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FEASIBILITY OF SEDIMENT REMOVAL AND REUSE FOR THE RESTORATION OF LAKE APOPKA

FINAL REPORT

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EXECUTIVE SUMMARY

Lake Apopka forms the headwaters of the Oklawaha Chain of Lakes, a eutrophic to hypereutrophic chain of lakes located in Central Florida approximately 25 km northwest of Orlando. Once a popular resort area noted for its game fishing, Lake Apopka is now ranked as the 17th most eutrophic lake in Florida, largely because of poor sewage treatment practices adopted by the City of Winter Garden and direct backpumping of nutrient-enriched irrigation water into Lake Apopka and the Apopka-Beauclair Canal from low-lying muck farms on the northern shores of the lake. Sewage discharges from Winter Garden on the south shore of Lake Apopka began ca. 1922-1927, followed by muck farm discharges starting in 1942. Although in all likelihood Lake Apopka has always been quite productive, primary productivity historically was dominated by dense stands of macrophytes. Despite high rates of external nutrient inputs, macrophytes continued to dominate until 1947, when hurricanes destroyed large amounts of the bottom vegetation. Opportunistic algal blooms appeared almost immediately and have persisted unabated through the present.

In 1979, the U.S. Environmental Protection Agency (EPA) published a final Environmental Impact Statement (EIS) on the restoration of Lake Apopka. The final EIS recommended a phased restoration program consisting of short and long term objectives. Short term objectives included continued monitoring of in-lake water quality and a demonstration project to examine lake drawdown as a restorative measure; long term objectives included "continued evaluation of restoration alternatives and methods which would address the lake's internal loading problem." The efficacy of the most promising technique, lake drawdown, was acknowledged to be uncertain and, should drawdown prove infeasible, EPA suggested that "the possibility of dredging the lake and marketing the muck should be pursued."

The St. Johns River Water Management District (SJRWMD) has been charged by the State of Florida legislature to assess the feasibility of restoring Lake Apopka to Class III water quality standards (Chapter 17-3, Florida Administrative Code). As part of this legislative mandate, this study revisits the feasibility of dredging Lake Apopka. The economics of sediment reuse, which previously had not been analyzed, are examined in conjunction

with recent data on sediment physical and chemical characteristics to develop a cost benefit analysis of dredging, coupled with sediment reuse to restore Lake Apopka to a less-enriched, more beneficial trophic state. Because of the uncertain economics of sediment reuse specific for Lake Apopka sediments, the objectives of this study were thus twofold:

1. Evaluate via the existing literature the feasibility of sediment removal as a means to restore Lake Apopka, using documented case studies of other systems as models in conjunction with extant data for Lake Apopka to assess the effects on surface chemistry of the lake.

2. Evaluate the market potential for recovered sediment and develop a cost/benefit analysis for using sediment removal to restore Lake Apopka.

Dredging has been used with varying degrees of success to restore a number of lakes in North America and Scandinavia. To a very large degree, the success of dredging relates to the adequacy of pre-dredging studies to define the magnitude of the problem. Dredging is generally most feasible in small lakes with organically rich sediment, low sedimentation rates, and long hydraulic residence times. Large lakes have been dredged, but economics become increasingly important as lake surface area increases. Cost increases in larger lakes are non-linear, reflecting not just concomitant increases in material to be removed in larger lakes but also increased pumping costs as a result of increased pumping distance (reflecting head losses due to friction in the pipe conducting dredged material onshore) across larger lakes. The largest lake dredged to date is Vancouver Lake, Washington (1,052 ha). By comparison, Lake Apopka is nearly 12 times larger (surface area = 12,400 ha).

Problems inherent in dredging as a general technique include short term pulses of nutrient release and liberation of toxic materials (e.g., trace elements and organic pesticides) due to sediment resuspension, oxygen depletion, and potential effects to fisheries, wildlife, and benthic fauna. Other issues concern the ultimate use and stability of dredged material, as well as the treatment and disposal of nutrient-enriched supernatant from dewatered sediments. Pumping costs clearly indicate the need to dispose of dredge spoils near the lake. Finally, the overall efficacy of dredging is still in question despite the number of lakes which have been dredged; documentation of post dredging effects on lake restoration has been characteristically poor, largely because of limited resources.

Lake Apopka sediments generally consist of a relatively uniform, organic, flocculent material underlain by mostly peaty deposits. In 1987, the organic floc averaged 117 cm depth compared to 80 cm in 1968. Interstitial nutrient concentrations in the floc exceed water column concentrations by over an order of magnitude, and resuspension of this easily disturbed material is believed to be a major contributor to sustained, high rates of algal productivity in the lake. One major area of uncertainty regarding the effectiveness of the dredging in Lake Apopka is the internal loading characteristics of the underlying peat once it is exposed to the water column by dredging. Interstitial concentrations in the peat also are quite high, and the dynamics of nutrient transport across an oxic peat-water interface are unknown. The peat is believed to be physically more stable than the surficial floc, and resuspension effects on nutrient release in all likelihood would be reduced significantly.

Dredging costs for Lake Apopka were based on removing as much of the sediment floc layer as practicable. A 24-inch is the largest dredge which could operate reasonably in Lake Apopka; with this size dredge, only sediments under the 1.2 m contour would be removed. Under these operating constraints, approximately 10,400 ha would be dredged, giving a total volume of 121.76×10^6 m^3 of sediment to be removed. With five 24-inch dredges operating, dredging of Lake Apopka could be accomplished in 5.9 years. Total dredging costs, exclusive of (1) spoil area land acquisition and clearing costs, and (2) upland acquisition costs for storage of dried sediment prior to reuse or sale, total $868,800,000.

Sediment reuse offers only limited ability to recover dredging costs. Approximately 1.43×10^6 metric tons of dried sediment will be removed from Lake Apopka during each year of dredging. The total value of this material as fertilizer approximates $55,000,000; use as a soil amendment has an estimated yield of $25,000,000 to $50,000,000. An upper limit on the economic reuse value of dried Lake Apopka sediment is $97,400,000; this estimate is based on using Lake Apopka sediment as a growth medium for the ornamental horticulture industry and assumes that the dried sediment has the same value as peat. In all likelihood, the dried sediment will not have the same bulk texture characteristics as peat, and its direct usefulness to the ornamental horticulture industry will be limited. With a 20 percent mix on Lake Apopka sediment in the growth medium, the current market for Florida peat would yield an estimated $3,200,000 annual return on Lake Apopka sediment reuse. The option of using Lake Apopka sediment as a potting or growth medium for the ornamental horticulture industry thus defines the minimum cost for dredging: $771,400,000, which assumes that the upper limit market value of $97,400,000 from use as a potting medium can be realized. Project costs almost certainly will be closer to between $814,000,000 and $844,000,000.

A number of assumptions were made in the cost/benefit analysis that should be examined in more detail before further consideration is given to dredging of Lake Apopka. Uncertainties lie in three main areas: (1) engineering aspects of dredging, (2) sediment reuse, and (3) internal loading aspects of the remaining peat sediments after the unconsolidated floc (UCF) and consolidated floc (CF) sediments have been removed. One major uncertainty considers redistribution of UCF and CF sediments from undredged areas into dredged areas. Over the relatively long span of the project (5.9 years), redistribution is very likely and may negate much of the perceived benefits of dredging. Moreover, only 84 percent of Lake Apopka can be dredged with a 24 inch dredge, and some of the nearshore sediments will redistribute into the open lake after dredging has been completed. Other studies need to be conducted on the drying and handling characteristics of dried Lake Apopka sediment as well as determining its effects on plant growth before the economic value of Lake Apopka sediments can be firmly established. These studies are useful for developing more realistic reuse cost benefits; nonetheless, the upper limit market value of $97,400,000 will not increase whatever the outcome of these studies.

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1.0 INTRODUCTION

Lake Apopka forms the headwaters of the Oklawaha Chain of Lakes, a eutrophic to hypereutrophic chain of lakes located in Central Florida approximately 25 km northwest of Orlando. Once a popular resort area noted for its game fishing, Lake Apopka and the downstream lakes have become increasingly more eutrophic, largely because of poor sewage treatment practices adopted by the City of Winter Garden and direct backpumping of nutrient-enriched irrigation water into Lake Apopka and the Apopka-Beauclair Canal from low-lying muck farms on the northern shores of the lake. Sewage discharges from Winter Garden on the south shore of Lake Apopka began ca. 1922-1927, followed by muck farm discharges starting in 1942. Although in all likelihood Lake Apopka has always been quite productive, primary productivity historically was dominated by dense stands of macrophytes. Despite high rates of external nutrient inputs, macrophytes continued to dominate until 1947, when hurricanes destroyed large amounts of the bottom vegetation. Opportunistic algal blooms appeared almost immediately, and have persisted unabated through the present.

The St. Johns River Water Management District (SJRWMD) has been charged by the State of Florida legislature to assess the feasibility of restoring Lake Apopka to a less-enriched, more beneficial trophic state. Despite reductions in external nutrient inputs to the lake, no improvement in trophic state has been quantified, and total nitrogen and phosphorus concentrations in excess of 4 to 5 mg N L^{-1} and 0.2 to 0.3 mg P L^{-1} typically are observed today (Reddy et al., unpublished data). Internal loading or sediment resupply to the water column appears to be important in maintaining high rates of algal productivity (cf. Pollman, 1983) and, in all likelihood, restoration of the lake will require minimization of sediment nutrient release in conjunction with further reductions in external inputs. Initial studies of sediment removal indicated that costs of dredging are prohibitively high ($127 million in 1978 dollars exclusive of disposal costs); nevertheless, final judgement on the feasibility of this option for restoration was never rendered because the economic benefit of sediment reuse to offset the costs of dredging has never been evaluated.

SJRWMD currently is examining a number of potential restoration schemes for Lake Apopka, including dredging coupled with reuse of the sediments to improve the cost/benefit of restoration. Because of the uncertain economics of sediment reuse specific for Lake Apopka sediments, the objectives of this study are thus twofold:

1. Evaluate via the existing literature the feasibility of sediment removal as a means to restore Lake Apopka, using documented case studies of other systems as models in conjunction with extant data for Lake Apopka to assess the effects on surface chemistry of the lake.

2. Evaluate the market potential for recovered sediment and develop a cost/benefit analysis for using sediment removal to restore Lake Apopka.

2.0 OVERVIEW OF SEDIMENT EXCHANGE PROCESSES

As detritus accumulates in surficial sediments, metabolism of accreting organic material produces concentrations of interstitial phosphorus and nitrogen (NH_4^+-N) up to several orders of magnitude greater than corresponding concentrations in the overlying water column. Pollman (1983; Brezonik et al., 1978) reported interstitial soluble reactive phosphorus (SRP) and NH_4^+- concentrations of 0.40 to 2.80 mg P L^{-1} and 16.3 to 49.0 mg N L^{-1} in surficial Apopka sediments compared to average in-lake SRP and NH_4^+-N concentrations of 0.050 and 0.078 mg L^{-1} respectively (Brezonik et al., 1981). Release to the overlying water may be accomplished by burrowing and irrigation activities of benthic organisms (i.e., bioturbation), by gas ebullition from anaerobic decomposition processes, by scouring of the sediment-water interface by wind-induced waves, and by simple molecular diffusion in response to the concentration gradient that usually exists between the sediment pore water and the water column. Detailed reviews of these processes and their relative importance in lakes are offered by Lee (1970) and Pollman (1983).

In Lake Apopka, the dominant release processes are believed to be associated with sediment resuspension and, to a lesser degree, diffusion (Pollman, 1983). Reddy et al. (1988) have identified two surficial layers of flocculent sediments with low particulate density, high water content, and high nutrient concentrations that overly a more stable peat layer (see Section 3). This material is easily resuspended by moderate wind activity on the lake, thereby releasing significant quantities of N and P into the water column via entrained porewater enriched in SRP and NH_4^+- as well as desorbed SRP (Pollman, 1983). Pollman estimated that only 6 to 25 resuspension events are required annually to maintain the high rates of primary production observed in the lake compared to an average of 74 thunderstorm days for the Orlando area (Davis and Sakamoto, 1976). Controlling internal loading in Lake Apopka has keyed on the sediments, including consideration of (1) stabilization of the bottom sediments to prevent resuspension, (2) reducing or inactivating the nutrient burden in the sediments, or (3) removal of the flocculent material to the peat layer to remove both nutrients and reduce the potential for resuspension. This report focuses on the latter approach, and the following section reviews case studies where sediment removal has been implemented for lake restoration.

3.0 CASE STUDIES OF SEDIMENT REMOVAL

3.1 OVERVIEW

Sediment removal has proven to be an effective lake restoration measure in a number of cases. The objectives of lake sediment removal projects are generally deepening, nutrient control, toxic substances removal, and/or macrophyte control. The techniques, environmental concerns, dredge selection, disposal area design, and selected case studies have been reviewed by Peterson (1982) and Cooke et al. (1986).

There is at present no commonly accepted procedure for evaluating lake restoration techniques. Peterson (1982), however, suggested a number of important factors that should be considered in the development of a lake restoration plan: (1) problem sources, (2) sediment characterization, (3) sediment removal depth, (4) environmental problems, (5) sediment removal methods, (6) sediment disposal area, and (7) most suitable lake condition.

Quantitative data are needed in the form of nutrient budgets in association with algal blooms or other problems. Most nutrient budgets estimate surface and ground water hydrological and chemical inputs and outputs. Internal cycling of nutrients such as phosphorus and nitrogen are estimated by difference. Supplementary information is often obtained on sediment release of nutrients by means of in situ and/or laboratory tests under varying environmental conditions (e.g., aerobic, anaerobic, temperature differences).

Sediments are characterized by means of sampling sediment cores for determination of important physical and chemical characteristics. Sediment types and depths are mapped and such characteristics as particle size distribution, organic concentration, bulk density, toxics concentrations, nutrient concentrations, and oxygen status are determined. In the case of excessive nutrient concentrations in sediments, it is important to determine the vertical as well as horizontal distribution of the key nutrient(s).

Several potential environmental problems must be evaluated. These have been summarized by Peterson (1979, 1982) and Cooke et al. (1986). Strict environmental legislation has greatly increased the importance of adequate evaluation of environmental concerns in the early phases of project design, particularly in a number of northeastern states (e.g., Carranza and Walsh, 1985). Sediment resuspension, nutrient release (especially phosphorus), increased macrophyte growth due to clarification, oxygen depletion, liberation of toxic materials, fisheries, waterfowl and benthic fauna considerations all have the potential of causing significant problems in project design or implementation. A number of additional problems may be associated with dredge spoils disposal sites, particularly dike failure, groundwater contamination with nutrients or toxics, recontamination of lakewater, and ultimate use of dredged materials. High population densities often make it difficult to locate disposal sites in sufficiently close proximity to the lake site to avoid excessive pumping costs.

Generally, small lakes with organically rich sediment, low sedimentation rates, and long hydraulic residence times are the most feasible for dredging (Peterson, 1982). Very large lakes have also been dredged, however, (Table 3-1), and economics will play a major role in this regard.

The relevance of cost comparison for sediment removal is questionable because so many variables affect the final cost (Cooke et al., 1986). Project size, equipment used, proximity of disposal sites, sediment bulk density, environmental considerations, and use of dredged materials all contribute to widely varying degrees to the overall project costs. Hydraulic dredging costs ranging from \$1.25 m^{-3} to \$1.75 m^{-3} are relatively common, however, and probably can be considered as "reasonable", (Cooke et al., 1986). Cost estimates for a number of hydraulic dredging projects are provided in Table 3-1, and illustrate the wide range encountered. An additional complication is that some projects report costs for dredging activities alone, while others include disposal costs, EIS preparation, limnological studies, etc. These are sometimes substantial. For example, containment area costs for the year constructed were reported by Carranza and Walsh (1985) for Nutting Lake, Bantam Lake, and Allentown Lake as equivalent to \$0.66, \$1.82, and \$1.37 per m^3 of dredged sediments. These additional costs increase substantially those included in Table 3-1 for many of the lakes. Documentation of project costs and follow-up limnological studies are often lacking. This is likely attributable, at least in part, to a scarcity of funds for lake restoration research. When faced with limited funding, lake resource managers will generally opt for an additional alum treatment, for example, rather than spend the available money on documentation (Peterson, personal communication).

3.2 SELECTED CASE STUDIES

Lake Trummen, Växjö, Sweden

The best example of a successful lake dredging project for the purpose of controlling internal nutrient loading is Lake Trummen, a 400 ha lake near the city of Växjö in southern Sweden. The formerly oligotrophic lake received domestic sewage and wastewater from a flax factory, particularly from 1936 to 1958. Prior to the 1920's the lake had been utilized as a water supply source for Växjö. Water quality declined rapidly after 1943 when the flax factory began discarding waste into the lake, and winter fish kills became common. Inflow of waste to Lake Trummen was halted in 1957-58 with the closure of the Flax mill and diversion of domestic sewage. Water quality did not improve, however. The summer transparency was only 20 cm, algae growth was excessive, and fish kills continued, despite over ten years without sewage discharge. It was clear that internal nutrient sources were important in the continued eutrophication. Limnological studies showed that the upper one meter of sediment was enriched in nutrients. Lake restoration was carried out in 1970 and 1971, and included removal of one meter of surface sediment. Recovery was dramatic, and has been extremely well documented in the scientific literature (e.g., Björk, 1972; Björk et al., 1972, 1979; Andersson et al., 1973, 1975; Bengtsson et al., 1975; Cronberg et al., 1975; Gelin and Ripl, 1978; Cronberg, 1982). Lake Trummen is thus important both as an excellent example of successful lake restoration by dredging, and also in terms of its documentation of limnological changes associated with the restoration. Total cost of the restoration was approximately \$500,000, while an additional \$400,000 was spent on research (Bengtsson et al., 1975).

Pre-treatment studies

Lake Trummen became a major environmental problem for the town of Växjö in the 1960's because plans to further develop the shoreline were hindered by nuisance algae blooms, expanding macrophyte vegetation, oxygen deficiency, and fish kills. A preliminary restoration plan was proposed in 1966, and was followed by intensive limnological investigations and finalization of the restoration plan in 1969 (Björk et al., 1972). A loose surface sediment layer of black gyttja, deposited during the recent pollution period, was up to 40 cm thick, and was underlain by a well consolidated brown gyttja. The release of PO_4 - P under aerobic conditions was estimated to be 1.7 mg m^{-2} day^{-1} for the surface sediment, compared to 0 for the underlying brown gyttja. Under anaerobic conditions, this release increased to 14 mg m^{-2} day^{-1} for surface sediment, as compared with 1.5 mg m^{-2} day^{-1} for the lower layer (based on laboratory experiments at 15°C) (Bengtsson and Fleischer, 1971). Release of NH_4 - N was also elevated in the surface sediment under anaerobic conditions (73 mg m^{-2} day^{-1} compared to 0 in the lower layer).

Dredging

In 1970, 0.5 m of sediment was removed by suction dredging, and an additional 0.5 m was removed in 1971. About 600,000 m^3 of mud and 300,000 m^3 of water were pumped to settling ponds constructed on a moraine area adjacent to the lake (from which the topsoil had been removed) (Björk, 1972) and by building embankments across some narrow bays (Gelin and Ripl, 1978). Runoff water from the settling ponds was a mixture of lake and interstitial water, and was very high in total phosphorus concentration. Aluminum sulfate was used for precipitation of suspended material and phosphorus in the effluent water, reducing the total P concentration from about 1 mg L^{-1} to 30 ug L^{-1} (Figure 3-1). Dried sediment was sold as fertilizer for lawns and parks.

Water chemistry

Water quality prior to restoration was highly variable. Although water renewal time was theoretically 3 months, the actual flow pattern of the tributaries showed a rapid water exchange in spring and fall, with stagnation in summer. The sediment-water interface usually became anoxic after establishment of ice cover and occasionally during calm summer days. Total phosphorus and phosphate usually showed two distinct maxima during the year, at the end of the ice covered period and during summer. These peaks were much reduced after dredging (Figure 3-2), and remained at the lower levels (Figure 3-3). After restoration silica was depleted at a much slower rate and reached a minimum in summer, corresponding to the abundance of diatoms (Cronberg, 1975; Bengtsson et al., 1975). Organic carbon concentrations decreased from approximately 80 mg C L^{-1} to 20 mg C L^{-1}. Diurnal fluctuations in oxygen, pH and alkalinity were reduced significantly after the restoration. Post-treatment water quality studies were carried out through 1985, and demonstrated continued low concentrations of total phosphorus and nitrogen for a fourteen-year period after dredging (Andersson, 1986).

Sediments

Prior to the recent eutrophication, deposition rates of organic matter, P, N, and metals were fairly low and typical for the region (Bengtsson et al., 1975). Surface sediment was enriched by at least 5 times in phosphorus and about 3 times in nitrogen, however. Increased organic load induced high microbial activity and a reduced sulfide-rich sediment layer, that released high amounts of phosphate and ammonia, especially under anoxic conditions (Bengtsson and Fleischer, 1971). After dredging, reduced sediment was found in less than 10 of 116 cores and never exceeded 5 cm in thickness (Bengtsson et al., 1975). The post-dredging surface sediment was less organic, more consolidated, and contained less N and P. Interstitial phosphate concentration decreased by 200-500 times (Table 3-2) and ammonia decreased to half the pre-restoration concentrations. Phosphorus release experiments with the new surface sediment confirmed the much reduced release rates.

Phytoplankton

Changes in phytoplankton abundance, size fraction distribution, and productivity in connection with the Lake Trummen restoration project were reported by Andersson et al. (1973), Cronberg et al. (1975), Gelin and Ripl (1978), and Cronberg (1982). The following discussion is taken from these studies.

During the period 1968-1978, the phytoplankton showed similar seasonal variations. In winter very few algae were found in the lake, mainly Chrysophyceae, Cryptophyceae, and small green algae, sometimes forming blooms for short periods. Blue-green algae started to develop in the beginning of June. Filamentous blue-greens dominated initially, but in July-August they were succeeded by Microcystis spp. In autumn a new maximum of diatoms appeared, consisting of Melosira and/or Synedra. Most algae disappeared when the ice cover developed. In the summers 1968 and 1969, i.e., before restoration, the total biomass of phytoplankton was high (Figure 3-3). However, there was a drastic decrease from the start of restoration in 1970 and onwards.

Before restoration blue-green algae were most important in the Lake Trummmen plankton community. In 1970 the biomass of blue-greens was reduced to 5% of the prerestoration values. Microcystis, especially M. aeruginosa, formed heavy blooms in 1968 and 1969, but was much reduced after restoration. It was succeeded by small blue-green algae such as Aphanothece, Synechococcus and Cyanodictyon.

Green algae developed large biomass peaks in spring and autumn before restoration. During restoration, and especially in 1971, the biomass of green algae increased, and the maximum appeared during summer. Many different species were represented at that time, but the most abundant genera were Pediastrum and Scenedesmus. Pediastrum boryanum was the most dominant Pediastrum species before restoration, but its biomass decreased thereafter. P. duplex and P. gracillimum appeared in great numbers during the restoration period. After restoration the biomass of the genus Scenedesmus decreased, and the species composition changed. During the whole observation period the genus was represented with 21 species. Initially the most common species were S. abundans, S. acuminatus, S. arcuatus, S. armatus, S. oahuensis, and S. quadricauda. After restoration they all decreased. During the course of restoration the number of large Scenedesmus species decreased while the number of small species, such as S. subspicatus, increased. After restoration the size of Scenedesmus coenobia also decreased. Other green algae that were reduced after restoration were Chlamydomonas spp., Micractinium pusillum and Chorella sp.

Chrysophyceae occurred before restoration at low densities in Lake Trummen. After restoration the number increased from 11 species to 50. The most important genera were Dinobryon, Mallomonas, and Synura. They increased immediately after restoration. The highest peak of Chrysophyceae was recorded in spring 1971, after which a spring maximum appeared every year, but with reduced size.

Before restoration, diatoms appeared with both spring and autumn maxima and high biomass. After restoration the seasonal pattern changed. Diatoms became more frequent during summer, but the total biomass decreased. Melosira was the most important diatom genus in lake Trummen. Before restoration Melosira formed spring and autumn maxima with high biomass. After restoration it appeared during summer, and the biomass was reduced by 57%. No changes in Melosira species composition were seen during the investigation period. The same species dominated, viz. Melosira ambigua, M. granulata var. augustissima and M. italica subsp. subarctica. Stephanodiscus hantzschii was reduced after restoration, but Cyclotella spp. seemed to increase.

More species of blue-green and green algae were represented in lake Trummen before than after restoration. The decrease in connection with restoration was mainly in the orders Chroococcales and Chlorococcales. After restoration on the other hand, the number of Chrysophyceae species increased threefold. The number of species of Pyrrhophyta, Diatomophyceae and Xanthophyceae remained more or less the same during the whole investigation

period. It was evident that the number of periphytic and benthic species was reduced (Chlorococcales), while true planktonic species increased (Chrysophyceae) in connection with the restoration.
The restoration of Lake Trummen induced an immediate and drastic reduction in phytoplankton biomass. Species diversity increased during the restoration period and a few years after, but stabilized at nearly the same level as before restoration. However, species composition changed completely as a result of the restoration (Cronberg, 1982).

The biomass of netplankton, especially Microcystis spp., decreased drastically, while nannoplankton (< 20 um) became more abundant. The maximal productivity per unit volume decreased from about 10 g C m^{-3} day^{-1} to 1-2 g C m^{-3} day^{-1}. The calculated mean annual productivity of the total phytoplankton community decreased from 370 g C m^{-3} yr^{-1} to 225 g C m^{-3} yr^{-1} (Gelin and Ripl, 1978). The mean biomass of phytoplankton from June until September decreased from 75 to 10 mg L^{-1} after restoration, due to the lower abundance of blue-green algae (Figure 3-4). The biomass increased somewhat after 1977, but stabilized at slightly less than 20 mg L^{-1} through 1984 (Anderssen, 1986). The number of aerobic heterotrophic bacteria in the water did not change after the restoration, but a marked decrease was observed in protein-, starch-, and glucose-decomposing bacteria (Cronberg et al., 1975).

Zooplankton

Prior to restoration, the zooplankton community was numerically dominated by rotifers in spring and rotifers plus cladocerans in summer. The restoration period itself (1970 and 1971) was characterized by a striking decrease in the abundance of cladocerans, while some rotifers were favored by conditions during the restoration (Andersson et al., 1973). After restoration, cladoceran abundance remained low and rotifer abundance decreased to half the pre-restoration values in summer. The most striking difference found before and after restoration with respect to zooplankton was that the numbers of some species declined dramatically, especially some species that are considered as indicators of eutrophy, e.g., Brachionus angularis, Trichocerca pusilla, Keratella quadrata, and Chydorus sphaericus (Andersson et al., 1973).

Macrobenthos

Before restoration the mud dwelling fauna was dominated by Oligochaeta and Chironomidae (mainly Chironomus plumosus), and fluctuated between 1000 and 2000 ind/m^2. This low abundance for total macrobenthos in the hypereutrophic Lake Trummen was of the same order of magnitude as in oligotrophic lakes in the same region. The extreme environmental conditions prevailing in the lake before restoration, especially oxygen content in near-bottom water, may have limited macrobenthos to a great extent. The main impact of dredging was an increase in the abundance of the tubificids and chironomids (Andersson et al., 1975). Surprisingly, the dredging in July, 1970, did not result in any profound decrease in the number of benthos as a whole. Regarding the chironomids, this might be due to larval mobility (Andersson et al., 1975).

Fish

Before restoration the biomass of the fish community, as indicated by catch size, was large and consisted mainly of roach (Rutilus rutilus), bream (Abramis brama), silver bream (Blicca bjoerkna), pike (Esox lucius), perch (Perca fluviatilis), eel (Anguilla anguilla), tench (Tinca tinca), and rudd (Scardinius erythrophthalmus). Interpretation of restoration impacts on the fish community was complicated by a severe fish kill during the hard winter of 1970 - immediately before the restoration. Almost all the bream and silver bream were killed during that winter (except some older specimens). All young roach were also killed (Andersson et al., 1975). A large influx of planktivorous cyprinid fish occurred in 1975, and may have been associated with the temporary increase in lakewater phosphorus concentration in that year (Figure 3-2, Cooke et al., 1986). From 1976 through 1979, large quantities of fish were taken from the lake and phosphorus concentrations remained low. When fishing stopped in 1979, the P levels began to rise again (Andersson, personal communication, cited in Cooke et al., 1986), suggesting that fish populations play a role in eutrophication (Cooke et al., 1986).

