SUMMARY REPORT ON POSSIBLE DREDGING OF LAKES IN THE ROTORUA DISTRICT

Report prepared for
Environment Bay of Plenty

By

Analytical & Environmental Consultants

February 2007

ANALYTICAL & ENVIRONMENTAL CONSULTANTS
LABORATORY SERVICES, ENVIRONMENTAL AND SCIENTIFIC CONSULTING SERVICES

Offices and Environmental Laboratory
91 Te Akau Road, Okere Falls
R D 4
ROTORUA
Phone/Fax 07 362 4488
E-mail millern@wave.co.nz

TABLE OF CONTENTS

EXECUTIVE SUMMARY AND RECOMMENDATIONS

The matter of dredging sediments from certain Rotorua Lakes is examined, with particular emphasis on the environmental, practical and economic aspects. It is suggested that the matter be pursued further.

The following recommendations are made:

- That Environment Bay of Plenty set up a small team to further investigate the dredging option. The team leader should have the power to co-opt expertise in dredging, soil science, environmental chemistry and industrial chemistry as required. This team could be based in Rotorua or Kawerau, or could be a sub-group of the existing sediments group.
- That investigations be carried out on the practicality, cost and procedures for conducting small-scale trial dredging of one or more suitable waterways, with a view to obtaining Resource Consents to conduct such trials. Such a trial would involve dredging a large proportion of the waterway(s) selected.
- That the dredging investigations should, from the beginning, involve a suitably experienced dredge operator as a partner rather than purely as a contractor.
- That Environment Bay of Plenty should fund investigations on the dewatering, environmental impacts and potential uses of dredged lake sediments. This should be given some urgency.
- Bench trials followed by field-scale trials (if appropriate)of dewatering of dredge tailings should be carried out before any large-scale dredging is attempted, on any lake. ‘Real’ rather than ‘simulated’ sediments should be used. A portable trial dewatering rig would be useful. This work could be carried out in conjunction with trial dredging in shallow water (below).
- Small scale dredging trials should be conducted, preferably in waters subject to anoxic episodes, to determine whether phosphorus, in denser and deeper sediments exposed by dredging, becomes available for release on a large scale.
- A suitable candidate for trialling of dredging in moderately deep lakes would be Lake Okaro.
- A suitable candidate for trialling of dredging in shallow lakes would be Okawa Bay, or Te Weta Bay, both in Lake Rotoiti. Both of these waterways experience severe water quality problems and behave largely as small lakes in their own right. In the case of Te Weta Bay, it is probable that suitable land could be accessed to carry out the sediment dewatering process.
- That when comparing costs of various lake remediation options, the costs should be amortised over the expected period of benefits.
- The costs of dredging are substantial, but the potential benefits, in some cases, may also be substantial and a careful cost-benefit analysis needs to be carried out, as should also be done with other major remediation proposals..
- Overseas experience has showed that, if the Consent process is not to be unduly prolonged, the public should be fully informed about dredging proposals from the very beginning.

INTRODUCTION

A variety of ‘engineering’ options are being studied for the rehabilitation of Lakes Rotorua and Rotoiti (and other lakes in the Rotorua District). Many of the water quality problems afflicting some of the lakes are derived from the recycling of nutrients, (particularly phosphorus and ammonium nitrogen) from enriched bottom sediments into the water column, during periods of anoxia. A question that often emerges at public forums on the lakes issue relates to the possibility of removing such sediments by dredging. As these lakes are large and deep, dredging has generally been regarded as impractical, due to the lack of suitable equipment and consequent high costs.

However discussions with an experienced dredging contractor, has produced a set of practical dredging proposals that could be applied to a number of the Rotorua Lakes, as appropriate. This report details those proposals and the investigative work that is underway and which would need to be completed before any dredging could be carried out.

The document also includes an outline Assessment of Environmental Effects (AEE). Obviously, at this stage it is not practical or necessary to prepare a full AEE, however the outline document gives guidance as to the specialised areas that would require professional attention in the event of the preparation of a full AEE becoming necessary, and it can form the basis for a full AEE.

This report attempts to give an impartial coverage of the matter. No direct comparison has been made between the various techniques (dredging, sediment capping, nutrient immobilisation etc) as this was seen as being outside the scope of this report.

N. C. Miller

N.C Miller
January 2007.

BACKGROUND DISCUSSION ON THE DREDGING OF LAKES

Dredging has generally received relatively little consideration when examining options for protecting or restoring lakes. However, in *Restoration and Management of Lakes and Reservoirs* (Cooke *et al* 1993 [1]), the subject of dredging for sediment removal has a number of pages devoted to it as part of a chapter on sediment removal, authored by Spencer A. Peterson. He comments that:

> "In cases where a significant nutrient loading from sediments can be documented, sediment removal might be expected to reduce the rate of internal nutrient recycling, thus improving overall lake and water quality conditions."

Peterson discusses a variety of concerns around in-lake effects of dredging (commonly relating to resuspension of sediment) and also those relating to the disposal of dredged material. A relevant comment is:

> "Another problem not uncommon to lake dredging is under-design of disposal area capacity. Unfortunately, these failings usually become apparent only after the project is fully operational. The problem may be associated with the slow settling rate of suspended sediment in fresh water and reduced ponding depth as the project proceeds. This may result in failure to meet the requirements of suspended solids discharge permits"

A number of case studies described by Peterson may be found later in this report, in the section titled 'Lessons learned from other dredging operations'.

It will become apparent throughout this report that the dredging option encompasses a wide range of factors. The dredging of lake sediments is a possible approach to the solution of some seemingly intractable water quality problems in certain lakes, and it is suggested that various apparent difficulties in the way should be approached in a practical and lateral-thinking manner. In particular, the problem of the disposal and use of dredged material should be viewed as a potential asset rather than a liability. If material can be processed in ways that help to solve other environmental problems (for example, the ever increasing stockpiles of wood-waste material in the Central North Island), or converted into other useful products, then such a broad-brush approach should be used, and the necessary research should be encouraged. It is recommended that a small team be set up to investigate the matter further.

THE DREDGING OPTION – PREVIOUS INVESTIGATIONS

Interest in dredging Rotorua lakes was first registered in 1971 (Rotorua Conservation Society 1971 [2]), however major investigations into the possibility of dredging Lake Rotorua were first carried out in the early 1990s (Duder and Venus 1991 [3]). The 1991 investigation was concerned with the possible use of dredging to control the lake weed infestation (then dominated by *Egeria densa*) at the city lake front by dredging and reclamation. The proposal under consideration was to dredge an area of lake bed between Ohinemutu (where the Utuhina Stream enters the lake) and Motutara Point, which is immediately to the west of the inflow of the Puarenga stream. It was concluded that 'there are no practicable alternative options to dredging which would provide long-term, maintenance-free, control of weed beds and weed stranding along the lake front of Rotorua City.' The areas that were proposed for dredging are shown below on Map 1.

Map 1. Areas proposed for dredging in 1991 report
From Duder and Venus 1991.

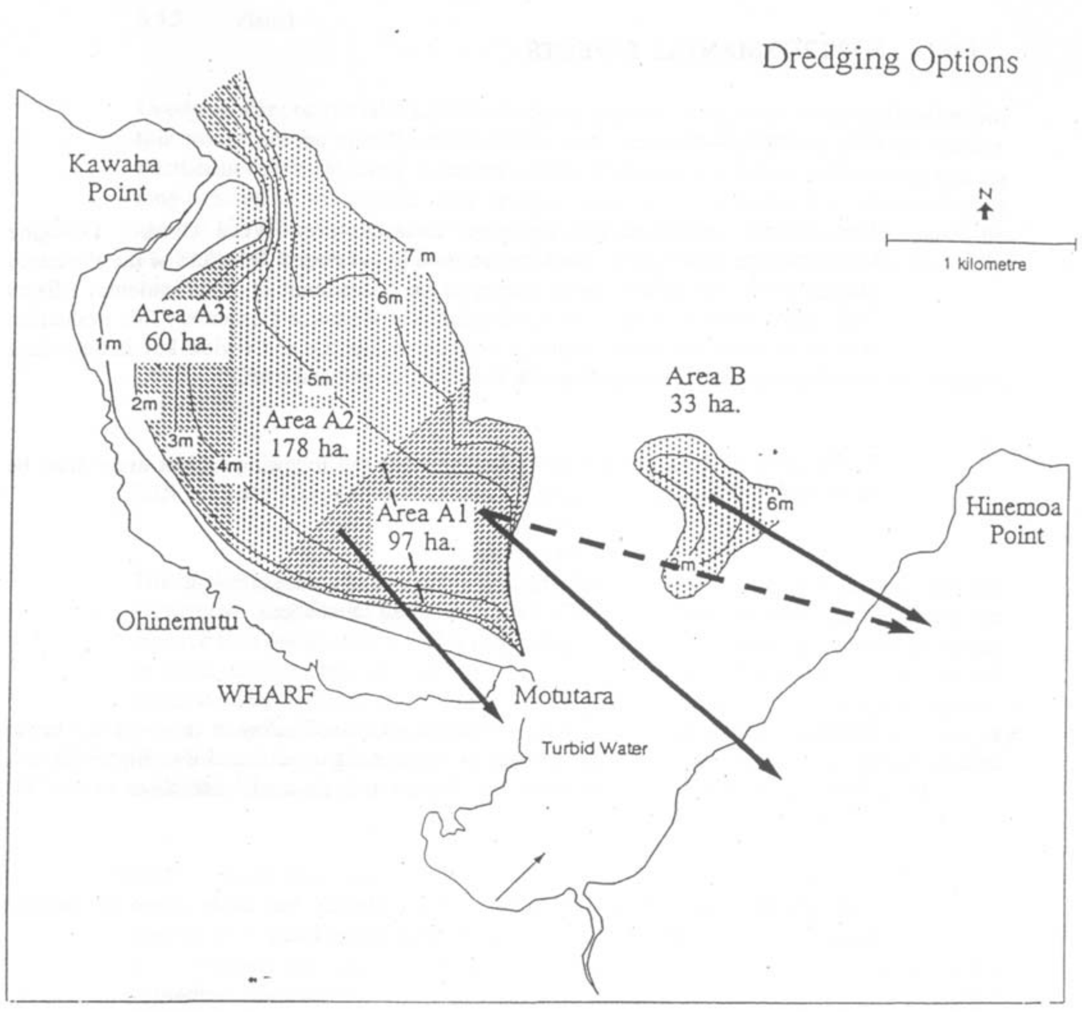


Diagram of proposed pumped disposal **of weed and dredgings from areas A1 & B**

This investigation was aimed at the potential for aquatic weed control only, and nutrient regeneration from sediments was not a consideration. The sediments in the area concerned were largely free from organics, due presumably to the constant reworking of shallow-water sediments due to wave action. These sediments are now known to be frequently composed of Kaharoa or reworked Kaharoa material (Hendy 2006 [7]). It was proposed to use a cutter suction dredge to remove aquatic macrophytes plus the underlying sediments. Possible disposal options for the material that would be removed included:

- Land reclamation in the vicinity of the CBD
- Filling rural land west of Vaughan Road (the favoured option) – much of this land is currently undergoing residential development.
- Creating an artificial island in Lake Rotorua.

