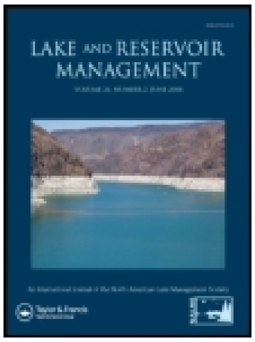

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RESTORATION OF SEBASTICOOK LAKE, MAINE, BY SEASONAL FLUSHING

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ABSTRACT

During the past century, increased fertilization and the resultant algal and macrophyte growths have severely impaired the quality and use of many lakes throughout the world. A notable case has been the deterioration of Sebasticook Lake. The lake began showing signs of cultural eutrophication in the early 1950's. By the late 1960's it had become hypereutrophic and has remained in that condition despite remedial efforts. Currently a major effort to restore the lake has been undertaken by the State of Maine, U.S. Environmental Protection Agency, U.S. Department of Agriculture and local communities. Estimates of annual external phosphorus loading range from 3,900 to 11,800 kg with an estimate of 9,000 kg considered as the most accurate estimate of the current load. Sources include 2,300 kg and 2,200 kg from the towns of Dexter and Corinna respectively, and 4,500 kg from nonpoint sources of which 85 percent is culturally generated from farmland. Using a mass balance model it is estimated that an annual external load of 4,500 kg of total phosphorus would maintain the lake at a desired concentration of 15 μg/l and suppress the chronic algal blooms. Strategy to control external sources includes advanced wastewater treatment to reduce the loading from Dexter and Corinna to 300 kg and 700 kg, and improved farm practices to reduce nonpoint sources to 3,500 kg. Since the recycle of phosphorus from the lake sediments is estimated to contribute 6,900-9,900 kg into the water column annually, control of internal recycling was also imperative. Because of the large size of Sebasticook Lake (1,798 ha) the most promising means to reduce internal phosphorus was to alter the flushing regime of the lake. Epilimnetic phosphorus reaches peak concentration during late summer stratification. At that time, the lake volume is reduced by one half, decanting the phosphorus rich epilimnetic water. Refill of the lake does not commence until the following spring when phosphorus-poor melt water is available. Drawdown of the lake is accomplished through constructing a 4-meter deep canal and gate structure at the outlet. Initial trials of the structure were estimated to export about 4,200 kg of phosphorus annually.

INTRODUCTION

During the past century, increased fertilization resulting in algal and macrophyte growth has impaired the use of many lakes throughout the world. One notable case has been the deterioration of Sebasticook Lake in Newport, Maine. First studied in 1965 and reported in a technical report (Fed. Water Pollut. Control Admin., 1966) and by Mackenthun et al. (1968), the lake began showing signs of cultural eutrophication in the early fifties. By the late sixties, Sebasticook Lake had become hypereutrophic and has remained in that condition despite remedial efforts. Currently, a major effort to restore the lake has been undertaken to limit external sources of pollutants and alleviate the effects of years of sediment accumulation.

BACKGROUND

Limnology

Sebasticook Lake is located in Newport, Maine, on the East Branch of the Sebasticook River (Fig. 1). The lake receives runoff from three main tributary streams: East Branch of the Sebasticook River, which is the largest and contributes about half the total inflow; Mulligan Stream; and Stetson Stream. Mean annual precipitation is 102 cm. The morphometric data for this relatively large, shallow lake are given in Table 1.

Lake water quality reflects conditions associated with advanced eutrophication (Table 2). The phosphorus levels are well above the 15 μg/l needed to stimulate phytoplankton in Maine water with spring turnover values in the range of 30 to 40 μg P/l. Consequently, the chlorophyll *a* values are substantially above the 8 μg/l concentration used as a guideline of eutrophic conditions for Maine waters. Similarly, the Secchi disk measurements are very low because of the high productivity. The dominant summer blooming algal species are *Aphanizomenon flos-aquae* and *Anabaena* spp.

Dissolved oxygen is depleted in the thermocline and hypolimnion during stratification, and during calm weather conditions, anoxia may extend as much as 2 meters into the epilimnion. Bottom conditions are such that only benthic organisms tolerant of low oxygen concentration can survive. Nolan and Johnson (1975) recorded midgefly larvae (*Chironomus riparius*) and worms (*Tubificidae*). In recent years, only epibenthic *Chaoborus* could be found in the profundal area of the lake in late winter because of the anoxic condition.

