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Chain Lake Restoration by Dredging and Hypolimnetic withdrawal

By:

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Management Perspective

This paper reviews the restoration of Chain Lake, British Columbia by a combination of two types of dredging and a bottom withdrawal project. The first phase of the study included the dredging of a hole near the lake outlet. The intent was to use this hole for enhanced nutrient removal either by subsequent dredging or bottom withdrawal. The second phase of the project involved development of innovative dredging equipment to remove organic rich sediments. This aspect was accomplished but land management of dredged sediments became too complex. The final phase, the bottom withdrawal project was successfully completed by collaboration between NWRI, UBC Civil Engineering, local residents and BC governments. The eutrophication of the lake was greatly reduced and the local citizens continue to maintain the bottom withdrawal themselves.

Abstract

Studies of sediment cores indicated that sedimentation rates had increased from 0.83 mm/yr to 9.3 mm/yr. The increased production could be related to the shallower water column or increased nutrient load from cottages. Sediment phosphorus release was a major factor resulting in production of blue-green algal blooms. Dredging projects attempted to first build a sediment trap for focusing of the most nutrient rich surface sediments. Subsequent dredging was done with simple equipment. Land management of the dredged sediments became too complex for a simple organization. The last effort was the installation of hypolimnetic water pipe into the dredge hole. The water clarity immediately improved with as good as a 5 m Secchi disk transparency.

Key Words: lake restoration, dredging, hypolimnetic withdrawal

Remise en état du lac Chain par dragage et par soutirage de la couche d'eau hypolimnétique

Sommaire à l'intention de la direction

Dans cet article, on explique la remise en état du lac Chain (Colombie-Britannique) par une combinaison de deux types de dragage et par un projet de soutirage de la couche d'eau du fond. La première phase des opérations comportait le dragage d'une fosse, près de l'exutoire du lac, afin d'y pratiquer une élimination plus poussée des nutriments par d'autres opérations de dragage ou par soutirage de la couche d'eau du fond. La seconde phase du projet comportait sur le développement de matériel de dragage innovateur pour l'élimination des sédiments riches en matières organiques. On a réalisé cette phase mais, à cause de problèmes d'aménagement du territoire dus aux sédiments dragués, les opérations sont devenues trop complexes. Grâce à la collaboration entre l'INRE, le Département de génie civil de l'Université de la Colombie-Britannique, des résidants et le gouvernement de la Colombie-Britannique, on a réalisé avec succès la phase finale, le soutirage de la couche d'eau du fond. Ces travaux ont permis de réduire fortement l'eutrophisation du lac, et les résidants poursuivent les opérations d'entretien par soutirage de la couche d'eau du fond.

Résumé

Selon des études de carottes de sédiments, les taux de sédimentation sont passés de 0,83 mm/an à 9,3 mm/an. On peut relier cette augmentation de la production à la colonne d'eau moins profonde ou à une charge de nutriments accrue due aux chalets. Le rejet de phosphore des sédiments était l'une des principales causes des proliférations d'algues bleues. Dans le cadre des projets de dragage, on a d'abord tenté de construire un piège à sédiments pour capter les sédiments de surface plus riches en nutriments. On a ensuite effectué des opérations de dragage avec un matériel simple, mais les problèmes d'utilisation du territoire liés aux sédiments dragués sont devenus trop complexes pour l'organisation. Le dernier effort portait sur l'installation d'une canalisation destinée à soutirer l'eau de la couche hypolimnétique de la fosse de dragage. La clarté de l'eau s'est immédiatement améliorée et on a obtenu une transparence pouvant atteindre 5 m sur l'échelle Secchi.

Mots clés : remise en état du lac, dragage, soutirage de la couche d'eau hypolimnétique

Chain Lake restoration by dredging and hypolimnetic withdrawal

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Introduction

Technical staff from provincial and federal governments, the University of British Columbia (UBC) and local citizens have implemented several lake management and restoration projects at Chain Lake, British Columbia. In approximately 1915 and 1950, the lake level was raised with dams to provide water storage. From 1963 to 1965, copper sulphate was used as an algaecide but the effectiveness was short lived. Windmill aeration was attempted unsuccessfully; aeration of shallow lakes is less efficient than of deeper lakes and perhaps the equipment was undersized. A water diversion was built in 1968 to flush the lake with high quality water, but the flushing rate was too small (Murphy, 1987). These restoration efforts have typically utilized local volunteered labour and supplies with guidance from government agencies.

In the 1980s the National Water Research Institute (NWRI) collaborated with local governments and citizens to conduct a number of dredging experiments to reduce eutrophication of Chain Lake. Initially, a commercial Mudcat™ dredge was used, but later simpler dredging systems were developed (Murphy *et al.*, 1990). At first, the simple dredging was very successful, but there were many unexpected technical and political difficulties. Eventually the restoration efforts had to be redirected. Fortunately the dredging had created a deep area of the lake which could be used for a very cost-effective hypolimnetic withdrawal. UBC engineers led the hypolimnetic withdrawal project.

Hypolimnetic withdrawal is the removal of water from the deepest part of a lake. Usually the engineering is designed to enhance the export of phosphorus and thus reduce eutrophication. Hypolimnetic withdrawal was first implemented as a lake restoration technique in Poland about 40 years ago (Olszewski, 1961) and it continues to be used in a few sites in North America and several sites in Europe (Cooke *et al.*, 1993).