Lake Trehörningen, Sweden

Lake Trehörningen, located near Stockholm in central Sweden, is a 0.65 km^2 urban lake that deteriorated in quality as a result of pollution from the Huddinge municipality. The lake is shallow, with a maximum depth of 3.5 m. Over 75% of the drainage basin is urbanized. The restoration project, carried out in 1975 and 1976, involved several phases (Ryding, 1982), implemented after application of advanced wastewater treatment and sewage diversion:

1. Impounding an overgrown bay of the lake (Lännaviken) to serve as a settling pond,
2. Diversion of urban stormwater through the Lännaviken settling pond,
3. Elimination of dense macrophyte vegetation,
4. Dredging surface sediment to a depth of 0.2 to 1.0 m (depending on thickness of nutrient-rich layer), and
5. Treating runoff water from the settling pond with aluminum sulfate for precipitation of phosphorus and suspended matter.

About 320,000 m^3 of reduced sulfide-rich sediment (gyttja) was removed by suction dredging and deposited, along with macrophytes, in the settling pond, which had an area of 150,000 m^2. Most of the macrophytes were removed from the lake, although some separate stands and small bays were left for waterfowl habitat. Limnological studies were carried out in 1975-1983 and reported by Ryding (1982) and Bergquist (1986).

Concentrations of phosphate and total phosphorus decreased in the eastern basin of Lake Trehörningen by 73 and 50%, respectively, between 1975 and 1978, based on average summer values. Organic matter content decreased by 22%. The N/P ratio increased from 6.5:1 to 14.2:1, and nitrate increased tenfold. In the western basin there were no changes in concentration of phosphorous or organic matter, but an increase was observed in all nitrogen fractions (Ryding, 1982). Total phosphorus concentration was monitored through 1983 and continued to decrease to approximately 20% of the prerestoration values (Bergquist, 1986) (Figure 3-5).

A more dramatic response was found for algal growth potential (number of cells and cell volume). The high values observed in the eastern basin prior to dredging did not occur in 1976 or 1977. Chlorophyll a decreased markedly through 1983 (Bergquist 1986, Figure 3-5).

The limited success of the Lake Trehörningen restoration project was attributed by Ryding (1982) to continued high external loading of nutrients. According to Vollenweider's (1968) external loading criteria, the areal nitrogen and phosphorus loads far exceeded critical levels after restoration. Subsequent efforts were geared towards additional treatment of inflowing waters from the major inlet rivers to Lake Trehörningen. Although the project did not achieve the dramatic changes observed in Lake Trummen, substantial improvements in water quality were observed. The experience of the Lake Trehörningen restoration project emphasizes the need for thorough evaluation of nutrient budgets prior to implementation of expensive dredging activities.

Lilly Lake, Wisconsin

Dunst (1982) reported twelve lake dredging projects in Wisconsin, carried out by the Office of Inland Renewal within the Wisconsin Department of Natural Resources (DNR). These included both natural and man-made lakes up to 205 ha in size and 1.7 x 10^6 m^3 of sediment removed. Reservoirs located on major river systems had sediment solids contents of 70-80%, whereas natural lake sediments were lightweight and organic, with 1-5% solids. The objectives of these projects were primarily to deepen the lakes for improved recreational use and/or to control aquatic macrophyte growth. One of the lakes, Lilly Lake, is a natural seepage lake that was experiencing excess nutrient levels and macrophyte growth, and is of interest with respect to the lake Apopka feasibility study. Results of the Lilly Lake dredging project were reported by Dunst (1982) and Dunst et al. (1984). Also of interest to the Lake Apopka study is the problem encountered by the Wisconsin DNR of site availability for disposal of contaminated sediments. Arsenic was the most troublesome element and reached concentrations up to 659 ug g^{-1} dry weight in some surface sediments (Kobayashi and Lee, 1978; Dunst, 1982). Groundwater contamination from the disposal sites was a major concern. The source of the arsenic apparently had been application of sodium arsenite for macrophyte control in the 1950's and 1960's.

Lilly Lake is a 37 ha seepage lake in southeastern Wisconsin with pre-dredging mean and maximum depth of 1.4 and 1.8 m, respectively. More than 10 m of organic sediments were present, having water content of 90-98%, and a dense cover of macrophyte growth was present. Winter fish kills were common.

The dredging operation removed 683,000 m^3 of sediment in 1978 and 1979 using a hydraulic cutterhead dredge and increased maximum lake depth to 6.6 m. Both inlake and disposal site effects were investigated and reported by Dunst et al. (1984). During the dredging activities lake levels dropped 1.5 m, producing an increased inflow of groundwater with flow reversal in all of the previous outflow areas. Lakewater chemistry therefore became more similar to groundwater chemistry. Conductivity and alkalinity increased. Because of sediment disturbance, ammonia nitrogen, total phosphorus, and biological oxygen demand also increased. Algal populations showed an initial increase in terms of chlorophyll a, gross primary productivity, and total biomass. No major changes were observed in algal diversity or relative composition, and in-lake dissolved oxygen did not change.

After restoration, the lake refilled to pretreatment levels and had higher concentrations of base cations, chloride, conductivity, and alkalinity than prior to the dredging project. Total phosphorus, however, was lower, especially NaOH extractable phosphorus. The sediments were still the most important reservoir of phosphorus after restoration, however. Groundwater furnished 46% of the hydrologic input in 1988 but only 9% of the phosphorus, based on measurements and predictive equations.

Dredged sediments were deposited primarily at a modified gravel pit. Two earthen dikes were constructed at the settling basin - one across the open side of the 18 ha gravel pit and a second through the middle, thus creating two subasins. In 1979, agricultural land was also used for sediment disposal. Dikes were erected on 15 ha of land, creating 6 individual basins capable of holding up to 2 m of sediment. Spray irrigation equipment was installed on 10 ha for dispersal of the sediment, but the fibrous organic sediments consistently clogged the 5 cm orifice nozzles. The irrigation technique was subsequently abandoned (Dunst 1982). Changes in groundwater systems were evaluated with observation wells at both disposal sites and drinking water wells at the gravel pit. Response time was generally related to soil permeability and distance from disposal site. Impact duration was short because the organic lake sediments quickly inhibited continued seepage of water away from the sites. In general, therefore, the surrounding groundwater was not much affected (Dunst et al., 1984). In 1983, the gravel pit was still retaining water, but sediments in the diked area were spread and dried and added to agricultural soils.

Laboratory, greenhouse, and field studies were carried out to determine the effects of dredged sediment on agricultural crops when the sediment was applied as a soil amendment. Results suggested that, of the factors measured, the only beneficial effect to crops from the application of Lilly Lake sediments could be an increase in nitrogen availability which would probably continue to be effective for a number of years. Crop yield, tissue concentrations (N, P, K, Ca, Mg, S, Fe, Mn, Cu, Zn, B, and plant uptake (N, P, K) were investigated. No harmful effects were apparent (Dunst et al., 1984).

Liberty Lake, Washington

Liberty Lake is a 288 ha softwater lake located near Spokane, WA. It is enclosed on three sides by low mountains (up to 900 m elevation), and most of the 3,445 ha watershed is forested with a mixed coniferous forest and aspen. The major tributary, Liberty Creek, flows along the margin of a

40 ha marsh before entering the lake. Residential areas occupy 87% of the shoreline. Domestic waste disposal had been by septic tank and a sewer system built in 1910. A new sewage collection system, installed in 1979 to serve 2000 permanent residents, diverted 95% of the domestic sewage from the lake basin. The lake has a mean residence time of three years and becomes weakly stratified for short periods in middle and late summer.

The Liberty Lake restoration project was initiated after several years of lake and watershed studies in response to massive blooms of blue-green algae (*Gloeotrichia*, *Anabaena*, *Aphanizomenon*). Nutrient sources were apparent in groundwater from near-lake septic tanks, in the marsh adjacent to the lake, in storm runoff from developed areas, and from heavy organic muck sediments (Lamb and Breithaupt 1986). Sediment release of phosphorus was estimated to account for almost half of the estimated aerial loading of 0.37 g P m^{-2} yr^{-1}. A restoration plan was prepared in 1979 that recommended construction of marsh flushing controls, dredging to remove nutrient-rich sediments from a portion of the lake bottom, an alum treatment, and preparation of a stormwater management plan. Construction of the wastewater collection system was already complete in 1979. Results of the multiphase restoration project were reported by Funk *et al*. (1982) and Lamb and Breithaupt (1986).

The first restoration measure was diversion of spring flood waters around the marsh. Phosphorus inflow in Liberty Creek was reduced from 148 kg P in 1977 to 59 kg P in 1980. Estimated groundwater input prior to completion of the sewer collection system was 150-300 kg P and 1700-3000 kg N. The P input was estimated to be reduced to about 25 kg P in 1982, and it was anticipated that several additional years would be required to leach the soils around the lake of excess nutrients (Funk *et al*., 1982).

Extensive lake sediment core samples were collected to determine sediment nutrient content and release potential (P and N), and to construct a map of sediment types. Laboratory tests revealed that two of seven major sediment types (refractory organic silt and heavy organic muck) contributed high levels of P loading under anoxic conditions. The 120 ha region of lakebottom containing these sediments was scheduled for dredging to remove the top 0.5 m of sediment, which was estimated to contain 70-90% of the phosphorus pool.

Unanticipated problems were encountered in the dredging operation. A standard cutterhead dredge was used for the first 2.8 ha. The contractor was unable to determine the location of the top 60 cm of light organic sediment. By the time the dredge intake vacuum guages indicated that they were removing sediments, they were already below the flocculant, nutrient-rich surface sediments. The contractor was unwilling, however, to use an alternative means of identifying the sediment surface. Dredging was halted after 25 days, but resumed in 1981 with a new contractor, a horizontal cutterhead (Mudcat) dredge, and an improved spoils disposal procedure. The operation removed an estimated 415,000 m^3 of spoils, containing 15,168 kg of sediment phosphorus (Lamb and Breithaupt, 1986).

Post-dredging scuba and sonar surveys showed that the horizontal cutterhead dredge had missed areas between the dredged swaths, resulting in a trough and mound situation and a portion of the dredged area still being covered by nutrient-rich surface sediments. Only about 40% of the dredged area was estimated to have been dredged efficiently. An additional complication resulting from the trenching was that some macrophytes were left along with surface sediment. This resulted in a rapid re-establishment of the macrophyte bed. The problem was apparently caused by free play in the dredge's drive cable which was stretched 490-600 m across the lake. It was impossible to remove all slack from the line, and the dredge was susceptible to being moved off line by winds or movement of the spoils discharge pipe line. Lamb and Breithaupt (1986) suggested that intermediate cable anchoring would be needed to shorten the effective length of cable if this problem was to be eliminated.

The two phase dredging of Lake Trummen (half meter each year) is another alternative, however. Because of the delay in the start of dredging, the planned whole lake treatment with 10 mg alum L^{-1} had to be made in two partial treatments: the northern portion in October 1980 and the southern portion following completion of dredging in May 1981. Significant impacts on water chemistry were short-lived. The overall effect on total phosphorus concentration was not clear and different sites showed different responses. This may have been due to mixing of treated and untreated waters during the two partial treatments (Lamb and Breithaup, 1986).

Annual phosphorus load values were much higher for the post restoration period (1981-84) than for the three years prior to restoration. This resulted from a dramatic increase in hydrologic inflow during the post restoration study period (almost 250% increase in 1980 and 1981). The trophic state of Liberty Lake did improve significantly after restoration, however, based on the ratio of trophic state index (TSI) to total phosphorus load (Lamb and Breithaup, 1986). In view of the complications caused by major hydrologic variation between pre- and post-restoration studies and the diversity of restoration techniques utilized, it is not possible to evaluate the success of the dredging project.

Sylvan Lakes, New Jersey

The Sylvan Lakes system is comprised of two small lakes, 1.6 and 5.6 ha in surface area, in central New Jersey. The watersheds are approximately 50% urban, and development plans call for 90% urban development. Approximately 0.6 m of organic silts have accumulated on the sandy clay lake bottom. Macrophytes cover the entire bottom of the upper lake and are also excessive in the lower lake. The potential sediment phosphorus release was estimated to be up to one-third of the total phosphorus load. Alternatives were evaluated for lake restoration, including dredging, sediment exposure and consolidation, bottom sealing, water level fluctuation, herbicide application, and macrophyte harvesting. Dredging was selected as the best measure for deepening the lake, removing existing macrophytes, and removing nutrient-rich sediments. A preliminary restoration plan was presented by Horstman and Copp (1985), but published data are not available for the dredging or post-restoration period.

Hydraulic dredging was selected as the most cost-efficient method for sediment removal because the sediments are extremely fine-grained organic silts. Two farms were selected as disposal sites for the sediment spoils. At one farm the sediments will be partially dewatered in a temporary diked area, and then applied by spreading. The dredge pipeline slurry will discharge directly to the second farm, where a 1 m dike will be built to contain the slurry. Estimated percolation and evaporation rates suggest that little discharge of water is expected from the farm basins.

<u>Vancouver Lake, Washington</u>

Vancouver Lake is located in the Columbia River floodplain adjacent to Vancouver, WA. Depth varies seasonally from less than 1 m in fall to about 4 m in early June. Prior to restoration, the 1100 ha lake had a flat bottom except where sediment was deposited from the major inlet. The hydrology is complex, involving three drainages in addition to the Columbia River. Burnt Bridge Creek flows through commercial and residential sections of the city of Vancouver, and provides high levels of nutrient loading to the lake. Lake stage is controlled directly by the stage of the Columbia River. During low water in late summer, the River has a daily tidal fluctuation of about 0.6 m, but tidal influence is reduced at high water.

Prior to restoration, Vancouver Lake was extremely shallow in summer, and contained high concentrations of nitrogen, phosphorus and Coliform bacteria. Use was restricted by the shallow depth, low transparency, algal blooms and wind resuspension of bottom sediment. Preliminary results of the three-faceted lake restoration project were reported by Raymond and Cooper (1984) and are summarized below.

The restoration plan included the following elements:

1. Introduction of low nutrient water from the Columbia River via a 3.6 km excavated channel,
2. Dredging to promote circulation of river water and to restrict the circulation of nutrient-rich Burnt Bridge Creek water, and

3. Imposition of water quality controls in the Burnt Bridge Creek watershed.

The dredging component of the restoration plan involved dredging channels 300-950 m wide along the sides of the lake, dredging sediment traps at the inlet from the flushing channel and the major river inlet, and extension of one channel near Burnt Creek Bridge. This plan involved removal of approximately 6.5 million m^3 of sediment from the lake in 1983.

Eight disposal sites were used, six on land and two in the lake itself. Dredge disposal site selection involved consideration of proximity to dredge site, suitability of sediment for intended site use, minimizing damage to wildlife habitat, suitability of on-site material for dike construction, and potential damage to existing structures or archeological sites. It was anticipated that sediment volume would increase by a bulking factor of 1.3 due to disturbance. In-water dikes were built to contain dredged material at the in-lake disposal sites, where islands were constructed.

Water quality restrictions required that all return flow from disposal sites had to return to the lake itself. Water quality was carefully monitored, with emphasis on controlling dissolved oxygen (target values: 4 mg L^{-1} in disposal site effluent and within dilution zone, 5 mg L^{-1} in the whole lake) and suspended solids (target values: 2000 mg L^{-1} in the disposal site effluent and dilution zone, 500 mg L^{-1} in the lake). A combination of multiple retention ponds and silt curtains was used to attempt to achieve a retention time of 8 days in order to facilitate sedimentation of solids.

A 26-inch (66 cm) hydraulic dredge was employed 24 hr day^{-1}, five days wk^{-1}. Although the 8-day retention time was not achieved, there was significant improvement in water quality as material moved through the retention ponds. An example given by Raymond and Cooper (1984) cited 1,000 mg L^{-1} suspended solids in the effluent from the first pond, which was reduced to 820 and 580 mg L^{-1} after the second pond and over the weir into the lake, respectively.

Initially, the silt curtain was extended to the lake bottom. However, settling material fell on the curtain, trapping it under water. This curtain could not be retrieved, and the contractor would no longer lower curtains completely to the bottom. When not in contact with the bottom, the curtains were not as effective. Watery sediment flowed as a turbidity plume beneath the curtain. In general, this was not a problem except when the water was mixed by wind. Turbidity problems were short-lived and water quality requirements were maintained for the lake as a whole.

Lake Kasumigaura, Japan

Lake Kasumigaura is located 70 km from Tokyo and is the second largest lake in Japan (22,000 ha). It is separated into three sub-basins, has an average depth of 4 m, and is highly eutrophic. There are 47 municipalities within the basin with a population of 720,000. Industries such as rice farming, hog raising, and carp cultivation are significant sources of nutrient loading. Heavy algal blooms of Microcystis develop in summer, sometimes covering the entire lake surface. An evaluation of proportional loadings of nitrogen and phosphorus in the largest sub-basin (Nishiura) in 1977 estimated that approximately 22% and 28% of the N and P loadings were from the sediments. Both implementation of effluent standards and dredging activities were proposed to mitigate the eutrophication.

Dredging began in 1975 and was reported by Murakami (1984). It was planned to dredge 300,000 m^3 during 7 years, 1975-81. At that time, the knowledge of sediment characteristics and volume was limited. A pneumatic pump dredge was used to discharge sediments into a barge which carried the material to an unloading station on shore. Transportation from the unloading station to disposal site was via pipeline. A solidifying agent was used prior to disposal. The first dredge was used for three years, and was not sufficiently efficient to dredge the planned volume of sediments because of its small size, frequent clogging, and interference between barge and fisheries activities. The second dredge was completed in 1978, and had an increased capacity, employed a swing arm system for moving the suction head, and used a booster pump for pipeline transportation of dredged materials. A screening system was used to remove large debris that could clog the booster pump. Supernatant from the disposal site was discharged directly into the lake, although Murakami (1984) reported that a treatment facility was in the planning stages.

The planned 300,000 m^3 of sediments were removed within the 7 year period, but no noticeable effects on lakewater quality were observed. Subsequent calculations estimated that approximately 20,000,000 m^3 of sediments would have to be dredged to reduce the organic loadings by 15% (Murakami 1984). A second stage dredging project is in the planning stages. Lake Kasumigaura is thus another example of the important need for thorough evaluation of nutrient budgets and sediment distribution and characteristics prior to implementation of a dredging project. The need for adequate pre-dredging studies is emphasized by Cooke et al. (1986) as the most important aspect of a dredging restoration project.

Gibraltar Lake, California

Gibraltar Lake is a water supply reservoir for the city of Santa Barbara, CA. Constructed in 1920, it has experienced siltation at an average rate of 275,250 m^3 for over 60 years. In 1975, it was deemed that additional siltation would compromise a valuable water source in an already water-short area. A pilot project was developed for the use of an Italian air pump system (Pneuma pump) for sediment removal, and was described by Spencer (1984). The major complication of the Gibraltar Lake restoration project was extensive mercury contamination of the silt. The relationship between low dissolved oxygen and potential effects of dredging is particularly important when considering release of mercury from suspended sediments. Mercury can be transformed to highly toxic and biologically mobile methyl mercury through microbial metabolism in anaerobic environments.

Although the experiences of the Gibralter Lake restoration project are not directly applicable to the objective of nutrient control in lake Apopka, this study (Spencer 1984) may be highly relevant if metal contamination is found in Lake Apopka sediments.

<u>Creve Coeur Lake, Missouri</u>

Creve Coeur Lake is located in the floodplain of the Missouri River just above its confluence with the Mississippi River. Since the early 1900's, the lake surface area and depth have declined substantially as a consequence of erosion and sedimentation. A 1971 engineering study indicated high pH (> 9.0), excessive nutrients, fecal coliform contamination, and excessive algal growth (> 10,000 mL^{-1}). Dredging was initiated in 1974 to increase lake size from 32 ha to 133 ha and depth from 0.8 m to 3.8 m. Sediment samples contained excessive nutrients and exceeded Missouri State Water Quality Standards for cyanide, mercury, phenols, iron, lead, nickel, and zinc. Sediment phosphorus ranged from 1,200 to 2,200 ug g^{-1}. Results of the restoration project were reported by Knauer (1984).

During the period 1977-1981, approximately 3,700,000 m^3 of dredged material (primarily clay) were removed from Creve Coeur Lake. Dredge spoils were transported by pipeline to several settling ponds near the lake. Fill areas were prepared by constructing containment dikes of surface soils (clays, and clayey and silty sands). The dikes extended 0.5 m above the expected fill elevation. Supernatant was drained back into the lake by adjustment of a wier overflow structure.

During the project feasibility study, sediment characteristics of the lake were evaluated by collection and analysis of 25 test borings and 18 hand samples. Subsequently, additional sediment samples were obtained to evaluate sediment chemistry and potential release into the water column during dredging. In addition to heavy metals, sediments were also tested for Kjeldahl nitrogen, total phosphorus, phenols, DDT, Endrin, and BHC.

Because mercury concentrations in the baseline water quality samples exceeded established Missouri standards, samples of fish were routinely analyzed for mercury during the project. No indication was found of Hg bioaccumulation during the project, and fish tissue concentrations remained well below the 0.5 ppm health standard.

Substantial changes in water quality were not observed during dredging operations or the following year. The major benefits of the project were related to the increase in lake size and depth, thus providing boating and fishing opportunities. The setting improved, with a more defined shoreline and creation of an island for wildlife habitat. Areas surrounding the lake that were used for settling basins of dredged materials were subsequently graded and seeded for park areas.

Fairmont Lakes, Minnesota

The Fairmont chain of lakes (George, Sisseton, Budd, and Hall) are located in southern Minnesota. The first three of these lakes were dredged between 1966 and 1980. The fourth, Hall Lake, was partially dredged in 1982 and 1983. Hanson and Stefan (1985) evaluated the Fairmont Lakes as a case study and used a dynamic water quality model as a tool in selecting dredging depths. The City of Fairmont began planning for dredging in 1953, and a 20-year plan was developed to dredge the lakes beginning with George Lake and working upstream. George Lake was dredged in 1966 and 1967. Dredge spoils were deposited at a 10 ha site that was later used for agriculture. Dredging did not control the excessive algal growth. Sisseton Lake was dredged 1967-1970. Work was interrupted by low water levels, diking problems, and a low estimate of sediment volume to be removed. The 32 ha disposal site was returned to agriculture and park use. Algal growth continued to be excessive after dredging. Budd Lake was dredged over a ten-year period, 1971-1980. Delays were caused by lack of suitable disposal sites, low lake levels, and the long distance to the last of a series of disposal sites utilized. The initial disposal site generated controversy because it was a shallow water marsh just off the lake. The Minnesota Water Resources Board allowed use of only 4 ha of the marsh for dredge spoils disposal.

After completion of the Budd Lake dredging project, the city became concerned about the high copper levels in Budd Lake sediments. Over 58 years 553,800 kg of copper sulfate had been applied for algal control.

Samples generally contained about 1300 mg Cu kg^{-1}, and some were as high as 5400 mg Cu kg^{-1}. Concentrations measured at the disposal sites ranged from 234 to 460 mg Cu kg^{-1} sediment. These concentrations were not considered toxic to crops, but they did exceed Minnesota Pollution Control Agency guidelines for sewage application to land (Hanson and Stefan 1985). An alum treatment was applied in 1980 to inhibit nutrient release from the sediments.

Hall Lake was dredged in 1982 and 1983, but an underestimate of the costs caused the city to adopt an alternative plan of dredging individual basins in the lake to the recommended 6.9 m depth.

The dredging activities in the Fairmont Lakes were only partially successful. Sediment resuspension was eliminated as a problem in George and Sisseton Lakes. As sediment turbidity decreased and depths increased, algal turbidity levels have increased. Additional measures will be needed to control the continued algal growth.

Northeastern U.S. Lakes

Carranza and Walsh (1985) evaluated the environmental constraints and costs associated with a number of dredging projects in the northeastern United States. The focus of their report was environmental issues and costs in general, rather than as a specific case study of a single lake. Information that may be quite pertinent for the Lake Apopka study was presented in this overview, and thus is included here. The following represents a summary of the major issues addressed by Carranza and Walsh (1985). They reported data on six northeastern lakes subjected to hydraulic dredging, as well as general considerations associated with a number of other dredging projects. In the northeastern U.S., engineering factors have been generally standardized into acceptable approaches for lake dredging. Related environmental management problems, however, have emerged as the limiting factors in determining lake dredging feasibility. According to Carranza and Walsh, the principal environmental restraints affecting lake dredging projects are, in order of importance, effects on wetlands or floodplains (including habitat considerations), water quality at the dredge site and downstream (particularly turbidity), and ultimate use and stability of dredged materials. Other environmental problems that have arisen on a few isolated projects are related to potentially toxic or hazardous dredged materials, archeological and historical concerns, noise control, and aesthetics. Environmental problems are especially significant when related to the dredging of highly organic sediments or very fine inorganic sediments. These have the potential to remain suspended for long periods of time, causing water clarity problems. Examples of several of these issues are given in discussions of specific lake dredging projects.

State wetland laws in Massachusetts, Connecticut, New York, New Jersey, and Rhode Island severely restrict, or in some cases virtually prohibit, alteration of wetlands, even if the wetlands have a deleterious effect on water quality. State environmental quality acts in NY and MA require EIS preparation that guarantees 1-2 year project delays and significant cost increases.

Dredging projects to date have demonstrated the economic need to dispose of dredge spoils in proximity to the lake site. Environmental restrictions in many states limit disposal options and resale of sediment has not often proven feasible in the northeast. Carranza and Walsh further conclude that if the dredged materials fail the toxicity tests for upland disposal, then it is a foregone conclusion that dredging will not be a feasible option. Although difficult to assess, environmental issue considerations add an estimated 10-30% to total project costs.

<u>University Lakes, Louisiana</u>

The University Lakes system includes five lakes (115 ha total) adjacent to Louisiana State University within the city limits of Baton Rouge, LA. Over the past 50 years, all aspects of the lakes deteriorated with massive fish kills occurring on a regular basis in summer. Plans for dredging were delayed because of costs associated with pumping spoils a long distance for disposal. Eventually, approval was given for 30% in-lake disposal in order to minimize costs. Dredging was carried out in 1981-83, removed 490,000 m^3 of sediment, and was reported by Knaus and Malone (1984) and Gremillion et al. (1985).

As of the report by Knaus and Malone (1984), the dredging activities had been completed and a commission had been formed to make recommendations on the future of the restored lakes. Landscaping, public access, and recreational potential were being investigated. Monitoring of lakewater quality was ongoing at Louisiana State University.

Hydraulic dredging and local sewage system repair led to a significant improvement in water quality. Successful reduction of nutrient levels, in turn, reduced the probability of fish kills (Gremillion et al., 1985). Improvements in water quality were obscured in University Lake, however, in 1983 by resuspension of sediments disturbed by dredging, resulting in low algal growth due to shading. As suspended sediments settled or washed out of the lakes, nutrient levels were reduced. Total phosphorus decreased from 0.4 mg L^{-1} to 0.1 mg L^{-1}.

The turbidity problem caused by resuspension of clay particles in University Lake was aggravated by the direct return of discharge waters from the shoreline spoils areas. The problem continued, with additional resuspension during windy periods, one year after dredging. Increasing transparency in City Park Lake, in contrast, led to an increased area of lake bottom to which light was available. Macroalgae then flourished. To some extent the phytoplankton problem was thus exchanged for a macrophyte problem. A similar fate was anticipated for University Lake once the transient turbidity from sediment resuspension subsided (Gremillion et al., 1985).

3.3 PHYSICO-CHEMICAL PROPERTIES OF LAKE APOPKA SEDIMENTS

Based on physical structure, Lake Apopka sediments can be classified into five major groups; unconsolidated floc (UCF), consolidated floc (CF), peat (P), sand (S), clay (C) and marl (M). The average depth distribution of each of horizon is given in Table 3-3. Detailed descriptions and spatial distributions of each horizons in Lake Apopka have been presented by Reddy et al. (1988). In this report, a brief summary of the surface horizons as they relate to the dredging of sediments will be presented.

Unconsolidated floc is distributed virtually throughout the lake, overlying more consolidated sediment, and averages 35 cm thickness. This layer consists of recent deposits of dead algal cells and allochthonous particulate matter. This layer appears very active in releasing nutrients to the overlying water column during moderate to high wind events. Below this layer, Reddy et al. define the CF layer, which is more compact and consolidated. Average depth of this horizon is about 82 cm. The ability of the CF horizon to release nutrients upon dispersal into the water column approximates the ability of the UCF horizon (cf. Tables 3-3 and 3-5; also, Reddy et al, unpublished data). As a consequence, both the UCF and CF horizons of the sediments must be dredged in order to reduce the overall nutrient release capacity of the sediments. Nearly 120 cm thickness of the sediment thus need to be removed from the lake, yielding a bottom substrate of peat (in peat dominated areas), sand, marl, or clay.