Cultural Development

Although located in Newport, that town has relatively little influence on the water quality of Sebasticook Lake as it is situated at the lake outlet and its waste discharges are downstream of the lake (Fig. 1). Development along the lakeshore includes about 250 residences, mostly summer cottages (200). Other population centers in the watershed include Dexter (1980 population 4,236) and Corinna (1980 population 1,887). Both are located on the East Branch of the Sebasticook River upstream of the lake and discharge their wastes into the East Branch. The wastewater from Dexter is currently discharged untreated, while Corinna has a secondary treatment plant.

The watershed is primarily rolling hills of mixed softwoods and hardwoods with about 20 percent of the land area devoted to agriculture. Sixty-seven farms are located in the drainage basin with dairy, livestock, potato, and poultry production being the principal activities (Penob. Valley Reg. Plan. Comm., 1980). Agriculture has been identified as a major contributor of nonpoint source nutrients to the lake.

At one time, industries were the largest source of nutrients to Sebasticook Lake. A potato processing plant located in Corinna processed about 160,000 kg of potatoes a day 9 to 10 months of the year until going out of business in 1968. Two woolen mills are located in Dexter and a third in Corinna. In 1966 the phosphorus discharge of Corinna was approximately 5,200 kg P with 66 percent from the potato processing plant, 16 percent from a woolen mill, and only 18 percent from domestic and other waste sources (Keup, 1968). One of the Dexter mills has now converted to a dry operation and the other has closed. The Corinna woolen mill now treats its wastewater jointly with the town.

HISTORY

Previous Studies

While the first major limnological study of Sebasticook Lake was undertaken in 1965, earlier surveys

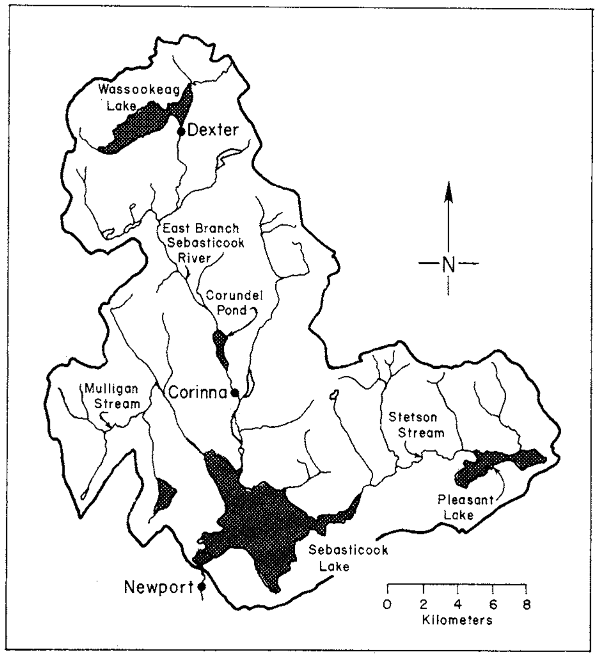

Figure 1.—Sebasticook Lake watershed.

Table 1.—Morphometric data for Sebasticook Lake.

Surface area	1798 ha	Volume	111 X 10^6 m^3
Mean depth	6.2 m	Maximum depth	18.2 m
Drainage area	32,600 ha	Hydraulic retention time	0.58 yr.

Table 2.—Water quality data for Sebasticook Lake.

