Floodplain Forest suggested a relatively immature (low diversity, early successional) forest. The high number of sapling-sized trees (3003/ha) and relatively low species richness, density, and total basal area, as well as the large number of standing dead in the canopy, helped to confirm this evaluation of the swamp. The prevalence of *A. rubrum* (a wind-dispersed, early colonizer) and the presence of *M. virginiana* (a bird dispersed species) in the swamp were affected by seed dispersal to the reclamation site. The lack of certain other species in both the canopy and subcanopy, but whose seeds were found in seed traps, suggested that the seeds did not originate in the Whidden Creek Swamp.

Site vegetation

Survival of planted seedlings varied with species and location. Soil moisture conditions contrasted between the two transects. GDN1 (the north–south transect) overall, had higher soil moisture conditions than GDN2 (the east–west transect). Percent survival, and growth of planted trees were higher on GDN1. In general, trees representing mesic species that were planted in transitional areas had lower survival than trees of hydric species. Survival of these trees is most probably a function of both species and location. Experience has shown that *C. occidentalis*, *C. bignonioides*, and *M. virginiana* have higher mortality rates than some other species. However, the fact that *C. occidentalis* was only found on the drier of the two transects probably contributed to its low survival. *M. virginiana* exhibited relatively low survival on both the dry and moist transects, but did show much lower percent growth on the drier sites than on the wetter.

Seed dispersal

Wind-dispersed seeds were an important component of the seed input to the Gardinier site, contributing hundreds of seeds per year to the areas immediately adjacent to the Whidden Creek Floodplain Forest. Distance to a seed source is a critical variable. Without seed islands within the mined landscape, the numbers of seeds in the regional seed rain averaged only about 51 seeds m^{-2} $year^{-1}$ (Table 4). Bird-dispersed seeds were less affected by distance to the seed source than by the availability of perching sites. Snags were heavily used as perches, as demonstrated by the large quantities of both tree and shrub seeds collected beneath them (Figs 7 and 8).

The species composition beneath snags was markedly different than the seed rain would suggest. *Lantana camara* and *Myrica cerifera* and an unidentified vine dominated. *M. cerifera* was absent in the initial seed rain, but this may have been the result of timing of seed collection. *Phytolacca americana*, *Vitis* spp. and *M. virginiana* were the dominant seeds found during the seed capture period, however they were not important in the vegetation beneath snags 7 years after installation. Many later successional forest species were dispersed to snags (i.e., *Magnolia virginiana* and *Persea palustris*), but none became established beneath the snags. A factor other than seed dispersal limits species establishment. The causes are not known, but may be attributable to high predation or lack of suitable soil. The data in Fig. 5 confirm this since, in April 1984, many *M. virginiana* saplings grew at the base of one snag that apparently did not survive.

The data given in Fig. 10 and Table 7 suggest that while numerous seeds were brought to the site by birds, conditions were not conducive for establishment. All snags were installed in upland locations, where desiccation could imperil both seeds and seedlings. A better practice may be to install snags in areas having soils with high moisture content such as seepage areas and wetland and lake fringes.

Water dispersal could play an important role in revegetation of mined lands, considering the densities of waterborne seeds (Fig. 11), as long as forested headwater areas exist as a seed source. Where water flowed from a mined area, practically no seeds were carried; but immediately downstream of a small remnant floodplain forest, the number of seeds carried in the same creek were comparable to other forested rivers (Wolfe, 1987).

CONCLUSIONS

Studies of the reconstructed topography in relation to surface and groundwater, growth and survival of planted tree species, seed dispersal by wind and birds, and site hydrology provide insights for planning reclamation on a landscape scale. The following are several important principles that have become clearer as the result of this reclamation effort and that we believe may help to increase the efficiency and long-term ecological and hydrological stability of reclaimed landscapes.

* Remnant forest islands are an important component of the reclaimed landscape since they provide habitat for wildlife and a source of seeds for the revegetation of mined landscapes. Wherever possible, forest islands should be preserved to accelerate and diversify landscape reclamation.
* Water dispersal of seeds can play an extremely important role in the revegetation and diversification of reclaimed floodplain forests if headwater wetlands are left intact and surface hydrology is restored.
* Bird dispersal and wind dispersal can add significantly to the seed bank in reclaimed wetlands and mesic communities at relatively minor costs compared to mulching.
* Bird perches and snags markedly increase the density of seeds dispersed by birds, however survival of seeds and newly germinated seedlings is limited by landscape position.
* Clay settling areas (which will comprise more than 60% of the phosphate-mined areas) will probably act more as sources of groundwater instead of surface water. The implications related to landscape-scale reclamation would suggest reclamation toward mosaics of seepage and groundwater-dominated wetlands interspersed with uplands instead of a dendritic pattern of flowing water wetlands.
* Groundwater elevations and resulting soil moisture significantly affect survival of planted vegetation. As a result, reclamation of phosphate-mined lands should proceed in stages. After recontouring, the site should be left for 1 year or more before planting to evaluate site hydrology and soil moisture conditions.
* Surface-water flows are difficult to predict within newly reclaimed landscapes. Therefore, planting of riparian wetlands should be delayed one or more years until surface hydrology has stabilized.

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