The report observed that various precautions would be needed to avoid release of nutrients or toxic substances (arsenic, mercury etc) into the water column or into the environment from the areas of dewatering spoil. Various dredging options were proposed:

- To dredge only the weed material and the root zone, which would require frequent dredging. This would cost an initial $1.6 to $2.0 million (1991 dollars) plus ongoing costs.
- To dredge to 5 metres, which would result in the inhibition of weed growth, due to the 'new' depth being near the depth tolerance (due to restricted light availability) of the aquatic weeds. This would take 10 dredge-years and cost $15 to $20 million (1991 dollars).
- To dredge to 7.2 m, which was described as the 'ultimate desirable option for permanent control of weed growth'. This would require the removal of approximately 1 x 10^7 m3 of material and, using the type of dredge under consideration at the time, would require 14 to 15 dredge-years to complete. The estimated cost was $20 to $27 million (1991 dollars).

The preferred option, as recommended, was to remove a mixture of weed root systems and surficial sediments, by means of suction dredging. It was proposed that:

- Approximately 70,000 m^3 of weed and sediments be removed from Area B (33 hectares, see map) at an estimated cost of $425,000 (1991 costs).
- Approximately 210,000 m^3 of weed and sediments be removed from Area A1 (97 hectares, see map) at an estimated cost of $1,230,000 (1991 costs).
- Approximately 360,000 m^3 of weed and sediments be removed from Area A2 (178 hectares, see map) at an estimated cost of $2,000,000 (1991 costs).
- Following these weed control measures (with a benefit life of 2-3 years) by deep dredging of Areas A1 and A2 (see map), removing approximately 4,500,000 m^3 of sediments at an estimated cost of $M15 to $M20 (1991 costs).

These recommendations were not taken up, presumably for reasons to do with cost and the general level of public and political complacency about the state of the Rotorua Lakes at the time.

Recent improvements in dredging equipment and techniques have lead to a substantial increase in 'sanitary dredging' to remove contaminated sediments, throughout the world, and such operations are frequently on a large scale.

Proposals have been put forward to dredge sediments from Lakes Rotorua and Rotoiti, convey them through a floating pipeline to a suitable land disposal area outside the lake catchments, dewater them, then use them for soil improvement in the disposal area. A shrouded suction dredge intake, with an auger, would be used, which ensures that release of dredged material into the water column is negligible. This type of dredge intake has been shown in Holland and other countries to cause minimal environmental effects in the water body being dredged (Arts et al 1995 [38]).

It has also been proposed to use wood wastes from the forest industries of the Central North Island as an additive to the sediments, thus reducing the problems caused by an accumulation of these waste materials. The combination of wood wastes and lake sediments is expected to provide a valuable soil amendment material, for use on the disposal site and elsewhere.

THE RATIONALE FOR DREDGING OF LAKE SEDIMENTS

Recent work has shown the pronounced influence of the release of nutrients from sediments on some of the Rotorua lakes. For example, the internal regeneration of phosphorus during episodes of hypolimnetic anoxia is estimated at between approximately 14 and 21 tonnes. yr $^{-1}$ for Rotoiti and in 2003 the release of sediment P into the hypolimnion of Rotorua was estimated at 24 tonnes (Hamilton *et al* 2003 [4]), with this release occurring over short time periods.

The same authors observe that the situation for nitrogen is complicated by nitrification and denitrification reactions that occur in the sediments and hypolimnion, however their analysis of data suggests that some 308 tonnes of Total Nitrogen were released into the water column of Rotorua during two stratification events early in 2003, with these events lasting approximately 10 days. These releases, together with shifts in nutrient ratios and dominant forms of nutrients, may have ecological effects. To quote from the Hamilton report:

> "Lakes that have progressed to the stage where internal loading is a prominent feature of the internal nutrient load are not easily or quickly rehabilitated through conventional nutrient management measures and if strongly anoxic, may have low N:P ratios as a result of sediment nutrient release and nitrogen loss through denitrification. This process may favour dominance of phytoplankton populations by cyanobacteria."

It is therefore deemed desirable to reduce or halt this major cycling of nutrients through and from the sediments. This could be carried out by preventing lake stratification – a task requiring the application of formidable amounts of energy, or by resupplying oxygen to the hypolimnion during stratification – also a major technological feat in the case of a large lake.

Research is being carried out on a variety of means of immobilising sediment nutrients or 'capping' sediments, using such materials as modified bentonites or zeolites, allophane clays etc. The cost of treating lakes with some of these materials is likely to be substantial, and on a similar scale to dredging costs, and the degree of longevity of the treatments is uncertain. For this reason, the idea of physically removing some of the nutrient- and organic-enriched sediments, by dredging, has captured the public imagination. Cost and efficacy comparisons with other rehabilitation methods are included in a later section of this report, which generally examines the practical details of dredging sediments.

INITIAL INVESTIGATIONS

The sediment coring operation, Lakes Rotorua and Okaro

In order to dredge sediments and dispose of them onto land, it is necessary to obtain information about the chemical, physical and biological nature of the sediments. Accordingly, a large-scale sediment-coring operation has recently been carried out, using a specially built vessel (see photo below) and appropriate coring apparatus. The sediment coring programme being carried out on Lake Rotorua is well advanced.

Associate Professor Chris Hendy (University of Waikato) has completed an initial report on the results of the first round of coring, which was carried out in November 2004 and involved the collection of 38 cores. Dr Hendy's initial report was presented in February 2005 and a further update was issued in January 2006, with further updating underway. Additional coring has been carried out over a grid pattern of 1 km grid size. The samples collected in this process are being analysed, and a draft report has been prepared. In addition, sophisticated sonar equipment is currently being used to carry out detailed bottom profiling of Lake Rotorua. This information will also be made available to interested parties. CHECK

In addition, Dr Hendy has carried out sediment coring operations on Lake Okaro, on behalf of Environment Bay of Plenty. Following the completion of this process it is possible that a similar operation will be carried out on Lake Rotoiti, should this become appropriate.

In this report, the results and implications of the Lake Okaro study are discussed first, as representing a less complex situation and a good introduction to the situation in other, larger, lakes. It should be commented that coring of lake sediments is a relatively difficult matter, with no one corer type being suited to all situations. In particular, the capture of very soft surface seston material is far from reliable (Assoc. Prof. Chris Hendy, University of Waikato, pers.comm.).

The 8 metre aluminium-hulled vessel commissioned by Hartley Contractors for the sediment sampling programme.

LAKE OKARO

The nature of the sediments – Lake Okaro

Lake Okaro is a small lake, 0.28km^2 (28 ha) in area and with a maximum depth of 18.0 m and mean depth of 12.1 m (Livingston et al 1986 [5]). The lake is subject to frequent and severe cyanobacterial blooms, and its lower waters are anoxic for much of the year, permitting release of phosphorus from the bottom sediments.

The details in this section come from a draft report prepared for Environment BOP (Hendy and Milicich 2005 [6]). Further technical details of the coring, sample treatment and analytical procedures are provided in that report. Cores were collected from Lake Okaro on 5th and 6th September 2005, with a total of 19 cores being collected. Three types of corer were utilised:

- A three metre piston corer, which encountered difficulties due to the 'stiff and sticky' nature of the Rotomahana mud (deposited by the Tarawera/Rotomahana eruption of 1886).
- A 600 mm gravity corer, which collected surface seston but was unable to penetrate far into the Rotomahana mud.
- A 1200 mm box corer, which captured both surface seston and the underlying sediments butt was not capable of producing fine resolution of the seston.

The stratigraphy of the sediments were therefore reconstructed using samples from all three corers.

Various features of interest arose from this study.

Sediment stratigraphy – Lake Okaro

The lower sediments, as sampled, are a grey coarsely laminated silt, which has been interpreted as being the Rotomahana mud phase of the Tarawera Eruption of 1886. Above this, in some samples, is a second less compact grey silt layer, with an intervening layer of several cm of compressed olive organic ooze. This has been interpreted as being the result of a short phase of rapid erosion of the Rotomahana mud-based soils following clearance of manuka shrubland during the 1940s and 50s, prior to the establishment of a pasture cover. It is believed that this feature is probably present across the entire lake but has been masked by coring problems. Above these layers is a olive-coloured organic ooze (seston) of low density, often strongly laminated and sometimes containing large gas bubbles (probably a mixture of carbon dioxide and methane). This seston layer has a water content of 90 to 95%.

Redox potential of sediment (pore water) – Lake Okaro

The pore waters of all samples collected fell into the moderately to strongly reduced category, and most appeared to be controlled by Fe^{2+} to $Fe(OH)_3$ and Mn^{2+} to MnO_2 transitions. In the case of two cores (17 and 19) it appeared than another redox reaction (possibly methane formation) is controlling the pH and Eh of the pore water. Further discussion is found in Hendy and Milicich (2005 [6]).

Available phosphorus – Lake Okaro.

Phosphorus concentrations in sediment pore water samples were analysed by ICP-OES and the concentrations found were very close to the (rather high) limits of detection (11 µg/L) for this analytical technique. For this reason the results were not regarded as reliable. Based on integration of the analytical results for the sediments as a whole, about 14.5 tonnes of phosphorus occur in the loose lake sediments. This occurs largely in the loose organic seston layer referred to above. To quote from Hendy and Milicich [6]:

> "If this loose sediment were to be dredged, a layer 0.3 m thick off an area of $3x10^4$ m^2 would remove almost all of the mobile phosphorus, giving approximately 100,000 m3 of sludge, which upon dewatering would yield approximately 25,000 tonnes of dried sediment. The phosphorus content of the then exposed sediment at the lake bottom would then be reduced to about 10% of that of the current lake/sediment interface."
>
> "The concentration of phosphorus in the sediment pore waters shows little significant change with depth except for an as yet unexplained drop below detection limits (by ICP-OES)[a] at about 10 cm depth in the surficial sediments. It is worth noting that W. Paul (pers.comm.) sees a drop to zero in particulate organic matter at this depth in the sediment. As a result, removal of the post Rotomahana sediments would leave the lake exposed to pore waters of similar phosphorus content to the present, but with very much lower porosity, would result in much reduced flux of phosphorus into the overlying water."