Date	Secchi disk (m)		Total Phos.	Chl *a*	Reference
	min	mean	mean (μg/l)	mean (μg/l)	
1965	0.8	1.4 (4)*	55 (15)*	11.6 (75)*	Anon. 1966
1972	0.8	1.2 (3)	73 (11)	27.1 (9)	NES 1974
1973	—	—	50 (2)	16.9 (6)	Nolan & Johnson 1975
1975	.08	1.9 (10)	—	—	MDEP data
1976	0.6	1.7 (28)	60 (22)	43.3 (4)	MDEP data
1977	1.3	1.6 (3)	60 (36)	—	MDEP data
1978	0.7	0.9 (3)	40 (9)	62.6 (3)	MDEP data
1979	1.1	1.8 (8)	—	27.1 (8)	MDEP data
1980	0.6	1.8 (9)	—	30.4 (9)	MDEP data
1981	1.2	1.9 (13)	46 (36)	20.5 (11)	MDEP data
1982	0.9	1.4 (6)	64 (33)	29.0 (7)	MDEP data

*Number of samples in parentheses

around 1949 were conducted by the Maine Department of Inland Fisheries and Wildlife. These surveys documented a change in fishery from trout and smelt to a warmwater fishery, a characteristic often associated with eutrophication. In the 1965 study, Sebasticook Lake was reported as "plagued with nuisance algal growths." The eutrophication could hardly come as a surprise, based on the conditions reported by the Federal scientists.

> The reach of stream from Corinna to the inlet of Lake Sebasticook was deplorably polluted. The river supported a luxuriant growth of aquatic slimes and contained several 'log-jams' of trash from the dump including discarded footballs, dolls, and barrels. The banks of the stream were spongy with a mat of wool fibers that has accumulated through time. Occasionally intermingled with the fiber were potato sprouts and rotting potatoes. The area was revolting to both the human eye and nostril. Proceeding downstream, a mat of floating wool approximately 6 inches thick and 400 feet long completely covered the river. Boat navigation was completely stopped by this 'wool-dam' and birds walked on it as conveniently as on land (Fed. Water Pollut. Control Admin., 1966).

Not surprisingly, blue-green algae dominate the phytoplankton found in the lake. Mackenthun et al. (1968) reported summer blooms dominated by *Microcystis aeruginosa* and *Anabaena* spp. The technical report concluded that indeed the lake was hypereutrophic, primarily because of the input of domestic and industrial wastes. They predicted that algal blooms would continue to exist until the lake water phosphorus concentration could be reduced. The report recommended 0.02 mg P/l as a goal based on the concentrations found in Wassookeag Lake, the headwaters of the East Branch of the Sebasticook River.

The second major study was also conducted by the Federal Government by Nolan and Johnson (1975) from November 1971 to August 1973. They found increased phosphorus levels in both Sebasticook Lake (approximately 0.10 mg/l, up from 0.05 mg/l in 1965) and its major tributary, the East Branch (approximately 0.15 mg/l, up from 0.07 mg/l in 1965). Excessive algal growths were also noted at concentrations similar to 1965 (chlorophyll *a* of 11.3 μg/l versus 11.6 μg/l in 1965). Although low-oxygen-tolerant benthic fauna such as midge-fly larvae and tubificid worms continued to exist, they did so at significantly lower populations than found in the 1965 study.

Nolan and Johnson (1975) concluded that Sebasticook Lake was hypereutrophic and the phosphorus loading from the East Branch was still excessive, despite the elimination of the potato processor which had been a major contributor of phosphorus prior to 1968. Nolan and Johnson also identified the lake sediment as a significant phosphorus reservoir and predicted that it would serve as a major source for many years to come. Previously, Mackenthun, et al. (1968) had not recognized the sediments as a source, but rather expected them to serve as a sink when nutrient inputs were controlled.

Sebasticook Lake was also studied in 1972 as part of the National Eutrophication Survey (1974) independently of the Nolan and Johnson study. The limnological data gathered basically agreed with the previous studies, i.e., Sebasticook Lake was highly eutrophic. In addition, an algal assay was performed, indicating the lake was nitrogen limited at the time of sampling. While nitrogen may be rate limiting, it does not mean that nitrogen is supply limiting as it can be obtained directly from the atmosphere by nitrogen-fixing blue-green algae.

Nutrient Budgets

Estimation of the first nutrient budget for Sebasticook Lake was one of the major accomplishments of the 1965 study (Fed. Water Pollut. Control Admin., 1966). However, time has proven it to be rather crude and probably in significant error. The budget was based on quarterly 1-week sampling periods. As a rule, composite samples were taken, except grab samples were made where water quality did not fluctuate markedly. Stream flows were based on actual measurements at the time of sample collection.