Porewater chemistry of sediments (shown in Table 3-3) represents the average concentrations of the sediments obtained from about 100 stations as shown in Figure 3-6 (Reddy et al., 1988). Data shown in Table 3-3 clearly show that both the UCF and CF horizons contain higher porewater concentrations for many of the chemical parameters compared to the peat, sand, or clay horizons. For example, porewater P concentrations of the UCF and CF horizons averaged 2.4 and 3.2 mg L^{-1}, respectively, compared to 2.7, 0.35, 1.1 and 0.28 mg L^{-1} for the peat, sand, clay, and marl horizons, respectively. Despite higher porewater P concentrations, exposed peat is hypothesized to release less P to the water column because it is not as easily resuspended as the less dense floc of the UCF and CF horizons. It should be noted that the values presented in Table 3-3 represent averages for entire horizons; diffusive fluxes in turn depend on the concentration gradient at the sediment-water interface, and the data in Table 3-3 provide only a comparative estimate of the magnitude of nutrient movement during sediment resuspension and diffusion.

Detailed vertical profiles of porewater ammonium N and soluble reactive P (SRP) concentrations are presented in Figures 3-7 and 3-8 for three stations in Lake Apopka (G7, D5, and K6). The data include analyses of three replicate cores obtained from each station (Moore et al., 1988). Porewater ammonium concentrations were lower at the sediment-water interface and increased with depth, approaching a maximum concentration of about 140 mg N L^{-1} at 58 cm depth at Station G7. However, at this station the porewater in the surface sediments (upper 5 cm) was less than 10 mg N L^{-1} (Figure 3-7a). Maximum porewater ammonium concentrations of less than 50 mg N L^{-1} were measured on the cores obtained at stations D5 and K6 (Figure 3-7b and 3-7c). Concentration gradients were much more pronounced for porewater SRP (Figure 3-8a, 3b and 3c), especially in the upper layers of the sediments. For all three stations, the surface 5 cm sediment contained negligible concentrations of SRP, indicating the zone of mixing during wind events. These results suggest that dredging the surficial UCF sediments alone will not be effective in reducing the nutrient loading to the water column, and dredging the entire UCF and CF horizons may be essential to obtain satisfactory results.

Potential nutrient release by the sediments can not be explained by the porewater concentrations alone, since a large reservoir of nutrients is present in the solid phase of the sediment in both organic and inorganic forms. Nitrogen is present in both organic and inorganic form with 99% of the total N present as organic N (Table 3-4). This organic N must be transformed biologically into inorganic N before it is available to primary producers.

The large pool of exchangeable ammonium present on the solid phase represents ammonium that can be released into the porewater when porewater concentrations become depleted (e.g., via diffusive exchange across the sediment-water interface). This ability of the sediments to buffer porewater concentrations at high levels is related in part to the partitioning of ammonium between the solid and aqueous phases which is a function of the relative adsorptive affinity (i.e., partition coefficient) and adsorptive capacity of the solid phase. It also reflects the accretion of ammonium that occurs as bacteria metabolize organic matter. Under anaerobic conditions (such as occur in Lake Apopka sediments), ammonium N tends to accumulate, resulting in high concentrations in the porewater and saturation of exchange sites. This ammonium is transported into the water column via sediment resuspension, gas ebullition, bioturbation, or by diffusion alone. At steady state, characteristic profiles such as shown in Figures 3-7a, 3-7b and 3-7c have developed where the diffusive flux of ammonium across the interface into the water column is balanced by fluxes of ammonium into the porewater as organic matter is metabolized.

Once ammonium N diffuses into and across the aerobic sediment-water interface, it is readily converted into nitrate or assimilated by algae and other macrophytes. Nitrate formed in the water column in turn suffers one of three fates: (1) it diffuses into the anoxic sediment zone and is lost through denitrification to the atmosphere; (2) it is assimilated by algae and other macrophytes; or (3) it is exported out of the lake via washout. Nitrate and ammonium concentrations in the water column of Lake Apopka are comparatively low, indicating that nitrification, denitrification and algal assimilation all occur rather rapidly. A detailed review on the nitrogen transformations functioning at the sediment-water interface is presented by Reddy and Patrick (1984).

Porewater P contributes 2.6 and 1.6 % respectively, to the total P reservoir in UCF and CF sediments in Lake Apopka, while the remaining 97% is present in the solid phase. Phosphorus in the solid phase is present as both inorganic and organic forms, with inorganic forms dominant. Inorganic P is present as nonapatite (NAIP) and apatite (AIP) forms. Results presented in Table 3-5 indicate that Lake Apopka sediments are dominated by apatite P and residual P (assumed to be organic P). A series of biogeochemical processes functioning in the sediments and the water column regulate the transformation of one form into another and its eventual availability to aquatic biota (Syers et al., 1973; Sonzogni et al., 1982; Froelich, 1988).

More organic P was observed in the UCF horizon than CF horizon, indicating the deposition of dead algal cells. Upon decomposition, organic P is mineralized into inorganic P and subsequently transformed into apatite. The forms of P present in the sediment will have special implications when these sediments are dredged and used as nutrient source for plants or as soil amendment.

Data in Table 3-6 present the bulk or total concentrations of selected elements in Lake Apopka sediments. With respect to plant nutrients, sediments are dominated by calcium, indicating the possibility of amendment on acid sandy soils. Data on total N and P storage and the amount of N and P removed by dredging is given in Tables 3-7 and 3-8, respectively. Dredging 120 cm sediment (both UCF and CF horizons) across the entire lake will remove 233,400 and 6,770 metric tonnes of N and P, which needs to be disposed of in an environmentally sound manner. Disposal on adjacent sandy soils or organic soils is one potential option and the implications of land disposal or soil amendment are discussed in Section 5.0 (Sediment Reuse)

Sediments dredged from the lake need to be stored until they are ready for disposal. Reduction in water content of the sediment may be essential prior to land application. During drying, the nutrient speciation and content within the sediment can be altered significantly. Results presented in Figures 3-9a and 3-9b show the effect of sediment drying on water soluble ammonium N and water soluble P of Lake Apopka sediments. Water soluble ammonium N decreased with increased drying of up to 40% (i.e., 40 percent of the initial water content removed). Soluble ammonium N can be lost through volatilization as the sediment dries, thus reducing the plant available N in the dredged sediment. Water soluble P decreased when water content of the sediment was reduced by 40%, probably from precipitation of soluble P with calcium during drying.

Studies need to be conducted to determine potential nutrient losses during storage and drying of the sediment before disposal on land. Biogeochemical processes occurring within the sediment during drying will alter labile forms of nutrients, thus affecting plant available nutrients. In addition, Lake Apopka sediments may contain toxic concentrations of heavy metals and pesticides which can affect sediment reuse potential. Gillespie (1976) found relatively high levels of arsenic in the sediment with about 50% present in water soluble form (Table 3-9). Further studies should evaluate the background levels of heavy metals and pesticides present in the sediment before dredged sediments are recommended for reuse.

Table 3-1. Sediment removal costs for hydraulic dredging aspect of lake restoration

Lake	Amount of sediment removed* (m^3)	Lake Area (ha)	Dredging Cost* ($\$m^{-3}$)	Reference
Nutting Lake, MA	273,600	32	1.44 (A)	Carranza and Walsh (1985)
Morse's Pond	199,000	45	1.56 (E)	Peterson (1979)
Collins Park, NY	79,000	21	0.89 (E)	Peterson (1979)
Lilly Lake, WI	596,000	36	0.27 (E)	Peterson (1979)
University Lakes, LA	390,000	115	5.40 (A)	Knaus and Malone (1985)
Lansing Lake, MI	1,230,000	182	1.00 (E)	Peterson (1979)
Henry Lake, WI	153,000	17	1.12 (E)	Peterson (1979)
Long Lake, MN	247,000	74	2.96 (E)	Peterson (1979)
Lenox Lake, IA	76,000	13	2.35 (E)	Peterson (1979)
Lake Trummen, Sweden	600,000	400	0.83 (A)	Bjork (1972)
Fairmont Lakes chain, MN	2,336,161	180	0.41 (A)	Hanson and Stefan (1985)
Hall Lake, MN	249,500	224	1.44 (A)	Hanson and Stefan (1985)
Bantam Lake, CT	176,320	360	1.52 (A)	Carranza and Walsh (1985)
Allentown Lake, NJ	117,040	12	1.37 (A)	Carranza and Walsh (1985)
Van Cortlandt Lake, NY	114,000	6	5.32 (E)	Carranza and Walsh (1985)
Blue Lake, IA	306,000	372	2.63 (E)	Peterson (1979)
Vancouver Lake, WA	6,117,000 to 11,469,000	1,052	2.29 (E)	Peterson (1979)
Long Lake, WA	259,000	56	3.16 (E)	Peterson (1979)
Lake Trehorningen, Sweden	320,000	65	6.25 (A)	Ryding (1982)
Sylvan Lakes, N.J.	41,700 (E)	7	4.80 (E)	Horstman and Copp (1985)

* Cost and volume estimates based on proposal and bids (E), or actual cost (A). Cost does not reflect dike construction, treating water returns, etc., except for Sylvan Lakes, Lake Trummen and Lake Trehorningen.

Table 3-2. Concentrations of phosphate (mg PO_4 - P L^{-1}) in interstitial water of Lake Trummen before (1969) and after (1973) restoration (from Bengtsson *et al*., 1975).

Sediment depth (cm)	1969 Feb. 2	1973 Feb. 13	1969 Sept. 4	1973 Sept. 5
0-10	2.38	0.006	2.39	0.099
15-25	1.14	0.020	1.49	0.154
30-40	0.65	-	0.72	-

Table 3-3. Selected physico-chemical properties of Lake Apopka sediments and porewater (Reddy et al., 1988). Lower row entries for each parameter represent sample standard deviation.

Parameter	Sediment					
	UCF	CF	Peat	Sand	Clay	Marl
Sediment depth,	35.3	81.8	22.1	18.4	9.5	12.6
cm	±22.4	±35.3	±23.2	±14.3	±5.2	±10.6
Water content	96.5	91.8	88.1	67.7	46.4	64.1
(%)	±2.9	±2.4	±9.6	±16.9	±14.0	±19.3
Bulk density	0.035	0.086	0.096	0.582	0.54	0.299
(g (dry wt) cm^{-3})	±0.014	±0.029	±0.051	±0.461	±0.24	±0.163
Porewater chemistry						
Alkalinity,	423	540	249	357	385	545
mg $CaCO_3$ L^{-1}	±100	±27.9	±202	±56	±134	±127
pH	7.0	7.1	7.7	7.6	7.5	7.5
Conductivity	801	908	532	633	610	865
(us cm^{-1})	±158	±348	±253	±47		±52
SRP	1.26	1.50	1.07	0.13	0.33	0.28
(mg L^{-1})	±1.24	±2.18	±1.85	±0.08	±0.56	±0.35
TP	2.42	3.19	2.68	0.35	1.05	0.52
(mg L^{-1})	±1.89	±4.44	±4.03	±0.35	±1.76	±0.38
Ammonium N	29.3	37.4	18.0	18.3	22.4	23.8
(mg L^{-1})	±19.9	±31.9	±18.4	±5.3	±19.4	±15.6
Dissolved organic	5.5	13.0	14.4	14.0	10.8	19.4
N (mg L^{-1})	±9.0	±13.6	±13.0	±10.3	±5.5	±29.1
Total organic N	9.3	17.2	23.4	26.5	17.0	27.6
(mg L^{-1})	±8.4	±20.6	±19.7	±22.1	±14.1	±30.8
Total organic C	32.5	34.0	109.5	54.2	50.6	107.7
(mg L^{-1})	±20.0	±22.0	±213.7	±15.4	±20.0	±138.0
Calcium	107.0	102.3	35.1	49.2	65.0	56.7
(mg L^{-1})	±20.5	±37.4	±26.2	±8.5	±29.8	±22.7
Magnesium	29.7	24.2	7.7	12.1	15.3	18.7
(mg L^{-1})	±7.6	±12.3	±4.4	±7.6	±8.8	±11.0
Potassium	12.4	9.3	7.4	6.0	9.8	7.6
(mg L^{-1})	±2.5	±3.7	±3.8	±2.9	±4.1	±3.6
Sodium	17.2	15.1	12.2	13.7	16.5	14.9
(mg L^{-1})	±2.7	±4.9	±3.8	±5.6	±4.9	±4.5
Iron	0.2	0.2	0.4	0.1		0.1
(mg L^{-1})	±0.2	±0.2	±0.9	±0.1	---	±0.2
Manganese	0.1					
(mg L^{-1})	±0.1	---	---	---	---	---

UCF = unconsolidated floc. CF = consolidated floc.

Table 3-4. Distribution of nitrogen forms in Lake Apopka sediment horizons and porewater (Reddy *et al.*, 1988).

N-fraction	Sediment					
	UCF	CF	Peat	Sand	Clay	Marl
	% of Total N					
Porewater						
Ammonium N	3.05	1.88	0.51	0.64	0.46	0.48
Organic N	0.97	0.87	0.66	0.93	0.35	0.56
Sediment						
Exchangeable ammonium N	0.90	1.04	1.03	2.18	4.88	2.84
Organic N	95.08	96.21	97.80	96.25	94.31	96.12

Table 3-5. Distribution of phosphorus forms in Lake Apopka sediment horizons and porewater (Reddy et al., 1988).

P-fraction	Unconsolidated floc (UCF)	Consolidated floc (CF)	Peat
	% of total P		
Porewater	2.6	1.6	3.9
Solid Phase			
NaCl extractable-P	7.8	4.2	4.4
Fe/Al-P	9.9	3.5	2.2
Ca bound-P	33.0	52.4	23.6
Residual-P (organic-P)	46.7	38.3	65.9

Table 3-6. Total elemental composition of Lake Apopka sediments on a dry-weight basis (Reddy et al., 1988). Lower row entries for each parameter represent sample standard deviation.

Parameter	Sediment					
	UCF	CF	Peat	Sand	Clay	Marl
Volatile solids (%)	54.6	58.9	72.9	11.4	16.3	28.8
	±14.6	±14.2	±24.1	±8.6	±10.9	
Total carbon (%)	30.2	32.5	40.9	3.9	7.2	13.9
	±8.3	±8.0	±11.2	±2.9	±6.2	±7.1
Inorganic carbon (%)	1.2	0.9	0.3	0.5	3.2	6.1
	±0.7	±1.2	±0.7	±0.9	±3.7	±3.0
Nitrogen (mg g^{-1})	23.7	22.4	26.1	6.0	4.2	8.8
	±7.5	±4.3	±8.3	±5.0	±3.3	±5.9
Exchangeable ammonium N (mg g^{-1})	0.21	0.23	0.27	0.13	0.21	0.25
	±0.16	±0.19	±0.23	±0.13	±0.22	
Phosphorus (mg g^{-1})	0.97	0.60	0.38	0.42	0.29	0.45
	±0.43	±0.37	±0.24	±0.38	±0.20	±0.35
Calcium (mg g^{-1})	48.88	48.14	24.48	72.77	36.08	207.14
	±26.31	±46.13	±39.54	±62.15	±39.14	±99.60
Magnesium (mg g^{-1})	4.19	3.11	2.02	2.44	8.46	6.02
	±1.33	±2.15	±1.50	±2.86	±4.19	±4.92
Potassium (mg g^{-1})	0.95	0.55	0.42	0.56	1.02	0.44
	±0.28	±0.40	±0.30	±0.28	±0.43	±0.25
Iron (mg g^{-1})	5.06	4.05	1.60	2.49	11.47	3.52
	±1.48	±2.86	±1.72	±2.37	±5.50	±2.50
Manganese (mg g^{-1})	0.09	0.06	0.05	0.07	0.10	0.14
	±0.03	±0.04	±0.04	±0.07	±0.03	±0.11
Aluminum (mg g^{-1})	8.98	6.72	2.42	4.65	22.29	5.73
	±3.52	±4.77	±3.26	±4.88	±10.77	±4.57
Copper (mg g^{-1})	0.07	0.01	0.01	0.02	0.02	0.01
	±0.29	±0.01	±0.01	±0.01	±0.02	±0.01

UCF = unconsolidated floc.

CF = consolidated floc.

Table 3-7. Total N and P storage in the sediment. (Average depths for UCF = 35.3 cm and CF = 81.8 cm). (Reddy et al., 1988.)

Component	Sediment UCF	Sediment CF
	---metric tonnes---	
Sediment (wet)	45.184×10^6	107.16×10^6
Sediment (dry)	1.544×10^6	8.794×10^6
Total N	36,586	196,856
Total P	1,498	5,276
Total N cm^{-1}	1,036	2,406
Total P cm^{-1}	42	64

Table 3-8. Nitrogen and phosphorus removal during dredging of UCF and CF horizons to various depths.

Dredging depth	Nitrogen	Phosphorus
---cm---	------------metric tonnes------------	
30	31,093	1,156
60	96,028	3,091
90	168,224	5,026
117	233,442	6,774

Table 3-9. Arsenic content of surface sediments of Lake Apopka (Gillespie, 1976).

Sampling Station	Arsenic ($\mu g\ g^{-1}$) dry weight	
	Water soluble	Total
1	4.08	6.31
2	2.82	6.21
3	0.86	3.32
4	1.89	4.51
5	1.62	4.30
6	2.51	5.01
7	4.74	7.81
8	2.58	5.90
Mean	2.64	5.42
SD±	1.27	1.42

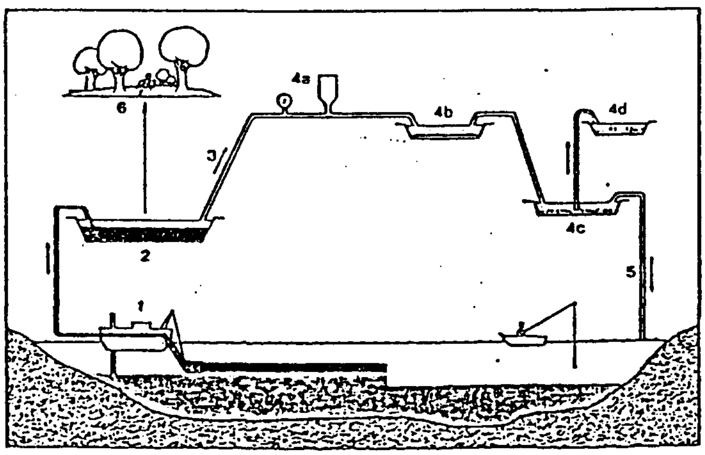


Figure 1 1. Suction dredger. 2. Settling pond. 3. Run-off water. 4. Precipitation with aluminum sulfate (4 a automatic dosage, 4 b aeration, 4 c sedimentation, 4 d sludge pond). 5. Clarified run-off water. 6. The dried sediment is used as fertilizer for lawns and parks.

Figure 3-1. Lake Trummen restoration project - schematic diagram. From Bjork (1972).

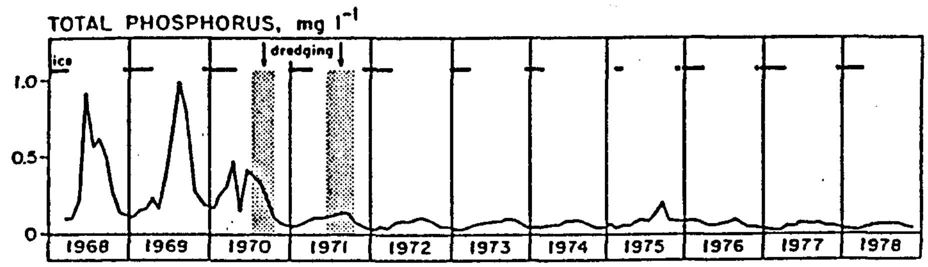
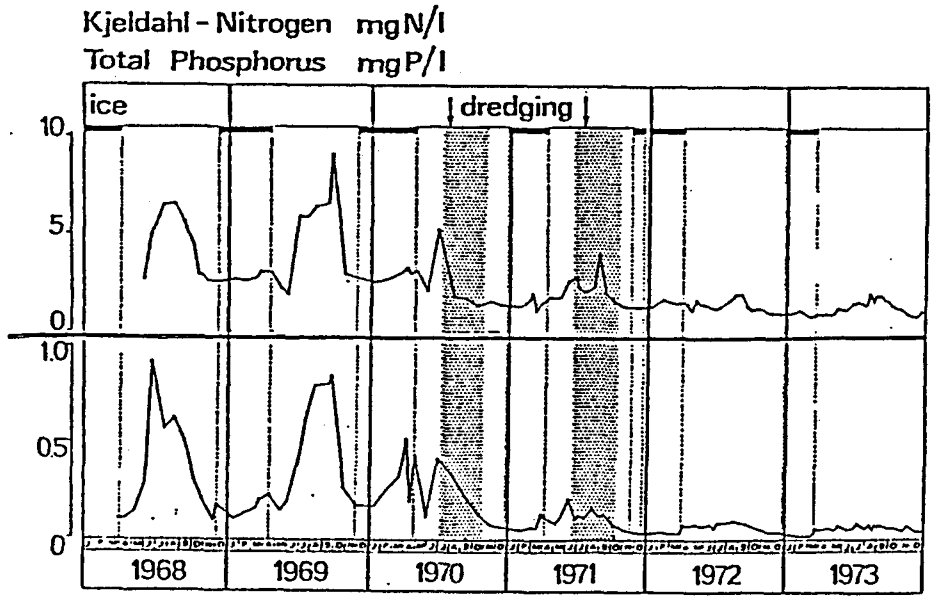
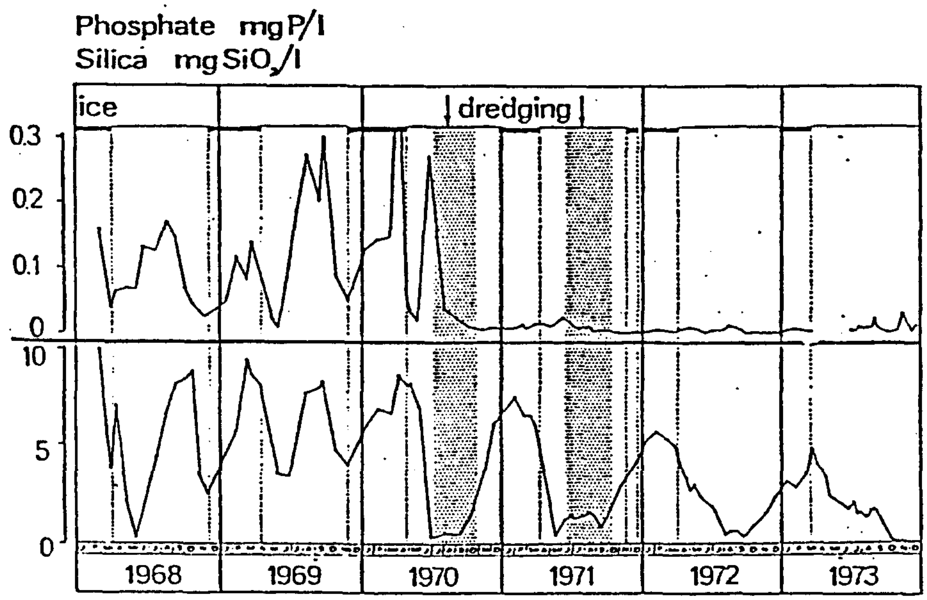


Figure 2 Total phosphorus concentration in Lake Trummen, Sweden, before and after dredging (courtesy of Gunnar Andersson, Department of Limnology, University of Lund, Lund, Sweden).

Figure 3-2. Total phosphorus concentrations in Lake Trummen, before and after dredging. From Cooke et al. (1986).



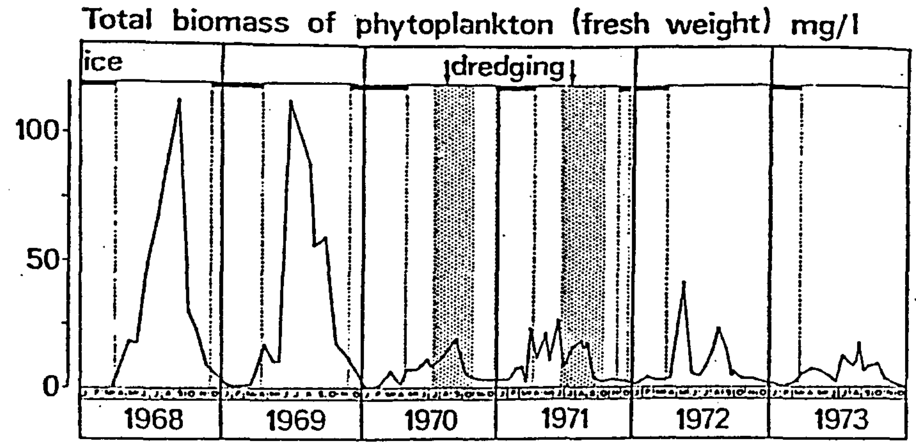
Kjeldahl-N and total phosphorus in lake Trummen (main sampling station, 0.2 m below surface) 1968—1973.



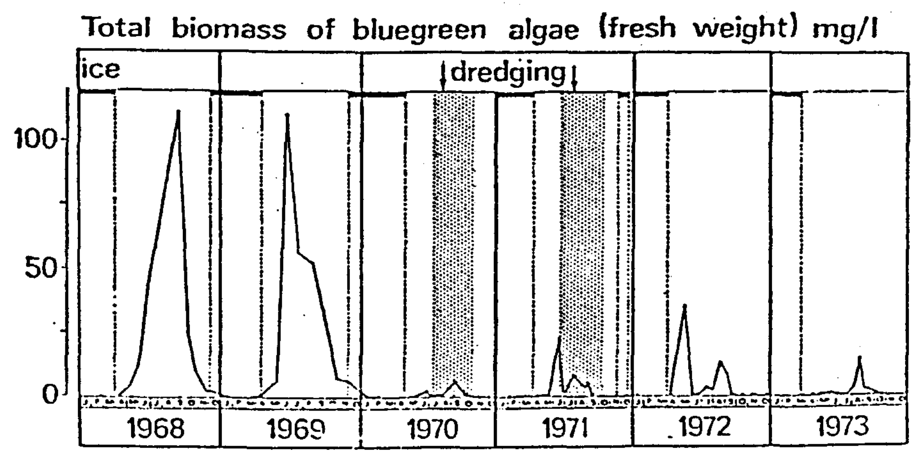
Phosphate phosphorus and silica in Lake Trummen (main sampling station, 0.2 m below surface) 1968—1973.

Figure 3-3. Concentrations of total Kjeldahl nitrogen (TKN), total P, ortho-phosphate, and silica in Lake Trummen from 1968 to 1973. From Bengtsson <u>et</u> <u>al</u>. (1975).

KBN



Development of phytoplankton biomass (fresh weight) during 1968—1973 at 0.2 m depth in Lake Trummen; Sweden.



Development of blue-green algae biomass (fresh weight) during 1968—1973 at 0.2 m depth in Lake Trummen, Sweden.

Figure 3-4. **Total phytoplankton and bluegreen algae biomass in Lake Trummen from 1968 to 1973. From Cronberg <u>et</u> <u>al</u>. (1975).**

KBN

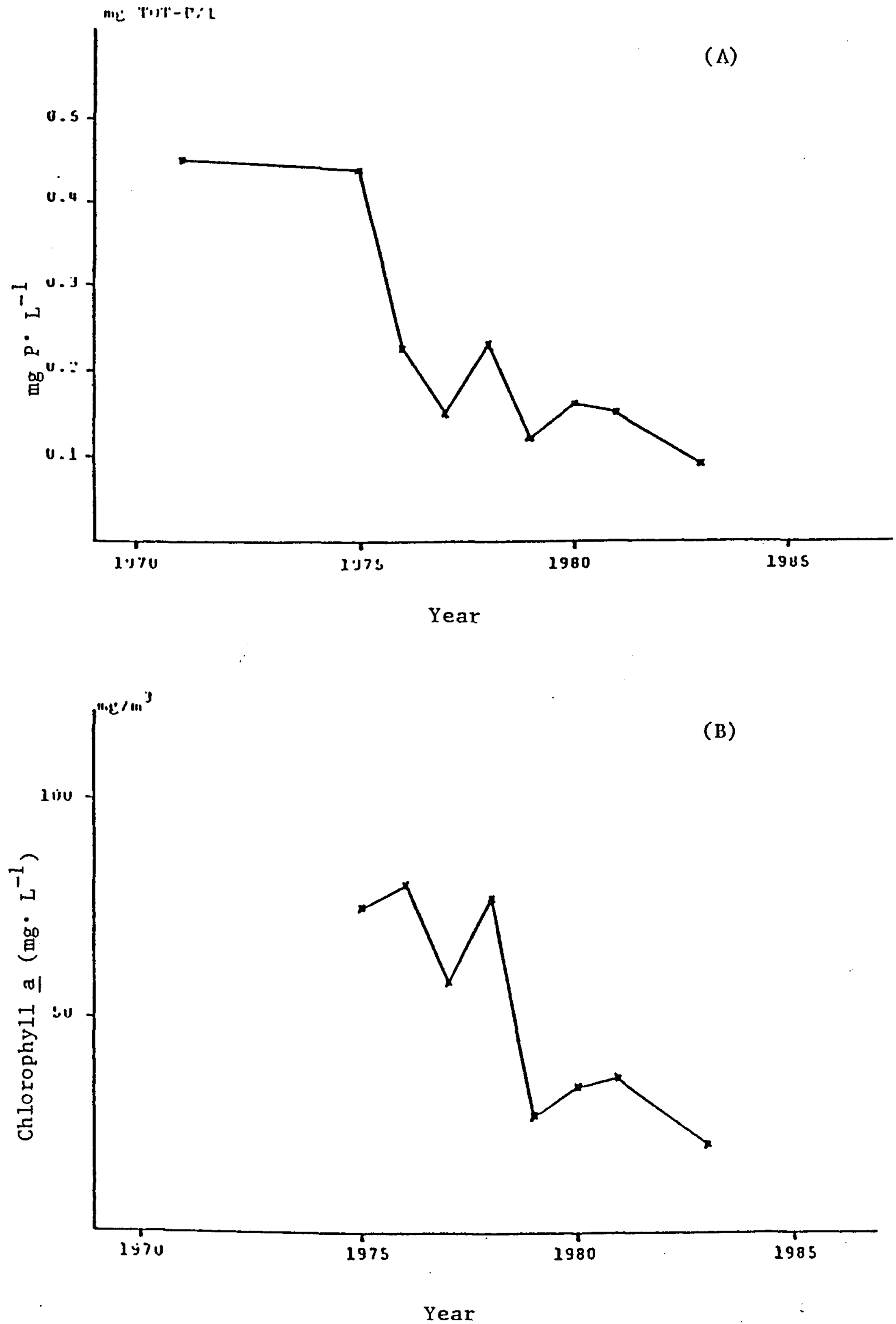


Figure 3-5. Concentrations of (A) total phosphorus (mg L^{-1}) and (B) chlorophyll a (ug L^{-1}) in Lake Trehörningen from 1975 to 1983. From Berquist (1986).

