Dredging as a Restoration Tool For Lake Water Quality Improvement

Updated for:

St. Johns River Water Management District

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Introduction

The deterioration of lakes through cultural eutrophication is a global problem. Research on lake restoration techniques has blossomed over the past 50 years and lake restoration methods have been developed and tested all over the world. A primary purpose of restoration research is to find techniques that will improve water quality sufficiently to meet local standards (Sondergaard et al. 2000). In Florida and elsewhere, many shallow lakes are considered impaired waterbodies due to excessive external nutrient loading and related parameters such as dissolved oxygen. As directed under the Clean Water Act, total maximum daily loads (TMDLs) are developed for an impaired waterbody to provide a "roadmap" to curtail external loading to restore the impaired waterbody by improving water quality. Communities with impaired waterbodies have latitude to use various technologies and strategies to meet nonpoint source load reductions. Because of this, the primary focus of Florida's watershed management program is management of external nonpoint sources of pollution, especially stormwater, which is responsible for greater than half of the loading to Florida's waterbodies (Livingston and Crane-Amores 2007). In addition to addressing watershed (external) loading of nutrients to lakes, many restoration techniques, including dredging, are "in lake" techniques. For an impaired waterbody, dredging is generally considered a technique to increase the assimilative capacity of the waterbody.

Rapid sedimentation (solids being brought into the lake from the watershed by nonpoint sources such as stormwater runoff) is one symptom of cultural eutrophication, and dredging is one restoration technique that has been used to remove sediments that hold high levels of nutrients. One rationale behind dredging to restore lakes is that removal of nutrient-laden sediments will curtail internal recycling of nutrients from the sediment layer. Based upon our review of recent literature, although improvement in water quality is an often cited objective for dredging, it is commonly not the primary justification for dredging (e.g. Allen 2000, and others). Other, more common justifications for dredging are to deepen areas for navigation and recreation, restoration of flushing, restoration of fisheries habitat, restoration of water holding capacity for power generation and/or flood control in reservoirs, and to remove contaminated sediments.

Literature covering the direct long-term effects of dredging on water quality is scarce, and an accurate assessment of the results of dredging is difficult. There are three factors that restrict the ability to assess the effectiveness of past lake restoration: the unavailability of data and insufficient analysis of data that are available, the task-oriented approach to dredging, and the lack of clear project goals and objectives (NRC 1992).

Continual surveillance of lake conditions for a sufficient period of time, both before and after dredging has been attempted, and has been conducted on few lakes. In some cases, sufficient data are collected, but analysis and interpretation of the data are deficient; therefore, a comparative analysis of lake conditions pre- and post-restoration dredging is inconclusive. Pierce (1970, as cited in Peterson 1982) reviewed 49 projects and concluded that none provided sufficient data to determine the overall effects of lake dredging. Currently, more long-term in-lake water quality monitoring data are available, but surprisingly few attempts have been made to evaluate these data for changes in water quality associated with dredging.

These data sets do not necessarily meet stringent statistical assumptions for analysis of effects of dredging on water quality, because the monitoring was not designed specifically for this purpose (Dierberg and Williams 1989).

A second problem with the assessment of sediment removal as a water quality restoration technique lies within the task-oriented approach to dredging activities. Sediment removal is often seen as the one-time, permanent solution to a lake's problems and not as an ongoing process. The potential adverse ecological effects of the "activity" are considered short term and secondary to achieving the project goals, and environmental impacts are infrequently and unsuccessfully monitored.

And finally, it is difficult to assess the degree of success of restoration projects when project goals and objectives are not clearly defined (NRC 1992). In some cases, the amount of sediment to be removed is not accurately calculated. More frequently, sediment volume is defined, but water quality improvement goals are not specifically defined, and other environmental parameters are not considered. In most cases where water quality improvement is cited as a project objective along with other goals, dredging is conducted and the project is declared successful on the basis of the other goals (e.g. restoration of navigable depths), and water quality is not specifically monitored post-dredging to determine if project objectives related to water quality improvement are met.

The purpose of this paper is to summarize available information on sediment dredging and its potential long-term effects on the water quality of shallow lakes. Current documentation of the beneficial effects of sediment removal on water quality appears to be equivocal; however, several points were repeated in the literature. Successful and unsuccessful dredging projects conducted globally over the past three decades have helped to define the possible responses lake water quality will have to sediment dredging operations. External loading must be adequately addressed prior to dredging to anticipate a successful outcome (e.g. Annadotter *et al* 1999, Birch and McCaskie 1999, IETC 2000, and others). Setting realistic goals, objectives, and cost estimates based on adequate pre-dredging studies of lake ecosystem characteristics, combined with correct dredge selection, competent dredge operation, and post-dredging monitoring will increase the possibility of sediment dredging operations improving lake water quality.

Dredging as a Restoration Technique

A major objective of sediment removal is to counteract cultural eutrophication through the removal of organic matter and nutrients that stimulate the growth of algae and macrophytes. Cultural eutrophication is the rapid and human-induced acceleration of the natural aging processes in lakes (Klein 1997). The results of cultural eutrophication are increased lake water fertility due to higher concentration of plant nutrients, primarily phosphorus and nitrogen. Elevated nutrient concentrations lead first to an increase in submerged and emergent plants, and then to algal blooms, because algae can eventually out-compete other plants for nutrients. Increased algae cause turbid water, the shading out of other native vegetation and increased sediment production. The new rapidly accruing layer of sediment may itself serve as a nutrient source fueling an internal nutrient cycle. Wildlife also is affected with less valuable fish species replacing game fish; this may be attributable to organic sediments covering sandy bottomed littoral zones, and loss of native macrophyte fish spawning beds (Allen 2002).

Both internal recycling and external loading of nutrients contribute to cultural eutrophication, and both need to be minimized in order to restore lake water quality. Internal nutrient recycling from aerobic and anaerobic sediments, from groundwater seepage, from decomposing macrophytes, and from organism activities, can add nutrients to the water column. Lakes in agricultural areas and in urban areas without stormwater treatment are likely to receive heavy external nutrient loads. The idea that dredging will restore water quality results from the desire to break the internal recycling of nutrients from the sediments. Removal may aid in controlling the release of phosphorus and other nutrients into the water column and will thus decrease the rate of cultural eutrophication. Studies have shown that in some lakes with significant internal recycling, as much as 66% of phosphorus loading can be attributed to sediment (Klein 1997). Thus, water quality improvement as a result of sediment removal is commonly listed as an objective of dredging projects.

Lake and Watershed Characteristics Affect the Outcome of Dredging

Lakes will respond differently to restoration techniques depending on their morphology, hydrology, and history of eutrophication (Van Liere and Gulati 1992). The understanding of lake behavior and lake characteristics is essential to predicting the effects dredging will have on the lake sediments. Morphology, hydrology, and basin land-use history are general lake and watershed characteristics that will influence the impact dredging has on water quality. These general characteristics of a lake and watershed are reflected more specifically in the sedimentation rate, water residence time, sediment distribution, phosphorus release rate, and external phosphorus loading. Understanding these characteristics and how they potentially affect the outcome of a dredging project should be evaluated prior to selection of dredging as a restoration technology for water quality improvement.