For the Dexter area, most of the nitrogen was contributed by the two woolen mills (65 to 85 percent), while practically all of the phosphorus came from domestic wastewater (87 to 93 percent). However, a sampling station (Lincoln Mills) 4 miles below Dexter indicated significant nutrient reduction had taken place in the stream reach below Dexter (about 20 percent for nitrogen and 30 percent for phosphorus). In the Corinna area, the woolen mill was the principal contributor of nitrogen (85 percent) whereas the potato processor was the main source of phosphorus (55 percent) (Mackenthun et al. 1968). Nutrient sources based on the data presented in the technical report are itemized in Figures 2a and 3a.

The technical report concluded that an 80 percent reduction in the waste inputs of Dexter and Corinna could reduce the loading to about 1,590 kg P/yr. Even if this were accomplished, the authors predicted it would take 10 years before the lake would be restored. It should be noted that authors labored under the misconception that the hydraulic retention time was 3.5 years. More recent computations have shown the retention time to be 0.58 years.

The nutrient budget developed for the National Eutrophication Survey was based on monthly grab samples collected from September 1972 through August 1973, except that biweekly sampling was done during April and May. Mean stream flow estimates were provided by the U.S. Geological Survey. The nutrient loadings for the Dexter area were based on literature coefficients rather than sampling data. The loadings for Corinna, however, were based on actual sampling. Although Keup (1968) reported that 29 percent of the phosphorus was assimilated by the river, this budget assumed that all nutrients reached the lake. The survey showed that 11,800 kg P and 283,200 kg N entered Sebasticook Lake on an annual basis (Figs. 2b and 3b). Nutrient discharge from the lake was measured at 8,350 kg P/yr and 210,300 kg N/yr so that phosphorus accumulation was estimated at 3,450 kg/yr and the nitrogen level in the lake increased by 72,800 kg/yr. Thus, 8 years after the Federal Water Pollution Control study recommended an 80 percent reduction in phosphorus loading, the input to Sebasticook Lake seemed to have increased, despite the elimination of the single largest source, the potato processor.

The National Eutrophication Survey concluded that at least a 70 percent reduction in the phosphorus loading from Dexter and Corinna would be required to significantly improve the trophic condition of Sebasticook Lake. It noted that an even higher level of removal would be necessary to compensate for the phosphorus already in the lake.

The most definitive phosphorus budget was that prepared by the Maine Department of Environmental

Protection (Dennis and Corson, 1979); however, they did not develop a nitrogen budget. Stream samples were collected at 11 stations on a biweekly basis. Eight nonrecording gauging stations were established by the USGS, while other flows were established by the proportional drainage area technique (Morrill, 1975). Mean seasonal phosphorus concentrations and hydrograph discharge estimates were used to calculate monthly and annual loadings.

The total external phosphorus loading was calculated to be 9,000 kg P from June 1975 through May 1976. During the same period only 5,500 kg P were discharged from the lake. Dennis and Corson (1979) noted that the usual fall drawdown of the lake did not occur; that would normally have resulted in another 3,000 kg P or more being discharged. The nonpoint fraction was estimated at about 50 percent based on an areal export of 18.3 kg/km^2. Like Mackenthun et al. (1968), Dennis and Corson found some loss of phosphorus downstream of Dexter's discharge to a small impoundment. They estimated this loss at 1,200 kg P. They also estimated a 500 kg loss of nonpoint phosphorus (Fig. 2c).

In addition to estimating the external phosphorus loading, Dennis and Corson calculated the internal phosphorus loading. During the summer of 1976, internal loading was estimated through mass balance equations to be 9,900 kg P and in 1977 it was 6,900 kg P. They observed that the summer internal loading nearly equaled the annual external loading and that it is recycled each year. The magnitude of the phosphorus source supported the earlier findings of Nolan and Johnson (1975) that the sediments could be a significant source of phosphorus for many years.