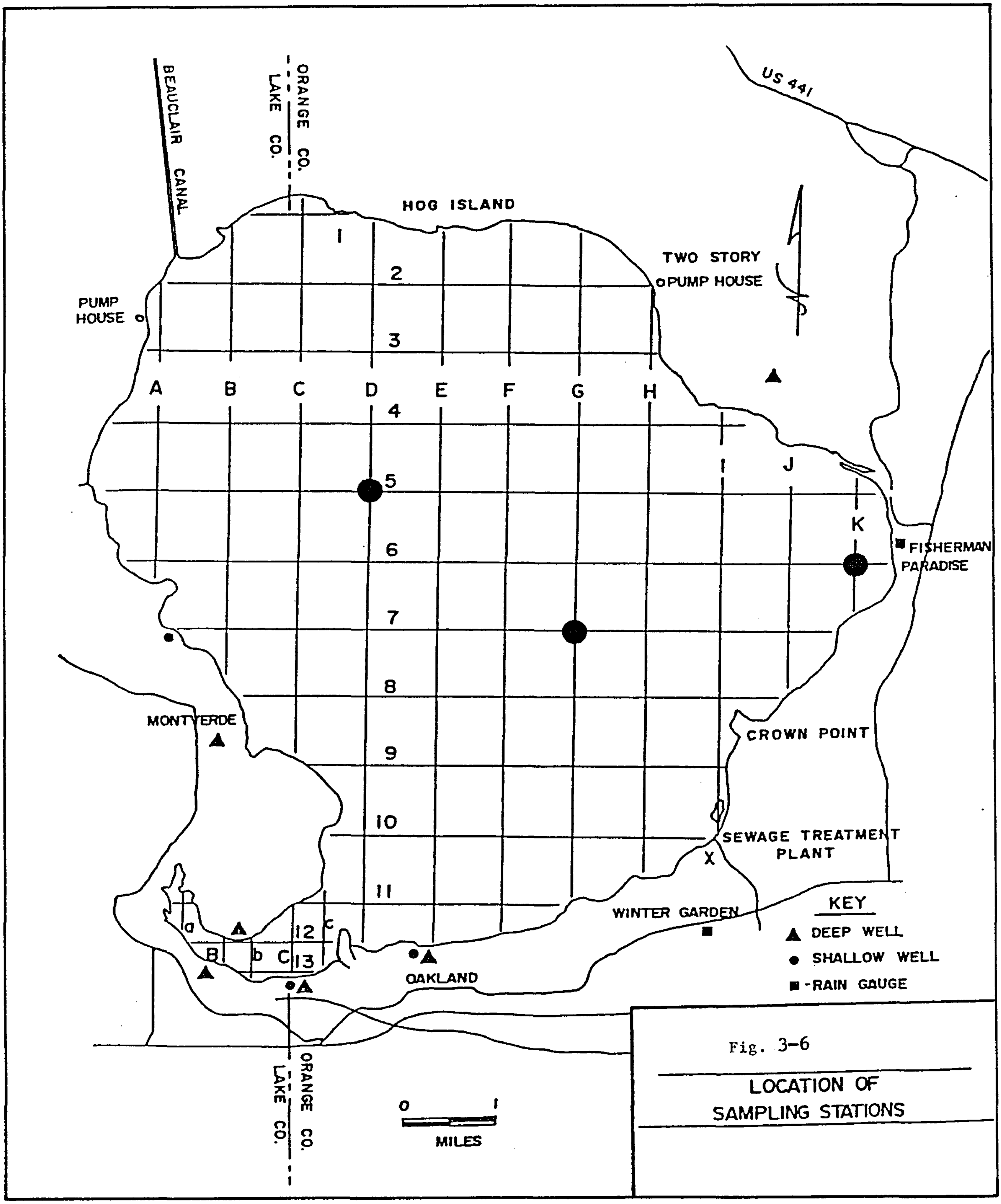


Figure 3-6. Map of Lake Apopka showing sediment 1987-88 sampling locations used by Reddy et al. (1988).

KBN

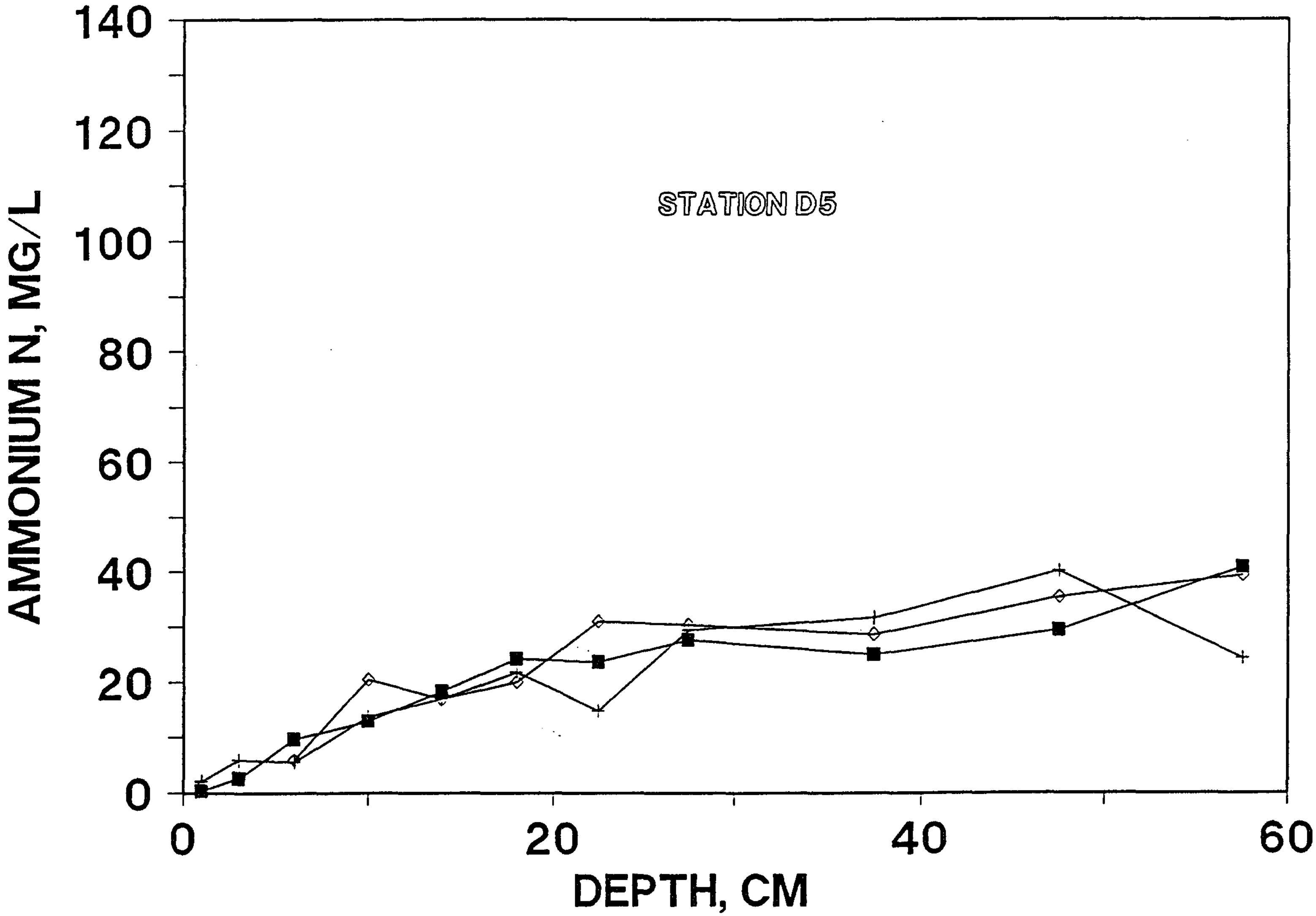


Figure 3-7a. Vertical distribution of ammonium-N in Lake Apopka sediment porewater, 12 February 1988. (A) Station D5. (B) Station G7. (C) Station K6. Results from three replicate cores are shown for each station.

KBN

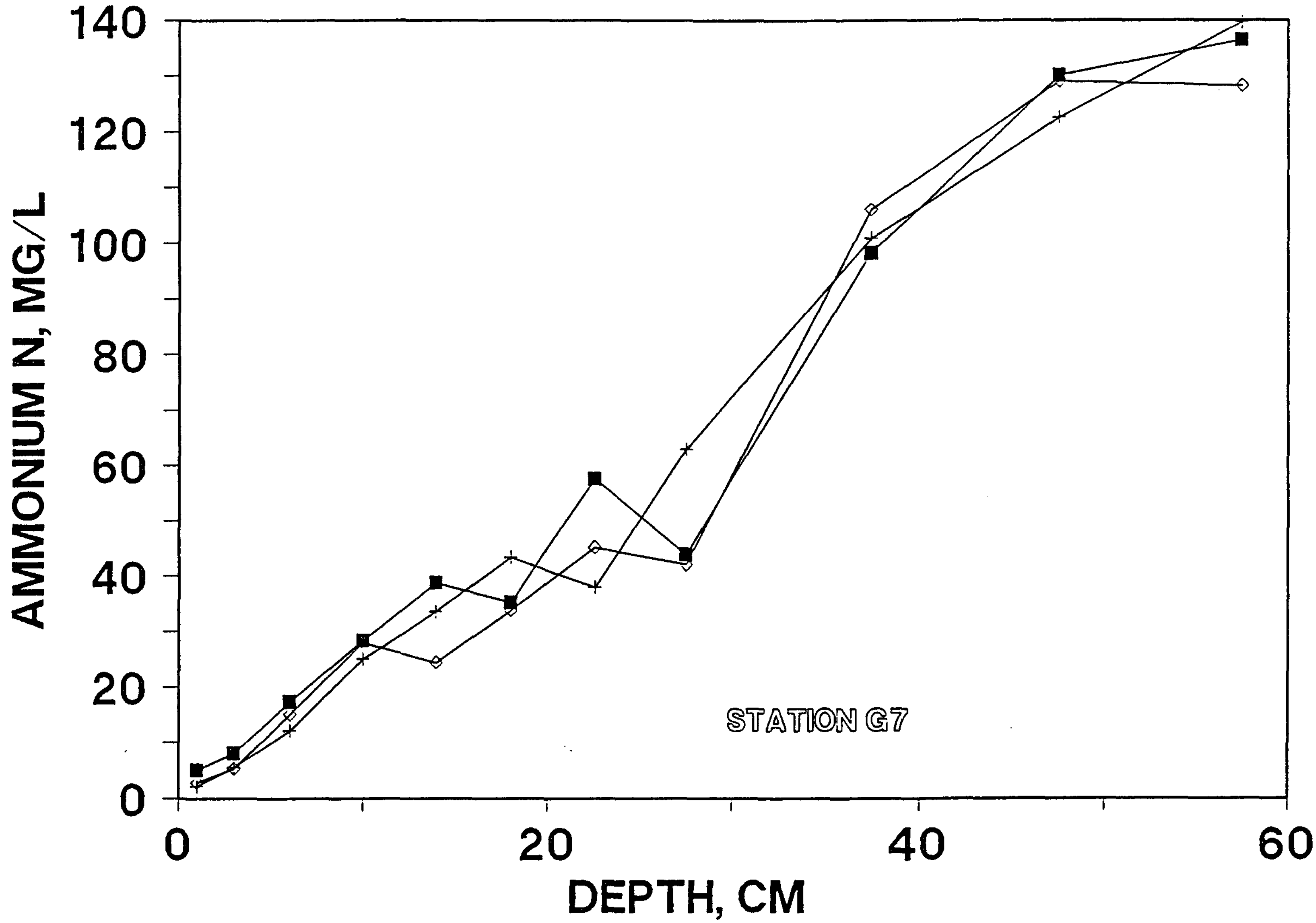


Figure 3-7b. Vertical distribution of ammonium-N in Lake Apopka sediment porewater, 12 February 1988. (A) Station D5. (B) Station G7. (C) Station K6. Results from three replicate cores are shown for each station.

KBN

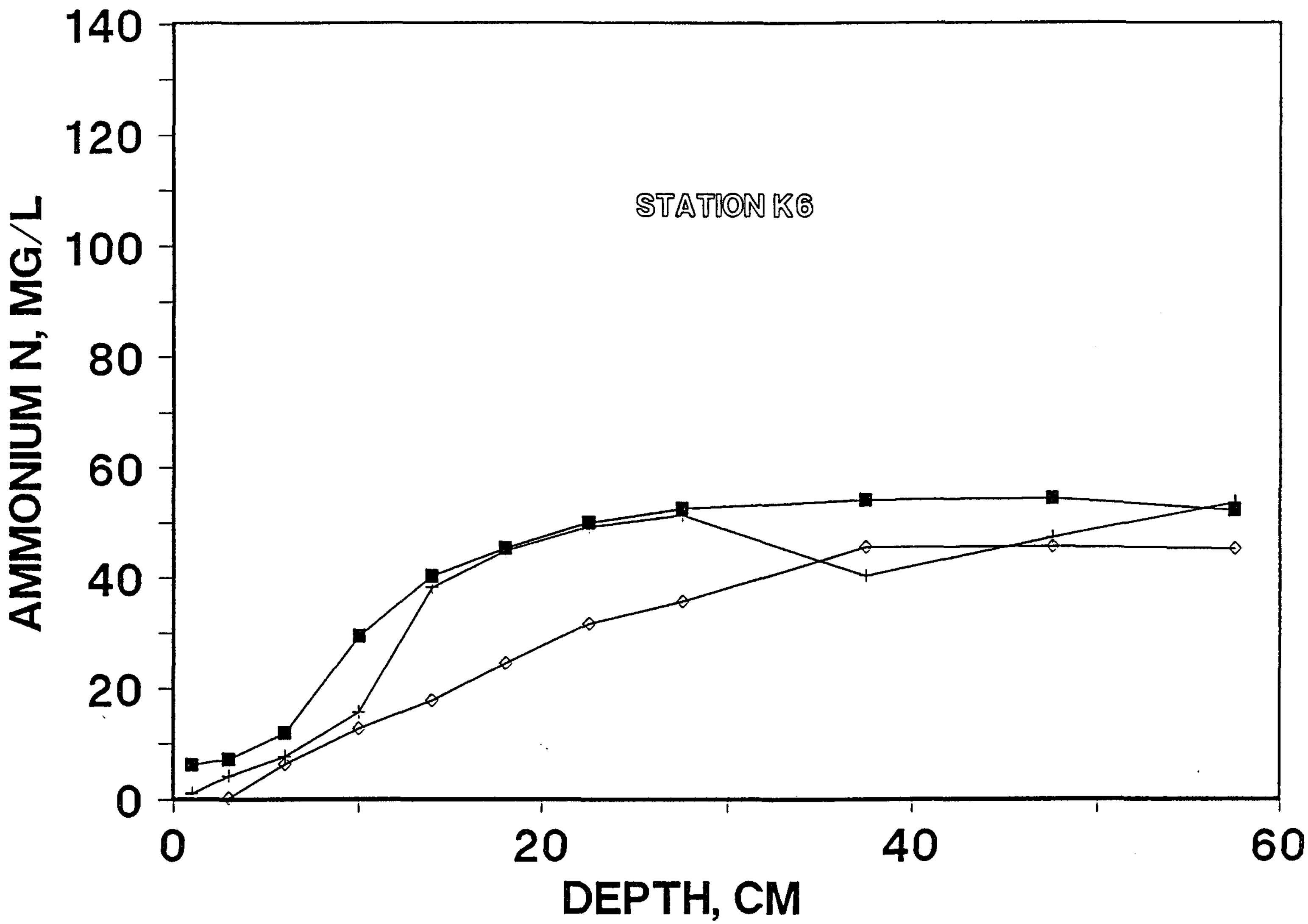


Figure 3-7c. Vertical distribution of ammonium-N in Lake Apopka sediment porewater, 12 February 1988. (A) Station D5. (B) Station G7. (C) Station K6. Results from three replicate cores are shown for each station.

KBN

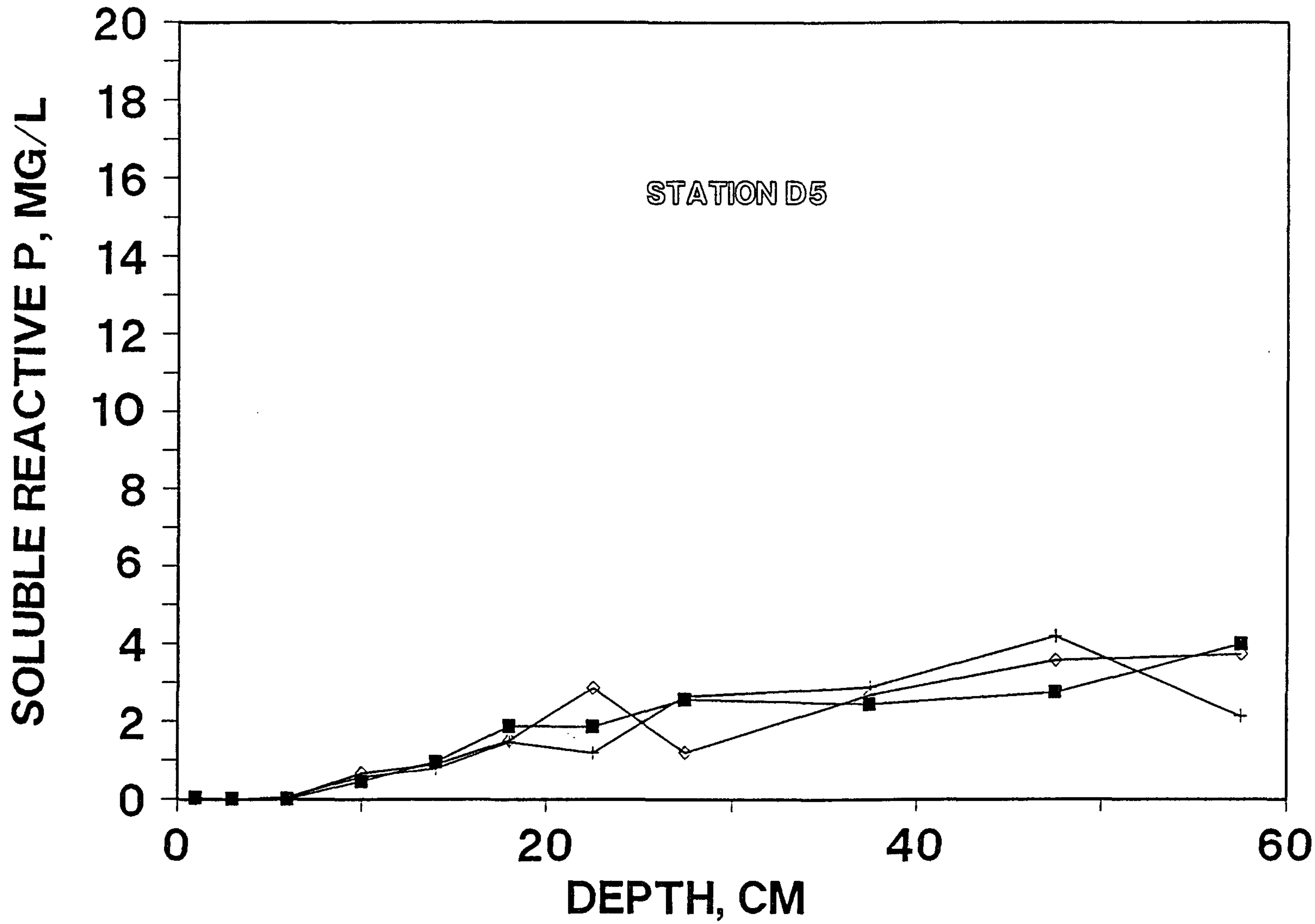


Figure 3-8a. **Vertical distribution of soluble reactive phosphorus (SRP) in Lake Apopka sediment porewater, 12 February 1988. (A) Station D5. (B) Station G7. (C) Station K6. Results from three replicate cores are shown for each station.**

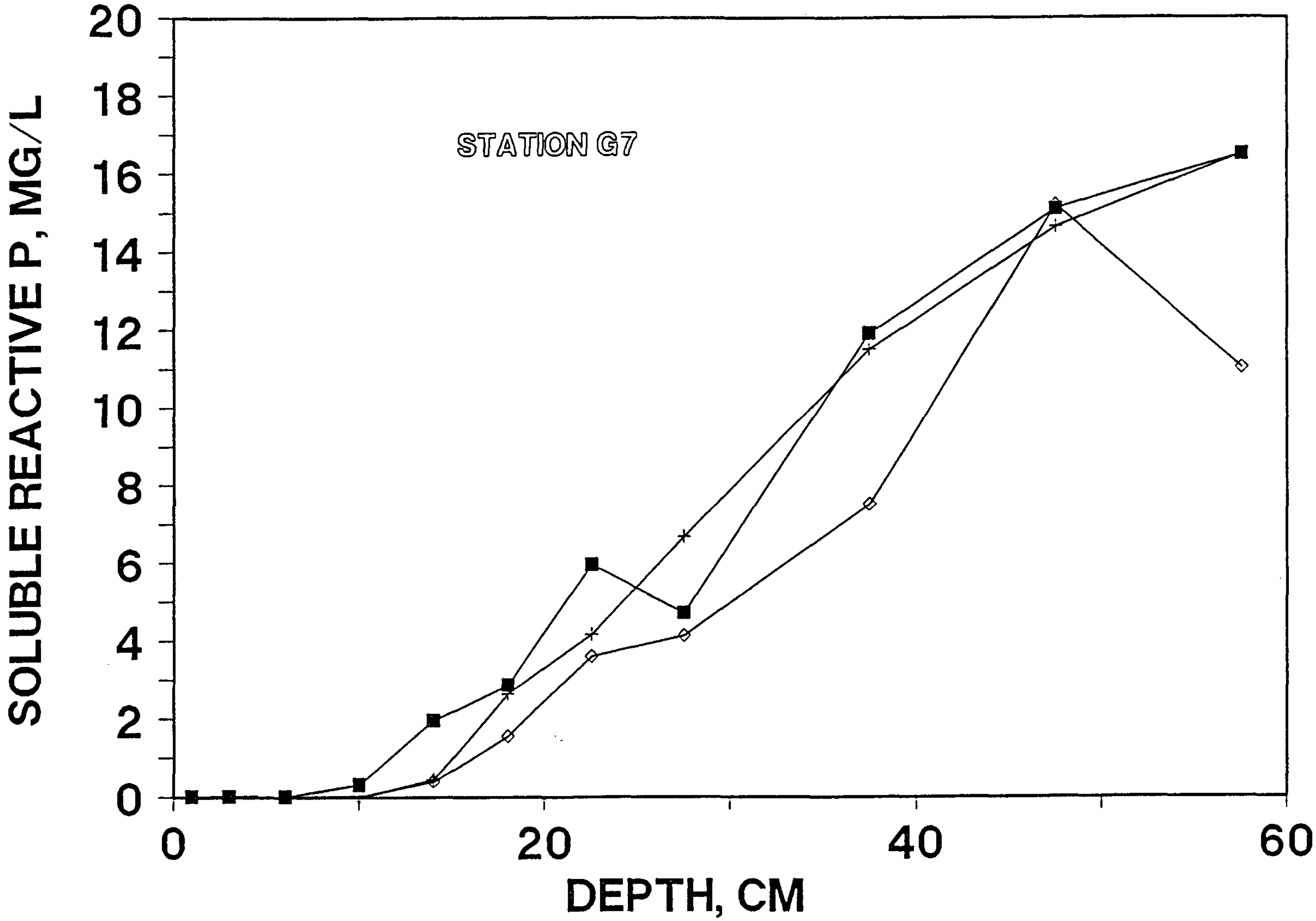


Figure 3-8b. Vertical distribution of soluble reactive phosphorus (SRP) in Lake Apopka sediment porewater, 12 February 1988. (A) Station D5. (B) Station G7. (C) Station K6. Results from three replicate cores are shown for each station.

KBN

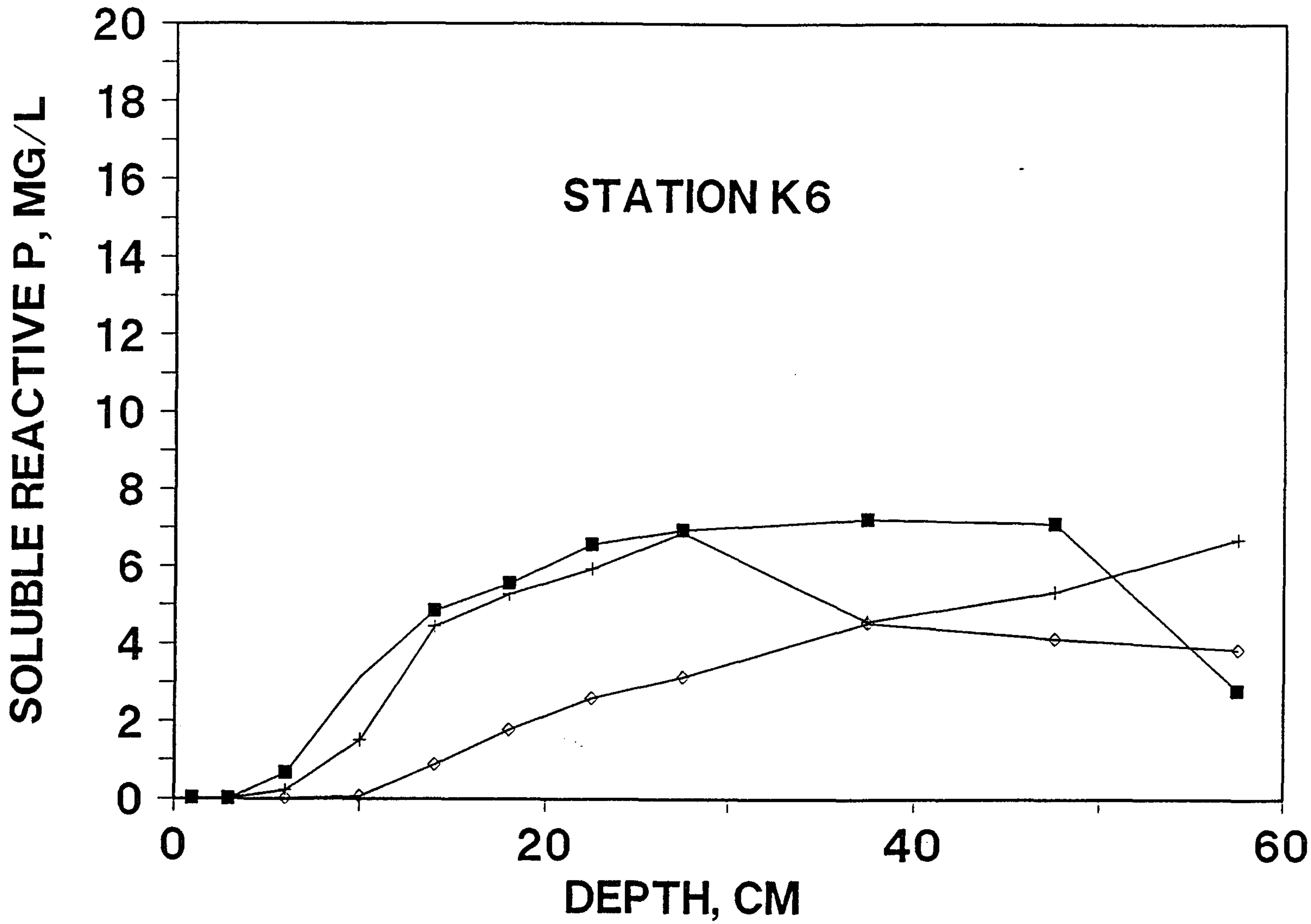


Figure 3-8c. Vertical distribution of soluble reactive phosphorus (SRP) in Lake Apopka sediment porewater, 12 February 1988. (A) Station D5. (B) Station G7. (C) Station K6. Results from three replicate cores are shown for each station.