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Site

Chain Lake is a 44 ha lake typical of many other small lakes in the interior of southern British Columbia. Chain Lake is located at an elevation of 1007 m on the Thompson Plateau in the interior Douglas fir biogeoclimatic zone (120°16'W, 49°42'N, Figure 1, Murphy, 1987). The bedrock in this area is a Jurassic volcanic intrusion that is rich in the phosphate mineral apatite (Cockfield, 1947; Rice, 1946), and the dissolved phosphorus concentrations of the springs in the Chain Lake valley are as high as 50 µg/L (Murphy, 1987). The natural loading of phosphorus has resulted in superior fish productivity. Chain Lake is considered one the prime fishing lakes in south central British Columbia. As the Okanagan Valley and other parts of British Columbia become more urbanized, many people are converting cottages in less developed sites like Chain Lake into primary residences. The increased nutrient load from simple sewage systems might enhance natural eutrophication, but there is too little historical data to test this hypothesis. Local reports suggest that dense blue-green blooms such as *Anabaena* and *Aphanizomenon* and associated fish kills have become worse. Another apparent reflection of algal toxins is the abortion of cattle downstream of the lake. Excessive algal growth has enhanced sedimentation and infilling of the lake.

The hydrology of the lake is important to the restoration efforts. As shown in Figure 1, Hayes Creek enters at the north end of the lake. Since the lake is near the top of the watershed, during summer this inflow can be insignificant (Macdonald, 1995). Once the snow melt is complete, surface water inflow only occurs during rain events. Hayes Creek leaves Chain Lake at the south end of the lake. This outflow slows to a virtual trickle during hot dry summers. To supplement the water flow, a diversion ditch from the Shinish Creek was built in the 1960s to bring cold, low nutrient water from the Shinish Creek into a point on the east side of the lake. The intent was to increase the hydraulic flushing of the lake. The diversion is licensed for up to 3.5 cfs (100 L/s), though in the past, physical flow constraints have limited flows to 25-50 L/s.

Lake sedimentation history

The diatoms in the sediments provide an excellent history of major changes in the lake. The sediments are a diatomaceous ooze [surface metre has a mean of 93% water; dry mass 77% SiO_2, 15% organic C, 2% organic N, 0.3% P]. In 1988, a 12.6 m sediment core was collected from the middle of the lake with a simple piston corer (McKean and Nordin, 1986; Murphy *et al.*, 1990). Clay near the bottom of the core probably reflects glacial activity. Glaciers left this area about 9600 B.P (Alley, 1976), so the mean sedimentation rate was 1.3 mm/yr. Unfortunately the high background concentration of naturally occurring ^{238}U (432 mBq/g dry mass) interfered with ^{14}C dating. Two other dating markers were used on this piston core; Mazama volcanic ash layer (706 cm from top, 6600 years ago), and ^{210}Pb (150 cm 150 yr). The respective sedimentation rates were; surface 0-140 cm, 9.3 mm/yr or 47 mg cm^{-2} yr^{-1}; mid zone 140-706 cm, 0.88 mm/yr or 10.5 mg cm^{-2} yr^{-1}; and below Mazama ash, 0.83 mm/yr or 9.33 mg cm^{-2} yr^{-1}. The recent higher sedimentation rates might