Obviously, it is essential to determine whether the removal of the post Rotomahana (i.e. modern) sediments from a lake would result in a reduced flux of phosphorus into the overlying waters. The best way to determine this would be to carry out small

---

[a] ICP-OES is Inductively Coupled Plasma-Optical Emission Spectroscopy

scale dredging trials and monitor phosphorus flux from the exposed pre-modern sediments over a period of one or more years.

Toxic trace elements – Lake Okaro

Only two toxic trace elements were considered in the survey, since a much more extensive survey in Lake Rotorua, using a variety of analytical techniques, failed to find other elements of concern [b].

Lead showed an average concentration of 10.8 mg/kg in Okaro sediments, compared with an average of 3.7 mg/kg in Lake Rotorua sediments, as found in the recent survey of Rotorua sediments (Hendy 2006 [7]). It is interesting that these lead concentrations are higher than those found in Lake Rotorua sediments, (which are subjected to inputs from industrial and urban land uses). However, they are below the mean level of 14 mg/kg found in soils representing all land uses in the Bay of Plenty region (Love 2004 [8]). These concentrations are below the trigger levels for agricultural land use or environmental quality (70 mg/kg) and residential land use (140 mg/kg) (Love 2004 [8]).

Arsenic concentrations, at an average of 22 mg/kg, were unusually low for the Rotorua Lakes with, for example, Lake Rotorua sediments containing an average of 70 mg/kg. This presumably reflects the lack of any known significant geothermal discharge into Lake Okaro or its catchment. This arsenic level is still higher than the mean level of arsenic (7 mg/kg) found in Bay of Plenty soils and probably is due to the fact that the lake and its catchment lie within an area with a history of volcanic and geothermal activity (there is significant surface geothermal activity within 1 km of Lake Okaro). These relatively low levels of arsenic mean that lake sediment material, if dredged, dewatered then applied to land, would meet the New Zealand Health and Environmental Guidelines for Selected Timber Treatment Chemicals (MfE and MoH, 1997 [9]) for arsenic concentrations on residential land use of 30 mg/kg arsenic. These guidelines are designed for the protection of human health and are those preferred for the purpose in the MfE hierarchy guidelines (MfE 2003 [10]).

Guidelines for the protection of ecosystem values are still under development, and are part of a science which has yet to mature, however the ANZECC Guidelines 2002 [11] appear to be acceptable at present. These specify , as an interim sediment quality guideline (ISQG), a low level (trigger) value of 20 mg/kg, and a high level value of 70 mg/kg. These values apply to concentrations in sediments, and their application to dredged sediments is somewhat unclear at present.

LAKE ROTORUA

The nature of the sediments – Lake Rotorua

A major sediment coring operation has been carried out on Lake Rotorua, supported by Harley Contractors Ltd, of Kawerau. Analysis of the results is still continuing, but an interim report has been published (Hendy 2006 [7]), and considerable information is now available on the nature of the Rotorua sediments. Some 130 cores have been

---

[b] Lake Rotorua is exposed to very much higher inputs from industrial and urban sources, than is Okaro. However, considering the highly pastoral nature of the Okaro catchment, it is recommended that analyses for sediment cadmium be carried out prior to any possible dredging programme. Cadmium is frequently found in significant concentrations in the phosphatic fertilisers used in New Zealand in previous decades. (This work has now been carried out, results are awaited.)

collected using a piston corer, augmented with a box corer and a gravity corer. It is hoped to collect another 30 cores to provide additional information (C. Hendy, pers.comm.). Cores were collected on a grid pattern at approximately 1 km intervals. More details of the coring operation are given in Dr Hendy's report. Analysis of the data collected to date is still underway.

Stratigraphy
Two tephra layers were commonly encountered. The Tarawera (1886) tephra (Rotomahana mud) was typically encountered as a 10 – 20 mm lens 300 to 900 mm below the sediment surface. The coarser Kaharoa tephra was encountered 2 to 3 m below the sediment surface in the deeper parts of the lake. In shallow areas, Kaharoa or reworked Kaharoa material often made up the surface sediments. The sediments are dominated by a diatomaceous ooze, particularly in deeper areas of the lake that are not subject to disturbance by wave and wind action. This diatomaceous layer may be up to 60 cm thick, and appears to contain a significant proportion of the available phosphorus in the Rotorua sediments. The deeper part of the lake (10 m or more), which holds this ooze layer, covers approximately 30 km^2.

Phosphorus
The results show that phosphorus is concentrated in the upper portions of sediment from the bottom of the lake at water depths greater than about 10 metres i.e. about 30 km^2 of the lake bed. Phosphorus concentrations tend to be highest in the upper 50 cm of sediment, with the maximum [P} in the top 2 – 3 cm of very fluid, loose, low density material. These top sediments in deep water are the ones which should be targeted for dredging. Concentrations of total extractable phosphorus ranged as high as 500 to 600 mg/kg in the deep water cores. There appears to be very dynamic P processing occurring in these sediments (C. Hendy pers.comm.), with an oxidised layer a few mm thick, at the surface, adsorbing P and various trace elements. Beneath this an active reducing layer occurs, which is a few tens of centimetres thick. Below this layer sulphate reduction occurs, bulk [S] rises and Fe disappears from the pore water. Pyrite balls may occur, often with significant [P].

In addition to in-sediment processes, it appears that a benthic nepheloid layer [c] (BNL) exists immediately above the upper surface of the sediments. Cadmium and arsenic are being released just above the sediments, according to the results of work carried out with 'peepers' partly sunk into the sediments. The interactions between nutrients in sediments and in the BNL is unclear, but it seems probable that there are some. Some studies have shown similarity between material in the BNL and the adjacent surface sediments (Hawley, 2004 [12]). It is probable that the BNL would be significantly removed, on a temporary basis at least, by the act of dredging. The duration of this removal is uncertain, but it seems probable that the removal of the semi-fluid sestonic surface sediments would inhibit or delay the reformation of a BNL. Small scale dredging trials, as recommended elsewhere in this report, would assist in resolving this question.

Dr Hendy estimates that in January 2006, a mean rate of 400 to 450 tonnes.annum-1 of P release was occurring across the 30 km2 of deep lake sediments. There is

---

[c] This is a turbid, nutrient-loaded, particle-rich zone that hovers just above the lake (or ocean) bed. It is believed that they are often caused or increased by seiching or internal wave activity. Nepheloid layers may also be associated with thermoclines or with surface layers.

obviously a large pool of available phosphorus in the upper sediments in deeper parts of Lake Rotorua, as has generally been believed. Release of this phosphorus into the water column, during periods of anoxia, is believed to be a principal driver of lake eutrophication. A similar situation may be expected in certain other lakes, such as Lake Rotoiti.

Nitrogen

No data is, as yet, available on the forms and concentration of nitrogen in the sediments, as sampled in the recent survey, although such data will eventually be available (Dennis trolle, University of Waikato *pers.comm.*). However, Duder and Venus 1991 [3] reported N concentrations up to 2100 mg/kg dry weight in the wave-sorted sediments near the city lake front. Most of this was present as TKN, with ammonium-N present at up to 260 mg/kg DW.

A more recent survey of sediments from a number of Rotorua lakes found TKN concentrations ranging from 8500 to 11500 mg/kg DW from three (relatively) deep water sites in Lake Rotorua. Again, TKN comprised the majority of nitrogen detected in the sediments (Blomkvist and Lundstedt 1995 [13]).

Arsenic

The deep water cores show some enrichment of arsenic in, typically, the top 10 cm. Mean arsenic concentrations in the sediments are around 70 mg/kg. This arsenic is presumably largely derived from geothermal sources. Because arsenic behaves very similarly to phosphorus in the aquatic environment, it is very probably also released into the water column during periods of anoxia. Apparently little research has been carried out on this. The arsenic is likely to be mostly in inorganic forms (C.Hendy, pers.comm.), but investigations should be carried out to determine this and to assess the bioavailability of this arsenic once sediments are removed and dewatered.

Mercury

The deep water cores show some enrichment of mercury in, typically, the top 10 cm. Mean mercury concentrations in the sediments are around 0.7 to 1.0 mg/kg. This mercury is presumably largely derived from geothermal sources.

Other metals

Other ‘heavy’ metals largely derived from human activities in the lake catchment are discussed in some detail in Dr Hendy’s report, which has yet to be finalised. Their concentrations are generally low.

DISCUSSION ON LAKE OKARO – A POTENTIAL SITE FOR TRIAL DREDGING

Lake Okaro, which is of modest size yet reasonably deep, appears to be a suitable candidate for a trial of sediment dredging, using equipment that is currently available in the Bay of Plenty Region. The fact that much of the available phosphorus is concentrated in the top 30 cm of sediments renders dredging a promising approach towards reducing the regeneration of sediment nutrients. Estimates by Hendy and Milicich suggest that approximately 100,000 m^3 of material would need to be removed, and this would yield about 25,000 tonnes of dried nutrient-rich sediment which appears to be suitable for application to farmland or forested areas. Much of the area of the lake is between 10m and 18m deep, which makes it a good candidate for trials on dredging larger lakes of similar depth, such as Lake Rotorua. It is recommended that this option be investigated further. The relatively flat, and rural, nature of the surrounding land means that a suitable dewatering site should not be difficult to find. A nearby sawmilling operation provides a supply of wood wastes to be composted with reclaimed sediments if that option is shown to be worthwhile.

The main requirements for a dewatering site are that it should preferably be outside the lake catchment (which is mostly to the northeast of the lake) and at a reasonable distance from the Haumi Stream, which drains Okaro and flows into Lake Rotomahana. One possible site would be the existing wood waste landfill at the CHH Rainbow Mountain Sawmill, which is 1 kilometre from Okaro – probably within the pumping capability of a single dredge pump, without a booster pump. The pumping head required appears to be less than 10 metres. The use of this site might assist in resolving problems at the wood waste landfill, by utilising a material that currently is deposited in an ever-growing landfill area. Carter Holt Harvey would definitely be interested in this proposal (Darryn Cosgrove, CHH Ltd. pers.comm.).

The Okaro sediments do not appear to contain toxic metals at concentrations to cause problems with sediment disposal and use [d]. Lead showed an average concentration of 10.8 mg/kg in Okaro, below the mean level of 14 mg/kg found in soils representing all land uses in the Bay of Plenty region (Love 2004 [8]). Arsenic concentrations, at an average of 22 mg/kg, were unusually low for the Rotorua Lakes. This arsenic level is still higher than the mean level of arsenic (7 mg/kg) found in Bay of Plenty soils and probably is due to the fact that the lake and its catchment lie within an area with a history of volcanic and geothermal activity (there is significant surface geothermal activity within 1 km of Lake Okaro). These relatively low levels of arsenic mean that lake sediment material, if dredged, dewatered then applied to land, would meet the New Zealand Health and Environmental Guidelines for Selected Timber Treatment Chemicals (MfE and MoH, 1997 [9]) for arsenic concentrations on residential land use of 30 mg/kg arsenic.