Dynamics associated with phosphorus recycling from sediments are known to affect whether or not water quality improvements will be delayed following reductions in external loading in shallow lakes (Boers 1991). Boers found that the concentration of phosphorus in the sediments and the P:Fe ratio influenced the extent of internal recycling, and the retention time of the waterbody influenced any delay in water quality improvement following restoration. Residual external loading may also lengthen or prevent water quality improvements. Experts agree that the most important factor associated with the success of dredging to reduce internal recycling is the control of external loading sources. Sediment accumulation rates associated with uncontrolled external nutrient loading will determine the amount of time before any potential benefits of dredging are lost. If external nutrient loading is uncontrolled or insufficiently controlled, any benefits of dredging will be short lived and the cost-efficiency of dredging will be low. Sediment removal would have to continue for long-term restoration, thereby increasing the cost of complete lake restoration (Peterson 1982). On the other hand, sediment accumulation without elevated nutrient concentrations entombs sediments with higher concentrations of nutrients at depth (GLCS, 1994, and others). In general, the smaller the ratio of watershed area to lake surface area, the greater the assurance lake dredging results will last.

Water residence time or flushing rate will influence the negative impact nutrient release will have in the water column. Dredging in lakes with a longer residence time will increase the time re-suspended sediments will remain in the water column post-dredging. Short residence times combined with good quality water supply may deplete the phosphorus load in the sediments and accelerate phosphorus removal (Van der Doeas et al. 1992). Knowing a lake's residence time allows researchers to forecast the flushing capabilities of the lake and to predict potential post-dredging results. In dredging operations where the goal of sediment removal is to increase lake depth, residence times often decrease. On the other hand, in reservoirs and lakes associated with rivers or coastal areas, dredging may restore beneficial flushing. In this case, the reinstituted flushing is generally the direct cause of any water quality improvement (Cooper Consultants, 1985).

Sediment characteristics and distribution will determine the dredging depth, the equipment used, and the cost and direction of dredging. Dredging may be more beneficial when sediments with high concentrations are addressed first and when the correct dredging depth is set. Dredging sediments with higher nutrient concentrations first, before less-contaminated sediments, could prove more cost-effective and take less time. Sediment distribution throughout the lake will influence the dredging depth. Certain areas may require greater amounts of removal than other areas. The dredging depth will therefore affect the time, cost, and equipment used. If a dredging depth is set deeper than the appropriate depth, greater cost will be incurred and alternative equipment may be required. If dredging depth is shallower than the required depth (for example Annadotter *et al*. 1999), costs will be reduced but the amount of sediment removed will not be sufficient to restore the lake. Conditions that are most appropriate for dredging are small lakes with organically rich sediment, low sedimentation rates, and long hydraulic residence times (Graetz *et a1*. 1988, IETC 2000). Dredging is also most successful in well-flushed systems.

Sediment phosphorus release rates decrease with sediment depth because, in general, older, deeper lake sediment was deposited during a period when the lake basin was less impacted by human activity and both the rate of deposition and the nutrient content were lower. Exposing sediment with slower nutrient-release rates will minimize the adverse impact of nutrients in the overlying water column, and result in a decrease of material to be dredged. Phosphorus-release studies from various depths need to be carried out before dredging commences to determine dredging depth. If phosphorus release rates from deeper sediment are less than release rates from surface sediments, then dredging depth would be minimized, the costs of dredging would decrease, and lake restoration might become more feasible. Lakes with enriched surface sediment relative to underlying sediment could benefit from dredging (Peterson 1976). If deeper sediment layers contain greater phosphorus concentrations, then dredging may expose the lake to higher sediment phosphorus recycling (reference we talked about).

Nutrients from sources such as sewage effluent and agricultural runoff enter the water body and stimulate production of organic material that creates enriched sediment. Any re-suspension of sediments may make sediment nutrients available again. For example, the external load into Lake Zuideinderplaus, Holland, was reduced by 90% and resulted in only a 46% decrease in phosphorus (Van der Doeas et al. 1992). In many cases, controlling external loading of nutrients is sufficient for restoration and will result in a proportional decrease in lake phosphorus concentration (Sas 19xx). However, in some lakes, the change in biota, loss of habitat, physical changes in bottom sediments, and lake hydrology have been so dramatic that reducing the external loading will not proportionally improve water quality within the desired amount of time (NRC 1992).

Controlling external as well as internal phosphorus loading is a very important feature in lake restoration. Reducing the external load into a lake will slow the re-accumulation of phosphorus in the lake sediment in the years after sediment dredging (Recknagel et al. 1994). Kleeberg and Kohl (1999) predict that dredging without reduction of the external loading may give only temporary improvement followed by a slow return to the present situation. In lakes where internal phosphorus loading is larger than the external, dredging is suggested. Failing to stop external loading into the lake in many cases will result in a failed restoration effort. Many examples may be found in the literature, of such failures. For example, in Lake Eola, dredging with drawdown was conducted in 1972, but the lake continued to degrade. Stormwater diversions were not attempted until 1979-1982 (Dierberg and Williams, 1989). See also IETC 2000, Jeppesen *et al.* 1999, Keizer *et al*. 1992, and others, for additional examples. External loading likely contributed to the outcome of some dredging projects in Florida lakes (see case studies below).

A dredging operation conducted by Martin Sondergaard et al. (2000) on Lake Braband, Denmark, showed that the dredging of the lake led to an increase in water depth and a reduction in phosphorus release from the lake bottom. The internal loading of the lake decreased significantly after the dredging, compared to other lakes where only the external loading had been reduced, but water quality remained below standard. The turbid state of the water in Lake Braband is due to the high levels of nutrients that continue to enter the lake through external sources. The results confirmed that dredging can reduce both the duration and the size of internal nutrient loading; however, external nutrients need to be stopped for dredging to be considered a long-term restoration technique (Sondergaard et al. 2000).

The cessation of external sources of nutrients is expected to be a necessary first step in a restoration process encompassing further remedial techniques. When the phosphorus input is reduced drastically, supplementary measures (e.g., dredging) will be more successful (Van Liere and Gulati 1992). Alternatively, once external sources are controlled, internal recycling of nutrients may quickly decrease, and less costly, in-lake restoration methods may be as successful.