In summary, several attempts have been made to estimate phosphorus and nitrogen loading to Sebasticook Lake. The first attempts (Fed. Water Pollut. Control Admin., 1966; Mackenthun et al. 1968) have been found to be in error, specifically the water balance. It is highly doubtful that the phosphorus input to Sebasticook Lake increased from 3,900 kg/yr to 11,800 kg/yr between 1966 and 1974; rather, it is likely that eliminating the 3,500 kg/yr contribution of the potato processor resulted in an actual reduction by 1974. Despite this reduction, lake productivity remained high because of internal phosphorus recycling. The phosphorus budgets by the National Eutrophication Survey (1974) and Dennis and Corson (1979) are actually quite similar, especially if 1,200 kg P assimilation loss in the Dennis and Corson budget is applied to both. Then, the difference is only 15 percent which would be within natural year-to-year variation. The major difference is the amount of phosphorus discharged by the lake, but normal drawdown did not occur in 1979. As noted by Dennis and Corson, drawdown would normally result in an additional 3,000 kg being discharged, making the two budgets nearly identical.

Since only two nitrogen budgets have been calculated and the Mackenthun et al. (1968) budget is suspect, it is most difficult to assess the accuracy of the nitrogen loading. Certainly, the nitrogen loading has decreased since 1966 as the major sources, two woolen mills, have either closed, switched to dry processes, or treat their wastes. While nitrogen has been shown to be limiting in the short-term, phosphorus control is believed to be the key to long-term recovery. Consequently, the major restoration effort has focused on phosphorus dynamics.

RESTORATION

Despite the criticism of the nutrient budgets of the first Federal Water Pollution Control Administration study, the report was right in regard to restoration. The report noted:

> Prerequisite to any efforts directed toward cleanup of Sebasticook Lake is the design, construction, and operation of secondary sewage treatment plants to accommodate the communities of Dexter and Corinna

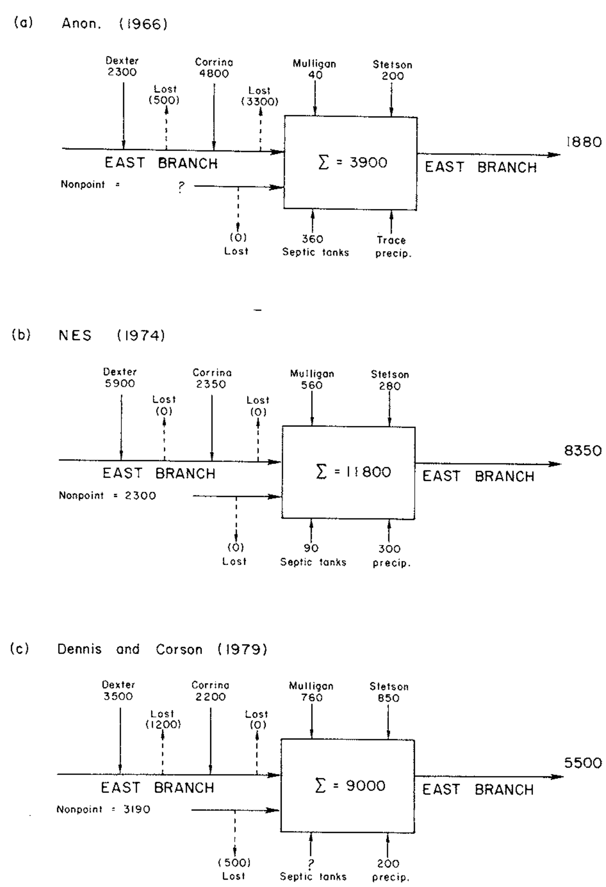

Figure 2.—Phosphorus budget estimates for Sebasticook Lake reported from three studies.

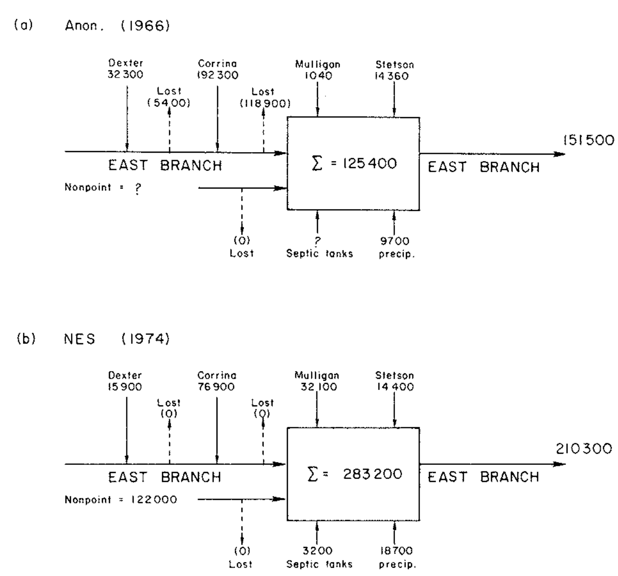

Figure 3.—Nitrogen budget estimates for Sebasticook Lake reported from two studies.