An outline of possible costs involved in dredging Lake Okaro may be found later in this document.

DISCUSSION ON LAKE ROTORUA

Lake Rotorua has been experiencing significant water quality problems for many years, with cyanobacterial blooms recorded as early as the 1980s and possibly earlier. The lake is relatively shallow (mean depth 11 m, maximum depth 45 m) and does not usually undergo long periods of hypolimnetic deoxygenation. Nonetheless, when the hypolimnion does become anoxic, significant nutrient releases from the sediments may occur (Hamilton *et al* 2003 [4]). At present, Lake Rotorua has a major impact upon the water quality of Lake Rotoiti, to which it is linked by the Ohau Channel. However, when the Ohau Channel Diversion Wall is completed (at the time of writing construction of this structure had very recently been approved by the Environment Court) this impact may be expected to be very greatly reduced.

---

[d] Data has been collected but has yet to be fully reviewed (C.Hendy, University of Waikato, pers.comm.).

Lake Rotorua is an obvious candidate for dredging operations, and such operations have been considered in the past, although for weed control purposes rather than water quality improvement (Duder and Venus 1991 [3]).

How much sediment to dredge from Lake Rotorua?

The data collected during the recent survey of sediment samples collected from Lake Rotorua is still being processed and analysed. The sediments regarded as most likely to be implicated in nutrient regeneration into the water column occupy approximately 30 km^2 (Lisa Pearson, University of Waikato, pers.comm.).

Every 10 cm of sediment removed from the lakebed over this 30 km^2 area would result in a total (wet) volume of 3×10^6 m^3. The bulk density of the Rotorua sediments ranges from 0.15 tonne/m^3 (at the surface) to 0.30 tonne/m^2 at 90 cm, with a mean of 0.20 tonne/m^3 and a reasonable mean value at 0.23 tonne/m^3 (Hendy 2006 [7]). Therefore on drying, each 10 cm of the sediments removed from 30 km^2 can be expected to result in approximately 700,000 tonnes of dried sediments. Obviously the precise thickness of sediments which would be removed by dredging needs to be carefully determined. It is probable that this thickness would vary from one area of lakebed to another, as determined by the data collected from the current sediment sampling programme. These volumes of material may seem formidable. But it may be commented that in the Netherlands, current plans are for some 200×10^6 m^3 of contaminated sediments to be dredged and dewatered over a fifteen year period. These sediments would be dredged from the semi-estuarine environment of the Ketelmeer. (Laboyrie 2000 [22]).

What to do with sediment from Lake Rotorua.

A major consideration when considering dredging of Lake Rotorua (or other large lakes such as Lake Rotoiti) is the dewatering and disposal of dredged material. The degree of development (commercial, residential and rural) around the lake shores means that suitable nearby sites for sediment dewatering and disposal may be hard to find. There are several possible options:

1. A dredging contractor has secured preliminary approval to use a site to the north of Lake Rotoiti (on the northern side of Rotoehu Road) as a site for carrying out sediment dewatering and composting operations. If this was to be used to receive sediments from lake Rotorua, this would involve either:
    - Pumping sediments through a floating pipeline running across Lake Rotorua to Lake Rotoiti, along Lake Rotoiti and coming ashore towards the eastern end of Lake Rotoiti. Booster pumps would be required.
    - Pumping sediments to the shore of Lake Rotorua and trucking them (possibly following some initial dewatering) to the disposal site.
    - Constructing a floating dewatering station on Lake Rotorua, then trucking the dried sediments to the composting or disposal site.

2. Reclaiming a portion of the lakebed of Lake Rotorua by constructing a coffer dam then pumping the sediments behind it and dewatering *in situ*. This was proposed by Duder and Venus (1991 [3]). Such land could be used for commercial or residential purposes, provided that the dewatered sediments could be shown to have suitable mechanical properties. The resulting area of

land could be much sought after, however obtaining the necessary Resource Consents might prove to be a difficult process. In addition, the resulting fill would be of a fine talc-like texture, of low mechanical strength and behaving poorly when exposed to seismic events – much like the material underlying the central business district of Rotorua (C.Hendy, pers.comm.). Recent techniques for mixing cement into air-assisted sediment flow through a pipeline can produce a fill with greater bearing strength and resistance to liquefaction (Sakamoto 1998 [14]).

3. Pumping sediments to the shore of Lake Rotorua and pumping or trucking them (possibly following some initial dewatering) to a suitable disposal site.

Dewatering lake sediments

The process of dewatering also requires detailed consideration. The wood waste stabilisation ponds at Kawerau and Kinleith rely on pumping the dredged material into large ponds from which water is decanted and/or drained into secondary treatment ponds. The rather fibrous nature of the wood waste means that dewatering is relatively fast and straightforward. In addition, once a head of water is established over the dredge tailings the tailings become compacted and their moisture content is significantly reduced. A freshly filled pond, once left to drain, will generally be able to be dug out (using mechanical diggers) within 2 to 3 weeks, depending on the weather and the time of year (P. Hartley, Hartley Contractors Ltd. pers. comm.).

On the other hand, the very fine textured diatomaceous ooze found in the upper layers of sediments in lakes such as Okaro or Rotorua can be expected to be much slower to dewater, and the ooze is likely to 'cake' as it begins to dry out (C.Hendy, pers.comm.). Alternative approaches to dewatering may be necessary. The admixture of fibrous materials, such as wood wastes, may alleviate these problems, and some research into the matter is desirable, and is therefore recommended.

Various materials may be added to dredge tailings in order to facilitate dewatering. A number of polymers and coagulants may be used to assist in precipitating out solids and some dissolved materials from tailings water. Some such compounds were tested during the Lake Okeechobee dredging trials, although these were primarily intended to achieve accelerated phosphorus removal from the tailings water, since the supernatant had been shown to achieve satisfactory suspended solids concentrations (40 to 50 mg/L) within 48 hours of decanting into settling ponds (EA 2002 [39]). Use of alum salts was ruled out due to potential for biotoxicity and it was concluded that iron (III) chloride hexahydrate (97%, A.C.S. reagent $FeCl_3.6H_20$) was the most suitable coagulant for the chemical precipitation tests. NALCLEAR 8184 (a high molecular weight polymer), manufactured by Nalco Chemical Company was selected as the flocculating agent. The flocculating agent binds together precipitated floc, to enhance the floc settling rate. A target Fe:P molar ratio of 145:1 was selected based on previous studies The polymer flocculation technology reduced supernatant total phosphorus concentrations to less than 40 µg /L in five out of seven tests. The total phosphorus limit was not attained in two of the tests due to inadequate addition of the ferric chloride. However, effluent requirements were not met by this technology, due to the elevated pH and iron concentrations in the effluent.

Some chitosan-based products have been used to enhance the separation of tailings water from the solids in the tailings (Macpherson *et al* 2003 [15]). Chitosan is produced by alkaline deacetylation of chitin (a natural polymer and polysaccharide, which is one of the main components in the cell walls of fungi, the exoskeletons of insects and other arthropods, and in some other invertebrate animals (Miller 2005 [29]). The chitosan forms a fibrous web linking sediment particles together in a three-dimensional matrix. When this matrix enters a sand filter it is trapped, but allows the water through, whereas other polymers and coagulants form a gelatinous, filter-clogging floc.

In the Lake Okeechobee dredging trials, the use of geotubes (made from a geotextile fabric) was evaluated as a means of accelerating the dewatering process. A simulated dredging tailings slurry was poured into a column with geotextile across the lower end of the column. The geotextile rapidly became clogged by an impermeable filter cake, and the trials were deemed a failure.

The production of gas (mainly methane) in the tailings, as they dewater, must also be taken into account. This commonly occurs in dredging programmes in the Netherlands, where computer programmes have been developed (Wichman et al 2000 [16]) to predict the output both of gas and of tailings water (composed of pore water and water entrained during the dredging process).

It appears probable that the dewatering arrangements would be similar to those used in the Ketelmeer dredging programme in the Netherlands. In the Netherlands, the philosophy is that emissions from confined disposal facilities for dredged material can be restricted in accordance with the ALARA principle (As Low As Reasonably Achievable). To this end, the following approach is used (Laboyrie 2000 [22]):

1) Assessment of the quality of the expelled pore water against target values for the groundwater. For contaminants that do exceed the target values Phase 2 must be carried out.
2) Assessment of the fluxes of the facility against permissible fluxes. It is not necessary to take isolation measures if no permissible fluxes are exceeded. If the permissible fluxes for one ore more contaminants are exceeded, Phase 3 must be carried out for these substances.
3) Assessment against dispersion criterion (permissible area of influence). If after a certain long period (e.g. after 10,000 years) the volume of the area that is affected by the emission of contaminants from a facility is still smaller than the volume of the facility, the use of isolation measures is often less urgent.. If after this period the affected area will take a greater volume than a volume equal to that of the disposal facility, it is necessary to attempt to take measures that are adequate to meet the criteria.

If, based on the tiered assessment, it is considered necessary to use isolation measures (specifically to meet the requisite dispersion criterion), one or more (combinations) of the measures/provisions given below can be selected. In the light of current experience and knowledge (Laboyrie 2000 [22]) these fall within the ALARA-principle.

a. Water level Control: prevention of infiltration/advective transport by means of the reduction of the hydraulic head between the upper and lower levels of the disposal facility.

b. Lining of the base of the facility with clay/clayey material that is rich in organic matter.
c. Covering the bottom and slopes by a sand/sandy layer that is rich in organic matter (for example, a layer that is 0.5 m thick).
d. The use of an effective geohydrological isolation system to limit the extent of the affected area (for example, a polymer membrane and/or subsurface drains).

In practice, this would require a series of dewatering ponds, possibly with impermeable sealing or a subsurface drainage network, a tailings water treatment system and suitable arrangements for mixing the dewatered material with wood wastes and/or native soil. In addition, because of the fine-textured nature of the sediments in those Rotorua lakes which have been sampled, it is probable that wood wastes would need to be added to the dredging tailings as they enter the ponds (see earlier).

It is quite clear that dewatering of dredged sediments must be based on the results of extensive bench testing, followed by field testing, and such trials are recommended to be carried out at an early stage in the decision-making process.. It is recommended that sediments be used that have been dredged from the lakes being considered for large-scale dredging. The use of ‘simulated’ slurries appears to give unreliable results, based on the work carried out at Lake Okeechobee. The use of a small dredge transported to the lake of interest and employed there for a day or two could save much grief later. Construction of a simple portable rig for trialling dewatering would also be of advantage. The production of transport water from dredging work may potentially be reduced by the use of compressed air assistance to move the tailings through a pipeline (Sakamoto 1998 [14]).