Pre-Dredging Studies Needed

Sediment investigation prior to the commencement of dredging operations is essential to ensure effective long-term restoration results. In addition to sediment characterization, a thorough evaluation of lake water chemistry both before and after dredging takes place is a necessity so that both long- and short-term changes due to dredging may be documented. Turbidity, total dissolved solids, conductivity, dissolved oxygen, and pH all need to be assessed. Adequate pre-planning studies will help to define the magnitude of the problem and will disclose unique lake characteristics that may help the appropriate use of dredging technology while preventing misuse. Feasibility studies for sediment removal of Lake Apopka (Graetz et al. 1988) [note to Larry from Sherry for follow-up: we need to look for more recent summary of decisions about dredging on these lakes] and Lake Okeechobee (SFWMD 2003) have resulted in decisions not to dredge. Both of these lakes are large with significant volumes of nutrient laden sediments. Cost was a major factor associated with the feasibility of dredging. One example of the effects of inadequate pre-dredging studies can be found in the attempted restoration of Lake Kasumiguara, Japan. The failure of this seven-year dredging project was due to inadequate pre-evaluation studies of nutrient budgets and sediment distribution and characteristics prior to restoration implementation. The removal of 300,000 m^3 of sediment over the seven-year period had no effect on the water quality of the lake. Subsequent calculations revealed that an estimated 20,000,000 m^3 of sediments would need to be removed for a 15% reduction in organic loading (Graetz et al. 1988; Murakami 1984). This example demonstrates the need for preliminary data collection in order to prevent project cost inefficiency, to provide realistic goal estimations, and to recognize that each lake contains unique characteristics that can affect the efficiency of restoration efforts. The cost efficiency of carrying out a 20,000,000 m^3 sediment removal project is questionable. Other restoration techniques might have been considered had a pre-evaluation taken place.

Cook *et al*. (1986, 1993) consider pre-dredging studies to be the most important aspect of a dredging project. Specifically, they suggest that a sediment removal project will be more effective if a thorough pretreatment evaluation of a nutrient mass balance – including behavior of the sediment and lake history from sediment core analysis – is conducted.

Peterson (1982) suggests an understanding of sediment characterization is essential before dredging is conducted. Sediment characteristics determine particle behavior during dredging and can help predict the appropriateness of dredging activities. For example, particle size will determine the nutrient concentration and the length and ability of the particle to be re-suspended. Smaller diameter particles often contain higher concentrations of contaminants, remain re-suspended for longer periods of time, and are more easily re-suspended (EPA 1993). The chemical composition and physical characteristics of the sediment also determine the release of contaminants into the water column pre- and post-dredging (EPA 1993). Pre-dredging studies need to include an evaluation of the sediment depth and distribution, mineralogy, tendency to deposit, organic content, bulk density, and toxicity content. Because of the high cost of dredging, dredging depths must be optimized to uncover strata containing less readily exchangeable forms of phosphorus. However, since net P release is a function of the P supply via sedimentation, reduction of P deposition rates by reducing external P loading may be more effective than dredging in many lakes (Kleeberg and Kohl 1999). The necessity for an in-depth pre-dredging study has been documented in successful projects and has been suggested as an improvement tool in failed projects

Understanding the unique qualities of each lake ecosystem before dredging is critical to restoration success. A project carried out on the Norfolk Broads, a series of shallow, man-made lakes in Eastern England required a thorough investigation to understand the high phosphorus peaks present in the lake. The lake experienced patterns of high phosphorus release as a result of periodic development of aquatic vegetation. The cyclical nature of aquatic plant growth created periods of peak phosphorus release from the sediments, which confused the interpretation of the impact of sediment removal on phosphorus release (Phillips et al. 1999). The natural but unusual lake patterns overshadowed the effects of dredging on the water quality. Realizing the cause behind the phosphorus peaks enabled a clearer understanding of the dredging results. Phosphorus did decrease after sediment removal, but levels remained higher than previous years due to cyclic highs.

Dredges and Equipment

Sediment removal to retard nutrient release may only be effective if the correct equipment is used. According to the U.S. Environmental Protection Agency (USEPA) (1993), there are no remedial technologies that can remove or treat contaminated sediment without some disturbance and consequent release of contaminants, in this case nutrients. Therefore, the selection of equipment used to dredge a lake should be based on its ability to minimize re-suspension.

Dredging equipment can be divided into four broad categories: mechanical, hydraulic, special purpose and pneumatic. All four types of dredges vary in their capabilities according to the sites in which they operate most efficiently, their production rates, the sediment re-suspension rates, and operational depths.

Mechanical dredges include clamshells, dippers, bucket ladder dredges, draglines, and conventional earthmoving equipment. Mechanical dredges operate most efficiently in near-shore areas that contain soft to stiff mud and have a limited operational depth of no more than 30 to 40m. Although mechanical dredging offers the advantage of high-density recovery, it generates high re-suspension of bottom sediment, particularly in the fine-grained range. Since the fine-grained sediment is often highly contaminated, the higher re-suspension can cause increased contaminant release (EPA 1993). The production rate is also relatively slow due to the time-consuming bucket swing, drop, close, retrieve, lift, and dump operating cycle. If properly operated, conventional clamshells can remove sediment with minimal loss of sediment. Modifications to the conventional clamshell – the closed bucket clamshell – are routinely used in contaminated-sediment dredging projects by the U.S. Army Corps of Engineers and reduce the amount of re-suspension material by 30% to 70%.

Hydraulic dredges include portable, hand-held, plain suction dredges, hopper dredges, cutter head dredges, and dustpan dredges. Hydraulic dredges generally exhibit higher production rates and lower re-suspension than mechanical dredges and, therefore, are more appropriate for environmental dredging. Hydraulic cutter head dredges are considered "environmentally cleaner" than other grab-and-bucket dredges because of the closed-cycle operation system. Other advantages include the ability of this type of dredge to remove large volumes in short times and to span any horizontal reach because of its floating platform (Peterson 1982). They are common in inland lake dredging projects because of this advantage. One disadvantage is the operational depth, which is determined by the ladder length or steel boom length.

Pneumatic dredges are within the forefront of dredging technology. Pneumatic dredges include airlift dredges, the Pneuma® and the Oozer®. These types of dredges produce slurries of higher solid concentrations than hydraulic dredges and cause less re-suspension of bottom materials. They operate most efficiently in soft, viscous sediment commonly found in many lakes and their operational depths are greater than 10m. Even though there are several advantages to using pneumatic dredges, they have not caught on in the United States or were completely unavailable (Cooke et at. 1993).

Special purpose dredges were created due to the challenge of the soft lake sediments. The special purpose dredges include the cutter-head design used on the Mud Cat®. Solid production rates are increased, re-suspension is minimized, and far less water volume must be contained at the disposal site with these dredges. This type of dredge is ideally suited to small lake restoration projects with operational depths of 3 to 18m (Cooke *et al*. 1993).

Another special purpose dredge created to be "environmentally cleaner" is the Ecograb dredge. It has many advantages, such as removing very thin layers of sediment with high precision. Turbidity and dispersion of silt particles are also avoided because all openings are sealed off. The Ecograb is best suited for small or shallow areas such as river banks. However, this new dredge has limited use due to budgetary constraints.