and their industries. To demonstrate the effects of reduced fertilization, it is proposed that phosphate removal facilities, such as alum or lime precipitation, be added to the secondary sewage treatment plants. Following the installation and functioning of nutrient control procedures, the lake's water level would be lowered during the summer's maximal algal growth and the lake subsequently filled with nutrient poor water (Fed. Water Pollut. Control Admin. 1966).

Obviously, both the external and internal phosphorus loadings must be significantly reduced if the objective of a 10 to 20 μg/l total phosphorus concentration is to be met. Currently, the springtime level of total phosphorus is between 30 and 40 μg/l (Dennis and Corson, 1979).

Reduction of Nutrient Input

The three major sources of phosphorus have been identified as Dexter, Corinna, and nonpoint inputs. Installation of secondary treatment at Dexter would reduce the present 2,300 kg P/yr by about 25 percent, while advanced phosphorus removal could be expected to reduce this discharge to 300 kg P/yr. Secondary land disposal of Dexter's waste could eliminate its phosphorus load altogether and is currently the most cost-effective treatment alternative. Although Corinna installed secondary treatment in 1970, it did not operate satisfactorily until about 1978. Since that time, the woolen mill, which contributes about 90 percent of the volume, has installed a number of water saving controls and the treatment plant has installed covers over the clarifiers to improve treatment during cold weather. The Maine DEP currently estimates the phosphorus discharge from Corinna at about 790 kg P/yr and agreement has been reached to license the facility at this rate. Dennis and Corson (1979) had estimated that with advanced wastewater treatment, phosphorus in the Corinna discharge could be reduced to 500 kg P/yr.

The reduction of nonpoint input depends upon improving farming operations as 85 percent of the nonpoint phosphorus comes from agriculture (Penob. Valley Reg. Plan. Comm., 1980). Runoff from cropland and livestock operations, particularly the winter storage and spreading of animal manure, has been identified as probable source of phosphorus. Control efforts directed at 25 of the 67 farms in the watershed are expected to reduce the overall nonpoint inputs by 25 to 50 percent.

A phosphorus model (Vollenweider, 1976) was used to assess the change in lake phosphorus concentration from various abatement alternatives for the external phosphorus sources. The results (Table 3) suggested that phosphorus reduction was needed at both Dexter and Corinna, and reduction in nonpoint loading was also necessary to reach the desired objective of 4,500 kg/yr. Alternatives B-F are the possible strategies which could achieve the objective; alternative C was selected as the most cost-effective technique (Table 3).

Reduction of Phosphorus Recycling

Since the recycling of phosphorus from the lake sediments each summer brings 6,900 to 9,900 kg P into the water column, it is imperative that the cycle be broken or at least minimized. While a variety of control techniques exist, most are economically infeasible because the lake is so large. The most promising techniques are seasonal drawdown or hypolimnetic discharge.

To evaluate the two techniques, Hannula (1978) developed a computer simulation model of the internal cycling of phosphorus in Sebasticook Lake. The model used seasonally varying rate coefficients for eddy diffusion, phosphorus release (aerobic and anaerobic), and sedimentation to produce water column phosphorus profiles similar to those observed in

Table 3.—Predicted total phosphorus concentrations in Sebasticook Lake for various external control alternatives.