Mechanical dewatering

In some dredging operations, mechanical intervention may be used to hasten the dewatering process. For example, in the programme to remove contaminated sediments from the lagoon of Venice (Italy) filter presses have been used to reduce the water content of the dredged material, prior to subsequent treatment or disposal (Gentilomo 1999 [17]).

The machinery used to thicken or dewater the silt consists of flat or strip filter press batteries, working in parallel. The flat filter presses comprise a series of sheets of synthetic filter material, mounted on vertical steel frames. The frames are moved longitudinally by hydraulic mechanisms. Material is supplied to the press by a feeder: the sheets are compressed by oil-pressure, and the desired part of water is separated from the silt. Basins are located beneath the presses to collect water running from the sheets and water used to wash the filters. The strip-presses are made up of two conveyor belts,
placed one above the other, each one fitted with sheets of synthetic filter material. The conveyor belts rotate in opposite directions with a slight convergence. Silt to be treated is delivered to the higher belt by a feeder, and is then transported by the conveyor belt which forces and compresses it through the convergent space (between the sheets of the upper and lower belt). When the belts separate, at the end of the belts’ course, the sheets draw apart and the thickened silt is unloaded in a continuous stream. The thickened material is then transferred to the deposit area.

After unloading, the sheets pass through a washing device. In this case as well, water from the thickening process and the water used to wash the sheets is collected in a basin provided for this purpose. Note that the output with flat filter presses is discontinuous and therefore the continuous production provided by strip-presses generally ensures higher output. However, the dewatering capacity of flat filter-presses is greater. The output of the press depends on:

- the characteristics of the silt and the amount of water it holds; the pressure applied by the plates (in the case of flat sheet presses);
- the pressure applied between the sheets of the conveyor belts and on the tension and speed of the belts (in the case of strip-presses);
- the nature and quantity of the additives used;
  the efficiency of flocculation (Poly-electrolytic additives (in concentrations of less than 1%) acting as flocculants are added to the silt, by a suitable meter-feeder, before it enters the presses.

One automatic strip-press and two automatic flat sheet-press have been installed at the Malcontenta plant. The treatment capacity is 500 m^3 per day of dredged material (which corresponds to 600 m^3 delivered by the barges, considering a transport water "enrichment" of 20%) for an output of 300 m^3 of dewatered material, working 24 hours a day, five days a week. After mechanical treatment, the silt must present a "dry" weight of no less than 50% that of the material prior to excavation. Lime is added to the basins to prevent anaerobic fermentation in the silt, with the release of unpleasant smells. This filtration process is similar to the pressure filtration that may be applied to sludge from wastewater treatment works.

Another approach mentioned by this author (Gentilomo) is flotation separation, where material with a specific gravity near to that of water (e.g. fluid lake sediments) may be floated by the injection of dispersed air (bubbles large than 100 µm) or dissolved air (bubbles in the 10 to 100 µm range). These bubbles attach themselves to the material and cause it to float, enabling its removal.

Once sediments are dewatered, they must then be used or disposed of. The sheer bulk of material removed during major dredging operations means that some type of land filling or land spreading operation will probably be involved. At this point the eventual land use of the affected area, together with potential or real contaminants in the dredged material, must be considered.

Contaminants in Lake Rotorua sediments

A variety of organic and inorganic contaminants may accumulate in lake sediments, and these materials may have widely differing behaviours, both *in situ* and also when retrieved from the lake. For example, some organic compounds, such as polycyclic aromatic hydrocarbons (PAHs), derived from a variety of combustion processes, have been shown to become phototoxic when PAH-containing lake sediments are recovered and exposed to light (Davenport and Spacie 1991 [18]).

It is unlikely that high concentrations of PAHs are to be found in the sediments of lake Rotorua, however certain other organic compounds, for example the timber preservative pentachlorophenol (PCP) and its associated dioxins (such as PCDDs) and furans (such as PCDFs), are known to be present. Only limited information is available on the presence of these compounds, as determined in a 1992 study (see below). However the following is known (summarised in Miller, 2003 [19]):

> PCP and PCDDs/PCDFs are present at elevated levels in fish, mussels and sediments in Lake Rotorua, and the Waipa Mill appears to contribute to these levels. As the measurements of contaminants were limited, it is not possible to reach firm conclusions regarding the significance of the contaminants. However, based on the few measurements taken:
>
> - The concentrations of PCP and PCDDs/PCDFs in the fish and mussels are within the criteria adopted in the study for adverse effects on biota.
>
> - Human consumption of lake trout would not result in the intake of PCP or PCDDs/PCDFs in excess of the criteria adopted in the study for adverse effects on human health, assuming the average long term consumption of lake trout does not exceed 3 servings per week. Further investigation is required to confirm this.
>
> - The PCP sediment concentrations in Lake Rotorua appear to be relatively high; however, this is based on only three samples, and further work is required to confirm the overall sediment PCP concentrations. The sediment concentrations of PCDDs/PCDFs appear to be less than the study criteria; however there is uncertainty in the analytical test work and further work would be required to confirm this.

A limited amount of sediment sampling and analysis for PCP and PCDDs/PCDFs was carried out in 1991 and 1992, as part of a pilot study carried out, at the Waipa Mill site, on risk assessment for PCP contamination (Camp Scott Furphy 1992 [20]).

The results from this study are listed below in Table 1.

It is interesting that the highest PCP concentration was found in the sediment sample that was collected from the site furthest away from the Puarenga Stream mouth. Bathymetric charts (within the limits of the rather wide depth contours) indicate a somewhat greater water depth at this site than at the other two, and it may be speculated that less sorting and resuspension of sediments (due to wave action) occurred at this site, leading to greater accumulation of contaminants.

Table 1
Concentrations of PCP and PCDDs/PCDFs in sediments of Lake Rotorua
(After Camp Scott Furphy 1992.)

Approx location of sampling site	**Approx distance from Puarenga stream outlet**	**PCP mg/kg (ppm)**	**PCDDs/PCDFs concentration μg/kg [3] (ppb)**			
			HpCDF 1,2,3,4,6,7,8	HpCDF 1,2,,3,4,7,8,9	HpCDD 1,2,3,4,6,7,8	OCDD
1.25 km west of Hinemoa Pt.	1 km	4	<10	<10	<10	<15
1 km west of Ngunguru Pt. [1]	3 km	1	<2	<2	4	24 [2]
1.25 km ESE of Te Kou Pt., Mokoia Island	5 km	22	<15	<15	<15	<20

[1] Ngunguru Point is adjacent to Rotorua Airport
[2] The total 2,3,7,8 TCDD Toxic Equivalent concentration for this site is estimated to be 64 μg/kg.
[3] Measured 2,3,7,8 congeners only are listed.

To quote from the Camp Scott Furphy report:

> "In the longer term, given that the discharge of PCP to Waipa Stream and Lake Rotorua will eventually cease, the PCP which is present in the environment will eventually degrade through photolytic and microbiological degradation. Some photolysis can be expected to occur at the surface of Lake Rotorua and in addition, some degradation (probably microbial) can be expected to occur in the sediments of Lake Rotorua where anaerobic conditions prevail. This has been found to occur in other PCP-contaminated bodies of water (Minister of Supply and services, Canada, 1989 [21]). Degradation in lake sediments, however, may proceed slowly given the low temperatures of the lake bed."

It is recommended that sampling and screening of selected Lake Rotorua sediments for organic contaminants such as PCP and dioxins be carried out in advance of any proposed dredging programme.

The following extract from a report on the dredging of contaminated sediments from Lake Ketelmeer (Netherlands) is of relevance (Laboyrie 2000 [22]) :

> "First an extensive program on the bioavailability and mobility of chemicals and the effects of contaminants on the ecosystem is undertaken. Interim results show that the present assessment system, which is directive on the handling of CDM (Contaminated Dredging Material could become insufficient. It is possible that an effect called "ageing" could be responsible for the fact that sediments become less harmful in time. With time the contaminants in the sediments acquire an increasing attachment to the organic matter in the

sediment so the desorption capacity becomes less in time. This phenomenon also affects the bioavailability of contaminants.

"Also, research is done on Confined Disposal Facilities. One of the physical processes to be looked at is the consolidation process. The material stored is a mix of solids and water and will be subject to consolidation: due to loading by subsequently disposed material pore water will be expelled and hence the volume will decrease. The effect of both the existence of gas (mainly being CH_4) within the CDM and the gas production after storage on the consolidation are not sufficiently clear as yet. Extensive research is being carried out on this subject. This gas-factor is dependent on the concentration of organic carbons in the sediment, the amount of organisms in the material which can convert the organic matter in to gas, the amount of cracks through which the gas can escape and other properties of the material. Recent research showed that the production of gas in the sediments could be much higher than expected up to now.

"Until recently it was practically impossible in the Netherlands to look at the possible option of storage of CDM in pits with a direct contact with surrounding surface water due to the lack of political leeway. New insights in partition coefficients and ageing of material gives reason to believe that the leaching and release of contaminants during disposal may be factors lower than recently assumed (Hartnak et al 1997 [23])."

Table 2 (below) shows the typical concentrations of a variety of inorganic and organic sediments from Lake Ketelmeer. These sediments come from the 'sink' of a waterway (the River Ijssel) with a long history of industrial discharges.

Table 2: **Typical concentrations of contaminants in the Lake Ketelmeer sediments** From Laboyrie and Flach 1998 [24]

Substance	**concentration (mg/kg)**
Cadmium	10 - 22
Chromium	145 - 470
Arsenic	37 - 85
Mercury	3 - 8
Lead	89 - 367
Zinc	700 - 2600
PCB-153	0.037 - 0.119
Fluoranthene	1.9 - 3.0
Benzo-(a)-pyrene	0.6 - 1.2

(Substances shown in shaded cells exceed Dutch threshold levels above which remediation of the situation has a high priority)

Arsenic concentrations in Ketelmeer sediments are typically at similar levels to those in the Lake Rotorua sediments, which have a mean concentration of 70 mg/kg. Mercury concentrations are significantly higher than in the Rotorua sediments.

Implications for land disposal of dredged sediment from Lake Rotorua

A number of potentially toxic contaminants occur in lake sediments. These can include a variety of metals, other inorganic compounds, and various organic contaminants.

In the case of the Rotorua lakes the metals of prime concern are arsenic (actually a semi-metal) and mercury. In order to satisfactorily dispose of dredged sediments to land, it would be necessary to ensure that concentrations of these metals on site are below commonly accepted environmental guideline values.

These guideline values are dependant on the proposed future land use over the sites in which sediments would be deposited. A potential disposal site has been identified and the expected future land uses would be forestry or agriculture.

For arsenic, the set of Guidelines that are recommended by MfE (Ministry for the Environment 2003 [25]) are the MoH/MfE 1997 [26]. These are shown in the summary of Guidelines (Table 2, below). No guidelines have been adopted for Forestry land use, so at this stage the value for 'Industrial unpaved' has been used.