Specialized dredging technology has been developed in Japan and the Netherlands to reduce sediment re-suspension. Specialized dredges typically have narrow or shrouded dredge head openings to minimize suspension and operate with slower productivity at a higher cost. The cost of dredging using conventional equipment is high, and lake restoration using this technology is often not economically feasible. Specialized dredges will reduce the environmental impact of restoration but with slower productivity, they will increase the length of the project and create an even higher cost. If feasibility and conditions permit, pneumatic dredges are recommended for environmental dredging. Pneumatic dredges are extensively used in Europe and Japan but have only limited availability in the United States. Dredging projects in the United States tend to use conventional hydraulic cutter head or horizontal auger dredges or mechanical clamshell dredges that cause higher re-suspension rates (Cushing 1998).

If specialized dredges are not feasible, other measures can be taken to reduce the re-suspension rates caused by dredging action. Re-suspension disturbance can be minimized by operational controls, including reducing cutter head rotation speed, slowing dredge head movement, reducing the depth of cut, and increasing the suction rate (Cushing 1998). Sustar (1979) concluded that the amount of sediment disturbance is related to the sediment type. Even well run equipment can cause high turbidity.

Unanticipated problems with equipment were encountered in the restoration of Liberty Lake, Washington. The equipment operator was not able to locate the top 60 centimeters of light organic sediment, and dredging began below the nutrient-rich surface sediment. Post-dredging studies indicated that the horizontal cutter head dredge 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 sediments. Only an estimated 40% of the dredged area was dredged efficiently. In addition, some macrophytes were left with the sediment, resulting in a rapid reestablishment of macrophyte beds. Other problems, including an increase of re-suspension, can be encountered when an incorrect dredge size is used.

Dredging Costs

Cost comparison among projects is difficult due to the large number of variables such as, type of equipment used, productivity rate, dredging time, type and amount of sediment to be removed, dredging depth, lake size, ecological considerations, the competence of the dredge operators, and the method of sediment transportation and disposal.

The cost of dredging has increased over the past two and a half decades. Cost analysis research conducted by Peterson (1981)_on 64 dredging projects revealed a cost range of $0.18 per cubic meter to approximately $10 per cubic meter-in: 1975. The cost analysis research found that costs from $0.95 to $1.33 per cubic meter were common and could be considered reasonable for hydraulic dredging (North American Lake Management Society 1988). More recent ranges are $0.36/m^3 to $21.00/m^3 without significant disposal issues (e.g. contaminants present). Because of the wide variability in costs, it is not helpful in estimation for a single project. Furthermore, this estimation does not include disposal, transport, or monitoring costs. EPA (1993) estimations for dredging costs range from $1 to $25/m^3 and dredging of contaminated sediments is even more costly. The typical range for contaminated sediments is $5 to over $25/m^3. Simple cost estimators are also available (Cervie *et al* 1999).

Initial costs of dredging for selected Florida lakes vary widely, by approximately one and one half orders of magnitude, and are sometimes as costly as sewage treatment plant effluent diversion projects (Dierberg and Williams 1989). Costs are primarily governed by the amount and quality of sediment to be dredged along with accessibility of dredge disposal sites. Cost information, when available, is included in the case studies presented below.

Environmental dredging usually has a higher cost due to the slower production rates. The slower production rates can be attributed to debris removal, shallower cuts, and delays due to sediment treatment. A detailed cost estimate could be calculated from specific information on the equipment to be used, the method of transporting the dredged material, and current prices for labor and fuel (Cooke et al. 1993).

Cost Reduction

Researchers are continually developing new ways to reduce the cost of dredging. Recently, two consulting firms in Florida working on the feasibility of restoring Lake Sippo developed an innovative process of dewatering lake sediments using a polymer process to reduce the dredging cost. The process reduced the cost of construction of sediment-drying areas and the anticipated dredging period from three years to one year. Shortening the dredging time reduced the total anticipated cost and made dredging a possibility (MS Consulting 2001).

Adequate pre-dredging studies will also reduce cost. Dredging is an expensive lake restoration technique that requires thorough investigation to ensure that any short- or long-term environmental benefits from using this technique counterbalance the cost of operation. Dredging is several times more expensive than nutrient inactivation in accomplishing the same short-term goals (minimization of internal nutrient recycling) if cost is the only consideration (Cook et al. 1986). Partial dredging (dredging only to a certain depth to remove phosphorus) has been evaluated for lakes such as Lake Okeechobee, in an effort to evaluate more cost effective dredging scenarios (Reddy *et al*. 2002, Reddy *et al*. 2007).

Lake Size

Technically, there is no reason why a large lake cannot be dredged, although the size of a lake must be taken into consideration before dredging begins. The size of Lake Kasumiguara was not adequately studied before dredging began and the project failed. Size of a lake will increase the cost of dredging, and budgetary aspects will often determine the feasibility of dredging a large lake. Sediment removal by dredging was considered for Lake Arre in Denmark, but due to the large surface area of the lake (approximately 20 km^2) the cost was estimated at $60 million (IETC 2000). Realistically, dredging is more efficient when applied to a relative small lake. Most dredging projects are undertaken on small lakes. Kampfe Lake, New Jersey was dredged from February 1986 to October 1989 with positive water quality results following the dredging. The surface area of the lake was 129,000 m^3 (Sebetich and Feniro 1997). As noted above, feasibility studies for dredging of Lake Apopka and Lake Okeechobee resulted in decisions not to dredge; costs of dredging these large lakes was prohibitive.

IETC (2000) recommends that a combination of techniques be used in lakes with larger surface areas, and not dredging alone.

Advantage of Dredging

There are many advantages of dredging and several goals can be accomplished using this type of restorative technique on lakes. Removal of toxic substances, macrophyte removal, phosphorus removal, and contour alteration for navigational purposes, restoration of fish habitat, and restoration of flushing are examples of goals that can be accomplished (Klein 1997). One positive restorative factor associated with dredging is the physical removal of nutrients contained in the sediment. An example of the removal of nutrients comes from Lake Trummen, Sweden. This lake was dredged and total phosphorus concentration in the lake dropped sharply and remained low for nine years. There is also a rapid long-term decrease in internal nutrient loading and nutrient concentration in the water column. Other dredging projects have also claimed improvements in water quality (Aron and Carr, ND), although some projects have employed more than one restoration technique so the results cannot be attributed solely to dredging (Gorini 1987).

Macrophyte control is an important reason dredging should be considered. A project conducted on Lake Lilly, WI was deemed a success story due to the control, not eradication, of macrophytes. Prior to dredging, Lake Lilly suffered from severe DO depletion and fish kills in the winter months. This was no longer a problem ten years after the dredging project and water quality showed an improvement as well (Cooke et al 1993); however, 20 years after the dredging, chlorophyll and TP, while still low, are three times higher than during the 10 year follow-up. In addition to macrophyte control, general habitat restoration, especially for fish, is a common goal associated with dredging projects. In Florida, Florida Fish and Wildlife Conservation Commission routinely plans and executes fish habitat restoration projects that include sediment and muck removal (Allen 2000). In Palm Beach County, the Lake Osborne Muck Dredging Project had stated goals of habitat restoration, improved recreation and water quality (Palm Beach County 2007).