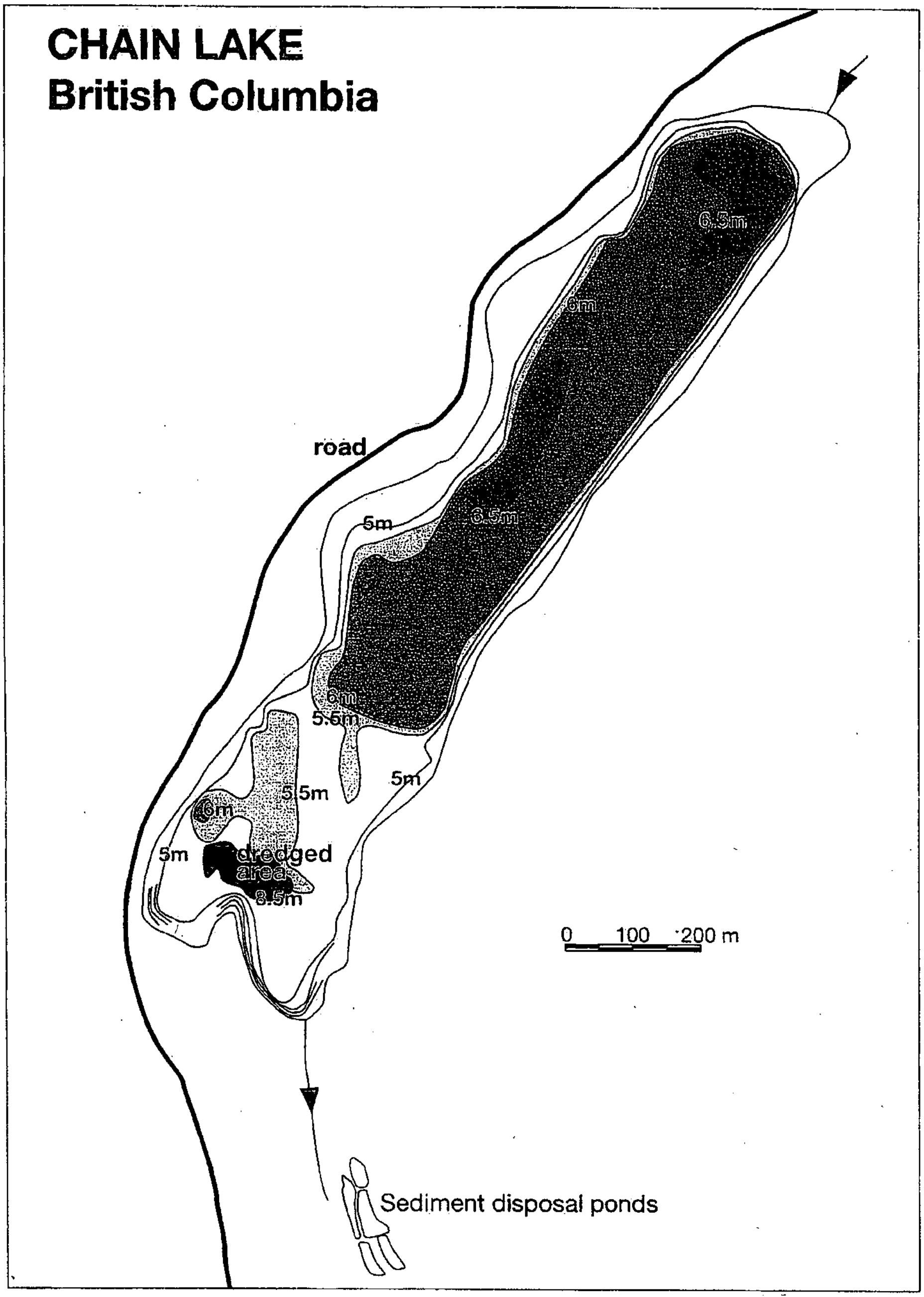

Fig. 1. Map of Chain Lake

reflect enhanced algal production, enhanced erosion in the drainage basin or decomposition of older sediments. However, the main component of the sediments was diatoms which did not dissolve or erode from the drainage basin. Thus, the great increase in sedimentation rate at the surface seems to indicate an enhancement of eutrophication by anthropogenic activities or a shallower water column. The biogenic silica sedimentation rates of the three layers is: surface 15.2 mg cm^{-2} y^{-1}, middle 5.46 mg cm^{-2} y^{-1}, bottom 5.42 mg cm^{-2} y^{-1}.

The limitation of this approach is that one core may not represent Chain Lake well and replication of piston core analysis is too expensive. The recent history was confirmed with two push cores (about 2.8 m long) and several modified KB corers (usually 80 cm long). The latter approach was particularly useful when using the copper rich layer that reflected use of copper sulphate in 1963-1965. The sedimentation of these recent sediments was 0.5 cm/y to 1.0 cm/y.

The diatom indicators of eutrophication such as *Melosira ambigua* show that Chain Lake has been eutrophic most of this century and in periods long before European settlers arrived. Two new diatom indicators of eutrophication *Asterionella formosa* and *Melosira granulata* were only present in the sediments associated with recent enhanced development of the lake. The occasional dominance of the diatom indicator of oligotrophic conditions, *Melosira distans* suggests there were three suppressions of productivity. It is possible that some of these changes were associated with changes in water depth. The lake's current water depth results in unstable stratification and rare

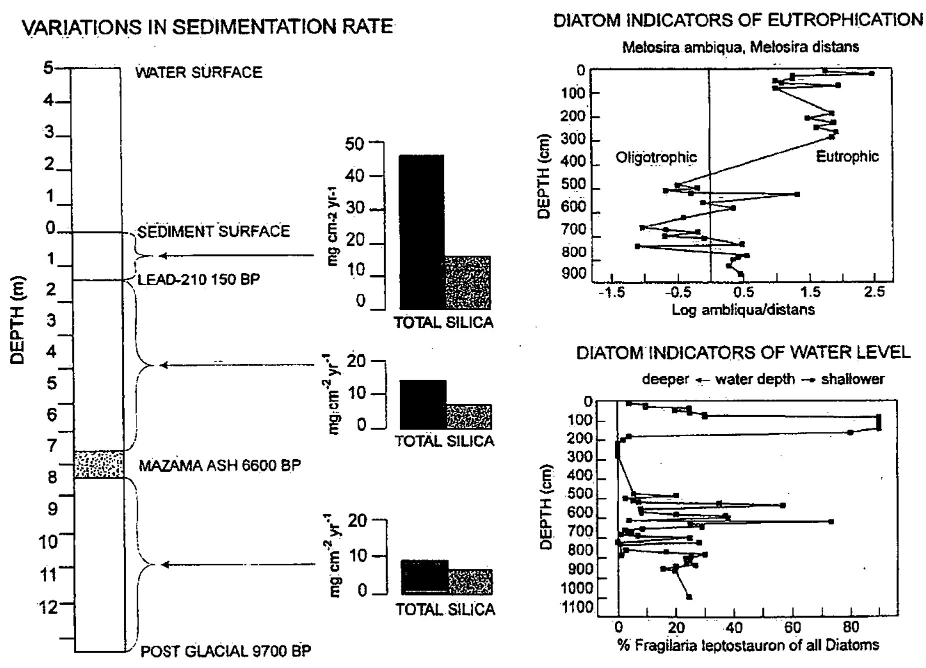

Fig. 2. Sedimentation history

periods of sediment resuspension. A slightly shallower water column would more readily permit nutrient recirculation into the photic zone. A deeper water column would retain nutrients more in the stratified hypolimnion (Riley and Prepas, 1985). The most remarkable change in eutrophication was a period of low algal productivity for 1000 years that followed the deposition of the 25 cm thick Mazama ash volcanic layer. This may have been the largest and most effective sediment "capping treatment". Another diatom *Fragilaria leptostauron* indicated three distinct periods of low water level presumably associated with prolonged droughts. The last collapse in the dominance of *Fragilaria leptostauron* coincides with the raising of the dam by 1-2 m in about 1915.

Lake restoration by hydraulic changes

Chain Lake was initially damned for flow control in about 1915, and the water level was raised by 1.2 m in 1957. This second raising of the dam was done to increase water storage for irrigation of downstream fields. Residents claim the colour of the lake water changed from brown to green; some improvement in water quality probably occurred. Raising the dam cannot be done again without flooding the houses and road or further flooding of an upstream wetland which was about 16 hectares (Ennis, 1972). The last raising of the dam has resulted in anoxic conditions in the sediments in this upstream wetland. At times, these black sulphide smelling wetland sediments were covered with dense floating mats of blue-green algae. In midsummer of 1988, water in the wetland had more than 1.0 mg/L of total phosphorus. At critical times, a major rainfall would result in an appreciable load of phosphorus from the wetland to Chain Lake. Before the Shinish Diversion was built, natural drawdown of the lake in summer from evaporation would have oxidized the soils in the wetland and decreased this problem.

The lake is maintained at its current water level by inflow of water from the 2 km long Shinish Water Diversion. Part of the Shinish Creek was diverted into Chain Lake in 1968 to reduce eutrophication. Calculations used to design the diversion did not include a groundwater flux of phosphorus or sediment phosphorus release. The sediment phosphorus release in August 1983 was approximately 10 mg m^{-2} d^{-1} (Murphy 1987). Economic restrictions also kept the diversion smaller than optimal.