For mercury, the set of Guidelines that are generally recommended by MfE are the Australian NEPC Guidelines [27]. This does not address agricultural land uses, and further investigation and discussion of alternative Guidelines (for example those of the USEPA) may be desirable. The NPEC Guidelines are also shown in the summary of Guidelines (Table 3, below).

Table 3
Typical Environmental Guideline values for arsenic and mercury in soils

Element	Mean concentration in sediments mg/kg	Guidelines used	Land use	Guideline value Mg/kg
Arsenic	70	MoH/MfE	Agricultural Industrial unpaved	30 500
Mercury (methyl)	<1	NEPC	Residential	10
Mercury (methyl)	<1	NEPC	Commercial/industrial	50
Mercury (inorganic)	<1	NEPC	Residential	15
Mercury (inorganic)	<1	NEPC	Commercial/industrial	75

It may be seen that mercury concentrations in the sediments are typically well below the NEPC Guidelines. Arsenic concentrations typically exceed, by a factor of 2, the MoH/MfE Guidelines for agricultural land use, but would be acceptable for industrial (and, presumably, forestry) land use. It is proposed that dredged sediments would be mixed with wood wastes, and possibly with on-site soils also, and provided the dilution rates were suitably chosen, the final arsenic concentrations would be expected to meet the MoH/MfE Guideline values for agricultural uses. Obviously, further extensive investigations into Guideline values and means of adhering to them would be carried out before any Resource Consents were applied for. This document is only an initial summary of the situation.

In addition, sediments that were applied to land would need to be carefully dewatered under controlled conditions to ensure that arsenic or mercury (or other metallic contaminants) were not mobilised to the extent that they entered the ground water table. Investigations into this would need to be carried out by suitably qualified personnel. It may be commented that arsenic in a well-drained soil is likely to be much less of an environmental concern than arsenic in lake sediments, which may be released into the water column during periods of anoxia.

If substantial quantities of arsenic were present in the tailings water that was released from dredged sediments, then steps would need to be taken to remove a substantial proportion of the arsenic from the tailings water. The use of filters using melter slag (from NZ Steel at Glenbrook) as a filter material is a promising approach. Melter slag has been shown to be effective at removing inorganic arsenic from water, including water that is rich in organic compounds such as tannins (NZ Steel 2004 [28]). In addition, melter slag has been shown to be effective at removing phosphorus from water (Miller 2005 [29]), and the discharge of phosphorus-rich waters into the environment should also be avoided.

Further investigations should be carried out into the best methods of dewatering sediments, such sediments being obtained through a small-scale dredging trial, possibly on one of the sheltered embayments, on Lake Rotoiti, that are displaying water quality problems. These trials should also examine the mixing of sediments with wood wastes, and the possible advantages and disadvantages of such a practice.

Uses for dredged sediments

Other potential uses for the sediments, once removed from the lake, should also be investigated. Some research work is underway on this matter at Waikato University, carried out by Shane Carter, with particular emphasis on the diatomaceous nature of many sediments (Assoc. Prof. Chris Hendy, Waikato University, pers.comm.).

Other possibilities include the following:

- The use of sediments as a source of material in the formation of biodegradable plastic composites. New formulations of bio-based plastic and biomass using different biomasses (waste streams) are continuously being sourced and processed. The dredged material, with or without the mill solids, could be suitable.
- As a carbon source for the production of feedstocks for further processing (eg the production of acetic acid through the application of anaerobic fermentation technology)

A preliminary cost estimate for a research programme into the admixture and use of sediments is perhaps within the range of \$40,000 - \$60,000 + GST per annum for 3 years. (Alison Slade, Group Leader Applied Technology Development, Eco-Smart Technologies, Scion™ pers.comm.).

Concerning the use of dredged sediments, Kurata (1994 [30]) described the suction dredging of organic matter rich sediments which was carried out in the basin of eutrophic Lake Biwa (Japan) to improve the water quality. Removed sediments were used after processing for various kinds of construction materials, such as bricks for pavement and walls of domestic houses, and ornamental materials for public buildings.

Darmody and Marlin (2002 [31]), investigating the uses of sediments dredged from lakes in Illinois, reported that, after dewatering, the physical properties of sediments tend to become similar to upland soils and the retention basins are then able to support conventional agriculture. Results indicated that properly handled dredge sediments could make high quality agricultural soils. In addition, sediment placement on poor soils could improve their productivity.

In some parts of the world, particularly Europe, dredged material is regarded as an asset rather than as waste, and considerable research goes into finding new uses for it (Paipai 2003 [32]).

Proposed sediment disposal site

A Kawerau dredging contractor has been involved in discussions with the owners of a block of land on the northern side of Rotoehu Road (north of Lake Rotoiti). This land contains a system of valleys and has been surveyed by MTec Consultants (Rotorua) who calculate that it has a capacity to receive up to 100,000,000 cubic metres of material. An initial calculation suggests that the volume of dewatered material resulting from dredging, to a depth of 0.5 metres, all of those areas of the Lake Rotorua lakebed below the10 m contour would be approximately 22,000,000 m^3.

Initial dredging trials

Provided that no major environmental issues arise as a result of the sediment coring and analysis project, an application could be made for Resource Consents to carry out small-scale dredging in Lake Rotorua, Okaro or or Rotoiti. This could be carried out using a dredge that was constructed by Hartley Contractors, and which they own and operate (**see photo to left**). A more recently constructed version than the one shown has the ability to dredge to 19 metres, rendering it suitable for use on Lake Okaro. Options include the pumping ashore and dewatering of sediments, then amending them with wood wastes, if this process is shown to be practical. This will give information on the behaviour of the sediments while being pumped and dewatered, and will also examine what materials are present

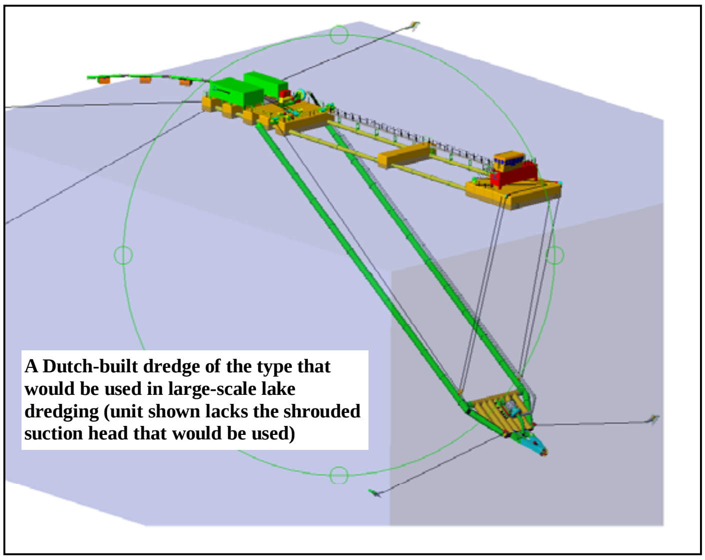
Small locally-built dredge of the type that would be used in initial trials

in the leachate. The suitability of the final dewatered or composted material will be assessed for horticultural, pastoral and forestry purposes.

If it is then decided that dredging is a feasible means of reducing the internal cycling of nutrients in Lakes Rotorua and Rotoiti, formal proposals could be presented to carry out large-scale sediment dredging as part of the management plans for the two lakes. This would entail raising the necessary funds and applying for Resource Consents. Such consents would need to cover both in-lake and on-land operations.

The lake dredging operation

A modular dredge could be imported from Holland. This is built from units with the same dimensions as standard shipping containers. These would be shipped to a suitable port, such as Tauranga, trucked to Rotorua, and assembled on the lake.
The dredge (**Diagram below**) is approximately 100 metres long, and has the ability to remove sediments in water depths ranging from 1.2 to 90 metres. It is a suction dredge, with an auger suction head that draws sediments in to the intake of the large suction pump. A protective shroud ensures that loss of disturbed material into the water column is minimal.



A Dutch-built dredge of the type that would be used in large-scale lake dredging (unit shown lacks the shrouded suction head that would be used)

The dredge is controlled by precision Differential GPS units and can control the position of the dredging head to within a few centimetres vertically and laterally, making precision dredging quite straightforward. Up to 3500 m^3 of water and sediments may be pumped every hour.

Alternatively such a unit could be built in New Zealand, where the appropriate heavy engineering capability exists (Paul Hartley, pers.comm.).

The dredged material is pumped through a floating high-density polyethylene (HDPE) pipeline which can be extruded *in situ*, or brought in as units which are welded together in the field. Booster pumps are included as necessary. The material is pumped ashore, out of the catchment, dewatered and amended with wood wastes.

Initial calculations suggest that to dredge 0.5 m of sediment (probably more than is needed) from all of those parts of Lake Rotorua deeper than 10 metres, would take approximately 4 years, and for Lake Rotoiti, 2 ½ years. This would be with the dredge operating 24 hours per day, 6 days per week. The dredging unit would then be used on other projects elsewhere in New Zealand.

PRACTICAL ISSUES WITH DREDGING

Positioning the dredge

Suction dredges of the type proposed to be used are generally positioned quite precisely by means of winches connected to three or more cables connected to fixed positions on adjacent land, or firmly anchored to the bed of the waterway being dredged. Modern dredges use precision GPS (Geographical Positioning System) units and high resolution sonar units operating through a computer to control their position to a precision of 0.02 metres.

The fact that cables stretch between the dredge and the land, or seabed/lakebed, means that care must be taken to prevent the cables becoming a hazard to other vessels (or low-flying aircraft). It is also important that the cables do not unduly disturb the sediments lying beneath the water column. This is particularly so if the sediments are highly charged with gases, such as methane, as occurs in the case of Lake Rotorua or, to a lesser degree, in Lake Okaro.

This problem may be overcome by securing the cables to (relatively) elevated land rather than the lake bed, or by buoying cables that are anchored to the lake bed (as was done in Ketelmeer (Arts *et al* 1995 [38]), or by equipping the dredge with a self-contained manoeuvring capability not using winches and cables (i.e. engines plus propellers/hydrojets/paddlewheels).

Positioning the dredge head

It appears that, at least in the case of Lake Rotorua, much of the readily available phosphorus is concentrated in approximately the top 10 cm of sediments. This top 10 cm also approximates to the seston layer – a layer of very soft, low density organic material, sometimes referred to as an ‘active’ layer. This is the layer which should be given top priority in dredging, as this is the layer which is likely to be contributing most to the nutrient regeneration during anoxic periods. In the interests of environmentally safe, cost-effective dredging, it is therefore important that this seston layer is specifically targeted by the suction head of the dredge. This implies that the dredge head must be accurately positioned in the vertical dimension. Since dredge head positioning is controlled by GPS location and sonar readings, it is necessary to determine whether or not the sonar bottom profiler can, in fact, accurately detect and locate the seston layer. Otherwise there is the risk that the suction head will concentrate on the underlying layer of denser sediments, with possible major disturbance of the seston layer and release of it into the water column.