One of the main advantages of dredging over other techniques is that dredging does not introduce foreign substances into the water body (Klein 1997). Other remedial techniques, such as alum treatment, introduce aluminum into the ecosystem, opening up the possibility for increased toxicity and harmful effects on the fauna and flora (Gensemer 1998).

Disadvantages of Dredging

Analysis of successful and unsuccessful dredging projects has revealed a high potential for negative impacts of dredging on lakes and their surrounding (North American Lake Management Society 1988). As previously mentioned, the primary concern lies with the possibility for the re-suspension of sediments that will result in an increase of nutrients into the water column. Even though Lake Lilly was considered a success, there were short-term adverse changes associated with the re-suspension of sediments. There was liberation of ammonium nitrogen from the contaminated sediment and total phosphorus increased due to re-suspended sediments (Cooke et al 1993).

Additional environmental impacts related to dredging include increased phytoplankton productivity, algal blooms caused by the movement of sediment into the euphotic zone of the lake by wind and dredge action, the potential for oxygen depletion, lake drawdown, toxic material release into the overlying water from contaminated sediments, and a temporary reduction in benthic fish food organisms (Peterson 1982).

The length of impact of dredging activities is undetermined and lake-dependent, however most adverse impacts are considered transient (Holdren *et al*. 2001). Temporary increases in turbidity, algal blooms, and dissolved oxygen depletions have been experienced during dredging; however, the potential for negative impacts can be reduced if the correct dredge is selected and operated by a competent worker, pre-dredging studies have been conducted, and external nutrients have been controlled (North American Lake Management Society 1988).

One of the biggest disadvantages of dredging, when compared to other restoration technologies, is the need for dredge material (spoil) disposal. Today's emphasis is on beneficial reuse of dredge materials. However, a variety of issues associated with sediment disposal have to be considered in the project design, including the possibility of nutrients or contaminants leaching into water from disposal sites placed next to waterbodies, dewatering, and other issues.

Cook et al. (1986) and others have found that environmental concerns associated with lake sediment removal appear to be less negative than might be expected. Case studies reveal that though adverse impacts do occur, they generally are not severe and are of short duration. There have been failures with dredging, but most of the failures can be attributed to inaccurate pre-dredging assessments and inadequate amounts of sediment removed.

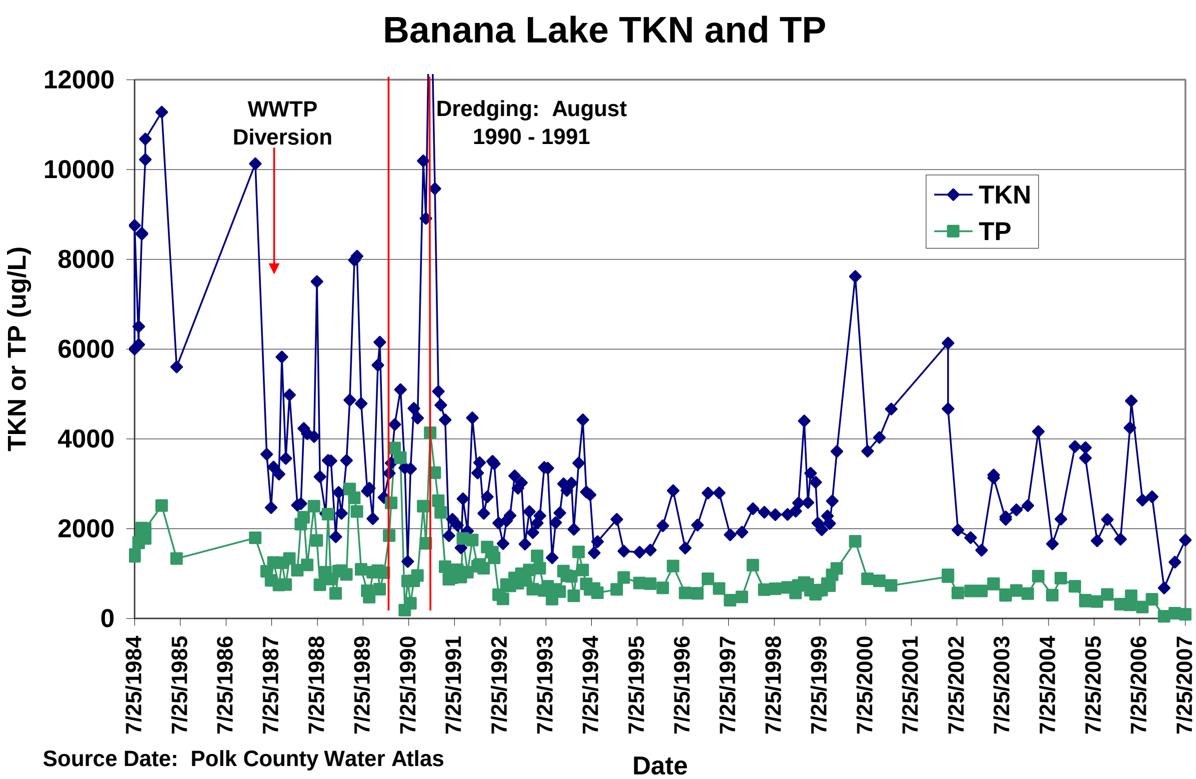
There are few examples where dredging alone has been proven to have a positive effect on water quality. Most successful projects incorporate dredging as part of a multiphase restoration effort encompassing other remedial techniques such as biomanipulation, alum treatment, and external nutrient divergence. In fact, the Lake Trummen dredging project was successful, but the return flow was treated with aluminum sulfate. Any positive effects of using dredging alone may be short lived, especially if external nutrients are not controlled. A variety of dredging projects have resulted in failure to improve water quality (for example: Birch and McCaskie 1999, Breithaupt and Lamb 1982) or to achieve water quality goals (Jeppesen *et al.* 1999).

SELECTED CASE STUDIES

Banana Lake, Florida

A second example of partial success is found in the restoration of Banana Lake which has shown modestly improved water quality (as indicated by the TSI), but additional restoration activities are necessary, as the lake remains impaired.

Banana Lake, historically, the most polluted small (approximately 340 acres) lake in Florida, according to trophic state index (Huber et al. 1982). From 1975 to 1987, a WWTP discharged an average of 6.4 MGD into a canal draining to Banana Lake. The effluent was diverted away from the lake in 1987. Nonpoint sources were not addressed prior to dredging. In 1989-1990, a restoration plan was developed which called for hydraulic dredging of the entire lake. Dredging began in October 1990 and proceeded for one year. Approximately 800,000 CY of sediment were removed; however, the lake remained eutrophic after sediment removal, and is currently listed as impaired for nutrients (USEPA, 2006). The main benefit of sediment removal for Banana Lake was a 50% reduction in chlorophyll *a* in the two years following dredging (Kelly et al. 1994). TSIs post dredging are frequently at or slightly below 80, but were consistently above 80 from 1984 until dredging was conducted.