The future of the diversion is at risk. Maintenance is required to repair landslide induced damage, cut down trees growing in the ditch, and remove sand that accumulates in slow moving areas. These problems reduced the actual flow but renovations beginning in 1994 increased the flow to near the licensed capacity. These efforts require continual awareness and coordination of volunteers and government staff. A solution to reduce maintenance frustrations might be to allow local ranchers to use a small portion of the diversion water for irrigation and have them maintain the ditch. This option is currently not accounted for in the water use licenses in the watershed. The diversion would be needed during dry conditions. Even in a single dry hot summer (e.g. 1994), the diversion's water flow was required to maintain the lake level. The diversion certainly would be an important asset during a prolonged drought. The sediment record indicates such droughts occurred infrequently. However, global warming could impose climatic changes as great as historical events. Furthermore, the diversion enhances the utility of the bottom withdrawal discussed later.

Dredging

When it was realized that sedimentation was particularly high, a dredging program was initiated. Local residents were receptive. They were aware of local lakes that were in various states of infilling. An upstream lake, has a large organic peat deposit around a relatively small lake and some lakes have completely converted to peat deposits. Moreover, immediately downstream of Chain Lake is a large alluvial deposit with a peat lens that must have represented part of a much larger lake. The concept that sedimentation was high was readily accepted. In fact, stories of rapid sedimentation caused by logging and weekend campers were very popular.

At first, a commercially operated Mudcat™ auger dredge (170 kW, 20 cm suction, 15 cm discharge hoses) removed 17,000 m^3 of sediments. A hole of 50 m by 110 m by 3 m was created near the outlet of the lake. It was assumed that sediments would concentrate in the dredged hole. Relationships developed by Stefan and Hanson (1980) indicate that with a lake length of 1.6 km and mean depth of 6.1 m, there should be occasional resuspension of sediments. Using the method of Carper and Bachman (1984), it can be predicted that a wind of 60 km/h would resuspend sediments in this lake. The surface 0-2 cm of sediments have twice the phosphorus content of the deeper sediments. Ideally storms would concentrate the nutrient rich surface sediments into the dredged hole, for subsequent removal. The plan assumed three degrees of sedimentation into the dredged hole. If sedimentation was rapid, a simple water pump would be used to remove the watery sediments that collected. If sedimentation was moderate, hypolimnetic withdrawal could be used. If sedimentation was very slow, the dredged hole could be used for lake aeration since a deeper water column allows for improved efficiency of oxygen dissolution.

The dredging was implemented with minimal disruption to the water column of the lake. The turbidity around the dredge was not significantly different from a control site at the other end of the lake. There was no increase in turbidity, nutrients or metals detected in the creek draining the lake. For at least four years after the dredging, there was little slumping of the gelatinous walls of the dredged hole.

However, the dredging project had a number of problems. At first the crews pumped a lot of water and filled the sediment disposal ponds with water. It had been planned that water would drain into the porous soils; however, the fine sediments quickly plugged the soils, self-sealing the ponds. New sediment disposal ponds were built with about three times the capacity. Later the dredgers adjusted their equipment to pump a solution of about 50% sediments. Still there was a problem with excess water. It had too much turbidity to be discharged into the creek. To continue the project required that surface water from the sediment ponds be pumped and sprayed onto a forest. The forest burst into growth and was much greener than the surrounding areas.

The construction of the sediment disposal pond containment berms was not ideal. The slope of the land and availability of large equipment complicated construction. The berms were 3-6 m wide and 2-8 m high. There was little slumping of the berms but tension cracks and erosion were obvious. The slope of the berms was too steep (actually 20° to 45°; ideally <30°).

Project management was difficult. In part, this reflects the experimental nature of the project and limited budget. The contracting might have had performance specifications that required the contractor to resolve the problem of the disposal ponds prior to payment. This option would have required better planning, monitoring, supervision and more cost. Without problems, the unit cost of dredging could have been as low as \$1.75/m^3; in fact it cost about \$5.00/m^3.

The problems with this dredging project led us to think that we could do a better job with simpler equipment, government technical staff, and the skilled volunteer labour of the residents. Moreover, the cost of the commercial dredging project (\$350,000 cash, >\$200,000 in-kind support, 1988) precluded that the project could be repeated.

The first experimental locally operated dredging system used a simple 3.7 kW trash pump with 15 m of fire hose and 624 m of 7.6 cm diameter irrigation pipe. In the initial test, the open head of the pipe was inserted into the sediments, but the efficiency was poor. It pumped too much water. Next a dredge head was built with two parallel circular disks to facilitate selective withdrawal of sediments (Figure 3). At first we pumped too dense a slurry, the pipe became plugged, and a hole had to be drilled in the top disk to allow more water flow. This system was functional but difficult to hold and move to maintain a flow of sediment, not water. It would be adequate for removing sediments from small areas around docks, but it was impractical for larger projects.

The problems with the simple disk dredge required that the dredge be rebuilt. The final configuration used a traditional cable system with turfers to pull the dredge across the lake (Figure 4). The rate of movement of the dredge was determined by the crew watching the turbidity of the pumped sediment through a small pitot tube, a short section of clear plastic in parallel to the main flow. When the pumped water became clearer, the crew pulled the dredge along the steel cable with a hand winch.

Fig. 3. Picture of laminar head for dredge head.