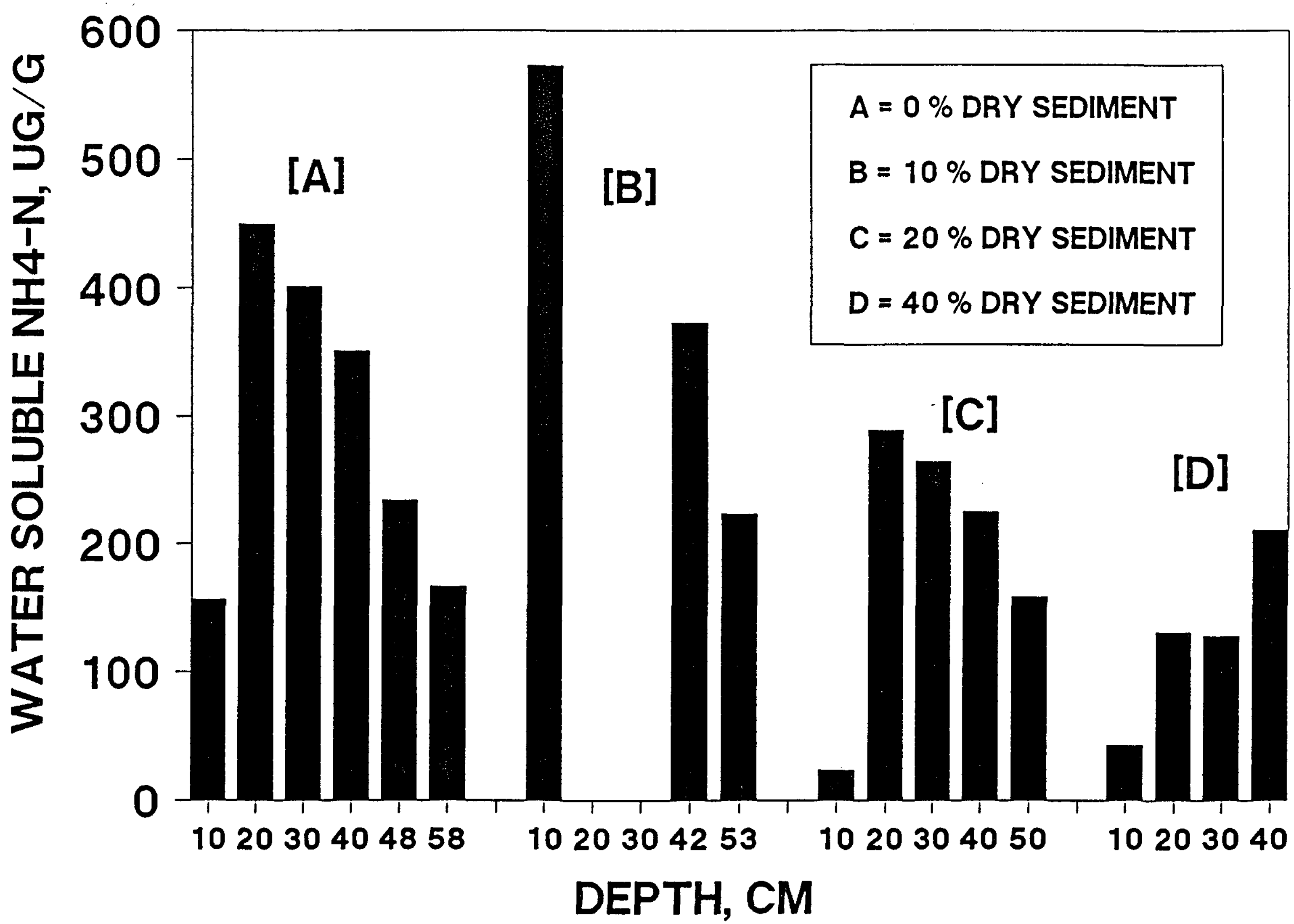


Figure 3-9a. Effect of sediment drying on nutrient speciation in Lake Apopka sediments. (A) Water soluble N (ug g^{-1} dry weight). (B) Water soluble P (ug P g^{-1} dry weight). Sediments were dried at 28°C. Percentage values refer to fraction of original sediment water content removed by drying.

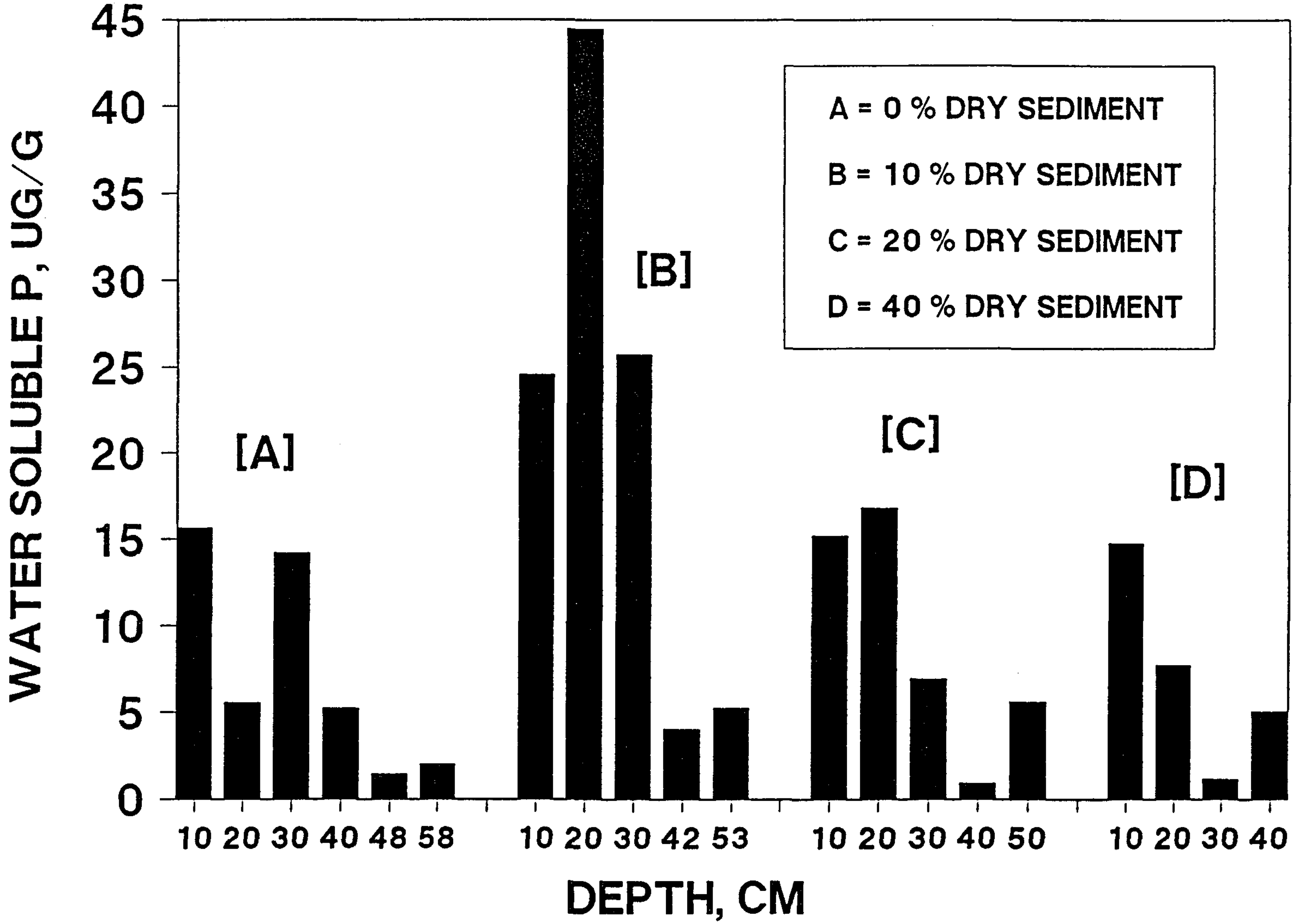


Figure 3-9b. Effect of sediment drying on nutrient speciation in Lake Apopka sediments. (A) Water soluble N (ug g^{-1} dry weight). (B) Water soluble P (ug P g^{-1} dry weight). Sediments were dried at 28°C. Percentage values refer to fraction of original sediment water content removed by drying.

KBN

4.0 SEDIMENT REMOVAL TECHNIQUES

At least three methods of sediment dredging or removal are potentially applicable for Lake Apopka sediment dredging: hydraulic dredging; clamshell excavation; or dragline excavation.

Because the sediments in Lake Apopka are extremely flocculent (average water ranges from 91.9 percent for the CF and 96.6 percent for the UCF horizons), hydraulic dredging can remove an estimated 859 $m^3 hr^{-1}$. By comparison, a clamshell or dragline could only remove approximately 27 or 86 $m^3 hr^{-1}$, respectively. Dragline or clamshell excavation would require barging the cut sediments to the drying/disposal areas; this would be relatively inefficient and therefore expensive. Hydraulic dredging would allow piping the sediments to the disposal areas; accordingly, this would be much more efficient and cost effective. Therefore, given the magnitude of sediment accumulation within Lake Apopka, hydraulic dredging is the only feasible method of removing lake sediments.

4.1 OVERVIEW HYDRAULIC DREDGING OF LAKE APOPKA SEDIMENTS

Hydraulic dredging and processing of the Lake Apopka sediments would include the following sequence of activities:

1. Removal of accumulated sediments from the lake bottom.
2. Pumping of the dredged sediment/water slurry to the sedimentation basins on the shoreline.
3. Separation of the dredged sediment/water slurry through settling of suspended material in a sedimentation basin followed by discharge of the clarified supernatant.
4. The dredged sediment/water slurry will be diverted to other sedimentation basins once the sedimentation basin has been filled. Water overlying the accumulated sediments in the basin will be treated in situ and the clarified water discharged, exposing the surface of accumulated sediments.
5. After a period of initial drying, accumulated sediments will be ditched to facilitate drainage, dewatering and drying of the

sediments. Based on studies performed by Fox (1977), volumetric consolidation of approximately 40 % can be expected during this drying.

6. After sufficient drying has occurred, the consolidated, dried material will be removed from spoil disposal basins and stored for later sale, shipping or other disposal.
7. After the material has been removed, the spoil area dikes will be repaired and the spoil area will be reused for sedimentation and clarification of the dredged sediment/water slurry.
8. This area will receive dredged sediment/water slurry until it is filled, at which time the sediment dewatering, drying, and removal process is repeated.

As noted above, sediment disposal basins will be rotated as they are filled, and the sediments are dried and removed. This cyclic process is continued until all lake sediment dredging is complete. Details regarding required spoil area, and other site and engineering details are presented later in this section.

4.2 HYDRAULIC DREDGING CONCEPTUAL DESIGN: SYSTEMS AND COMPONENTS

The following summarizes the various systems and/or facilities which would be necessary to remove sediments from Lake Apopka by hydraulic dredging.

Sediment Dredging (including Pumping to Shoreline Basins)

As previously noted, hydraulic dredging is the most feasible means to remove large volumes of sediments from Lake Apopka. This section summarizes various details regarding dredge size and performance. Based on available sediment data and dredge engineering/performance data, the following conceptual design parameters were developed:

1. Sediment will be cut from the lake bottom using a 24 inch (61 cm) hydraulic dredge cutting at a design rate of 859 m^3 hr^{-1} or 15,242 m^3 day^{-1}, considering dredge down time for moving, maintenance, etc. A 24 inch hydraulic dredge is the largest

dredge which could reasonably be expected to operate in Lake Apopka and therefore offers the maximum dredge rate for sediment removal. Because of the relatively shallow depths in Lake Apopka, special modifications probably would be required to allow a 24 inch dredge to operate in the lake.

2. Sediment survey results indicate the average thickness of sediments to be removed is removed 120 cm (Section 3.3). Given a minimum operational draft of a specially constructed (e.g. low draft), 24 inch hydraulic dredge of 2.44 m, only sediments lying at or deeper than the 1.22 m contour can be removed. [Note: In these areas, the dredge would start in deeper areas and proceed into shallower areas, creating the necessary water depth in the process.] Bathymetry developed by Schneider and Little (1968) indicates approximately 10,400 acres of Lake Apopka are deeper than 1.22 m (at a lake level of 20.3 m MSL). Given the area suitable for dredging due to the dredging depth limitation and the average depth of sediments to be removed, approximately 121,763,000 m^3 of sediments will be removed.

3. Because of the total volume of sediments to be removed, we have assumed that 5 dredges will operate in the lake. With this number of dredges, completion of all dredging will take approximately 5.9 years. Details regarding sediment volumes, dredge rates and related data are summarized in Table 4-1.

4. Cut sediments will be pumped through a pipeline to shoreline sedimentation basins; to compensate for energy losses in the pipeline and to maintain flow, pump stations are required at 3,050 m intervals. For the purposes of this analysis, we have assumed that cut sediments would be pumped an average of 7,620 m across the lake and an additional 3,050 m over land to the spoil sedimentation basins. This total distance would require the use of an average of 3 in-line pump stations. [Note: These estimates

reflect anticipated average distances during the life of the dredging project; actual distances will vary based on the exact location of the dredge(s) and active sedimentation basins.] For the purposes of this analysis, sedimentation basins were assumed to be located in the northwest quadrant of the lake shore, immediately west of the Apopka-Beauclair Canal. Exact location of spoil retention basins would be subject to land acquisition by the SJRWMD prior to project execution. Details regarding dredge sizing and capacity are presented in Appendix A.

<u>Sedimentation Basin and Sediment Processing Areas</u>

As previously summarized, sedimentation basins will be used to remove suspended sediments from the sediment/water slurry resulting from dredge activities. After these basins are filled with sediment, the sediment will be dewatered, dried and removed from these spoil disposal basins, and stored for later sale, shipping or other disposal. We have assumed that sedimentation basins will be located nearshore, immediately west of the Apopka-Beauclair Canal. Exact location of spoil retention basins will be subject to land acquisition by the SJRWMD prior to project execution.

This section summarizes the land area required, and the anticipated requirements for sediment drying, removal, and hauling for upland storage and/or disposal.

1. For the purposes of this analysis, a nominal 64.8 ha sedimentation cell was assumed as a unit size. Operationally, the pumped dredged sediment/water slurry from a single dredge would be discharged into this cell until the sediment accumulates to a depth of 1.5 m. Once the sedimentation basin has been filled, the pumped dredged sediment/water slurry is diverted to other 64.8 ha sedimentation basins, and the process continues. Details regarding the loading and filling of these 64.8 ha cells are presented in Tables 4-2, 4-3, and 4-4. [Note: The estimated basin surface loading rate is substantially lower than the recommended

maximum rate of 10.5 m^3 day^{-1} m^{-2} determined in previous treatability studies performed for Lake Apopka sediments Ross, Saarinen, Bolton, and Wilder (RSBW, 1978). Therefore, clarified water from the basin can be expected to be relatively free of suspended sediments.]

2. After this sedimentation basin is filled and the pumped dredged sediment/water slurry has been diverted to other sedimentation basins, the water overlying the accumulated sediments will be treated to clarify the water and reduce phosphorus concentrations to less than 0.5 mg P L^{-1}. Clarified supernatant will be pumped out of the cell, exposing the surface of the accumulated sediments and allowing drying of the sediments to begin. During the entire drying/removal process, water will be pumped out of the cells to facilitate drying and equipment operation. Details regarding spoil cell spillway size, ditching requirements, and pump estimates are presented in Tables 4-5 through 4-6. Details regarding water treatment volumes are presented in Table 4-7.

3. After this period of initial drying, accumulated sediments will be ditched to facilitate drainage, dewatering, and drying of the sediments. Based on studies performed by Fox (1977), volumetric consolidation of approximately 40 % can be expected during this drying. After sufficient drying has occurred, the consolidated, dried material will removed from these spoil disposal basins and stored for later sale, shipping, or other disposal. Details regarding removal rates and equipment requirements are presented in Tables 4-8 and 4-9.

4. After the material has been removed, the spoil area dikes will be repaired and the spoil area will be reused for sedimentation and clarification of the dredged sediment/water slurry. Details regarding diking requirements are summarized in Table 4-2.

Based on these data, total spoil sedimentation area required is estimated to be 1222 acres, exclusive of dike area, access, buffers, or related ancillary facilities or requirements.

<u>Upland Storage and Disposal Facilities</u>

For the purposes of this analysis, we assumed that upland areas would be used for storage of dried sediments until sale, use, or disposal. Based on the above engineering data, dried sediments would be produced at a rate of approximately 45,725 m^3 day^{-1}. Assuming a maximum on-site storage of 90 days of production and a stacking height of 6.1 m, approximately 67.6 ha would be required for sediment storage, exclusive of access, buffers, dike area, etc. Details regarding sediment storage are summarized in Table 4-9.

Table 4-1. Dredge operational design data.

Dredge size	24 inches (61 cm)
Average daily operation	20 hr day^{-1}
Average monthly operation	27 day $month^{-1}$
Dredge operational factor	74%
Design dredge cut rate (based on 3 pump stations)	859 m^3 hr^{-1}
Average cut/spoil rate	15,242 m^3 day^{-1}
Average depth of sediments	1.17 m
Total lake area greater than 4 feet in depth	10,400 ha
Design volume of sediment to be removed	121,763,000 m^3
Overdredge (non-pay)	0%
Total volume of sediment to be removed	121,763,000 m^3
Number of dredges	5 dredges
Time required to remove all sediments	2,160 days
	5.92 years

Table 4-2. Dredge spoil sedimentation area design information.

Nominal cell area	64.8 ha
Nominal cell area	647,500 m^2
Total perimeter diking (assuming square area), per cell area	3,220 m
Internal diking (to divide total area into 4 sub-cells)	1,610 m
Total length of diking	4,830 m
Minimum water depth for adequate sedimentation	1.22 m
Minimum allowable freeboard	0.91 m
Maximum accumulated sediments	1.52 m
Total dike height	3.66 m
Dike side slopes	3 : 1
Dike crest width	3.66 m
Dike cross-section	53.5 m^2
Dike unit volume	53.4 m^3 m^{-1}
Total dike volume (per cell)	258,379 m^3
Fraction of dike which has to be rebuilt after each use	20%
Total diking volume per cell use	51,675 m^3
Total quantity of spoil material placed in cell	986,870 m^3
Diking volume per spoil volume	0.040 m^3 dike m^{-3} spoil
Design volume of material to be removed from Lake Apopka	121,763,000 m^3
Initial dike construction volume	4,869,000 m^3
Reconstructed dike volumes	5,402,000 m^3
Total dike construction volume	10,271,000 m^3

Table 4-3. Spoil sedimentation cell capacity and surface loading rates.

Spoil Area Cell Capacity	
Nominal spoil area cell size	64.8 ha
Final spoil thickness	5 feet
Total spoil cell volume	986,870 m^3
Average cut/spoil rate per dredge	15,242 m^3 day^{-1}
Spoil cell life at average cut/spoil rate	65 days
Spoil Area Hydraulic Loading	
Sediment/water ratio	25%
Total inflow rate	60,700 m^3 day^{-1}
Total inflow rate	0.705 m^3 sec^{-1}
Average surface loading rate for spoil area/sedimentation basin	0.0941 m^3 day^{-1} m^{-2}

Table 4-4. Spoil sedimentation cell material filling and removal rates and acreage requirements.

Spoil Area Fill Schedule	
Spoil cell life at average cut/spoil rate	65 days
Sediment Removal Schedule	
Initial dewatering and ditching	30 days
Drying time (prior to initiation of bulk excavation)	45 days
Allowable time for bulk excavation	90 days
Dike repair and repreparation of spoil area for return to service	15 days
Total duration the spoil area is out of service (per filling)	180 days
Spoil Area Acreage Requirements	
Total number of cells required per dredge	3.8 cells
Nominal spoil area cell size	64.8 ha
Total spoil acreage (rotating) required per dredge	244 ha $dredge^{-1}$
Number of dredges	5 dredges
Total spoil area required (exclusive of buffers, dike area access, etc.)	1,222 ha

Table 4-5. Spoil sedimentation outflow design.

Total inflow into spoil cell	0.705 $m^3\ sec^{-1}$
Percent settleable solids	25%
Total outflow for cell	0.530 $m^3\ sec^{-1}$
Number of spillways/risers per cell	4
Total outflow per spillway/riser	0.133 $m^3\ sec^{-1}$
Diameter of each spillway/riser	0.914 m
Weir length of each spillway/riser	2.87 m
Water level above crest to discharge required rate	0.085 m
Total number of disposal cells	19 cells
Total number of spillways/risers	76 spillways

Table 4-6. Spoil sedimentation cell dewatering requirements.

Effective width of dewatering trench	61 m
Nominal spoil cell size	64.8 ha
Linear distance of dewatering trench	10,620 m
Number of times area will have to be trenched to effectively dry the spoiled material	3 times
Total linear distance of dewatering trench per cell use	31,870 m
Total quantity of spoil material placed in cell	986,870 m^3
Linear distance of dewatering trench per cubic volume of spoil material	0.0323 m m^{-3}
Total volume of material to be removed from Lake Apopka	121,763,000 m^3
Total linear distance of dewatering trench required during total project	3,932,000 m

Table 4-7. Spoil supernatant and dewatering volumes (for chemical water treatment).

Total sediment dredge volume	121,763,000 m^3
Dredge operational percent solids	25%
Dredge operational sediment/water ratio	3 : 1
Total dredge supernatant volume	365,289,000 m^3
Anticipated consolidation during dewatering	40%
Water released and discharged during consolidation/dewatering	48,705,200 m^3
Total water to be chemically treated and discharged	413,994,200 m^3

Table 4-8. Bulk excavation of dried, consolidated material.

Consolidation after drying	40% reduction
% of initial volume	60% of initial volume
Initial volume of spoil material in spoil cell	986,870 m^3
Volume of dried material in spoil cell	592,120 m^3
Bulk excavation rate (per scraper)	717 m^3 day^{-1} $scraper^{-1}$
Allowable time for bulk excavation	90 days
Number of scrapers required for bulk excavation per cell	9.2 scrapers

Table 4-9. Upland storage requirements for dried, consolidated material.

Wet sediment production rate (per dredge)	15,240 m^3 day^{-1}
Consolidation after drying	40% reduction
Consolidated sediment production rate (per dredge)	9,145 m^3 day^{-1}
Number of dredges	5 dredges
Total consolidated sediment production rate	45,725 m^3 day^{-1}
Allowable stacking height of stored sediments	6.1 m
Maximum storage quantity	90 days
Required upland storage area	67.6 ha

5.0 SEDIMENT REUSE

5.1 INTRODUCTION

A significant concern of lake restoration via sediment removal is disposal/utilization of the sediment. Options should be considered which deal with disposal/utilization methods using the "raw" sediment as well as with methods which involve subsequent processing of the sediment such as drying and grinding into small pellets.

In this analysis we have assumed that both the unconsolidated and consolidated floc layers of the sediment will be dredged from the lake. The combined average depth of these two sediment layers is 117 cm (Section 3.2), which gives a total bulk volume 146 x 10^6 m^3. Operating constraints imposed by using a 24 inch dredge limit dredging to below 1.22 m water depth (see Section 4.1); as a result, an estimated total bulk volume of 121.8 x 10^6 m^3 will be removed the lake. This volume of bulk sediment is equivalent to 8.60 x 10^6 metric tons of dry material which must be utilized or disposed of.

The primary alternatives available for utilization/disposal to be considered herein are: disposal in muck farmlands recently obtained by the District; use as a component of growth media (potting soil) in the nursery industry; and land application to muck and mineral soils as a soil amendment and/or slow release fertilizer.

5.2 RECREATION OF WETLANDS

One possibility of using the raw sediment is for the filling of recently-acquired farmed mucklands in the Lake Apopka area. This may be feasible for Lake Apopka because of the recent acquisition of nearby muckland by the District. This area has experienced considerable subsidence (3 cm yr^{-1}) due to oxidation of the muck soil, and reclaimed sediment could be used to compensate for this subsidence. An estimate of the amount of muck farmland that could be augmented or "restored" with Apopka sediment is calculated as follows:

1. Final sediment water content of 30 percent after drying.

2. Particulate densities ranging from 1.2 to 2.65 g cm^{-1} (the range of densities for organic matter and mineral soils [Brady, 1974]). Pollman (unpublished data) estimates particulate densities for unconsolidated Apopka sediments ranging from 1.8 to 2.4 g cm^{-3}) with an average bulk (dry + wet) density of 1.02 g cm^{-3}.

3. Total solid mass (non-water) in the unconsolidated and consolidated sediments is:

<u>Unconsolidated sediments</u>

3.671×10^7 m^3 x 1.024[1] x 10^3 kg m^{-3} x 3.42 % dry material = 1.286×10^9 kg dry material

<u>Consolidated sediments</u>

8.507×10^7 m^3 x 1.062×10^3 kg m^{-3} x 8.1 % dry material = 7.318×10^9 kg dry material

4. Total volume of dried material at 30 percent water content ranges from:

<u>Unconsolidated sediment</u>

Water mass = 0.551×10^9 kg = 0.551×10^6 m^3

Particulate volume = 1.286×10^9 kg x $(2.4 \times 10^3 \text{ kg m}^{-3})^{-1}$ =
0.536×10^6 m^3 (low estimate)
= 1.286×10^9 kg x $(1.8 \times 10^3 \text{ kg m}^{-3})$ =
0.714×10^6 m^3 (high estimate)

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[1]From Table 5-1

Consolidated sediment

Water mass = 3.136×10^9 kg = 3.136×10^6 m^3

Particulate volume = 7.318×10^9 kg x $(2.4 \times 10^3 \text{ kg m}^{-3})^{-1}$ =
3.049×10^6 m^3 (low estimate)
= 7.318×10^9 kg x $(1.8 \times 10^3 \text{ kg m}^{-3})$ =
4.066×10^6 m^3 (high estimate)

Consequently, the estimated total volume of dried material ranges from 7.27×10^6 to 8.47×10^6 m^3.

At an application rate of 1 m of dried material, the muck farm areal requirements for disposal would range from 730 to 850 ha. Wetland vegetation could then be reestablished on the filled area. It should be noted that these calculations provide no indication of the usability of the dried material without further processing. Laboratory drying studies conducted by Pollman (unpublished data) indicate that unconsolidated sediments from Lake Apopka will become very hard and brick-like once moisture content falls below 90 percent; moreover, once dried, the material does not rewet. In all likelihood, dried sediments will have to be ground into small particles before the material is acceptable for wetland reconstruction or, for that matter, other reuses as well.

From an administrative perspective, filling of existing wetlands does not appear to be an acceptable alternative. The Warren Henderson Wetlands Preservation Act limits wetland filling activity in Florida (although it is not clear how this augmentative action would be interpreted according to the act); in addition, Federal law (Section 404 of Public Law 92-500) prohibits filling of wetlands greater than 10 acres (4.0 ha) in size without a permit (Cooke et al., 1986).

5.3 GROWTH MEDIA FOR THE NURSERY INDUSTRY

Assuming that the sediment can be adequately dried and prepared, there are several potential uses of the resultant product. One potential use involves the 0.5 billion dollar ornamental horticulture industry which is centered largely in central Florida and particularly around the Lake Apopka area. This industry uses significant quantities of growth media for container grown plants. A large portion of the Florida landscape and foliage crops (85% of the total value) is produced in containers (Ingram, 1988). Moss peat, i.e., peat formed from moss, is the most common organic component used in this growth media. This type of peat has a fibrous quality which provides high internal water holding capacity with adequate drainage. Muck, which is a more decomposed form of peat, is not a good component for growth media, because of its fineness. Based on the characteristics of superficial sediments of Lake Apopka, these sediments would likely closely parallel the characteristics of "muck". This would limit the potential use of sediments as a direct component of growth media.