Alternatives	Load (kg/P)	Predicted spring total phosphorus conc. (μg/l)
A. No change in loading		
Dexter	2200	
Corinna	2300	30
Nonpoint sources	4500	
	9000	
B. Dexter—land treatment	0	
Corinna—land treatment	0	15
NPS	4500	
	4500	
C. Dexter—land treatment	0	
Corinna—flow reduction[1]	800	14
NPS controls	3500	
	4300	
D. Dexter—land treatment	0	
Corinna—advanced treatment[2]	500	13
NPS control	3500	
	4000	
E. Dexter—advanced treatment	300	
Corinna—flow reduction	800	15
NPS control	3500	
	4600	
F. Dexter—advanced treatment	300	
Corinna—advanced treatment	500	14
NPS controls	3500	
	4300	

1. Flow reduction assumes water savings technology and for reduced production capacity at the expense of the woolen mill.
2. Advanced treatment assumes tertiary treatment with effluent total phosphorus $\leq$ 0.5 mg/l.

Sebasticook Lake. The model supported the hypothesis that there is a significant internal source of phosphorus during the summer. Simulation runs confirmed that the current phosphorus loading, even coupled with the available 1.5 m late summer drawdown, resulted in a buildup of phosphorus in the sediments. Increasing the drawdown to 3.5 m would produce a small net export of phosphorus from the lake.

If drawdown is to have a major impact, the model demonstrated that external inputs must be significantly reduced. When the external phosphorus input was reduced by 45 percent and combined with a 3.5 m drawdown in late summer with spring refill, a net export of 3,000 to 4,000 kg P/yr was predicted. This resulted in a spring phosphorus concentration of 23 μg/l at the end of year 1. Although the model only simulated 1 year, additional reduction in the phosphorus concentration would be anticipated so that the 10 to 20 μg P/l goal could be reached.

In addition to the drawdown alternative, Hannula (1978) also modeled the use of a constant hypolimnetic discharge. This technique was shown to be the most effective, resulting in a net export of 4,800 kg P. Even so, Hannula cited two reasons for not recommending this strategy: (1) the cost of implementation would be high since the deepest section of the lake is several kilometers from the outlet; (2) the discharge of anaerobic water would require treatment before discharge to the outlet stream. In conclusion, Hannula decided that the extended drawdown technology effectively exported phosphorus released from the sediment and would be easier to implement.

Restoration Plan

The $1.2 million restoration plan adopted by the Maine DEP called for constructing a 4.0 m deep, 512 m long discharge channel at the lake outlet with a new control dam. Coffer dams at the inlets to the lake were included to protect upstream wetlands during drawdown periods. Completed in 1982, the new lake level control structure allows a 3.5 m drawdown, reducing lake volume by 51 percent. In the initial year of operation, 3,800 kg P were removed by a partial drawdown of 2.7 m compared with 2,400 kg P if the usual 1.5 m drawdown had been used.

Plans have been made to control point discharges from Corinna and Dexter. While improvements at Corinna have reduced its phosphorus input to an acceptable level, a wastewater treatment plant proposed for Dexter remains at the planning stage and actual construction is not scheduled until spring 1984. Anticipated design calls for spray irrigation of the wastewater. Engineers estimate the land wastewater treatment system at Dexter will cost $3.0 million, excluding sewers.

The U.S. Soil Conservation Service and Agricultural Stabilization and Conservation Service have instituted a nonpoint control program at a cost of another $1.3 million. The main focus of the program is construction of manure storage facilities for area farms along with contour farming, buffer strip projects, winter cover crops, and other conservation practices to reduce erosion and surface runoff. By 1982, 20 percent of the farms (the largest ones were treated first) had completed their projects; it is expected this will treat 30 percent of controllable phosphorus from winter spreading of manure.

SUMMARY

It is apparent that the lake has been receiving excessive nutrients for at least 30 years, but restoration is sought more quickly. The unanswered question is: How much time will the reversal take?

The restoration project is based on two concurrent strategies: reduction of external loading, and depletion of the available phosphorus from the sediment. Control of all external phosphorus loads is expected within a few years. Lake drawdown has been chosen as the most promising technique for flushing sediment phosphorus from the lake. To a large extent, the effectiveness of drawdown depends upon the amount of phosphorus available from the sediments. Lake recovery will be relatively quick only if a large fraction of the sediment-bound phosphorus remains in the sediment. Computer simulation of the internal phosphorus cycle suggests that drawdown will be effective and an initial trial has shown that drawdown can be effective in remvoing substantially more phosphorus than would be expected by natural conditions.

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