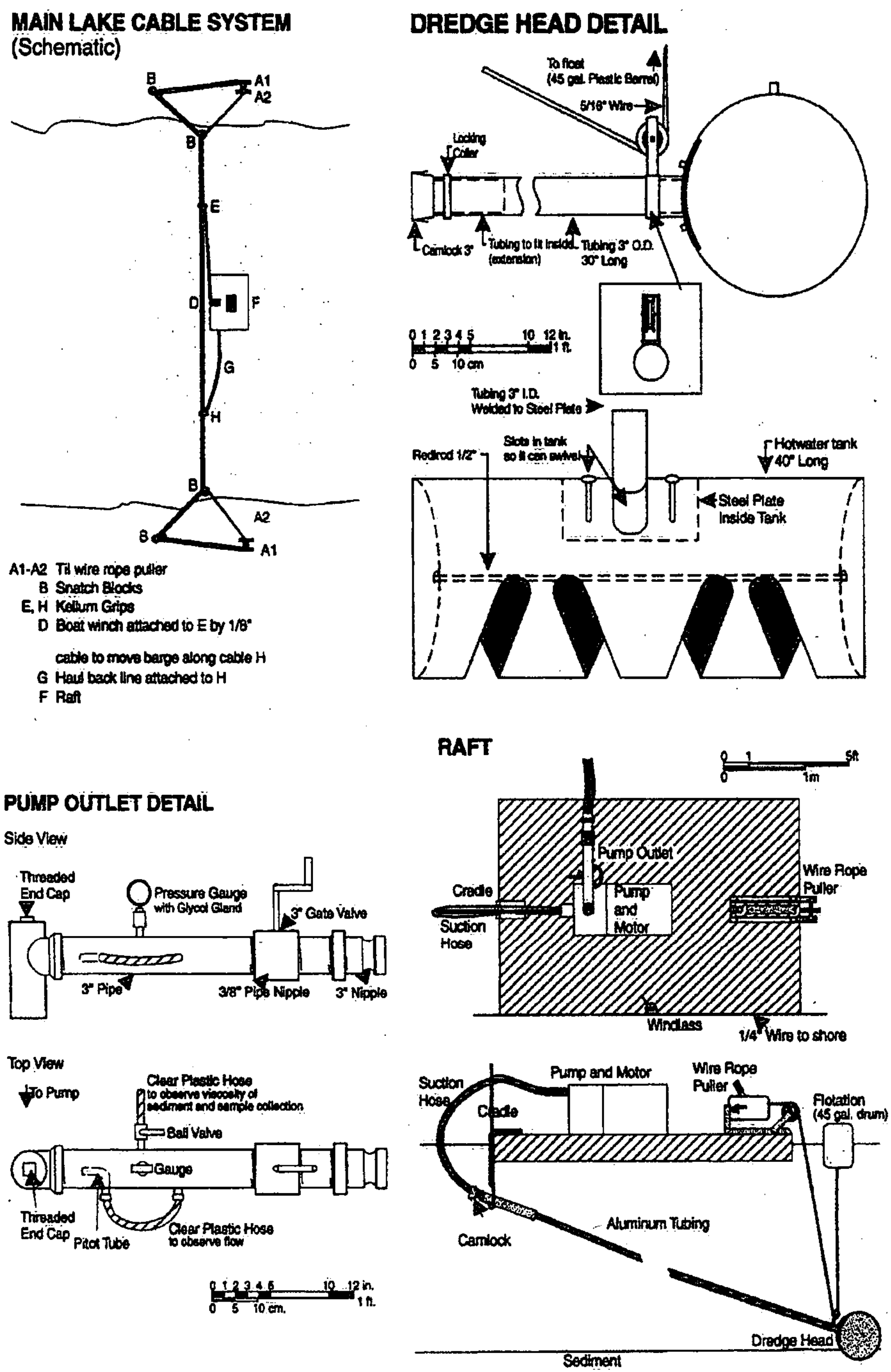

Fig. 4. Parts and configuration of our most complex "simple" dredge.

The unit was built with a 13.4 kW Monarch trash pump. The operation of the system was optimized to pump a mean (n=95) solution of 28% sediment. The maximum sediment composition pumped was about 60%. Higher concentrations of sediment would plug the pipe. The system pumped about 950 L/min of slurry or about 16 m^3/h of sediment.

Sedimentation calculations using the ^{210}Pb and copper data, indicated that to maintain the lake volume required about 11 days of dredging a year with the last dredge design. This effort was maintained for two years near the lake outlet. At first we planned to work only at the dredged hole as "maintenance" dredging to remove newly deposited sediments, but the dredging system could effectively pump the surface metre of sediment from most of the lake. Once a storm deposited a 2 cm layer of nutrient rich sediment in the dredged hole but this rate of sediment movement was not detected again in several further samplings with coring equipment over 3 years, indicating that it was an unusual occurrence. Since sedimentation was not fast into the dredged hole, there was no further advantage in dredging there.

Land management of dredged sediments

There were a number of technical problems with sediment disposal which were difficult but manageable. At first, plants grew poorly in the sediment disposal ponds and on the berms. To assist drying, *Typha angustifolia* (cattails) were planted in the disposal ponds but most died. Various local grasses were planted on the berms to control erosion and dust, but they would not grow well. It was discovered that oxidation of pyrite (0.7%) in the dredged sediments, exposed and dried on the pond edges was forming sulphuric acid. The pH of the ponds was as low as 3.5. The acid problem was solved by spraying the site with lime (calcium hydroxide). The desiccation on the berm was alleviated by covering parts of the sandy berms with lime amended sediments. To reduce erosion on the berms required either regular watering to facilitate growth of the grasses or installation of a geotextile cover.

Self-sealing of the ponds prevented most of the sediments from drying and oxidizing. It was particularly fortunate that the project had scientific support so that the site could be managed. The problem with the oxidation of pyrite was anticipated from laboratory studies. We had tried to grow plants on soils amended with these lake sediments. Although the nutrient composition of the sediments was high, plants grew poorly. Once lime was added, plants grew well, but the sediment matrix was too fine for good drainage and the swelling and drying behavior was not good for potted plants. For alkaline soils of the Okanagan Valley, the acidity of oxidized Chain Lake sediments (24-79 mg $CaCO_3$/g) would be beneficial. Wholesale distributors were interested in buying the sediments. However the soils needed to be dried, screened and bagged.