Nevertheless, it may be possible to use the dried sediment as a small component of the growth media, i.e., 5, 10, or 20% of the total mix. It is estimated that 1.5 million cubic meters of growth media are used in Florida on an annual basis (C. A. Conover, personal communication). This would utilize 75,000, 150,000 and 300,000 cubic meters of dried sediment annually. The industry presently pays about \$11.50 m^{-3} for Florida peat. Assuming they would pay the same for dried Lake Apopka sediment, the potential value of this market would range from \$800,000 to \$3,200,000 annually. The <u>maximum</u> gross market value of Apopka sediment (30 percent water content) would be \$97,410,000 (\$11.50 x 8.47 x 10^6 m^3).

Materials such as municipal sewage sludge and solid refuse have been composted with woodchips and the resultant product has been used to replace bark and peat, at least partially, in growth media (Ingram, 1988). Therefore it may be possible to compost sediment with bark, sawdust, wood shavings, or municipal solid waste and sewage sludge to make an acceptable growth media component. This type of application, however, would utilize considerably less sediment than if used directly as a growth media component.

5.4 LAND APPLICATION

A second potential use of the sediment would be as a soil conditioner or amendment. Soil conditioners/amendments are used to improve soil characteristics such as porosity, water holding capacity and nutrient retention capacity. In some cases, the sediment may also act as a slow release fertilizer. Dredged sediments have been applied to agricultural land in several lake restoration projects: Lake Trummen, Sweden; Nutting Lake, Massachusetts; Lake Paradise, Illinois; Lilly Lake, Wisconsin; and Lake Springfield, Illinois. Sediment from Lake Trummen was sold as top soil for about \$2 m^{-3} and Nutting Lake sediment was sold for about \$1.40 m^{-3} (Peterson, 1981). Dredged Lake Springfield sediment produced higher yields of sudangrass compared to an unamended clay loam soil (Olson and Jones, 1987). Lembke et al. (1983) predicted a \$40 ha^{-1} (\$100 $acre^{-1}$) increase in returns due to increased corn yields and lower fertilizer requirements when Lake Paradise sediment was applied to the land.

Dried Lake Apopka sediment has potential as a soil amendment because of its high organic matter content, high pH, and relatively high levels of nitrogen and phosphorus (Table 5-2). It is likely that the sediment would increase the soil pH and act as a slow release fertilizer. The sandy, acid soils of Florida should benefit significantly from the addition of sediment. Whether the water holding capacity of the soil would be improved is unknown because of the potential rewetting problems of dried soil. Laboratory studies would be required to evaluate the effect of dried sediment on moisture retention in Florida soils. Other studies would be needed to determine the mineralization rates of the sediment organic component to determine its value as a slow-release fertilizer.

Small plot field-scale studies would need to be done to determine appropriate application rates and to define quantitatively the benefits of sediment to the soil and to crop yields. As a first approximation, an application rate of 60 dry metric tons ha^{-1} yr^{-1} is reasonable. Using values of 2.0% nitrogen and 0.07% phosphorus, this amount of sediment would provide 1200 and 42 kg ha^{-1} of nitrogen and phosphorus, respectively. Approximately half of these nutrients could be considered available to plants. At current market prices for nitrogen and phosphorus, the value of 60 metric tons of sediment is $300 for nitrogen and $50 for phosphorus. Estimated annual rates of sediment removal are 20.3×10^6 m^3 sediment yr^{-1} (121.8×10^6 m^3 over a 6 year period) with a dry weight (30 % water content) of 1.43×10^6 metric tons; this total amount of sediment mass has a maximum market value of $50,000,000 ($350 x $8.60 \times 10^6 \times 60^{-1}$). Twenty-three thousand nine hundred ha crop land would be required for each year of dredging.

Application of "liquid" sediment to agricultural land via a travelling irrigation gun has been suggested for disposal of sediment from Lake Paradise in Illinois (Lembke et al., 1983). They proposed applying 2.5 cm of wet sediment (90% water) per week for a period of 24 weeks. Lake Apopka surface sediments may lend themselves to this type of application method due to their high water content. However, many sediments are not fluid enough to pump through an irrigation system as evidenced by experiences with the Lilly Lake restoration project (Dunst, 1982).

If we assume that Lake Apopka sediments can be applied to the surrounding muck farms at bulk rates up to 30 cm ha^{-1} yr^{-1}, the total muck area of 7,300 ha (18,000 acres) could easily accommodate the estimated yearly dredging (20.3×10^6 m^3) from Lake Apopka. There are also 11,000 ha (28,000 acres) of citrus and 1,400 ha (3,400 acres) of other crop land in the Lake Apopka drainage basin potentially available for application of some of the sediment. Temporary loss of cropland during and after the dredging operation would have to be taken into consideration along with the environmental implications of nutrient laden drainage water and possible toxic substances getting into the food chain.

Table 5-3 presents a summary of potential uses for the dredged sediment with estimated market values. We believe that disposal of the sediment for creation of wetlands on muckland or application of the sediment to muck soils in agricultural use would have no marketable value. However, if the dried sediment is processed and pelletized, it may be marketed as a fertilizer material. The total N available in the dredged UCF and CF horizons is about 195,800 metric tonnes. With an estimated fertilizer N value of \$500 tonne^{-1}, the total return on dredged material used as fertilizer would be about \$97,900,000. This value is based on total N content and assumes that all of the N in the dredged material is available for plant uptake. If only 50 % of the N were available to plants, then the actual market value would be reduced to nearly \$50,000,000.

Phosphorus and potassium provide additional economic value to dredged Lake Apopka sediment used as fertilizer. The market values for P and K are \$500 and \$300 tonne^{-1} respectively, yielding additional returns of \$2,800,000 and \$1,600,000. Considering the combined contributions of N, P, and K, we estimate that the total return on Lake Apopka sediment used as fertilizer would approximate \$55,000,000. As a soil amendment, it has a potential market value of 30-70 million dollars. Use of sediments as a component of growth media in the nursery industry has a limited value due to unsuitability of the sediment by itself as a growth media.

Table 5-1. Physical properties of Lake Apopka sediments.

Component	UCF	CF
Depth, cm	35.3	81.8
Surface area dredged m^2	10.4×10^7	10.4×10^7
Sediment volume, m^3	3.671×10^7	8.507×10^7
Bulk density, g (dw) cm^{-3}	0.035	0.086
Wet weight (total), metric tons	37.391×10^6	89.177×10^6
Dry weight (total), metric tons	1.278×10^6	7.318×10^6
Porewater, metric tons	36.113×10^6	81.859×10^6

Table 5-2. Storage of nutrients in Lake Apopka sediments. Values shown in parentheses represent percent of total element content. Sediment depth: UCF = 35.3 cm and CF = 81.8 cm. Lake surface area = 12,500 ha.

Component	UCF	CF
	---metric tons---	
Carbon		
Porewater		
Inorganic	2,030 (0.44)	6,849 (0.24)
Organic	1,237 (0.26)	3,366 (0.12)
Sediment		
Inorganic	15,885 (3.41)	70,534 (2.47)
organic	446,632 (95.89)	2,777,140 (97.17)
Total	465,784	2,857,889
Nitrogen		
Porewater - Total	1,438 (3.93)	5,467 (2.78)
Ammonium N	1,115 (3.05)	3,731 (1.90)
Organic N	323 (0.88)	1,706 (0.87)
Sediment		
Exchangeable Ammonium N	329 (0.90)	2.059 (1.05)
Organic N	34,819 (95.17)	189,360 (96.18)
Total Kjeldahl N	36,586	196,856
Phosphorus		
Porewater		
SRP	48 (3.20)	150 (2.84)
Total P	92 (6.14)	318 (6.03)
Sediment		
[1]Dilute acid extractable P	338 (22.56)*	1,053 (19.96)*
[2]Strong acid extractable P	757 (50.53)*	2,798 (53.03)*
Residual P (organic P)	741 (49.46)	2,478 (46.96)
Total (Strong acid extractable plus residual)	1,498	5,276

* Includes porewater P.

[1]Dilute acid = 0.05N HCL + 0.25N H_2SO_4
[2]Strong acid = 0.5N HCL + 0.25N H_2SO_4

Table 5-3. Potential uses and total market value for dredged Lake Apopka Sediment.

Potential use	Area required	Estimated total value
	hectares	--$ X 10^6
1. Disposal		
A. Wetland reconstruction	730 to 850	- 0 -
B. Muck farm application of sediment slurry	7,300	- 0 -
2. Growth media	--	0.8 - 3.2 yr^{-1}
3. Land application of dried sediment		
A. Fertilizer[1]	43,000	25 - 50*
B. Soil amendment[2]	23,900	30 - 70

*Requires processing.

[1] Fertilizer Value:
1 ton of N = $500
1 ton of P = $500
1 ton of K = $300

[2] Soil Amendment
Marketed at 30% water content, at $3 - 6 m^{-3}.

6.0 COST BENEFIT ANALYSIS

This section integrates the cost analysis for dredging of Lake Apopka sediments (Section 4) with the reuse economic analysis presented in Section 5 to estimate the net range of likely costs to be incurred for the project.

Estimated project dredging costs were prepared based on anticipated quantities and unit costs associated for the various components. Unit costs data were prepared based on available and applicable data. Dredging unit cost data were developed using USCOE estimating techniques and data (see Appendix A); other unit costs were developed using 1988 Means Cost Data (R.F. Means Co., 1987).

Total project dredging costs were estimated based on the following components:

1. Initial sedimentation area dike construction costs (Table 6-1);
2. Sediment dredging and pumping costs (Table 6-2);
3. Dredged sediment dewatering and drying costs (Table 6-3);
4. Estimated costs of chemical treatment to clarify water and remove phosphorus during sediment dewatering (Table 6-4);
5. Bulk excavation and hauling costs of consolidated sediments to an upland storage area for sale and/or ultimate disposal (Table 6-5); and
6. Sedimentation area dike reconstruction costs after bulk sediment removal (Table 6-6).

Total dredging costs are presented in Table 6-7. These costs do not include spoil area land costs, spoil area land clearing costs, upland land costs for storage of dewatered sediments prior to sale or disposal, or any costs associated with sale or ultimate disposal of the dewatered sediments. Total dredging costs approximate $868,800,000. As noted, this is exclusive of spoil area land costs, spoil area land clearing costs and upland land costs for storage of dried sediments prior to sediment sale or disposal. Costs associated with these items will further increase the project cost. Finally, these costs have been developed assuming (1) a 24 inch dredge, and (2) dredged material is pumped an average distance of 7,620 m across Lake Apopka plus an additional 3,050 m on land (Section 4.1). Use of a smaller dredge, or pumping greater distances, may reduce significantly the dredge production rate and increase the per unit dredge costs.

The sediment reuse with the greatest potential to offset dredging costs is as fertilizer, which has an estimated market value of $55,000,000. Use as a soil amendment has an estimated yield of $25,000,000 to $50,000,000. Assuming that dried Apopka sediment has the same reuse value as peat as a potting or growth medium defines an <u>upper</u> limit market value of $97,400,000. As mentioned in Section 5.3, this reuse is constrained by the size of the local market, which in turn is related to the percentage of dried sediment can be accommodated in the total mix. Also, it is highly unlikely that dried sediment from Apopka will have nearly the same value as peat as a growth medium.

The minimum cost of the dredging project, including the upper limit value conceivable for reuse, is $771,400,000 (i.e., $868.8M - $97.4M). In all likelihood, project costs will be closer to between $814,000,000 and $844,000,000.

One potential problem regarding dredging Lake Apopka is the time frame of sediment removal. As discussed in Section 4.1, dredging the lake will take approximately 6 years. During that period, substantial redistribution of resuspended surficial, unconsolidated sediment is likely to occur in response to wind-driven currents. The likelihood of this occurrence is exemplified by the remarkable consistency in the chemistry and physical characteristics of Apopka sediments throughout the basin (Pollman, 1983; Reddy <u>et</u> <u>al</u>., 1988). Since only a small amount of unconsolidated material is necessary to drive high rates of internal loading (i.e., 10 to 20 cm), the efficiency of dredging is questionable. Clearly, the most important benefit of removing the UCF and CF layers of sediment is to reduce the likelihood or frequency of sediment resuspension and concomitant releases of nutrients. Unless measures (e.g., diking) are taken to prevent sediment redistribution, resuspension may persist, and the benefits of resuspension on reducing internal loading in Lake Apopka may be minimized.

Table 6-1. Estimated spoil area preparation costs (exclusive of land costs and land clearing costs).

Initial Dike Construction	
Initial dike construction volume	4,869,000 m^3
Dike construction unit cost	\$2.014 m^{-3}
Initial dike construction cost (exclusive of land costs and land clearing costs)	\$9,807,000
Spillway/Riser Construction	
Number of spillways/risers	76
Unit cost	\$4,000 $spillway^{-1}$
Total spillway/riser construction cost	\$304,000
Initial Spoil Area Preparation Cost	\$10,110,000

Table 6-2. Estimated dredging costs.

Dredge Mobilization	
Number of dredges	5 dredges
Mobilization cost per dredge	\$1,000,000 $dredge^{-1}$
Total mobilization cost	\$5,000,000
Sediment Removal (including Pipeline and Booster Pumps to Convey Dredge Slurry to Shoreline Sedimentation Areas)	
Total volume of sediments to be dredged from Lake Apopka	121,763,000 m^3
Unit cost of dredging sediments	\$2.799 m^{-3}
Sediment dredging costs	\$340,800,000
Dredging Costs (including Mobilization, Pipeline, and Booster Pump Costs)	\$345,800,000

Table 6-3. Estimated dewatering and drying costs.

Ditching/Trenching Costs	
Total linear distance of dewatering trench required during total project	3,932,000 m
Unit cost for ditching/trenching	\$1.903 m^{-1}
Total ditching/trenching costs	\$7,480,000
Pump Installation Costs	
Total number of disposal cells	19 cells
Number of pumps per cell	2
Total number of pumps	38 pumps
Unit price of pumps	\$25,000 $pump^{-1}$
Total pump installation cost	\$950,000
Pump Operation/Maintenance Costs	
Daily operation	12 hours day^{-1}
% of days in operation	67%
Total duration of project	2,160 days
Total number of hours of operation during entire project	659,900 hours
Hourly cost for pump operation and maintenance	\$10 $hour^{-1}$
Total pump operation and maintenance cost	\$6,600,000
Total dewatering and drying costs	\$15,030,000

Table 6-4. Estimated costs for clarifying and removing phosphorus to 0.5 mg P L^{-1} during dewatering of dredged sediment/water slurry. Costs from bench scale studies on Lake Apopka sediments conducted by Ross, Saarinen, Bolton, and Wilder RSBW (1978).

Total water volume to be chemically treated and discharged	413,994,200 m^3
Estimated unit volume water treatment cost	\$0.01962 m^{-3}
Total water treatment cost	\$8,120,000

Table 6-5. Estimated cost of bulk excavation and hauling of consolidated sediments to an upland area storage area for sale/disposal.

Total wet volume of sediments to be dredged from Lake Apopka	121,763,000 m^3
% consolidation	40% reduction
Total consolidated volume of sediments dredged from Lake Apopka (to be removed from spoil area and hauled to storage area for sale/disposal)	73,057,500 m^3
Unit cost for bulk excavation and hauling (3,050 m haul)	\$5.474 m^{-3}
Total cost for bulk excavation and hauling consolidated sediments to an upland area storage area for sale/disposal	\$399,880,000

Table 6-6. Estimated dike reconstruction costs after removal of dried, consolidated sediments.

Dike reconstruction volume	5,402,000 m^3
Dike reconstruction unit cost	\$2.014 m^{-3}
Total dike reconstruction costs (after removal of dried, consolidated sediments)	\$10,880,000

Table 6-7. Summary of estimated project costs.

Initial spoil area preparation cost, exclusive of land costs and land clearing costs (Table 6-1)	$10,110,000
Dredging costs, including mobilization, pipeline, and booster pump costs (Table 6-2)	$345,800,000
Total sediment dewatering and drying costs (Table 6-3)	$15,030,000
Cost for bulk excavation and hauling consolidated sediments to an upland Area storage area for sale/disposal (Table 6-4)	$399,880,000
Total dike reconstruction costs, after removal of dried, consolidated sediments (Table 6-5)	$10,880,000
Total water treatment cost, including dredging supernatant and dewatering waters (Table 6-6)	$8,120,000
Subtotal	$789,820,000
Contingency and miscellaneous -- 10%	$78,980,000
Estimated total project dredging costs[1]	$868,800,000

[1]Estimated costs exclusive of spoil area land costs, spoil area land clearing costs and upland land costs for storage of dried sediments prior to sediment sale or disposal.

7.0 ADDITIONAL STUDIES

Cost estimates of dredging and estimates of the economic value of removed sediment involved a number of assumptions regarding the characteristics of Lake Apopka sediment that may affect the cost/benefit analysis. In general, the cost/benefit analysis was structured such that the aggregated costs presented in Section 6 represent the minimum estimated costs of the project. Nonetheless, some uncertainties exist in the analysis which should be evaluated if dredging of Lake Apopka is still considered a viable restorative measure. These uncertainties also transcend simple economics of dredging and reuse; the efficacy of dredging leading to an improvement in lake trophic state is still in question. This section presents the types of studies that should be implemented before a dredging program is implemented in Lake Apopka.

7.1 ENGINEERING ASPECTS OF DREDGING

Sediment Redistribution

As previously discussed in Section 4, the conceptual engineering feasibility analyses were developed based on two critical engineering constraints: (1) the total duration of the project, and (2) the minimum depth of dredging. Both factors afford substantial potential for sediment redistribution during and after the proposed project.

First, total project duration has been minimized, but is estimated to be approximately 5.9 years; to accomplish the necessary dredging within the time period, five dredges will be required. In consideration of the total number of dredges, the ancillary facilities and the related support and coordination activities required, this is a realistic estimate of the minimum duration of the project. During this 5.9 year period, there is considerable potential for substantial redistribution of the undredged sediments into the areas where dredging is complete. The mean depth of Lake Apopka is only 1.7 m, and the combination of highly flocculent sediments and shallow water column depth coupled with a broad effective fetch indicates that wind-wave induced resuspension and redistribution of undredged UCF and CF sediments is highly likely.

Second, due to the depth constraints of the dredges, only 10,400 ha of the total 12,400 ha lake area can be dredged using large and cost effective dredges. As such, at project completion, at least 16 percent of the lake bottom still will be covered with unconsolidated and consolidated flocculent sediments. Again, given the shallow nature of the areas of the lake, the associated potential for wind-wave induced resuspension, significant redistribution of sediments from the nearshore undredged areas to previously dredged areas is likely.

Before dredging is implemented, additional studies should be pursued which examine sediment redistribution and its effects on the recovery of Lake Apopka. These studies should focus on quantifying the potential for sediment redistribution, estimation of the time scales over which redistribution will occur, estimation of redistribution volumes, and the limnological or water quality impacts of such sediment redistribution on the overall project goals and objectives.

Dredge Material Settling Properties and Supernatant Water Quality

The conceptual engineering feasibility analyses developed in Section 4 made a number of assumptions regarding dredged material settling properties and treatability. These assumptions directly affect the project design relating to dredge material settling areas (e.g., sedimentation depths, total land area required) and to discharge water quality (e.g., suspended solids in settled water, chemical treatment and dosage, suspended versus dissolved constituents, etc.). Bench scale settling tests, including treatability and water quality studies, would afford better definition of these issues and allow a more accurate conceptual design and cost estimate.

7.2 SEDIMENT REUSE

Disposal of sediment in an environmentally safe manner is an important criterion for using dredging to restore Lake Apopka. A number of disposal methods have been identified as part of this study, including: (1) disposal on muck lands adjacent to Lake Apopka; (2) land application to muck and mineral soils as a soil amendment and/or slow release fertilizer; and

(3) use as a component of growth media in the nursery industry. Although these disposal alternatives appear to be promising, very little or no information is available on the behavior of these organic sediments upon application to soil. We have proposed a series of additional studies which will aid in making rational recommendations for economic disposal of dredged sediments yet still afford environmental protection. The following research tasks will provide information on developing the guidelines for land application of sediments in relation to optimal plant growth and acceptable water quality.

<u>Drying, Handling and Processing Characteristics</u>

1. **Determine the drying characteristics of the sediment with respect to physical characteristics (cohesiveness, hardness) at different degrees of dryness.**

The intent of this study is to evaluate how the sediment characteristics such as cohesiveness and hardness change as drying occurs. Do cohesiveness or hardness change to a significant degree at a given water content? Do characteristics of the sediment such as organic matter, clay content, or marl content affect the drying characteristics of the sediment?

2. **Evaluate the effect of varying degrees of water removal on handling, processing and storage characteristics of the sediment.**

This study is needed to evaluate the handling characteristics of the sediment as it dries. At what stage of water removal could the sediment be manipulated with mechanical loaders, etc.? Processing of the sediment for various uses likely would require anything from simple mixing to pulverization. At what stage of dessication does the sediment lend itself to these types of manipulation? Once the sediment is processed, what are its storage characteristics? Can it be stored in large piles open to the weather such as is now done with potting mixes? Can it be stored in bags for marketing?

3. **Evaluate the water quality of leachate during the water removal process as affected by environmental factors such as temperature and rainfall.**

Since leachate from the dewatering process will either have to be collected and treated or will leach through the soil profile potentially reaching the groundwater, its nutrient and toxic substance content must be known both qualitatively and quantitatively. This would be particularly true for toxic metals which tend to solubilize during sediment drying.

Laboratory Incubation Studies

Laboratory incubation studies should be conducted to determine the biogeochemical changes that arise in organic and mineral soils as a result of Lake Apopka sediment application. These studies should focus on related effects on crop nutrition and water quality. Specific studies should include:

- Determination of the fertilizer value of the sediments under varying conditions,
- Decomposition of organic matter and microbial respiration, mineralization of organic nitrogen, and accumulation of plant available nitrogen,
- Nitrogen losses as a result of denitrification,
- Changes in phosphorus retention and release capacity of muck and mineral soils,
- Changes in mineralogical composition of soils, changes in physical properties (such as bulk density, water holding capacity) of the soils, and
- Heavy metal and toxic substances accumulation in amended soils and the solubility of these contaminants.

Greenhouse Studies

Greenhouse studies should be conducted to accomplish the following tasks:

- o Screening and selection of plants suitable to culture in sediment-soil mixtures,
- o Development of optimal loading rates without causing detrimental effects on plants and water quality,
- o Evaluation of the optimal method of application of sediment to soil -- e.g., surface application versus direct incorporation,
- o Determination of the optimal water content of the sediment for application, and
- o Column studies to determine the movement of nutrients in the soil profile in relation to the geochemistry of both the applied sediment and the amended soil.

Field studies to evaluate land application of sediments

1. **Evaluate the effect of sediment application rate to mineral and organic soils on crop yield, nutrient and toxic metal uptake, soil physical and chemical characteristics and leachate quality.**

Dredged Lake Apopka sediment should be applied to small scale field plots over a range of application rates for a minimum period of two years. Selected sites should include both mineral and organic soils. Application rates should be based on results of previous greenhouse studies. Additional fertilizer requirements should be determined by previous nutrient analysis of the sediment. Normal agricultural practices should be followed for crop management.

Crop parameters to be measured at the end of each cropping season include biomass yield, nitrogen and phosphorus uptake, and toxic metal uptake. Soil pH, electrical conductivity, and extractable nutrients should be measured initially and at the end of each cropping season. Soil solution samples below the average rooting depth of the crop should be monitored quarterly for the duration of the study.

7.3 INTERNAL LOADING CHARACTERISTICS OF PEAT SEDIMENTS

Disregarding the issue of cost, the major benefit of sediment dredging in Lake Apopka is viewed as removing sediment which carries a large nutrient burden and which, because the sediments are readily resuspended, continually reintroduces large quantities of inorganic N and P into the water column. By removing the flocculent UCF and CF horizons and exposing the underlying peat, internal loading is expected to be reduced, principally because the peat sediments are believed to be more stable and resistant to resuspension compared to the algal derived UCF and CF sediments. This expected result has yet to be verified empirically and should be investigated, particularly because porewater nutrient concentrations in the peat layer are still comparatively high.

Bottom substrate stability may be further enhanced by a resurgence of rooted macrophytes accompanying dredging. Recent studies in Lake Apopka indicate that the rooted macrophyte, Vallisneria, has appeared in enclosures which have been protected from wind-induced sediment resuspension by physical barriers (Stites, personal communication). In situ studies in which UCF and CF sediments are removed from within enclosures and compared to both the open water and enclosures in which the sediments are allowed to remain intact would address the questions of both internal nutrient release and macrophyte colonization following dredging.

8.0 CONCLUSIONS

Dredging has been used with varying degrees of success to restore a number of lakes in North America and Scandinavia. To a very large degree, the success of dredging relates to the adequacy of pre-dredging studies to define the magnitude of the problem. Dredging is generally most feasible in small lakes with organically rich sediment, low sedimentation rates, and long hydraulic residence times. Large lakes have been dredged, but economics become increasingly important as lake surface area increase. Cost increases in larger lakes are non-linear, reflecting not just concomitant increases in material to be removed, but also increased pumping costs per unit distance as a result of increased pumping distance and associated head losses due to friction in pipes conducting dredged material onshore. The largest lake dredged to date is Vancouver Lake, Washington (1,052 ha); Lake Apopka is nearly 12 times larger.

Problems inherent in dredging as a general technique include short term pulses of nutrient release and liberation of toxic materials (e.g., trace elements and organic pesticides) due to sediment resuspension, oxygen depletion, and potential effects to fisheries, wildlife, and benthic fauna. Other issues concern the ultimate use and stability of dredged material, as well as the treatment and disposal of nutrient-enriched supernatant from dewatered sediments. For a lake the size of Lake Apopka, pumping costs clearly indicate the need to dispose of dredge spoils near the lake. Finally, the overall efficacy of dredging as a general technique is still in question despite the number of lakes which have been dredged; documentation of post dredging effects on lake restoration has been characteristically poor, largely because of limited resources.

Lake Apopka sediments generally consist of a relatively uniform, organic, flocculent material underlain by mostly peaty deposits. In 1987, the organic floc averaged 117 cm depth compared to 80 cm in 1968. Interstitial nutrient concentrations in the floc exceed water column concentrations by over an order of magnitude, and resuspension of this easily disturbed material is believed to be a major contributor to sustained, high rates of algal productivity in the lake.

Dredging costs for Lake Apopka were based on removing as much of the sediment floc layer as practicable. A 24-inch is the largest dredge which could operate reasonably in Lake Apopka; with this size dredge, only sediments under the 1.2 m contour would be removed. Under these operating constraints, approximately 10,400 ha would be dredged, giving a total volume of 121.76 x 10^6 m^3 of sediment to be removed. With five 24-inch dredges operating, dredging of Lake Apopka could be accomplished in 5.9 years. Total dredging costs, exclusive of (1) spoil area land acquisition and clearing costs, and (2) upland acquisition costs for storage of dried sediment prior to reuse or sale, total $868,800,000.

Sediment reuse offers only limited ability to recover dredging costs. Approximately 1.43 x 10^6 metric tons of dried sediment will be removed from Lake Apopka during each year of dredging. The most promising reuse possibility of Lake Apopka sediment is as fertilizer with a total economic yield of $55,000,000; use as a soil amendment has an estimated yield of $25,000,000 to $50,000,000. We have calculated that an upper limit on the economic reuse value of dried Lake Apopka sediment is $97,400,000; this estimate is based on using Lake Apopka sediment as a growth medium for the ornamental horticulture industry and assumes that the dried sediment has the same value as peat. In all likelihood, the dried sediment will not have the same bulk texture characteristics as peat, and its direct usefulness to the ornamental horticulture industry will be limited. The estimated <u>minimum</u> cost for dredging is $771,400,000, which assumes that the upper limit market value of $97,400,000 from use as a potting medium can be realized. Project costs almost certainly will be closer to between $814,000,000 and $844,000,000.

A number of assumptions were made in the cost/benefit analysis that should be examined in more detail before further consideration is given to dredging of Lake Apopka. Uncertainties lie in three main areas: (1) engineering aspects of dredging, (2) sediment reuse, and (3) internal loading aspects of the remaining peat sediments after the UCF and CF sediments have been removed. One major uncertainty considers potential redistribution of UCF and CF sediments from undredged areas into dredged areas. Over the relatively long span of the project (5.9 years), redistribution is very likely and may negate much of the perceived benefits of dredging. Moreover, only 84 percent of Lake Apopka can be dredged with a 24 inch dredge, and some of the nearshore sediments will redistribute into the open lake after dredging has been completed. Other studies need to be conducted on the drying and handling characteristics of dried Lake Apopka sediment as well as determining its effects on plant growth before the economic value of Lake Apopka sediments can be firmly established. These studies will help develop more precise estimates on reuse economic value but will not affect the upper limit reuse market value of $97,400,000.