As mentioned elsewhere in this report, initial dredging trials should examine the question of whether a new active layer forms after dredging, and if so, at what rate.

Design of dredge head

The design of the dredge head is critical to the success of dredging operations. The following requirements must be satisfied:

- Capable of removing all the solid and semisolid material along the swathe being dredged, to the required cutting depth.
- Capable of removing dredged material with minimal loss to the water column.

- Able to withstand encounters with rocks, submerged logs, lost outboard motors and other debris.
- Able to pump the sediment slurry with a minimum need to entrain water from the water column (in the interests of increasing dredging efficiency and speeding up the dewatering process).
- Able to be accurately positioned in the horizontal and vertical dimensions.
- Big enough to handle the job, allied with suitable pumps, pontoons etc.
- Able to cope with gas trapped in the sediments.
- Safe to operate.

A variety of different types dredging heads are used. For 'sanitary' dredging, the options are rather more restricted. A brief discussion of some types follows, in the section titled 'Lessons learned from other dredging operations'.

Methane in sediments

Submerged sediments are often sites for gas generation. The Rotorua lake sediments are no exception. The organic ooze that forms the surface layers of sediments from Lake Okaro are described as "sometimes containing large bubbles (probably a mixture of carbon dioxide and methane)" (Hendy and Milicich 2006 [6]). In Rotorua sediments, the organic ooze layer is also gas generating, together with the underlying layers to at least 10 m down. The bubbles in these sediments have been shown to be composed largely of methane. Initial estimates by Olivia Drake (University of Waikato) put the annual methane production from Lake Rotorua sediments at 1 to 2 million cubic metres (C. Hendy, University of Waikato, pers comm.).

These gas-rich sediments can cause problems both for sediment coring and also for dredging. Once the sediments are disturbed, the trapped gas tends to rise, entraining sediment and water with it, with potential contamination of the water column. In addition, gas in sediments can cause substantial problems for suction dredges. As the dredged material is drawn towards the surface, the trapped gases tend to expand and become released due to reduced pressure. This can have severe effects on the efficiency of dredge suction pumps and the resulting pump cavitation may cause physical damage and accelerated corrosion of pump components (Paul Hartley , Hartley Contractors Ltd., pers comm.).

However, there are ways to circumvent these problems. The use of a shrouded suction head, principally deigned to reduce sediment loss into the water column, also reduces or eliminates gas loss to the water column, provided that the shroud is correctly designed and built. In addition, suction dredges may be fitted with degassing systems, which work by removing trapped gases before they can enter the suction pump (which is usually located on the dredge itself, rather than in a submerged position near the dredge head.

The author of this report has viewed such a device, designed and built by Hartley Contractors on a recently built dredge designed to work on wood waste stabilisation ponds. It operates by using a separate water flow, directed through a venturi device, to form a partial vacuum which is applied to the dredge suction pipe near the dredge head. This results in the majority of the trapped gases leaving the suction pipe and thus avoiding the main suction pump. It is proposed to extend this system to provide a number of gas draw-off points along the length of the suction pipe, thus resulting in very little gas passing into the suction pump (Paul Hartley, Hartley Contractors ltd., pers comm.).

A different principal was used in one of the various suction heads used in the dredging trials that were carried out in Lake Ketelmeer (Arts *et al* 1995 [38]). In this case the 'baldachin' (essentially a canopy or shroud) that surrounded the augur head of the dredge was equipped with valves that released trapped gas as it accumulated. When dredging 'gassy' sediments such as those in Lake Rotorua, it may be expected that this arrangement would be less effective than the locally designed active venturi system described above.

Where methane needs to be extracted from the dredged sediments, it is worth investigating the option of using it to power the diesel engines of a dredge or booster pump. The practicality of this would depend on the amount of gas available, the methane content, and the presence of impurities.

LESSONS LEARNED FROM OTHER DREDGING OPERATIONS

Ketelmeer (Netherlands)

For the initial Ketelmeer trials, two main types of dredging heads were used, both successfully (Arts *et a*l 1995 [38]):

- A modified auger dredger (the 'Willem Bever') was equipped with an 8 m wide auger head, the auger diameter being 1.25 m. Dredging was performed in 7 m wide tracks, allowing for a 1 m overlap between swathes. Using 6 positioning winches a horizontal positioning accuracy of <0.25 m was obtained. The positioning cables were buoyed to keep them from disturbing sediments. A vertical positioning accuracy (for the dredge head) of <0.01 m was obtained. This dredging was carried out in relatively shallow water, and in deeper waters a lesser degree of vertical positioning accuracy might be expected. Computerised speed control of the underwater dredge pump resulted in the dredge slurry containing up to 80% sediments (i.e. little entrainment of transport water from the water column). A debris screen in front of the suction mouth resulted in few problems with debris. The dredge was capable of removing up to 0.85 m thickness of sediment at one pass. The maximum horizontal speed of the dredge was 7 metres/minute. The sediment gas entrapment system resulted in few problems with cavitation, and there was minimal loss of material to the water column.

- The second dredge trialled at Ketelmeer was an environmental disc cutter dredge (the 'Vecht'). This type of head was developed at the University of Delft and commercialised by Boskalis Dolman bv.. This type of dredge head looks rather like a large 'squirrel cage' centrifugal blower, mounted on a vertical axis of rotation, but running in reverse. This acts as the cutter, and a suction intake is located inside the cutter. The rotating action of the cutter forces sediment into the suction mouth. There is a full height screen around the back part of the cutter with a height-adjustable screen around the front (leading) part, to reduce sediment losses into the water column. The cutter diameter is 3 m, permitting up to 50,000 m3 of material to be dredged per week. Dredging accuracy is claimed to be ± 10 cm.

Further trials were carried out in 1996 at Ketelmeer, using two other dredge types (Arts and Kappe 1996 [33]):

- The sweep dredge is a modification of an earlier version, the scoop dredge (Vandycke 1996 [34]). The sweep dredge, suitable for operating in water depths from 3 to 14 metres (as built), swings its dredge head in an arc from side to side of the direction of movement of the dredge. A movable visor on the dredge head enables sediment collection during both phases of the swing. Sediment is collected by a scraping action and is fed into a suction intake. The sweep dredge can remove sediment selectively in layers up to 20 cm thick. The Ketelmeer trials shows that the sweep dredge produced slightly more loss of material into the water column and was slightly less accurate, but had higher sediment removal rates, with low requirements for transport water. A degasification system was installed to reduce cavitation from trapped gases.

- The other dredge trialled at Ketelmeer was a modified bucket dredger which relied on barges to transport the dredged material to shore. For this reason it is not discussed further.

Full reports of the Ketelmeer dredging trials do not appear to have been published in English as yet.

Okeechobee (USA)

Trial dredging has also been carried out in Lake Okeechobee, Florida (EA 2002 [39]). A bottom-sliding suction dredge , with the proprietary name of SEDCUT® was used. The unit was designed to selectively remove a relatively thin layer of mud from the bottom of Lake Okeechobee with minimum pickup of the denser substrate that supports this mud layer. In addition, the dredge head was configured so that a minimal amount of dilution (transport) water from the overlying water column would be collected by the submersible pump. The general principle was to feed the mud layer into the inlet of the pump by adjusting the forward travel rate of the dredge head through an adjustable inlet frontal area (i.e. mouth opening) so that the pump's discharge rate would be equal to or less than the gathering rate of the head. The dimension of the inlet area for the dredge head was designed so that a very slow rate of advance would occur during the dredging process, to minimize the resuspension of the mud layer.

Design of the dredge head connection to the pivoting arm permitted the head some degree of vertical freedom so that it could slide on and follow the denser substrate underlying the mud layer. To enable the unit to maintain a horizontal advancement path, a series of skis were attached to the lower lip of the mouth opening to prevent the unit from digging into the underlying substrate. The following design considerations were used:

- Contact Pressure: The ability to vary the dredge head contact pressure was part of the original design concept, utilizing variable buoyancy tanks. Bench-scale tests using core samples obtained from the PDS revealed that the underlying substrate had measurable, consistent, but very low shear strength values 7.03

g/cm^2 to 16.88 g/cm^2]). Accordingly, variable buoyancy ballast tanks were sized to reduce the unit's contact pressure to this range.

- Intake Visor**:** To vary the vertical height of the intake opening, an adjustable intake visor was installed at the top of the mouth area. The visor was designed to allow the intake opening to adjust from 30 cm (100% of the mud layer thickness) to 5 cm (16% of the mud layer thickness).

- Pumping system**:** A 15 cm discharge diameter hydraulic-drive submersible pump, capable of delivering a maximum flow rate of 5700 L/min], was mounted aft on the dredge head. The projected output of the overall pumping system applied to the specific site conditions for the demonstration project would be as follows:
  Static lift at dredge head 3.66 m
  Terminal lift at tank barge 2.44 m
  150 m of pipeline with friction head (with a dredge slurry of 1:1sediment:transport water) of 7.9 m
  Elbows and couplings 3 m head
  Total Dynamic Head 17 m
  The manufacturer's pump curve shows that the pump would have a flow rate of approximately 4900 L/min at 17 m Total Dynamic Head (TDH).

- Advance rate: The travel rate calculations were based on a constant pump rate of 4900 L/min and the assumption that the volume of material in a 1.8 m wide swath removing a 0.3 m thick mud layer would remain constant. However, since the mud has extremely low shear strength values and behaves as a fluid, it was believed that a 6 1.8 m opening width would influence a swath width greater than 1.8 m. Therefore, a calculated travel rate of 9 m/min was estimated to be the maximum limit for a 30 cm dredge head intake opening.

Obviously, this was a small prototype dredge, and a number of problems were experienced, largely related to size. To quote from the EA report:

> "The hull size of the prototype dredge (7.9 m x 2.4 m) and the associated floating transfer lines—compared to what would be used for a full-scale dredging operation needed for Lake Okeechobee—left the operation notably vulnerable to rough lake conditions. Moreover, due to Lake Okeechobee's large size and very shallow depth significant wave action can quickly build up under even moderate winds. Wave heights of 0.6 m–1.2 m occurred regularly with wind velocities ranging from 12 knots – 20 knots. These conditions prevailed throughout most of the operating period. Sustained winds below 12 knots were only observed in three of the 23 days of the dredging operations. These lake conditions made operation of the dredge and adjustments for the position of the travel cables to which the dredge was attached both difficult and, at times, dangerous. Thirteen days were either lost entirely or consumed in dealing with the effects of these conditions."

Dredged sediments were transported to a disposal facility by barge, which proved inefficient and difficult due to the shallow water and problems with wind and wave action.