Another local technical issue added further complexity to soil management. The dredged sediments contain a naturally high level of radioactivity. Specific concerns were never raised, but a good management plan would have addressed this aspect. A large part of the Okanagan area has high background radiation and the Chain Lake sediments were typical of many soils in this area (Boyle and Ballantyne, 1980; Boyle, 1982; Culbert *et al.*, 1984). The presence of uranium (432 mBq/g, dry) in the Chain

Lake sediments indicated that groundwater was flowing through the sediments. By comparison this is about 10 times the U^{238} concentration in sediments of Lake Ontario. Uranium is soluble in oxidized groundwater which locally contains up to 66 µg/L of uranium. Uranium is adsorbed to silica and organic matter, especially in anoxic environments (Benson and Leach, 1979). This geochemistry has potential effects on the dredged sediments and general soil management of this area. For radiation control, it was optimal to keep these stored sediment wet and anoxic. As ponds, the disposal site produced many frogs and attracted many ducks. It was beyond the scope of this study to determine if ducks should have been encouraged or discouraged.

The risks from radioactivity of this deposit were not greater than other local sources. Well water was not routinely monitored, but we found significant concentrations of uranium and related elements in groundwater. Radon can easily enter and accumulate in simple housing. We measured radon in one house upstream of our disposal site that had significant concentrations of radon (444 Bq/m^3). Conventional risk analysis assumes no threshold and calculations could estimate an equivalent health risk of smoking of almost a packet of cigarettes a day (444 Bq/m^3, La Fontaine, 1989). However, radiation may induce repair mechanisms and recent research is casting doubts on this type of calculation (Raabe *et al.*, 1993; Cohen, 1995; Académie des Sciences, 1997). It now seems very possible that these low levels of natural radiation were not a health risk, but at the time of the work, it seemed possible that they were. We adapted a plan that was much more cautious than other local land management.

The natural radioactive deposits must be influenced by land management actions. As an example, consider what would happen if a farmer downstream of Chain Lake installed tile drainage in these reduced peat soils. Uranium would likely be dissolved and mobilized. Appropriate monitoring and risk management should be used to confirm the technical safety of land or sediment management programs. However, risk analysis for this type of problem is an ongoing active research topic (Dupont, 1999) so it is premature to recommend monitoring of wells and houses or propose a watershed management plan.

Even without full technical awareness of the complexity of this site, the political problems of site management became unworkable. First, was a concern about liability. Legal advice was conservative; take all reasonable precautions. A fence was built around the sediment disposal site. Physical risks were no greater than those which existed in the wetland above the lake or around the lake itself. However, people were attracted to the site and the potential danger of the wet sediments was serious. Risks would have been considerably lower if the area of the ponds could have been larger and the layer of pumped sediments shallower.

The last and final problem that terminated the dredging project was the request from the provincial government that the federal government take full responsibility for the site and pay a dredging license. The scientist leading the research was based in Burlington and could neither reasonably oversee the site nor pay a dredging fee from a research budget. The technical aspects of the site were complex. The project had relied heavily upon cooperation of volunteers and governments. The death of a serious dedicated volunteer facilitator limited communications. The technical risks of such a project in an isolated site should have been small, but without good local management, the liability risks were probably high. Politically, it was a major problem to allow a government project to circumvent the provincial rules. Local governments were not financially able to provide staff to manage the project. A lake association was formed, but it could not save the dredging project. Also the owner of the land with the sediment disposal ponds was not keen to continue this liability risk forever. Closure of the ponds cost >$20,000 to add lime and to cover the sediments with soil. The limed and covered sediments are now better "managed" than the downstream natural peat deposits.

Professional management with some occasional professional technical support would be required to manage a complex dredging site like Chain Lake. Integration with other professional organizations would have been critical. Probably some type of fertilization of the forest with the nutrient rich water pumped with the sediment could have been set up. Students could have had regular employment maintaining this system, perhaps in conjunction with maintenance of the water diversion and public campgrounds. To maintain a dredging program at Chain Lake would have required a permanent sediment disposal site and associated long-term management.

Long-term management of these rich lakes in the mountains is required or they cannot survive for more than a few generations. The political and technical organizations necessary to run complex sediment dredging and associated land management projects like this do not exist in Canada. Examples from other countries do not help much. At one time in the mountainous areas of Korea, the emperor would order the dredging of the reservoirs and no one could refuse. Even prior to their recent recession, the Koreans could not decide on whether to dredge or use other lake treatments. In Japan, water regulation was an integral part of the rice culture and again no one could refuse to cooperate. Now, in Japan some dredging projects are extremely large and expensive (billion Canadian dollars, Toya, 1997) with no reported reduction in eutrophication. Few countries and certainly no recreational lake association could ever use this approach. For comparison, the tax base for Chain Lake residents consists of 57 properties. The maximum tolerable tax income for lake management from this base is in the range of $3000 per year.

Hypolimnetic water withdrawal

Since the dredging project was technically difficult and politically impossible to maintain, a different approach was required. Hypolimnetic withdrawal was proposed to utilize the following special circumstances; the dredged hole, the water diversion, the outlet dam, and the lake restoration committee. The design makes use of a sliding plate valve on an existing culvert pipe installed through the dam when its level was raised in the 1950s. A smaller coffer dam was built around the lakeside end of this culvert to provide a hydraulic seal between the lake and the existing culvert. The bottom withdrawal pipe was extended from the dredged hole to the coffer dam. Thus, the opening of the culvert valve draws water out of the bottom of the lake (Figure 5). The flow is driven by gravity and requires no mechanical pumps. For this structure, flows of 80 L/s are possible with a head loss of 7.5 cm. A fountain/aerator was added to the outlet of the culvert pipe to increase oxygen concentrations 1.5 to 2.0 mg/L. The fountain/aerator also acts as a fish barrier to prevent coarse fish from entering the lake.