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APPENDIX A

NOTE TO READER REGARDING UNITS

The following dredging unit cost analysis is largely based on spreadsheet courteously provided by the U.S. Army Corps of Engineers-Jacksonville District. This extensive spreadsheet was developed in English units; the following are appropriate metric conversions.

1 cubic yard (cy)	=	0.7647 cubic meters
1 acre	=	0.4047 hectares
1 ft	=	0.3048 meters
1 ft^2	=	0.0929 $meters^2$
1 gallon	=	3.785×10^{-3} cubic meters
1 ft^3	=	0.0283 $meters^3$

TITLE __________ DATE ________ INVIT. NO. __________

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M MENU SELECTIONS FOR DIFFERENT SIZE DREDGES

****

			REMARKS
1 CURRENT FUEL PRICE		$0.75 /GAL	
2 AVERAGE PLANT USEAGE		12 MO/YR	
3 CURRENT INTEREST RATE		10 % /YR	
4 MENU ITEM SELECTED.....>	5	24 " DREDGE	BID ESTIMATE
DREDGE SIZE ITEM NUMBERS		3,000 HP	MAIN ENGINE
12 INCH (BID)....0 (MOD)....8			
14 INCH (BID)....1 (MOD)....9		$29,791 /MO	PLANT OWNERSHIP COSTS
16 INCH (BID)....2 (MOD)...10			
18 INCH (BID)....3 (MOD)...11	+	$461,828 /MO	OPERATING COSTS ($218,912 /MO PAYROLL)
22 INCH (BID)....4 (MOD)...12			
24 INCH (BID)....5 (MOD)...13	=	$491,620 /MO	TOT. DREDGE COSTS (AVE. CREW RATE= $20.75
27 INCH (BID)....6 (MOD)...14			
30 INCH (BID)....7 (MOD)...15			INCLUDING FRINGE BENEFITS
5 BOOSTER INFORMATION		3,000 HP	PUMP MOTOR
6 COST PER BOOSTER		$120,000 /MO	(INCLUDES LABOR, OPER. & OWNERSHIP)
7 NUMBER OF BOOSTERS	x	3	(MOBILIZATION & DEMOB. INFORMATION)
8 TOTAL BOOSTER COST	=	$360,000 /MO	(MOBILIZATION & DEMOB. INFORMATION)

9 FLOATING PIPELINE		1,900 LIN. FEET @	$4.60 PER L.F./MO (MUD RATE) =	$8,740
10 SUBMERGED PIPELINE	+	36,100 LIN. FEET @	$3.00 PER L.F./MO (MUD RATE) =	$108,300
11 SHORELINE	+	10,000 LIN. FEET @	$1.80 PER L.F./MO (MUD RATE) =	$18,000
12 TOTAL PIPELINE	=	48,000 LIN. FEET	(MOBILIZATION & DEMOB. INFORMATION)	$135,040

ESTIMATED BY FVK CHECKED BY ____________

TITLE ________ DATE ________ INVIT. NO. ________

PIPELINE DREDGE ESTIMATE

A

YARDAGE ESTIMATE

BID ITEM # 2

1 PROJECT ____________________

2 LOCATION ____________________ INVIT. NO. ____________

3 DESCRIPTION OF WORK ____________________

4 EXCAVATION

			REMARKS
A. REQUIRED		159,250,000 C.Y.	
B. PAY OVERDEPTH	+	0 C.Y.	
C. MAX. PAY YARDAGE	=	159,250,000 C.Y.	(YARDAGE USED ON BID FORM)
D. O.D. NOT DREDGED	-	0 C.Y.	
E. NET PAY YARDAGE	=	159,250,000 C.Y.	(YARDAGE USED TO FIGURE UNIT PRICE PER C.Y.)
F. NON-PAY YARDAGE	+	0 C.Y.	
G. GROSS YARDAGE	=	159,250,000 C.Y.	(YARDAGE USED TO FIGURE PRODUCTION TIME & COST)

ESTIMATED BY ________ CHECKED BY ________

TITLE ________ DATE ________ INVIT. NO. ________

PRODUCTION WORK SHEET

3 BID ITEM # 3

PIPELINE DREDGE TIME

			REMARKS
1 SIZE OF DREDGE....PIPELINE........>		24 INCH	
2 POWER OUTPUT......MAIN PUMP........>		3,000 HP	
3 MAXIMUM LINE LENGTH		48,000 L.F.	
4 AVERAGE LINE LENGTH		35,000 L.F.	
5 NUMBER OF BOOSTERS IN LINE		3	
6 PRODUCTION.........(BASED ON)......>		8,750 L.F.	(AVERAGE PIPELINE LENGTH PER PUMPING STATION)
A. CHART PRODUCTION		885 C.Y./HR	
B. POWER FACTOR	x	1	(IF CHART IS NOT USED, FACTOR = 1)
C. BOOSTER FACTOR	x	0.7	10% LOSS IN PUMPING TIME PER BOOSTER
D. MATERIAL FACTOR	x	2.5	MUD (3.0 >= MUD >= 2.0 > SAND >= 0.
E. BANK FACTOR	x	0.68	3.8 FT. AVERAGE BANK HEIGHT
F. OTHER FACTOR	x	1	
G. NET PRODUCTION	=	1,053 CY/HR	
H. OPERATING HRS/DAY	x	20	
I. OPERATING DAYS/MONTH	x	27	
J. CUBIC YARDS/MONTH	=	568,701	
K. DREDGE TIME		280.02 MONTHS	159,250,000 C.Y.(GROSS) DIVIDED BY 568,701
L. CLEANUP	+	0.00 MONTHS	0% ADDITIONAL DREDGING TIME
7 TOTAL DREDGE TIME	=	280.02 MONTHS	18,695 GROSS CU.YD./DAY

ESTIMATED BY ________ CHECKED BY ________

TITLE ________ DATE ________ INVIT. NO. ________

PRODUCTION WORK SHEET

C BID ITEM # 2

EXCAVATION COSTS

				REMARKS
1 PLANT OWNERSHIP COSTS			$29,791 PER MO	
2 OPERATING COSTS		+	$461,828 PER MO	
3 PIPELINE COSTS BASED ON	MUD			DETERMINED BY MATERIAL FACTOR ON SHEET B, ITEM 6
A. FLOATING PIPELINE		+	$8,740 PER MO	1,900 LIN. FEET @ $4.60 PER L.F./MO
B. SUBMERGED PIPELINE		+	$99,300 PER MO	33,100 LIN. FEET @ $3.00 PER L.F./MO
C. SHORELINE		+	$0 PER MO	0 LIN. FEET @ $1.80 PER L.F./MO
D. PARTIALLY UTILIZED PIPELINE		+	$20,367 PER MO	13,000 LIN. FEET @ $1.57 PER L.F./MO(5
4 BOOSTER(S)		+	$360,000 PER MO	3 BOOSTERS @ $120,000 EACH
5 SPECIAL COSTS		+	$0 PER MO	
6 TOTAL MONTHLY COST		=	$980,027	
7 DREDGE TIME		x	280.02 MO	
8 SUBTOTAL		=	$274,431,069	
9 ADDITIONAL COSTS		+	$0 L.S.	
10 SUBTOTAL		=	$274,431,069	
11 O.H. & BOND	13.0%	+	$35,676,039	
12 SUBTOTAL		=	$310,107,108	
13 PROFIT	10.0%	+	$31,010,711	
14 NET PAY YARDAGE COST		=	$341,117,819	
15 NET PAY YARDAGE		/	159,250,000 CY	FROM SHEET A, ITEM 4 E.
16 UNIT COST		=	$2.14 PER CY	
17 MAX PAY YARDAGE		x	159,250,000 C.Y.	FROM BID SCHEDULE (SEE SHEET A, ITEM 4 C.)
18 TOTAL DREDGING COST		=	$340,795,000	FOR BID SCHEDULE

ESTIMATED BY ________ CHECKED BY ________

TITLE _________ DATE ________ INVIT. NO. _________

****

PRODUCTION WORK SHEET

P BID ITEM # 2

PRODUCTION FACTOR COMPUTATIONS

****

PRODUCTION FACTORS FOR A 24 " DREDGE

STANDARD DREDGE PRODUCTION BASED ON PIPELINE LENGTH

UP TO	5,000 L.F. OF PIPE	1,200 C.Y./HR
AT	10,000 L.F. OF PIPE	780 C.Y./HR
AT	14,000 L.F. OF PIPE	330 C.Y./HR

8,750 L.F. PER PUMPING STATION
885 CY/HR

BANK FACTORS

BANK	FROM CHART FACTOR	INTERPOL FROM CH IF
0	NA	(bank<1)
1	NA	(1<=bank<2)
2	0.46	(2<=bank<3)
3	0.6	(3<=bank<4)
4	0.7	(4<=bank<5)
5	0.84	(5<=bank<6)
6	0.98	(6<=bank<7)
7	1.1	(7<=bank<8)
8	1.1	(8<=bank<9)
9	1.1	(9<=bank)

3.8 FT OF BANK HEIGHT
0.68 BANK FACTOR

MATERIAL FACTORS

DESCRIPTION	INPLACE DENSITY		FACTOR
MUD & SILT	1200	GR/L	3
MUD & SILT	1300	GR/L	2.5
MUD & SILT	1400	GR/L	2
LOOSE SAND	1700	GR/L	1.1
LOOSE SAND	1900	GR/L	1
COMP. SAND	2000	GR/L	0.9
STIFF CLAY	2000	GR/L	.5-.7
COMP. SHELL	2300	GR/L	.4-.6
SOFT ROCK	2400	GR/L	.3-.5
BLASTED ROCK	2000	GR/L	.2-.3

(3.0 >= MUD >= 2.0 > SAND >= 0.7 > ROCK)

MENU ITEMS:
0 MUD
1 SAND
2 ROCK

MENU ITEMS:
0 BID ESTIMATE
1 MOD. ESTIM.

MATERIAL FACTOR CHOSEN = 2.5 MUD

PIPELINE COSTS PER L.F. PER MONTH

TYPE OF PIPELINE	MATERIAL PUMPED MUD	SAND	ROCK
FLOATING	$4.60	$6.10	$9.50
SUBMERGED	$3.00	$4.00	$6.50
SHORELINE	$1.80	$2.70	$4.30

MENU ITEM AUTOMATICALLY CHOSEN:
(0 MUD,1 SAND,2 ROCK) 0 MUD

FLOATING	$4.60
SUBMERGED	$3.00
SHORELINE	$1.80

ESTIMATED BY ____________ CHECKED BY ____________

TITLE ________ DATE _______ INVIT. NO. ________

D MOB & DEMOB BID ITEM # 1

24 " Dredge

	MOBILIZATION			DEMOBILIZATION		
	# DAYS	$/DAY	TOTAL	# DAYS	$/DAY	TOTAL
1. PREPARE DREDGE FOR TRANSFER	5 x	$9,076 =	$45,379	5 x	$9,451 =	$47,254
2. PREPARE PIPELINE FOR TRANSFER	10 x	$5,211 =	$52,108	10 x	$5,586 =	$55,858
3. TRANSFER ALL PLANT 500 MILES @ 100 miles/day =	5 x	$25,072 =	$125,362	5 x	$25,072 =	$125,362
4. MARINE INSURANCE	L.S.	=	$8,000	L.S.	=	$8,000
5. PERMANENT PERSONNEL & MISC.	L.S.	=	$9,482	L.S.	=	$7,982
6. PREPARE DREDGE AFTER TRANSFER	5 x	$9,906 =	$49,531	5 x	$9,406 =	$47,031
7. PREPARE PIPELINE AFTER TRANSFER	10 x	$7,041 =	$70,412	10 x	$6,541 =	$65,412
8. OTHER		=	$0	L.S. (CLEANUP)	=	$0
	SUBTOTAL MOBILIZATION		$360,275	SUBTOTAL DEMOBILIZATION		$356,900

9. SUBTOTAL MOBILIZATION & DEMOBILIZATION		= $717,174
10. OVERHEAD & BOND	13.0%	+ $93,233
11. SUBTOTAL		= $810,407
12. PROFIT	10.0%	+ $81,041
13. TOTAL MOBILIZATION & DEMOBILIZATION		= $891,448

ESTIMATED BY ____________ CHECKED BY ____________

TITLE __________ DATE ________ INVIT. NO. __________

****

E MOB & DEMOB BID ITEM # 1

****

24 " Dredge

1. PREPARE DREDGE FOR TRANSFER	MOBILIZATION	DEMOBILIZATION
15 men @ 8 hr/day refurbishing @ $20.76 per hour =	$2,491	$2,491
Supplies & small tools @ $500 /day	$500	$500
Support equipment with operators @ $1,000 /day	$1,000	$1,000
Plant ownership		
Basic plant $29,791 /month		
Booster(s) $118,800 /month (3 @ $120,000 x 33%)		
$148,591 /month divided by 30.42 days/month =	$4,885	$4,885
Fuel (plant idle) @ $200 /day	$200	$200
Subsistence 15 men @ $25.00 per day =	----	$375
COST PER DAY	$9,076	$9,451

2. PREPARE PIPELINE FOR TRANSFER	MOBILIZATION	DEMOBILIZATION
15 men @ 8 hrs/day @ $20.76 per hour =	$2,491	----
15 men @ 8 hrs/day @ $20.76 per hour =	----	$2,491
Supplies & small tools @ $500 /day	$500	$500
Pipeline ownership $135,040 /month		
divided by 30.42 days/month x 50% =	$2,220	$2,220
Subsistence 15 men @ $25.00 per day =	----	$375
COST PER DAY	$5,211	$5,586

ESTIMATED BY ____________ CHECKED BY ____________

F MOB & DEMOB BID ITEM # 1

24 " Dredge

3. TRANSFER PLANT	MOBILIZATION	DEMOBILIZATION
14 men/shift (2-12 hour shifts/day) @ $20.76 per manhour =	$6,975	$6,975
Plant ownership per day =	$4,885	$4,885
Pipeline ownership per day =	$2,220	$2,220
Plant costs $242,917 /month (Operating costs minus payroll)		
divided by 30.42 days/month x 50% =	$3,993	$3,993
Subsistence 28 men @ $25.00 per day =	$700	$700
Towing vessel(s): 1600 H.P. Rental Tug @		
$4,200 per day (towing)		
$2,100 per day (return to port)		
$6,300 per day x 1 towing vessel(s) =	$6,300	$6,300
COST PER DAY	$25,072	$25,072

4. MARINE INSURANCE $8,000 each tow (MOB & DEMOB)

5. PERMANENT PERSONNEL & MISC.	MOBILIZATION	DEMOBILIZATION
30 men @ 8 hrs/day @ $20.76 per hour @ 1 DAY	$4,982	$4,982
Travel Expenses $100 per man	$3,000	$3,000
Local hire @ $1,500 /day	$1,500	----
TOTAL	$9,482	$7,982

TITLE __________ DATE ________ INVIT. NO. __________

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8 MOB & DEMOB BID ITEM # 1

****

24 " Dredge

6. PREPARE DREDGE AFTER TRANSFER	MOBILIZATION	DEMOBILIZATION
20 men @ 8 hrs/day @ $20.76 per hour =	$3,322	$3,322
Support equipment with operators @ $1,000 /day	$1,000	$1,000
Plant ownership per day =	$4,885	$4,885
Fuel (plant idle) @ $200 /day	$200	$200
Subsistence 20 men @ $25.00 per day =	$500	----
COST PER DAY	$9,906	$9,406

7. PREPARE PIPELINE AFTER TRANSFER		
20 men @ 8 hrs/day @ $20.76 per hour =	$3,322	$3,322
Pipeline ownership per day =	$2,220	$2,220
Subsistence 20 men @ $25.00 per day =	$500	----
Support equipment with operators @ $1,000 /day	$1,000	$1,000
COST PER DAY	$7,041	$6,541

ESTIMATED BY _____________ CHECKED BY _____________

APPENDIX B

ANNOTATED BIBLIOGRAPHY

Alhonen, P. 1985. Lake restoration: A sediment limnological approach. Aqua Fenn. 15:269-273.

A survey was made of methods proposed for reducing nutrient levels in polluted lakes. When a lake becomes badly polluted and has developed a deposit of black gyttja containing reduced sulphides, effective restoration requires radical conservation measures. Characterization of the bottom sediments can provide a good indication of the prevailing water quality and hints for the selection of suitable restoration methods. Quite often these take the form of removal of the bottom sediment by suction dredging or its isolation to prevent remobilization of the nutrients. A summary is given of the treatment methods recommended for each stage of pollution.

Andersson, G., G. Cronberg, and C. Gelin. 1973. Planktonic changes following the restoration of Lake Trummen, Sweden. Ambio 2(1-2):44-47.

This paper reports some of the changes in phytoplankton and zooplankton communities in Lake Trummen before (1969) and shortly after (1972) lake restoration. The most striking difference between pre- and post-dredging studies was the observed dramatic decline in some zooplankton species that are generally considered as indicators of eutrophy. Planktonic changes were difficult to interpret in view of the limited data and meteorological differences between pre- and post-restoration samplings.

Bengtsson, L., S. Fleischer, G. Lindmark, and W. Ripl. 1975. Lake Trummen restoration project I. Water and sediment chemistry. Verh. Int. Verein. Limnol. 19:1080.

This paper reported on water and sediment chemistry changes in Lake Trummen in conjunction with the restoration project. Alkalinity and inorganic carbon before restoration were strongly fluctuating. The restoration measures included a phosphorus precipitation step by means of aluminum sulfate addition to the runoff water from the sedimentation ponds, which reduced the phosphorus content by ca. 90%. This agent acidified the lake water and alkalinity dropped to about 10 eq/l. When the dredging procedure was completed, the alkalinity increased.

After restoration organic carbon was about 20 mg C/l during summer compared to 80 mg C/l before restoration, and only a minor part was ascribed to particulate organic matter. The earlier heavy algal blooms induced very rapid pH fluctuations and on calm summer days pH values up to 10.5 were observed. In the bottom layers the pH dropped to considerably lower values. This phenomenon showed diurnal character with night values of pH lower than 8. Diurnal oxygen, pH, and alkalinity fluctuations were significantly reduced due to restoration. After restoration the pH still increased, however, in the late summer period for a couple of weeks in connection with the appearance of nitrogen fixing species.

Brannon, J.M., R.H. Plumb, Jr., and I. Smith, Jr. 1980. Long-term release of heavy metals from sediments. pp. 221-266. Contaminants and Sediments, Vol. 2: Analysis, Chemistry, Biology. Ann Arbor Science Publishers, Inc. Ann Arbor, MI.

Sediment constituent mobility is a function of many factors. Even though dredged material may be grossly contaminated, the conditions which favor interaction between water and dredged material may be such as to preclude significant movement of contaminants into the water column. The purpose of this investigation was to observe the release of chemical contaminants from a wide variety of dredged sediments and to determine possible relationships between long-term net mass release and short-term chemical characterization of the same sediments. The leaching was conducted with water obtained near each collection site and under chemical conditions similar to those found at aquatic disposal field sites. This chapter presents 1) results of long-term aerobic leaching and the net mass release of trace metals associated with dredged material to the overlying water and 2) an examination of the relationship between long-term mass release and trace metal release from the same dredged sediments in the elutriate test and other short-term chemical leaching tests.

Buckler, J.H., T.M. Skelly, M.J. Luepke and G.A. Wilken. 1988. Case Study: The Lake Springfield Sediment Removal Project. Lake and Reservoir Management 4:143-152.

Lake Springfield, a 1,635 hectare reservoir, was formed by the construction of Spaulding Dam across Sugar Creek, a major tributary of the Sangamon River in central Illinois. This paper presents an overview of the "project feasibility investigation" commissioned by the City of Springfield. Disposal site configuration consisted of two large settling ponds (69 and 29 hectares each) surrounded by 12 hectares of buffer cropland. The storage capacity of the two cells was over 1.5 million cubic yards or approximately 20% more than the projected volume of sediment to be removed from the lake. Based on engineering costs, construction costs and land acquisition costs, the unit price of the disposal site was calculated to be $1.23 per cubic yard of dredged sediment. Direct unit cost for dredging was $1.66 per cubic yard of dredged material. Dredging operations were initiated in June, 1987. It has been determined that the disposal site could be reclaimed to farmland property following project completion.

Cooke, G.D., E.B. Welch, S.A. Peterson, and P.R. Newroth. 1986. Lake and Reservoir Restoration. Butterworth, Boston, 392 pp.

This text deals with the eutrophication process and methods to restore and manage lake and reservoir systems. The chapter on sediment removal, prepared by S.A. Peterson, presents an excellent overview of the purposes, methods, costs, and environmental concerns of lake dredging. The Lake Trummen and Lilly Lake case studies are also discussed.

Cronberg, G., C. Gelin, and K. Larsson. 1975. Lake Trummen restoration project II. Bacteria, phytoplankton, and phytoplankton productivity. Verh. Int. Verein. Limnol. 19:1088.

This paper reported changes in bacterial and phytoplankton populations following the dredging of Lake Trummen. Although a marked decrease was observed in some bacteria groups, the number of aerobic heterotrophic bacteria did not change after lake restoration. The mean biomass of phytoplankton from June until September decreased from 75 to 10 mg/l due to the lower abundance of blue-green algae. Mean annual productivity decreased from 375 to 225 g C m^{-2}, but productivity of nannoplankton (mean diameter < 45 m) did not change. Phytoplankton diversity increased after restoration.

Delfino, J.J., L.K. Marble and K.M. O'Neal. 1987. Potentially toxic contaminants in aquatic systems. Final Report to the Florida Dept. of Environmental Regulation, Contract No. WM144.

Sediment samples were collected from six study sites located within Florida for the purpose of assessing the presence of potentially toxic organic contaminants. The study sites were: (a) Amelia River in Nassau County, (b) Key Largo in Monroe County, (c) Lake Apopka in Lake and Orange Counties, (d) Lake Munson in Leon County (e) Newfound Harbor and Sykes Creek in Brevard County and (f) Turkey Creek and Palm Bay in Brevard County. In addition catfish specimens were obtained from Lake Apopka. As a part of the study, a rapid and sovent-conservative analytical protocol adopted for this study proved to be quite adequate for screening purposes.

Low concentrations of organochlorine pesticides were detected at each study site. The most widely detected pesticides were p,p'DDE, p,p'DDt and lindane. With few exceptions, the concentrations of the pesticides and metabolites were generally less than 0.1 ug/g on a sediment dry weight basis. The metaoblite p,p'DDE was found in the catfish tissue from Lake Apopka, but not at concentrations generally regarded to pose a threat to consumers of the fish. In areas where organic matter content in sediments varied, the samples having higher organic matter levels generally had high contaminant levels.

Dooris, P.M., V. Ley and D.F. Martin. 1982. Laboratory experiments as an aid to lake restoration decisionmaking. Water Resources Bulletin 18:599-603.

The authors of this paper recommend that a series of laboratory studies should be conducted prior to choosing a lake rehabilitation technique. They present their studies of Sawgrass Lake in Pinellas County, Florida as an example of what should be done for other lakes being considered for restoration. Studies conducted were drawdown simulation (drying and consolidation), rehydration of sediment, resuspension of sediment and chemical analysis of the sediment (water content, organic content, toxic materials and nutrients). Based on the results of their studies, drawdown was not recommended while dredging to remove toxic materials and nutrients was the technique of choice.

Dunst, R.C. 1982. Sediment problems and lake restoration in Wisconsin. Environ. Internat. 7:87-92.

Twelve dredging projects underway or in the planning stages in Wisconsin were reviewed in this paper. These include both natural and man-made lakes, with lake size and sediment removal up to 205 ha and 1,70,250 m^3, respectively. Solids content of the sediments ranges from 70%-80% to 1%-5%. The projects were designed using a mixture of on-site data collection, predictive models, and professional judgement. Sediment disposal has limited project implementation, with arsenic being a special problem. Theoretically, sediment concentrations below 4 ug/g could produce unacceptable contamination of groundwater at the disposal site. Organic sediments from Lilly Lake were deposited in an active gravel pit and within diked areas on agricultural land. Passage through a spray irrigation system proved impractical. Rapid infiltration of water into the bottom and sides of the settling basins was short-lived due to the self-sealing characteristics of these sediments.

Dunst, R.C., J.G. Vennie, R.B Corey, and A.E. Peterson. 1984. Effect of dredging Lilly Lake, Wisconsin. U.S. Environ. Protect. Agency. EPA-600/S3-84-097.

Lilly Lake is located in southeastern Wisconsin. The basin contained up to 10.7 m of lightweight, organic sediments. Recreational activity was severely restricted due to periodic winter fish kills and dense growths of macrophytes throughout the summer. During the open water periods of 1978 and 1979, 683,000 m^3 of sediment were removed with a 30-cm cutterhead dredge and transported via pipeline to two disposal sites. The dredging operation deepened the lake to a maximum of 6.6 m and afforded an excellent opportunity to evaluate the inlake and disposal site effects of the project. The inlake portion of the investigation included an assessment of water quality, aquatic biology, sediments, and hydrology before, during, and after completion of dredging. The evaluation of sediment disposal emphasized the impact on the nearby groundwater system and the value of using hydrosoils to enhance agricultural crop production.

Gallagher, J.L. and P.L. Wolf. 1980. Field bioassays for the role of plants as vectors in contaminant transfer from dredged material. pp. 445-463. Contaminants and Sediments, Vol. 2: Analysis, Chemistry, Biology. Ann Arbor Science Publishers, Inc. Ann Arbor MI.

The purposes of the studies were twofold. The first was to study several questions concerning the uptake of toxaphene from contaminated sediments by the salt marsh plant Spartina alternifloria. These questions are relevant to the possible impact of contamination on the detrital food web in the marsh and the possible duration of the impact once the source of contamination is removed. The second facet of the program was to test a technique designed to be used to evaluate the response of indigenous plant species grown in contaminated dredged material prior to making final disposal plans. The technique involves the use of a bioassay experiment unit which can be filled with dredged material and planted with sprigs in the laboratory, transported to the field, implanted onsite and removed for evaluation at a later date. The method is not intended as a quantitative procedure of estimating the flux of contaminants through the soil-plant complex. Its purpose is to alert project designers at the planning stage that the contaminant is being mobilized and that further consideration should be given before the project continues.

Gambrell, R.P., V. Collard and W.H. Patrick, Jr. 1980. Cadmium uptake by marsh plants as affected by sediment physicochemical conditions. pp. 425-443. Contaminants and Sediments, Vol. 2: Analysis, Chemistry, Biology. Ann Arbor Science Publishers, Inc. Ann Arbor, MI.

The mobility and biological availability of sediment-bound toxic metals are affected by the physicochemical properties (pH, oxidation-reduction potential and salinity conditions) of soil and sediment-water systems. It is important to understand how these parameters may influence uptake of potentially toxic metals by plants that become established on contaminated dredged material applied to upland or intertidal sites.

This chapter reports results of a study to determine the effects of pH and oxidation-reduction conditions of the rooting medium on uptake of cadmium by marsh plants. Information of this type will be useful in selecting sound disposal methods for contaminated dredged materials.

Gambrell, R.P., R.A. Khalid, M.G. Verloo and W.H. Patrick, Jr. 1977. Transformations of heavy metals and plant nutrients in dredged sediments as affected by oxidation-reduction potential and pH, Volume II: Materials and Methods/Results and Discussion. U. S. Army Engineer Waterways Experiment Station, Contract Report D-77-4.

A study was conducted to determine the effects of pH and oxidation-reduction potential on the capacity of the sediment to retain high levels of added toxic metals. Results indicated that these two parameters do influence the chemical form and distribution of the metals studied, although the response to changes in the physicochemical environment were frequently not the same for the different metals. Soluble and exchangeable levels of mercury were not greatly influenced by changes in pH and oxidation intensity. Soluble and especially insoluble large molecular weight humic materials were principal regulatory factors controlling the retention and availability of mercury. Levels of soluble and exchangeable lead were less affected by oxidation intensity than pH and increased considerably when pH was lowered to 5.0. Cadmium release to soluble and exchangeable forms was favored by oxidized conditions. As oxidation intensity increased, the cadmium was apparently released from large molecular weight organics.

The report also discusses the effects of pH and redox potential on the chemical transformations of iron, manganese, zinc, copper, phosphorus and ammonium-nitrogen in the sediments studied. Regulatory processes involved included precipitation with sulfide, adsorption or coprecipitation with colloidal hydrous oxides and complex formation with soluble and insoluble organics. In many cases, changes in acidity or oxidation-reduction potential conditions resulted in considerable transformations among potentially available forms, but little conversion to the soluble and exchangeable forms thought to be most readily available. Cadmium was a notable exception.

Results of these studies and their applicability to upland disposal methods suggest that plants should be included in research of this type to determine if conditions enhancing chemical availability also increase bioavailability of these metals to flora and fauna when dredged materials are introduced to upland ecosystems.

Gelin, C. and W. Ripl. 1978. Nutrient decrease and response of various phytoplankton size fractions following the restoration of Lake Trummen, Sweden. Arch. Hydrobiol. 81(3):339-367.