Source Date: Polk County Water Atlas

Battersea Park Lake, London England

The dredging of Battersea Park Lake did not produce the desired improvements in water clarity because the significant external loading source was not controlled prior to dredging.

Battersea Park Lake in London, England is the largest lake in the urban park system. It was constructed around 1860, and is approximately 8 ha with an average depth of less than 1 m. It was recognized that both external loading and recycling of nutrients from the sediments needed to be reduced to improve water quality. The lake is used recreationally, and historically was dominated by macrophytes, rather than phytoplankton. The lake was dredged in the early 1980s "at great expense, but with no lasting effect on water clarity" (Birch and McCaskie 1999). However, at that time, external loading (top off water supplied from the nutrient rich Thames River and other sources) were not controlled. By 1994, fish kills were occurring due to low dissolved oxygen. The available water quality data was post dredging, 1993 to 1996.

City Park Lake, Louisiana

The long-term water quality trends indicate that the 1984 restoration of City Park Lake was successful in short-term improvements in water quality conditions in the lake that have persisted for many years. However, the beneficial effects and expense of the restoration have been severely undermined by the lack of implementation of long-term watershed and in-lake nutrient management strategies (Ruley and Rusch 2002), and the lake had returned to pre-dredged water quality by 2000.

City Park Lake in Baton Rouge LA is a shallow (mean depth = 1.2 m), small (surface area of 0.23 km^2), hypereutrophic urban lake, with an urban watershed covering 1.922 km^2. By the late 1970's the lake was suffering from frequent, severe algal blooms and fish kills, prompting a major restoration begun in 1983 that included dredging and repair of sewer infrastructure to reduce external loading. Combined funding for the project was approximately $4.5M. A total of approximately 100,000 m^3 of sediments were dredged. Due to concerns about metals in some surficial sediment adversely impacting the disposal area, these sediments were moved to one side, deeper, cleaner sediments were dredged, the metal laden sediments were then moved to the newly dredged area and covered with cleaner sediments. Overall, the mean depth of the lake was increased by approximately 0.3m. Post-dredging monitoring (1984) documented immediate improvements in oxygen storage capacity in the lake and improved water column transparency, and the frequency of algal blooms diminished for the remainder of the 1980s. The lake transitioned from hypereutrophic to eutrophic status. Large blooms of benthic filamentous algae began to cause floating scum in the 1990s. Studies in the early 1990s demonstrated that water column total P levels fell slightly between pre-dredging and 1991, and algal densities dropped dramatically. Nutrient levels, however, remained high. External loading (from a bayou, and continued problems with sewage leakage) were identified. By this time, the lake was again considered hypereutrophic. By 2000, the mean summer TP and Secchi depth had returned to pre-dredging levels. However, summer chl a and mean summer TKN remained much lower. It was concluded that the lake was now nitrogen limited+.

Cockshoot Broad, England

The dredging of Cockshoot Broad, a shallow lake in England, as a short-term solution, demonstrates the need for additional restoration techniques. The results of isolation and the removal of a meter of phosphorus-rich sediment by suction dredge (1982) were almost immediately positive. Total phosphorus concentrations quickly fell, and dense submerged-plant communities established in a sheltered part of Cockshoot Broad. Total phosphorus remained low from late 1982 until the summer of 1985, when there were indications of an increase. There was a decline in aquatic plants in Cockshoot Broad in 1984 and 1985, and an increased concentration of phosphorus was found in the summer and autumn of 1987 and 1989 (Moss et al. 1996). Additional measures were needed – and later undertaken – to ensure long-term restoration of Cockshoot Broad.

Lake Finjasjon, Sweden

Dredging was determined to be an inappropriate restoration technique for Lake Finjasjon, Sweden, because water column phosphorus concentrations were not reduced and chlorophyll *a* actually increased.

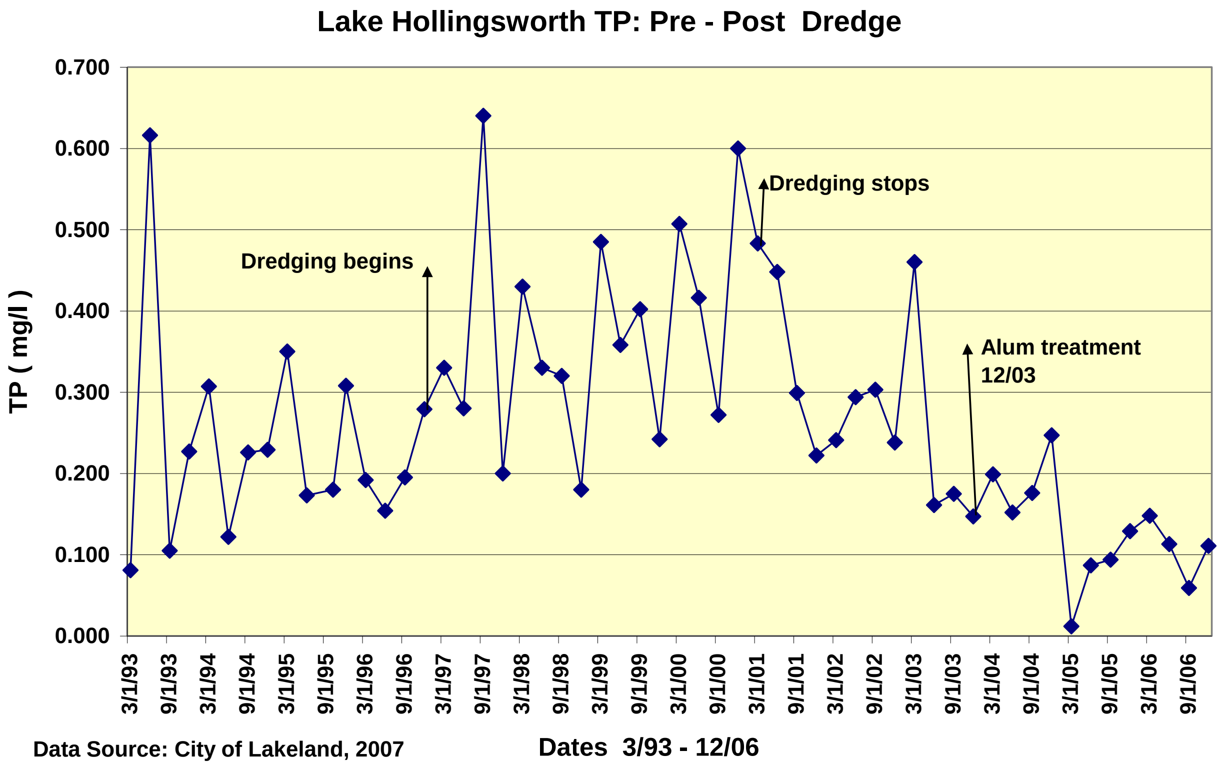
Initially, external nutrients were reduced and dredging lake sediment was introduced to control internal nutrient loading in Lake Finjasjon. After years of unsuccessful results, however, dredging was replaced by biomanipulation (Annadotter et al. 1999). Reducing the external nutrients into Lake Finjasjon did not assist in the recovery of the lake – there was actually an increase in chlorophyll *a* – and dredging did not decrease phosphorus concentrations. For Lake Finjasjon there was a non-explicit relationship between the trophic level and the phosphorus content of the sediment. Instead, the phosphorus concentration in the pore water was believed to reflect the trophic level of the lake. Lake managers concluded that continual dredging would not produce a clear lake, and dredging was deemed an inappropriate method of restoration. Biomanipulation was successfully used as a secondary method to restore Lake Finjasjon (Annadotter et al. 1999).