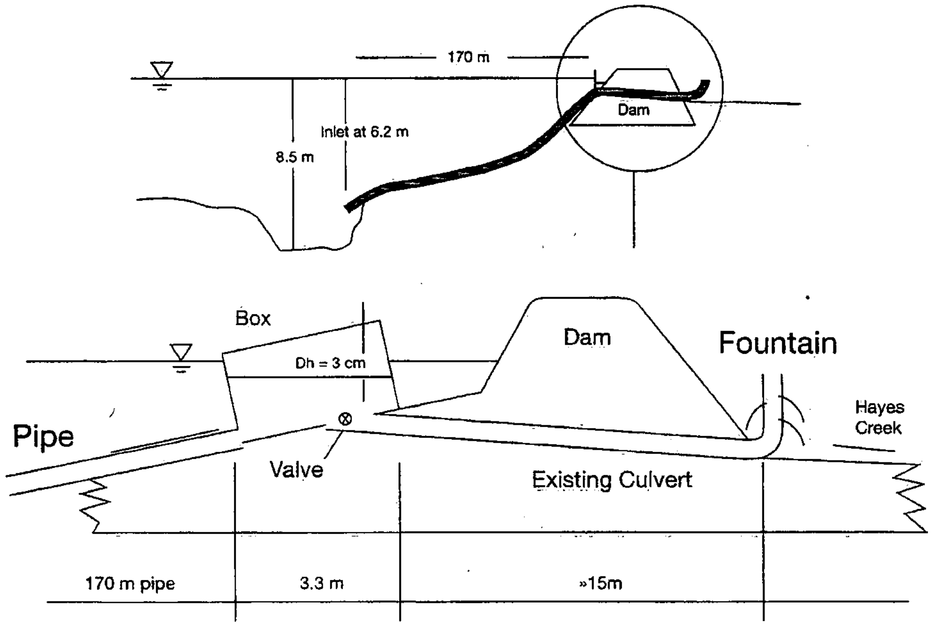

Fig. 5. Bottom withdrawal engineering.

The dredged hole provides a quiescent region at the deepest part of the lake to allow for selective withdrawal of the bottom water into the outlet pipe. A detailed thermister record was maintained in 1993 and 1994 and indicated that no seiching action or summertime overturn reached the deepest part of the lake (Macdonald, 1995). The dredged hole was isolated from the intermittent stratification and wind mixing of the main lake water column. As a result, the outflow from the pipe in summer was consistently 4-5 °C cooler than the surface outflow. It also contained higher levels of phosphorus than the surface water. By withdrawing the most nutrient rich water from the lake, the export of phosphorus is now 40 kg/yr to 60 kg/yr greater than with flow from the surface outlet alone which results in a net export of phosphorus from the lake. The quantity of phosphorus in the sediment is very large so it may take many years for the lake to fully respond to this treatment.

The bottom withdrawal project was completed for less than $100,000 including only $30,000 in cash for equipment and materials. The project was done with little money by using professional support from the University of British Columbia, Environment Canada, and local volunteer labour. More details of the hypolimnetic project can be found in Macdonald (1995).

The first year of operation of the hypolimnetic withdrawal resulted in a great increase in Secchi depth and a major change in the appearance of the lake. From midJuly until early August the Secchi visibility was about 5 m. In previous years, an algal bloom would form in July and produce a Secchi visibility of about 1 m or less. A dramatic increase in macrophytes (native plant, *Myriophyllum* sp.) was observed in the first year of operation. This shift was probably due to increased water clarity which exposed more of the sediment surface to sunlight. Quantification of the macrophyte response was not possible but public concerns were recorded. The plants interfered with swimming and some people were confused over what this response meant. Small scale "weed" treatment around docks took place by hand picking and lime treatment. Wildlife officers were happy since these plants supported a high concentration of chironomids which are excellent fish food for the only fish in the lake, rainbow trout.

Legal status

Just prior to the initiation of the first year of withdrawal, environmental and legislative concerns were raised during discussions with the British Columbia Ministry of Environment. Through no fault of any of the parties involved, the operation of a withdrawal does not fit neatly into any legislated category. For example, since the withdrawal was considered not to be a discharge (under the British Columbia Waste Management Act), no discharge permit was required. It was acknowledged that the withdrawal would periodically contain anoxic water and high levels of phosphorus, iron, manganese, and possibly even sulfide. To ensure due diligence, the Ministry of Environment requested that an impact statement be provided to them, that a public meeting be held to inform the local residents, and that all the water licensees be notified of the project. This review was accomplished to their satisfaction and operation commenced June 20, 1994.

This review process highlighted the uncertainty of the project's legal status. It was not a waste discharge and was handled by the water licensing branch of the Ministry of Environment. The top 1.2 m of the lake are dedicated as water storage, and water licenses are in place for this capacity. Theoretically, the withdrawal would not affect the water licensees because the intent was not to lower the lake level but to remove bottom water in lieu of surface water that would naturally overflow the outlet weir of the lake. In the event of excess removal, the withdrawn water was to be replaced with diverted water from the Shinish Creek. Future applications of hypolimnetic withdrawal should be explained and reviewed with water licensing agencies early in the planning process.

Spring operation

The management plan called for the operation of the withdrawal as early as possible in the year following ice-off from the lake. A winter stratification has been observed with associated anoxia at the lake bottom. Elevated levels of phosphorus, iron, and manganese were observed in samples taken from the dredged area (under ice cover) during February 1994. Since the dredged area is resistant to mixing in the spring (Macdonald, 1995) operation early in the year would remove significant concentrations of nutrients accumulated during the winter. Operation of the withdrawal during ice-on periods is not considered safe due to the potential risk to snowmobilers and skaters.

Initiating the withdrawal operation early has been a difficult task. In the first year, there were the Ministry of Environment requirements mentioned above. In the following years, the withdrawal was run by local residents, the majority of whom were vacationers and not full-time residents. The annual lake resident's meeting during the May long weekend (approximately May 24th), coincided with the initiation of bottom withdrawal. By this time, 4-8 weeks of ice free withdrawal with a potential to reduce spring nutrient levels had been lost. It was only by 1998, several years after initiation, that the withdrawal has been operated significantly earlier in the year.