The eutrophicated Lake Trummen, Sweden, was restored by removal of the uppermost 0.5 m nutrient-rich sediment layer by suction dredging in 1970 and 1971. Release of phosphorus from the sediment was reduced, resulting in a decreased summer PO_4- concentration in the water from about 200 g P l^{-1} before restoration to < 10 g l^{-1} after restoration. The phytoplankton community changed from blue-green algae (netplankton) to communities with greater diversity and nannoplankton (< 20 m) became more abundant. Secchi disc transparency increased from about 20 to about 70 cm (June through September). The light-saturated photosynthetic rate per unit water volume of the total phytoplankton community in late summer decreased from about 10 g C m^{-3} day^{-1} to < 2 g C m^{-3} day^{-1}. The average annual phytoplankton productivity decreased from 370 g C m^{-2}, of which about 60% was contributed by algae passing through a 45 m plankton net, to 225 g C m^{-2} after restoration, of which 85% was contributed by algae passing through a 45 m net and 60% by algae passing through a 10 m net (nannoplankton).

Gibbons, M.V., F.D. Woodwick, W.H. Funk, and H.L. Gibbons. 1984. Effects of multiphase restoration, particularly aluminum sulfate application, on the zooplankton community of a eutrophic lake in eastern Washington. J. Freshwater Ecol. 2:393-404.

Zooplankton populations of Liberty Lake, Washington were investigated over a span of four years to determine the short-term effects of a series of multiphase lake restoration measures on lake zooplankton. The effects of the treatments, particularly of suction dredging of lake bottom sediments and of a two stage whole-lake aluminum sulfate application, were assessed by analyzing population density and biomass fluctuations of Rotifera, Cladocera, and Eucopepoda for several years before and after the treatments were completed. Suction dredging had no apparent effect upon the zooplankton. The gross effects of aluminum sulfate applications were also minimal.

Gremillion, P.T., D.G. Burden, and R.F. Malone. 1985. Transient sediment resuspension associated with the hydraulic dredging of the University Lakes. pp. 113-117. In: Lake and Reservoir Management. Proc. Fourth Annual Conf. and Internat. Symp., North Amer. Lake Manage. Soc., McAfee, N.J.

The University Lakes in Baton Rouge, LA., a system of six hypereutrophic urban lakes ranging in size from 1.2 to 89.2 ha surface area, were the object of a restoration effort. Restoration consisted of hydraulic and mechanical dredging, repair or diversion of the municipal storm and sanitary sewerage system, and lake shore stabilization. Hydraulic dredging of the two larger lakes, University and City Park, was completed in May of 1983, increasing mean lake depth from 0.61 to 1.24 meters in University and 0.73 to 1.17 meters in City Park Lake. Hydraulic retention times were increased from 49 to 101 days in University Lake and from 47 to 56 days in City Park Lake. Improvements in water quality during the summer of 1983 were obscured by the constant resuspension of sediments disturbed by the dredging, resulting in high lake nutrient levels and low algal growth due to shading. As suspended sediments settled or were washed out of the lakes, nutrient levels were reduced. Post-dredging data showed a decrease (from .39 mg/l) to 0.10 mg/l total phosphorus. One year after completion of dredging, however, temporary resuspension of sediments by wind mixing continues to occur. This contrasts to the smaller, mechanically dredged lakes that were not subject to sediment resuspension.

Khalid, R.A., R.P. Gambrell, M.G. Verloo and W.H. Patrick, Jr. 1977. Transformations of heavy metals and plant nutrients in dredged sediments as affected by oxidation reduction potential and pH, Volume I: Literature Review. U. S. Army Engineer Waterways Experiment Station, Contract Report D-77-4.

This report, which includes a bibliography of 414 references, discusses literature on the occurrence and chemistry of selected trace metals and plant nutrients in sediment-water systems. The effects of pH and oxidation-reduction conditions on metal and nutrient chemistry were stressed, where this information was available. the toxic and nutrient elements included are lead, cadmium, mercury, arsenic, selenium, copper, zinc, manganese, iron, nitrogen, phosphorus and sulfur. The report also reviews the scope and limitations of various selective chemical fractionation procedures developed to determine the chemical forms of trace metals and nutrients in soil and sediment-water systems. This review determined that many laboratory studies simulating the transport of reduced sediments to an oxygenated environment have reported some release of toxic metals and biostimulants and others have shown no release of many elements. However, too few studies of actual dredging and dredged material disposal operations have been completed to draw broadly applicable conclusions regarding the effects of dredging on water quality. Where dredging activities have resulted in minimal change in metal ion concentration, it may be that some regulating processes influenced by oxidation-reduction reactions tend to be activated as others are inactivated.

Because of the numerous potential interactions of dredging and dredged material disposal with surrounding ecosystems, it is suggested that some site-specific evaluation of possible adverse environmental impact should be conducted for each proposed dredging project. Though adsorption and release reactions in disturbed sediment-water systems are frequently not of the magnitude predicted from metal-ligand solubilities and thermodynamic considerations of simple aqueous systems, it is apparent from the literature that pH and redox potential do influence the availability of metals and plant nutrients by affecting regulatory processes. Studies of the effects of redox potential and pH in sediment-water systems should therefore be useful in determining the nature of the regulatory process involved and the sediment-water characteristics which may contribute to significant release of metals and nutrients to benthic and aquatic organisms.

Lamb, D.S. and S.A. Breithhaupt. 1986. Project completion summary of the effects of restoration procedures at Liberty Lake, Washington. Lake and Reservoir Manage. Proc. Third Annual Conf., North Amer. Lake Manage. Soc. pp. 204-209.

The implementation phase of the Liberty Lake restoration project included construction of marsh flushing controls, dredging of 21 ha of the lake bottom, and treatment of the lake waters with aluminum sulfate. This work was started in November 1979 and completed in May 1981. After four years of post-restoration water quality monitoring nutrient levels in the lake and inflowing waters have been reduced, and the trophic state has declined toward a more mesotrophic condition. Comparison of pre- and post-restoration nutrient budgets indicates that a reduction in phosphorus loading of 34 percent was achieved. It appears that the sewering was primarily responsible for this reduction. Although the desired changes in the phytoplankton community (from primarily blue-green to primarily green algae) did not occur, indications are that long-term productivity and incidence of blue-green blooms has been significantly reduced. In addition, if the restoration had not been done when it was, water quality in Liberty Lake would have been severely degraded because of high flood flows and nutrient loading through the marsh system.

Lee, C.R., B.L. Folsom, Jr., and R.M. Engler. 1982. Availability and plant uptake of heavy metals from contaminated dredged material placed in flooded and upland disposal environments. Environ. Int. 7:65-72.

The availability and plant uptake of heavy metals was evaluated from contaminated dredged material placed in flooded and upland disposal environments using a solid-phase plant bioassay. The objective of the study was to verify previous dredged material research results and to develop a plant bioassay procedure that could indicate phytotoxicity and bioaccumulation of heavy metals in contaminated dredged material.

The plant bioassay indicated more uptake and bioaccumulations of cadmium and, to a lesser extent, zinc when contaminated dredged material was placed in an upland environment where the sediment was allowed to air dry. Factors that influenced the availability and plant uptake of heavy metals included sediment oxidation-reduction potential, organic matter content, total sulfur content and pH.

Lee, C.R., R.E. Hoeppet, P.G. Hunt and C.A. Carlson. 1976. Feasibility of the functional use of vegetation to filter, dewater, and remove contaminants from dredged material. U. S. Army engineer Waterways Experiment Station, Tech. Report D-76-4, 83 pp.

Information was compiled and an assessment was made of the feasibility of using vegetation to filter, dewater and remove contaminants from dredged material slurry in confined disposal sites. A summary was developed to provide a listing of plant species that might be propagated on disposal areas. It was concluded that the physical and chemical interactions of selected vegetation with dredged material slurry would improve the quality of the discharge water from containment areas. Significant amounts of nitrogen and phosphorus could be removed from discharge waters by the use of selected vegetation. The use of vegetation to remove large amounts of heavy metals has limited feasibility. The intolerance of some plants to certain contaminants will preclude their usefulness in dredged material disposal operations. Vegetation was helpful in dewatering and consolidating fine-textured materials. The presence of vegetation also will improve the appearance of confined disposal areas.

Lee. C.R., R.K. Peddicord, B.L. Folsom Jr. and J.G. Skogerboe. 1987. The use of bioassay and associated tests in dredged material and disposal management. Hydrobiologia 149:81-86.

Physicochemical changes that occur after dredged material is placed in a disposal site are important to predicting contaminant mobility. Little change has been observed in the physicochemical nature of dredged material placed in an aquatic environment where it stays chemically reduced. This paper discusses what happens to contaminants in a confined upland environment. A significant increase in the dissolved form of Cd, Zn, Cu, Ni, and Mn were observed after the sediment had dried and this was reflected in plant uptake of these metals. Management options suggested to reduce soluble metal concentrations in surface runoff and in plants were: 1) keep the sediment wet to prevent sediment oxidation, 2) surface application of limestone to maintain a pH of neutrality and to adsorb and precipitate soluble metals and 3) cover the contaminated sediment with a cleaner sediment so that surface runoff waters would not carry contaminants.

Lembke, W.D., J.K. Mitchell, J.B. Fehrenbacher, M.J. Barcelona, E.E. Garske and S.R. Heffelfiner. 1983. Dredged sediment for agriculture: Lake Paradise. Research Report UILU-WRC_83-75, Water Resources Center, University of Illinois, 58 pp.

Sediment from Lake Paradise, Illinois, was evaluated for its potential for application to agricultural land and its effect on crop yields. Three methods of land application were considered: hauling of sediment removed by drag line, hydraulic dredging and application to terraces, and hydraulic dredging and application to the land via a traveling irrigation system. The later method was not evaluated experimently. Application of "hauled" sediment to a depth of 18 inches resulted in a corn yield of 144 bushels per acre compared to 115 bushels per acre on soil receiving no sediment. Both treatments received inorganic fertilizer based on soil test results. There was a predicted $100 per acre increase in returns due to the increased yields and lower fertilizer requirement of the sediment treatment compared to the zero sediment treatment.

The hydraulically dredged sediment was applied to basins formed by terracing sloping land. Each basin was subdrained with three-inch corrugated plastic drains. Three methods of installation were studied: 1) tubing was laid on the ground surface and overlain by filter sand to the predicted depth of the sediment; 2) tubing was placed in a 12 inch deep trench which was then backfilled with filter sand; and 3) tubing was placed in a 12 inch deep trench which was then filled with gravel. Treatment 3 allowed sediment to move with the drainage water and was therefore not recommended. The treatments containing filter sand prevented sediment movement with treatment 1 being most effective in removing water.

Lembke, W.D., J.K. Mitchell, J.B. Fehrenbacher and M.J. Barcelona. 1983. Dewatering dredged sediment for agriculture. Transactions of ASAE: 805-813.

The application of dredged sediment from Lake Paradise, Mattoon, Illinois, to agricultural land was studied primarily from the standpoint of application and drying techniques. Two approaches ere evaluated. One technique involved the use of a "hauled" sediment which was removed from the lake by dragline at a relatively low moisture content. Sediment depths up to 0.46 m were applied to the land. After one month the area was planted to corn. At that time the sediment was crusted on the surface but was "wet"at depths greater than 0.2 m. The sediment plots produced a significantly high corn yield than the check plots.

In a second study, "hydraulically dredged" sediment was applied to specially-designed terraces to a depth of 0.9 m. Surface drains removed supernatant water during the sedimentation process and removed surface water during sediment consolidation. The subsurface drains served as outlets for water in cracks of the sediment crust thereby speeding the consolidation. The dewatering process occurred with a minimal effect on lake water quality. The combination of surface and subsurface drains was an effective method of dewatering the sediment. No crop production data were presented for this phase of the study.

McVay, M.E., P.E. Heilman, D.M. Greer, S.E. Brauen and A.S. Baker. 1980. Tidal freshwater marsh establishment on dredge spoils in the Columbia River Estuary. J. Environ. Qual. 9:488-493.

Intertidal shore lands were used as a deposition site for the disposal of spoils from dredging of the Columbia River. The rapid establishment of marsh vegetation to stabilize these deposits was considered the best means to reduce adverse effects of this spoil deposition. The objective of the study was to develop techniques for establishing marsh vegetation and to evaluate the influence of fertilizer and elevation on survival and growth of tufted hairgrass and slough sedge, two commonly-found plants in coastal marshes. Direct seeding and transplanting were evaluated for stand establishment. Direct seeding was not a satisfactory method for establishing either of these species. Since the spoil was a sandy type material (92% sand), natural fertility was quite low. Fertilizer application increased growth especially with the tufted hairgrass. Both species were judged to be satisfactory for marsh establishment under the environmental conditions of this study.

Moore, B.C., W.H. Funk and J. Lafer. 1988. Long-term effects of dredging on phosphorus availability from Liberty Lake sediments. Lake and Reservoir Management 4: 293-301.

Liberty Lake is a 288 ha lake with an average depth of 6 m located near Spokane Washington. The lake was the site of a major restoration effort that included a proposed removal of 50 ha of sediment to a depth of 0.6 m. The primary purpose of the dredging was to reduce the large reservoir of phosphorus contained in nutrient-rich sediments in the shallower southern end of the lake, exposing less nutrient-rich deeper sediments. Sediments were of a heavy organic muck material having high phosphorus release rates. The underlying sediment was also more consolidated and stable. Exposing more stable sediments to the open water was expected to decrease the amount of materials resuspended in the water because of wind-generated turbulence.

Sediment removal operations were conducted using barge-mounted dredges. Because of lack of sufficient control of the movement of the barges, the sediment was not removed uniformly resulting in a series of trenches across the lake. Also, instead of removing 0.6 m of sediment, the trenches were often 2 to 3 m deep. This resulted in a redistribution of the phosphorus-rich surface sediment which exposed more of this sediment to the overlying water. Thus, there was no actual reduction in the pool of available phosphorus. The dredging was therefore not as successful as anticipated. Recommendations for future dredging operations included 1) contractor be properly equipped to control and position the barge and cutterhead in three dimensions, and 2) require monitoring of the operation by the contractor to assure that a proper removal pattern is being achieved. It was also strongly recommended that dredging contractors be selected who can demonstrate previous experience in sediment removal for <u>internal nutrient cycling reduction</u>.

Murakami, K. 1984. Dredging for controlling eutrophication of Lake Kasumigaura, Japan. pp. 592-598. <u>In</u>: Lake and Reservoir Management. Proc. Third Annual Conf., North Amer. Lake Manage. Soc., Knoxville, TN.

Lake Kasumigaura, the second largest lake in Japan, is an extremely eutrophicated lake, yet is one of the most important water resources around the Tokyo metropolitan area. It is a shallow lake with an average depth of 4 m. Nutrient exchange between the lake water and sediments was found to be the major factor affecting the nutrient balance within the lake. Therefore, it was decided to carry out dredging of sediments along with other measures to control eutrophication of the lake. To dredge fluffy sediments on the top layer effectively and to avoid excessive disturbance of the sediments, a special purpose dredge equipped with the Oozer system was built, and later, a modified version was constructed. The engineering aspects of dredge efficiency are summarized in the paper based on the 5-year experience. Lake water quality was not improved by the dredging activities.

Murphy, T. 1986. Sediment phosphorus release reduces the effect of the Chain Lake water diversion. Annual International Symposium, Lake and Reservoir Management: Influences of Nonpoint Source Pollutants and Acid Precipitation, P. 15.

In 1968, a 2-km water diversion was built to flush Chain Lake, British Columbia, with nutrient-poor subalpine water. However, in some years, blue-green algal blooms and fish kills still occurred. The incomplete success of the diversion appears to be related to the asynchrony of water flow and phosphorus release from the sediments. Internal loading represented about 78 percent of the phosphorus supply to the lake in summer when water flow was minimal. Phosphorus was five times more concentrated in the surface sediment than in sediments deeper than 80 cm. Although a large water diversion should reduce eutrophication, sediment dredging may be a more suitable in situ treatment.

Olson, K.R. and R.L. Jones. 1987. Agronomic use of scrubber sludge and soil as amendments to Lake Springfiled sediment dredgings. J. Soil and Water Conservation Jan.-Feb., pp.57-60.

Lake Springfield is a 1,600 ha reservoir in central Illinois which is being adversely effect by sedimentation primarily due to erosion of surrounding farmland. Sediment removal is being considered to restore the water storage capacity of the lake. Because of its physical and chemical characteristics, it was suggested that the sediment would have an agronomic value. At the same time, the city of Springfield had a scrubber sludge disposal problem from its electric plant. Thus this study was conducted to evaluate the effect of various combinations of soil, sediment, and scrubber sludge on sudangrass yield. Soil mixtures containing 0, 25, 50, 75, and 100% sediment were amended with 0, 1, 2, 4, and 8% scrubber sludge. The main effect of the scrubber sludge was to increase the pH of the soil, i.e., it acted as a liming material. Since the lake sediment already had a high pH (pH 7), the scrubber sludge had little effect on plant growth with soil/sediment mixtures. Plants grown on soil containing 75 and 50% sediment produced greater yields than soil with 0 or 25% sediment. No adverse effects of sediment were observed on sudangrass.

Olson, K.R. and R.L. Jones. 1988. Effects of scrubber sludge on soil and dredged sediment aggregation and porosity. Soil Science 145:63-69.

The effect of scrubber sludge, basically calcium sulfate from a electrical power plant scrubber, was evaluated as a means of improving the physical characteristics of Lake Springfield (Illinois) sediment. The scrubber sludge increased transmission pores within the sediment resulting in a higher rate of saturated flow of water in the sediments. Bulk density and water storage of the sediment decreased with addition of scrubber sludge. The presence of sludge also reduced surface-cracking during desiccation.

In-lake water chemistry studies were also conducted before, during and after dredging. Runoff from above-normal rainfall amounts apparently affected water quality more than the dredging operation. Post-dredging water quality indicated no adverse effect of dredging on water quality.

Peterson, S.A. 1982. Lake restoration by sediment removal. Water Resources Bulletin 18:423-435.

An overview of lake restoration by sediment removal is presented. Topics covered include 1) purposes of sediment removal, 2) considerations for sediment removal, 3) case histories of sediment removal, and 4) costs of sediment removal.

Peterson, S.A. 1981. Sediment removal as a lake restoration technique. United States Environmental Protection Agency Report EPA-600/3-81-013, 55 pp.

The status of various lake sediment removal projects in the United States through 1980 are summarized in table form. Information presented includes objective, type of lake pretreatment, sediment removal method, volume of sediment removed, % of lake basin dredged, post-treatment physical and chemical data, cost, sediment removal dates, duration of effectiveness, side effects and other concurrent treatment. In addition, an overview of lake restoration by sediment removal is presented. Topics covered include 1) purposes of sediment removal, 2) considerations for sediment removal, 3) case histories of sediment removal, and 4) costs of sediment removal.

Raymond, R. and F. Cooper. 1984. Vancouver Lake: Dredged material disposal and return flow management in a large lake dredging project. pp. 580-585. In: Lake and Reservoir Management. Proc. Third Annual Conf., North Amer. Lake Manage. Soc., Knoxville, TN.

The restoration of Vancouver Lake required the dredging of 6.5×10^6 m^3 of material from the lake, the construction of 17 km of land based retaining dikes to enclose 180 ha of disposal area, and the disposal of nearly 3×10^6 m^3 of material in the lake to form an island. The requirement that all dredge return flow be returned to the lake necessitated careful control of dredging activity and the imposition of several design and operation features to control the quality of the return flow water. Some of the measures used included multiple, or settling basins, extended weir length to reduce crest height, silt curtain enclosures around dredge disposal site outfalls, rapid alteration of dredge disposal sites, and careful monitoring of dredging activity and return flow quality. These measures enabled the project to be completed with no serious violation of water quality standards. Observations and data on water quality conditions during construction and the efficacy of specific dredging and sediment containment methods were described.

Ryding, S.O. 1982. Trehörningen restoration project. Changes in water quality after sediment dredging. Hydrobiologia. 92:549-558.

An increased load of domestic wastewater to Lake Trehörningen induced oxygen-poor water conditions and the development of a reduced sulphide-rich sediment layer. Severely polluted, the lake did not recover, even after advanced wastewater treatment and sewage diversion. Restoration measures with suction dredging and macrophyte elimination were applied in 1975 and 1976. The loose topmost sediment was pumped into an embanked and overgrown bay which was used as a settling pond. The activities also included a restoration of the shorelines. This project is the largest restoration programme carried out in Sweden on a single lake, corresponding to a cost of about U.S. $2,000,000.

The restoration of Lake Trehörningen was followed by a highly intensive research programme which included water chemistry and algal assays. The concentrations of phosphate and total phosphorus decreased by 73 and 50%, respectively, as summer average values, two years after the restoration. However, the concentrations of phosphorus are still too high to permit this element to act as a prime algal growth-limiting nutrient. The algal biomass has also remained at the same magnitude as before the restoration. Nitrate-N concentrations showed a tenfold increase, based on average values for the summer period. However, based on the results of the algal assays, a rapid and marked response was obvious, with a drastic decline in the algal growth potential. In addition, the water quality of the tributaries frequently contained excess nutrients (0.1-0.2 g P m^3). The nutrient loading from these sources exceeds the critical level for the lake, and additional treatment of the inflowing waters for the removal of phosphorus is necessary.

Sly, P.G. 1976. Some influence of dredging in the Great Lakes. pp. 435-443. In Interactions Between Sediments and Fresh Water, Ed. H.L. Golterman, Junk Publishers, The Hague.

In studies before, during, and after maintenance dredging at Port Stanley (Lake Erie) and Bronte Harbour (Lake Ontario), it was shown that total and reactive phosphorus levels increased rapidly in the receiving waters both at the removal site and at the open-lake dumping site. Similar increases in other nutrient elements and heavy metals were also observed. However, as a result of particle settling and dilution, elevated concentrations decreased rapidly and background conditions in the overlying water were generally re-established within a few hours. Because of the influence of wave activity in Lake Erie the dumped materials were rapidly redistributed and no evidence was obtained to indicate a long term influence on water chemistry. At Thunder Bay in Lake Superior, however, recent evidence suggests that harbour materials disposed of in deep water, below wave base, may continue to influence overlying waters for extended periods.

Soedergren, A. 1984. The effect of sediment dredging on the distribution of organochlorine residues in a lake ecosystem. Ambio. 13:206-210.

The distribution of DTT and PCB residues in water, sediment and fish was monitored in Lake Truman, Sweden, before, during and after a dredging operation. The dredging removed a major part of the residues form the lake. However, during the operation no changes in the residue load were observed in either the suspended matter of the water column. A mixing of the sediment occurred which resulted in deeper penetration of the remaining residues into the sediment. No significant differences were noted in the residue level in fish after the operation. PCB content in the surface sediment had increased, probably as a result of the internal circulation of residues from areas not dredged and/or contributions from sources outside the lake.

Tent, L. 1987. Contaminated sediments in the Elbe estuary: Ecological and economic problems for the Port of Hamburg. Hydrobiologia 149: 189-199.

The Port of Hamburg is situated in the Elbe estuary and requires water depth maintenance by dredging. Dredged material was previously used to create new industrial and agricultural areas. However, recent concern about toxic material contamination of the sediment has led to a reexamination of disposal practices. Since 1950, about 700 ha have been "elevated and covered with dredging material to fertilize the land for agricultural use". Soil analysis of dredged materials in 20 and 30 year old sites indicate that toxic metal contamination is not a new phenomena. Crops grown on the disposal areas have had cadmium concentrations exceeding acceptable standards. Research on soil-improvement measures has been initiated. At present, a covering layer of uncontaminated soil is regarded as the only long-term remedy to reducing heavy metal uptake by plants.

White, D.H. and E. Cromartie. 1985. Bird use and heavy metal accumulation in waterbirds at dredge disposal impoundments, Corpus Christi, Texas. Bull. Environ. Contam. Toxicol. 34:295-300.

During 1979-80, several large impoundments (dredge-pits) on the south shore of Nueces Bay were filled with sediments from dredging operation. Waterbirds were observed using these impounded areas as feeding and resting sites. The authors determined the extent to which aquatic birds use dredge-pits and evaluated the accumulation of selected heavy metals in the tissues compared to non-industrialized areas.

APPENDIX C

FOR 86-464A

KBN

JAN 25 1989

23 January 1989
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Dr. Michael F. Coveney
Environmental Specialist
St. Johns River Water Management District
Highway 100 West
Palatka, FL 32077

RE: Final Report "Feasibility of Sediment Removal and Reuse for the Restoration of Lake Apopka" (10 150 01-43-213 SWIM)

Dear Dr. Coveney:

At the recent informational exchange session on Lake Apopka hosted by the District, Mickey Bryant from FDER raised questions regarding our estimates for the cost of excavation and hauling consolidated sediment to upland disposal storage areas (Table 6-5 and line item in Table 6-7). In our original analysis, we developed a complete cost analysis for removing the sediment from Lake Apopka, processing the sediments, and transporting the material to a centralized point for sale or disposal. The criticism raised by Mr. Bryant was that the latter cost item could be eliminated by using the dewatering basins or spoil area for storage. KBN has considered the merits of this criticism, and we offer the following comments.

Should the spoil area be used for storage and direct sale of the recovered sediments, the effect of this proposed option may translate to some reduction in the \$399,880,000 line item originally specified for scraping, hauling, and storage. Nonetheless, the cost of excavation of the sediments from the spoil area still needs to be considered as part of the combined dewatering and storage area scenario proposed by Mr. Bryant; over a average haul distance of 2140 m (one half of the spoil area side length if the 1833[1] hectares spoil area assumes a square configuration), the unit cost for this activity is \$4.473 m^{-3} or a total cost of \$326,800,000. Also, acquisition costs for the additional 611 hectares of spoil area would have to be considered. Pumping costs to deliver bulk sediment to the expanded spoil areas (an increased average distance of 400 m) would increase by perhaps \$2,000,000. We estimate a <u>maximum</u> net savings from the combined dewatering and storage option of \$73,080,000 (\$399,880,000 - \$326,800,000), subject to some reduction because of increased land acquisition and pumping costs.

[1]This areal requirement includes an additional 611 hectares (1510 acres) land that would be required to accommodate increased spoil area requirements.

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The total estimated cost of the project exclusive of reuse benefits (and including the limitations regarding land acquisition, etc. noted in our original analysis) is thus $788,414,000. Tables 6-5 and 6-7 from the original report have been modified accordingly (see Tables 6-5a and 6-7a, attached) to reflect the estimated costs for the combined dewatering and storage area scenario. With an upper limit reuse cost return of $97,400,000, the minimum cost dictated by this scenario is thus $691,014,000. Consistent with our estimate of the true market value of the dried sediment, the net costs of dredging Lake Apopka are likely to range from $733,414,000 to $763,414,000.

In conclusion, the recommendation of using the sediment dewatering area as the final storage area of the dried sediment before it enters the market (or is otherwise disposed of) may offer some savings to the project. However, these savings may be offset or negated by the increased costs of land acquisition related to the expansion of the spoil areas to accommodate sediment storage onsite. If the project does indeed move forward, the District should consider such an option for sediment dewatering and storage. Should you have further questions, please do not hesitate to call.

Sincerely yours,

Curtis D. Pollman, Ph.D.
Principal Scientist

CDP:mla

cc: F.V. Ramsey, ATM

enclosure

Table 6-5a. Estimated cost of bulk excavation of sediments from combined dewatering and sediment storage area prior to final sale or disposal.

Total wet volume of sediments to be dredged from Lake Apopka	121,763,000 m^3
% consolidation	40% reduction
Total consolidated volume of sediments dredged from Lake Apopka (to be removed to the edge of the spoil area for sale or disposal)	73,057,500 m^3
Unit cost for bulk excavation	\$4.473 m^{-3}
Total cost for bulk excavation of sediments	\$326,800,000

Table 6-7a. Summary of estimated project costs, assuming that spoil area used for sediment dewatering will also be used for sediment storage until final disposal is effected.

Initial spoil area preparation cost, exclusive of land costs and land clearing costs (Table 6-1)	$10,110,000
Dredging costs, including mobilization, pipeline, and booster pump costs (Table 6-2)	$345,800,000
Total sediment dewatering and drying costs (Table 6-3)	$15,030,000
Bulk excavation costs during removal of consolidated sediments from combined dewatering/storage area for sale or disposal (Table 6-5)	$326,800,000
Total dike reconstruction costs, after removal of dried, consolidated sediments (Table 6-6)	$10,880,000
Total water treatment cost, including dredging supernatant and dewatering waters (Table 6-4)	$8,120,000
Subtotal	$716,740,000
Contingency and miscellaneous -- 10%	$71,674,000
Estimated total project dredging costs[1]	$788,414,000

[1]Estimated costs exclusive of spoil area land acquisition and clearing costs.