Lake Hollingsworth, Florida

In Lake Hollingsworth, nutrients and other water quality parameters were lower on average, post-dredging, but additional in-lake and watershed restoration efforts have been necessary to further curtail nutrient loadings, and the lake remains impaired.

Lake Hollingsworth is one of the most popular recreational lakes in Polk County. On average, over 2,000 people per day use the lake and shoreline for recreation. Currently, Lake Hollingsworth has an average depth of 3.6 ft, with a surface area of 358.15 acres. Lake Hollingsworth serves a drainage basin area of 1,647.49 acres which includes the Lake Morton and Lake Horney watersheds. The lake experiences high bacterial counts, especially during the winter, which curtails its use. Fifty seven stormwater outfall pipes discharge into the lake, and a variety of retrofit projects are planned or underway to curtail external loading to the lake.

The watershed management plan developed for the lake and watershed recommended dredging of the entire lake as a means of restoration (City of Lakeland, 1995). Hydraulic dredging was selected, with an estimated cost of $6.4 M dollars (City of Lakeland 1994). Dredging was initiated in 1996. Dredging was suspended on March 5, 2001 due to the extreme low water levels in the lake. Two years of extreme drought combined with the water loss associated with the dredging process resulted in record low water elevations in Lake Hollingsworth. As a result of the dredging through March 2001, approximately 75% of the planned dredging volume was removed from the Lake. Two years post-dredging a one time whole lake alum application was conducted. The City of Lakeland is planning to resume dredging in the future.

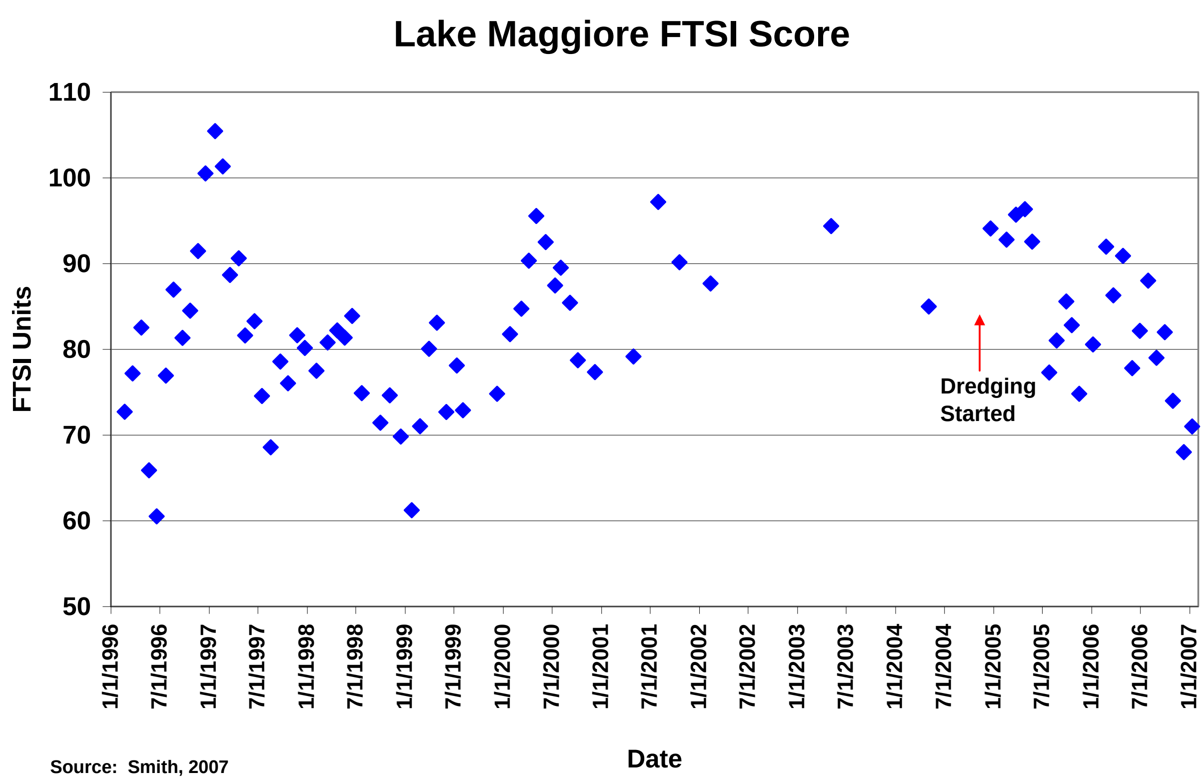


Interpretation of available water quality monitoring data is confounded by the extended drought conditions post-dredging and the addition of the second lake restoration technology. However, TP, TN, and chlorophyll a concentrations remain lower than pre-dredging conditions, and Secchi depths are deeper post-dredging. TSI which averaged above 80 units prior to dredging is now averaging around 70 units. Lake Hollingsworth remains eutrophic to hypereutrophic, and stormwater treatment systems were considered necessary to curtail external loading. The South Landing treatment wetland was completed on the south shore of the lake in 2006.

Lake Maggiore, Florida

Expected benefits from the Lake Maggiore restoration projects which included dredging include: improved water quality, improved recreational use and public access, and improved fishery and wildlife habitat. The project is only shortly post-dredging with the initial modest effects noted below, and monitoring will continue of Lake Maggiore to document these anticipated improvements.

Lake Maggiore is a 380 acre water body located in southern Pinellas County. The TSI of Lake Maggiore has historically remained above 80, which ranks it as a highly productive, hypereutrophic lake. Development within the watershed primarily occurred prior to implementation of current stormwater management regulations. A diagnostic study undertaken in 1989 concluded that water quality was poor due to untreated stormwater runoff and large quantities of organic muck on the lake bottom contributing to nutrient enrichment in the lake. A variety of restoration projects have been completed including, but not limited to retrofitting of the stormwater conveyance system and addition of five alum injection facilities to treat stormwater runoff (built prior to dredging) and dredging of approximately 1.5 MCY of sediment from the lake bottom. Expected benefits of the restoration include improved water quality, improved recreational use and access, and improved habitat. Routine water quality monitoring was initiated in 1996 and continues to date (Smith 2007), and comparisons pre and post dredging to date have not shown statistically significant trends among the parameters of interest including Total P, Total N, and chlorophyll.