Summer operation

In the second year of operation, beavers fouled the outlet and forced the bottom withdrawal to be turned off during mid summer. The fountain/aerator at the withdrawal exit provides a fish barrier to prevent coarse fish from entering the lake. The barrier is a vertical section of culvert pipe, through which the water flows out from the center through 10 mm by 60 mm slits cut into the pipe. This is the aerator 'fountain' and combined with a minimum 30 cm vertical drop from the lowest slit to the ambient water surface is considered an effective barrier against coarse fish entry. However, in 1995, beaver dams raised the ambient water level above the level of the lowest slit thus removing the 'jumping' barrier and potentially allowing coarse fish to enter. Coarse fish are not expected in the downstream creek as they were removed in the early 1980s and barriers were established at the lake, and 3 km downstream of the lake. All of these coarse fish barriers must be maintained to protect the significant fisheries value of the lake.

The management of the beaver population is complicated as individual land owners perceive the beavers to be either pests, or natural wildlife, and conflicts over their trapping occur between downstream landowners. As well, the removal of beavers and beaver dams is an on going process requiring a lot of manpower which is not always available at the lake.

As mentioned, the usual summer algal bloom was delayed several weeks later than normal. The excellent response of the lake to the bottom withdrawal in the first year occurred in spite of a conservative operation. In this year, any chance of disruption of a lake use by excessive drawdown was to be avoided. Also the easiest management option for the residents was to run the withdrawal at a constant rate through the summer. In retrospect, the withdrawal could have been operated much more aggressively during mid summer, allowing the lake to draw down by 15-30 cm (within historic drawdown ranges), and then slowed after turnover or in the fall. For example during mid 1994, the withdrawn water was completely anoxic, and contained up to 300 μg/L of total phosphorus. The withdrawal could have been operated at a high rate, thus exporting significantly more nutrients than actually occurred. This operation strategy would be reliable if the Shinish Creek water diversion is running properly and providing replacement water.

The optimal operation of the hypolimnetic withdrawal might require a knowledgeable lake manager to make decisions about the rate of water removal. Verbal and written guidance has been provided to the residents mostly through the personal relationships with UBC personnel. In the long term, this lake and many others will probably require a resource group to assist local residents in self management of lakes.

Monitoring

The year before the withdrawal operation and the first year of the operation included intensive water sampling both in the lake and in the downstream creeks on a bi-weekly basis (Macdonald, 1995). In the second year of operation, monthly samples were collected which reduced the ability to follow trends of water quality. Throughout this period Secchi measurements were made by local residents on an almost daily basis. In the following years, this Secchi record was the only monitoring data available. Furthermore the V-notch weir measuring station where the diversion reaches the lake has fallen into disrepair and records of the diversion flow have been sketchy.

The Secchi record may be the most appropriate tool for local residents to use at this site. Secchi data shows the seasonal variation of water clarity from spring blooms and declining visibility, a small improvement in June, and a return of algal blooms (Secchi <1m) some time in the summer. These observations are not absolute in terms of the timing of these changes. Year to year differences in weather and hydrology affect when the blooms appear. The most expected benefits of the withdrawal are improved water clarity for the majority of the year, and to delay the onset of the summer algae bloom. This delay would be considered a significant success because the blooms used to start in July, a time of high lake usage. Other aspects of monitoring required to assess the withdrawal effect are probably beyond the local residents' resources. The nutrient and chlorophyll *a* monitoring detected improvements in the quality of water between the baseline year and first year of operation in summer, but maximum measured chlorophyll *a* and total phosphorus were only 10-20% lower in the second year. Detecting slow, long-term improvements from a highly variable year to year record will require a long monitoring period of Secchi measurements. It is expected that the accumulation of several years of observations will show the effect of the diversion.

It is not expected that the withdrawal can remove enough nutrients to create an oligotrophic lake condition. As such, there is no expected reduction in the recreational fishery from the withdrawal operation.

Potential

In spite of the difficulties with the withdrawal to date, there is a strong case for optimism about the future of Chain Lake. Theoretically the combination of the water diversion and the hypolimnetic water withdrawal is effective. Technically the withdrawal from the dredged area can be optimized more than it has been in the past. Furthermore the management of the bottom withdrawal is technically and politically much easier than the management required for sediment dredging. While the improvements in the lake quality have not been large, the casual observation of the residents is that it is "not as bad as it used to be". Maintaining the lake with the pressures of development will be a challenge.

Another argument for optimism is the increased organization of the lake restoration association. In the past a small dedicated group of volunteers led most of the management projects. In more recent years, the restoration efforts have been coordinated by a resident's association that is more inclusive of all property owners. In spite of conflicting interests and divergent management problems, the association has had some success. For example, the local residents have levied taxes upon themselves (collected by the regional district and administered by the residents) to fund the withdrawal pipe ($10,000 raised from 57 properties) and collected about $3000 annually for repairs to the diversion. There is a strong feeling among the residents that the lake management can only be conducted by themselves. As well, many of the residents have a sense of the urgency about these measures. In British Columbia, the support and resource organizations (governmental, lake management society or informal) are still in their infancy. However, as more property owners become full-time residents, and as the perceived value of recreational lakes becomes greater, it is likely that the need to manage this type of resource will increase.

Summary

Studies of sediment cores indicated that sedimentation rates had increased from 0.83 mm/yr to 9.3 mm/yr. The increased production could be related to the shallower water column or increased nutrient load from cottages. Sediment phosphorus release was a major factor resulting in production of blue-green algal blooms. Dredging projects attempted to first build a sediment trap for focusing of the most nutrient rich surface sediments. Subsequent dredging was done with simple equipment. Land management of the dredged sediments became too complex for a simple organization. The last effort was the installation of hypolimnetic water pipe into the dredge hole. The water clarity immediately improved with as good as a 5 m Secchi disk transparency.

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