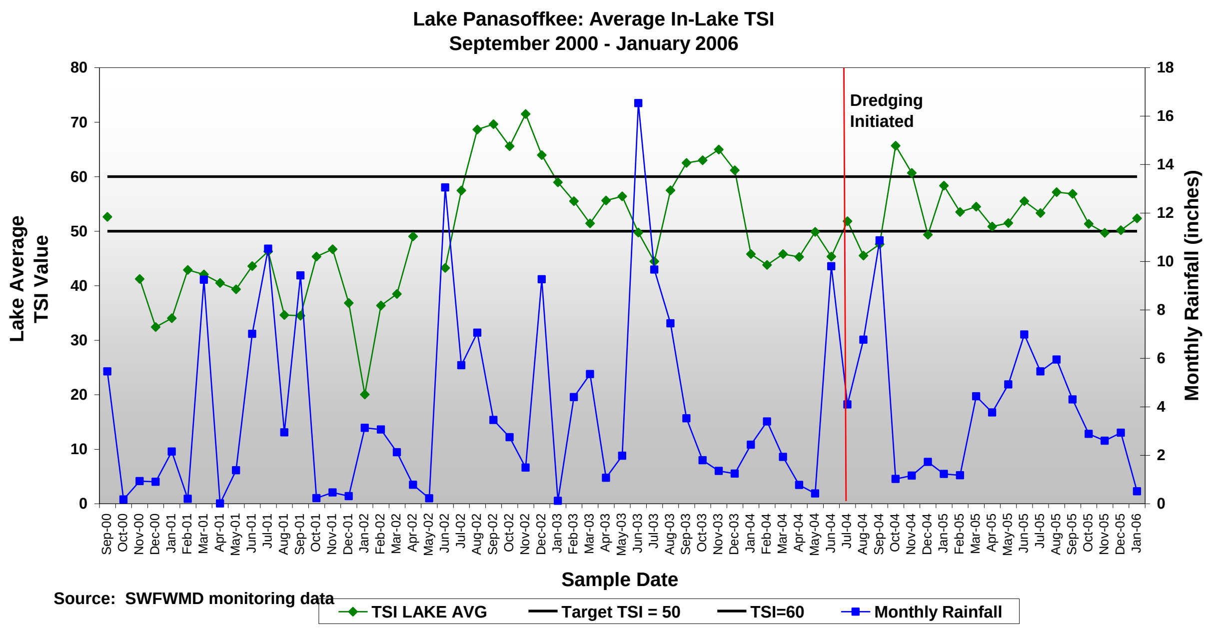


There has been an increase in conductivity (from chloride in the groundwater) which is likely due to increased seepage of groundwater following soft sediment removal, an effect that was predicted in the preassessment studies (Smith 2007).

Lake Panasoffkee, Florida

The dredging of Lake Panasoffkee continues to date, and post dredging monitoring continues. To date water quality improvements have not been observed, but fisheries habitat restoration and navigation, not water quality improvement are the stated goals for this project.

Lake Panasoffkee at approximately 920 of open water acres and approximately 2000 acres in total, is the third largest lake in western Florida. Historically, the lake was known nationally for its redear sunfish fishery. The Florida Department of Environmental Protection (FDEP) designated Lake Panasoffkee as an Outstanding Florida Water. The lake is also one of the priority water bodies in the Southwest Florida Water Management District's Surface Water Improvement and Management (SWIM) program. In recent times, the fishery had declined, and this was attributed, at least in part, to loss of nursery habitat as organic sediments covered historically sandy lake bottom and emergent aquatic plants covered areas of historically open water. A multiphase dredging plan was developed with the objective of restoring fisheries habitat, historic shoreline and improving navigation. Improvement in water quality was apparently not a major objective of this restoration, and TSI data have remained relatively constant during the dredging to date. The ambitious dredging plan calls for the removal of over 8 MCY of soft sediment. Dredging began in July of 2004 and is scheduled to be completed in 2008. The total cost of the restoration is estimated to be $26M.



Peterson (1982) provides additional examples.

Lake Trehorningen, Sweden

A multiphase restoration project at Lake Trehorningen, Sweden, was only partially successful because of continued external nutrient loading after treatment. Dredging was one phase of a five-phase project to restore Lake Trehorningen.

After dredging, phosphate and total phosphorus decreased by 73% and 50% respectively, between 1975 and 1978. Organic matter content decreased by 33%, the nitrogen-to-phosphorus ratio increased, and chlorophyll *a* decreased dramatically through eight years following dredging. Although substantial improvements in water quality were observed, the Lake Trehorningen restoration project was rated as having only limited success. The areal nitrogen and phosphorus loads far exceeded critical levels after restoration. The limited success was attributed to continued high external loads of nutrients. The experience at Lake Trehorningen demonstrates once again the need for thorough evaluations of nutrient budgets prior to the implementation of expensive dredging activities (Graetz et al. 1988).

Lake Trummen, Sweden

Lake Trummen is an example of a successful lake restoration project that combined dredging with external load reductions and some chemical amendment treatment. The lake was dredged in 1970 and 1971 to control an internal nutrient loading problem. One meter was removed from the bottom of the 400-hectare lake using a suction dredge. Approximately 600,000 m^3 of mud and 300,000 m^3 of water were pumped through settling ponds. The mixture of interstitial and lake water required an alum treatment before re-entering the lake. As a result of dredging, organic carbon concentrations decreased from approximately 80 mg C L^{-1} and diurnal fluctuations in oxygen, pH, and alkalinity were reduced significantly after the restoration. Post-treatment water quality studies were carried out for more than 14 years, and low concentrations of total phosphorus and nitrogen continued (Graetz 1988). Post-dredging interstitial phosphate concentrations decreased to 0.5% to 0.2% of pre-restoration concentrations. Total biomass of phytoplankton decreased drastically, and there was a decrease in the type of zooplankton commonly associated with eutrophic conditions. Dredging was combined with external nutrient divergence and alum treatment to obtain these results.

Conclusion

An evaluation of the available literature on dredging and its effects on water quality indicates that dredging should be seen as an additional tool for water quality management and not as a primary method of restoration. Although many techniques are potentially available to restore degraded lakes, the science of lake restoration is inexact and the outcome of applying a given technique to a particular lake is difficult to predict (NRC 1992). Understanding the complexity of the transition that takes place within a lake when it deteriorates to a eutrophic state highlights the reverse process that needs to take place during restoration.

The failure of projects to restore lake water quality to adequate standards is the result of inadequate pre-dredging studies, the continuation of external nutrient loading, high re-suspension rates, and the misunderstanding that dredging alone can restore water quality. Many studies indicate that dredging alone will not provide long-term restoration. Sediment removal after source control, and potentially followed by other restoration techniques offers the most reliable route to long-term restoration (Phillips et al. 1999).

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