However, the dredging technology being trialled gave promising results. From the EA report:

> "Results indicate that SEDCUT® technology was very successful in achieving the goals of the project. Using a 15 cm mouth opening and travel rate of 13 m/min, the SEDCUT® dredge head successfully removed a dredge slurry containing up to 65% target mud and 35% dilution water, which translates into 93% removal efficiency when compared to the predicted (theoretical) production rate.
> "The success of dredging (i.e. accurately removing the target mud layer) was determined by comparing the bulk density and gain size distribution properties of the dredge slurry to the target material. Results indicate that the unit performed most effectively at a 15 cm mouth opening and a travel rate of 13 m/min.
>
> "It was also observed that the profile of the dredged material closely matches the profile of the mud layer with the exception of the bulk density of the extremely low travel rates. The efficiency and production rates of the dredging operations were determined by the relative ratio of mud versus dilution water in the dredge slurry.
>
> "Comparison of different travel rates indicated that the faster travel rates generated a higher relative percentage of mud in the dredge slurry than water. Since the winch system could not travel faster than 13 m/min, it is unknown if a faster travel rate would have generated a higher relative percentage of mud in the dredge slurry."

It may be noted that the maximum efficiency was obtained using travel rates that were higher (by 44%) than the previously calculated maximum limit (9 m/min) for a 30 cm dredgehead intake opening. At present there are no plans to dredge Lake Okeechobee, due to cost factors, coupled with the large size of the lake, but some useful lessons were learned from the initial trials.

It is clear from these reports, and from New Zealand experience, that dredging technology already exists which is capable of dredging lake sediments with a minimum of sediment release into the water column, and which can operate efficiently. Equipment is already in the country which is capable of carrying out small-to-medium sized trials. Such smaller dredging equipment might be expected to experience difficulties in wind-prone large lakes such as Rotorua (viz the Okeechobee experience, above), but would be suitable for smaller bodies of water.

Other lakes

Peterson (1993 [35]) describes a number of case studies. Virtually all such projects have been carried out on small lakes. Some examples are:
Lake Trummen, Sweden (100 hectares). External nutrient inflows over several decades lead to a marked decline in water quality in this shallow lake (maximum depth 2.5 m). There was no apparent improvement following nutrient diversion measures, and major internal nutrient cycling was detected. Removal of 1 metre of sediment (3×10^6 m^3)in 1970 and 1971lead to significant reductions in [TP] and [TN], followed by increases in algal biodiversity and an increase in Secchi Depth, together with a large reduction in cyanobacterial biomass, and an overall reduction in

phytoplankton productivity. The resulting improvement has endured for more than 25 years

Lilly Lake, Wisconsin (37 hectares). A closed basin lake, with a small agricultural watershed. Infilling by sedimentation and aquatic plant growth lead to a decision to deepen part of the basin by dredging sediment (665,000 m^3) in 1977. This action was accompanied by short-term adverse effects, including a n increase in [TP}(due to resuspension of sediment), [TIN] (due to liberation of ammonium-N from the sediment) and an increase in phytoplankton productivity. After dredging had been completed, these variables gradually fell to near or below pre-dredging levels. This work was carried out to provide more storage capacity and water depth for recreational activities, together with macrophyte control, rather than to improve water quality. The lake remains dominated by macrophytes and phytoplankton production remains low, with reasonably high Secchi depths (3.2 to 5.9 m). For unexplained reasons, macrophytes, while still abundant, no longer reach the lake surface to the same extent as they did before dredging. There was an interesting macrophyte succession from dominance by *Potemogeton robbinsii*, before dredging, through *Chara* spp. following dredging, then to a mixture of *Chara* and *Myriophyllum* spp., then back to *P. robbinsii*. The dredging was considered a successful approach towards macrophyte control. In contrast, three other small, shallow Wisconsin lakes with similar problems (Bugle Lake, Lake Henry, and the Upper Willow Flowage) also received similar treatment, but with generally unsatisfactory results. Following dredging, infilling occurred much more rapidly than had been expected, and the lesson to be drawn from this is that infilling rates should be carefully calculated before dredging is commenced..

Lake Springfield, Illinois (1635 hectares). This is a water supply reservoir, relatively shallow (mean depth 4.4 m), that had accumulated much sediment from its 689 km^2 watershed, resulting in a 13% reduction in its original storage capacity since its original impoundment in 1935. A decision was made to dredge, following a two tear study. Hydraulic dredging was selected because of its efficiency and proven record in lake dredging. Sediment was to be disposed of into a series of large shallow settling ponds constrained by levees. Average retention time in the retention ponds, as constructed, was 8.7 days. A study of the sediment showed that the sediment disposal sites could be reclaimed for farmland (with improved fertility) at the completion of the project. Chlordane and Dieldrin levels in the sediments were initially an issue, but were eventually shown by the USEPA to be below hazardous waste criteria levels. Following a lengthy consenting period, the project was implemented and completed in two years. It appears that some of the delays in gaining consents could have been reduced if the public had been fully informed from the beginning.

Other dredging work has been carried out in various shallow lakes in Europe. Some of these projects are briefly discussed below.

Van der Does *et al* (1992 [36]) reported on dredging as an additional measure which was carried out twice in the peat lake Geerplas. In contrast, in the Nieuwkoop Lake only the external phosphorus loading was substantially reduced from 0.9 to 0.2 g P m^{-2} y^{-1}. Provisional results of these two Dutch shallow peat lake rehabilitation projects focussed on eutrophication abatement with and without dredging, were presented. Both show a decrease in phosphorus concentration in the lakes.

Sven-Olof Ryding (1982 [37]) reported on the results of dredging Lake Trehörningen (Sweden) , where an increased load of domestic wastewater had induced deoxygenation conditions and the development of a reduced sulphide-rich sediment layer. After advanced wastewater treatment and sewage diversion the lake did not recover. Suction dredging and macrophyte elimination were applied in 1975 and 1976. This project was the largest rehabilitation programme carried out in Sweden on a single lake, corresponding to a cost of about US $2,000,000. The concentrations of phosphate and total phosphorus decreased by 73 and 50% respectively, as summer average values, two years after the rehabilitation. However, the concentrations of phosphorus were still too high to permit this element to act as a primary algal growth-limiting nutrient. The algal biomass has also remained at the same magnitude as before the rehabilitation. Nitrate-N concentrations showed a tenfold increase, based on average values for the summer period. However, based on the results of the algal assays, a rapid and marked response was obvious, with a drastic decline in the algal growth potential.

The nutrient loading from external (stream) sources exceeded the critical level for the lake, and measures have now been carried out to treat all the inflowing waters for the removal of phosphorus.

It could be commented that in this case it might have been better to have carried out control of external nutrient sources before dredging was contemplated.

IMPACTS OF DREDGING ON THE WATERWAY

Release of sediment material into the water column

A well designed dredge, properly operated, is claimed to be able to remove sediments from a waterway with minimal loss of disturbed material into the water column. A series of dredging trial carried out in Holland is relevant to this matter, and these trials are described below (Arts *et al* 1995 [38]). A more detailed set of trials carried out in Florida is also discussed (EA 2002 [39]). Discussion of the equipment used in these trials occurs earlier in this report.

The Netherlands trials were carried out on Lake Ketelmeer, a major freshwater lake in The Netherlands. Located in the delta of the Ussel River, this shallow (typical depth 2 to 6 m) lake was constructed in the 1950’s as part of the ongoing land reclamation efforts in The Netherlands. The lake is 38 km^2 in area, and sediments over about 28 km^2 became contaminated over the period 1950 to 1980. The main contaminants were heavy metals and PCBs (polychlorinated biphenyls). It was decided that this situation would be best remedied by dredging out the contaminated sediments, which have an average thickness of 0.55 metres. Because of the large area to be dredged, it was necessary to ensure that only that material which needed to be removed should be, in order to contain dredging and disposal costs. Accordingly, trials on high accuracy dredging were initiated, and as part of these trials, assessments of sediment spillage and impacts on turbidity were carried out.

Using high accuracy GPS and bathymetric methods, it was found possible to position the dredge head within 0.02 metres in both horizontal and vertical (depth) dimensions. Depending on the type of dredge being trialled, spillage (defined as all material that is loosened by the dredging technique without entering the sediment transport system) ranged from 0.00 to 0.05 m (i.e. equating to a layer 0.05 m thick). Against a background turbidity [e] of 25 to 40 mg/l, the increased turbidity resulting from dredging was described as 'insignificant'. The dredging equipment transported between 150 to 450 m^3/hour (water plus sediment), with the transport rate of solids ranging from 100 to 300 tonnes dry solids/hour. The proportion of solids/water was influenced by the amount of gas trapped in the sediments, averaging between 5 to 10% v/v. The installation of de-gassing systems (type not specified) successfully limited the negative effects of trapped gas.

Another relevant, and more detailed, report deals with the pilot dredging project conducted on Lake Okeechobee, Florida (EA 2002 [39]). Lake Okeechobee is a large multi-function lake/reservoir located at the center of both the Kissimmee-Okeechobee-Everglades aquatic ecosystem and the Central and Southern Florida Project. The lake has an area of 1900 km2 and an average depth of 3.5 m. This lake provides regional flood protection, water supply for agricultural, urban, and natural areas as well as critical habitat for fish and wildlife in south Florida. However, the environmental health of this critical water body has deteriorated over the past century, largely because of increased nutrient inputs. To quote Dr Del Bottcher (2004 [40]):

> "Over the past forty years, fishermen have noted increases in algal blooms and exotic macrophytes. These observations are supported by measured increases in phosphorus (P) levels in the lake. Though fish populations do not appear to be adversely impacted at this time, lake access and aesthetic degradation (odours and unsightly conditions) have been a problem. A macrophyte control programme has been very costly and has had secondary consequences of localized increased soluble nutrient concentrations and associated algal blooms."

In preparation for a proposed dredging programme, trials were carried out on dredging a limited area of the lake bed. This work was combined with sediment surveys, water quality surveys and a variety of other investigations. While the physical dredging operations were being carried out, water quality monitoring for a variety of physico-chemical parameters was carried out upwind of, in the immediate vicinity of, and downwind of the dredging activity. Representative results from this monitoring are available, but not included in this report.. Bear in mind that this data was collected from a shallow lake, subject to wind events, where the water depth is such that manoeuvring vessels themselves have the potential to disturb the bottom sediments.

It may be seen from examining this data that the lake, at the time of sampling was turbid, with very low Secchi depths. The lake is very shallow, and during the period of the trial strong winds halted operations on a number of occasions. In addition, tugs, support craft and 'spud' barges (used to protect the dredge unit from wave action) caused disturbances to the lake bed.

To quote from the EA report:

> **"**Turbidity monitoring data indicated no significant impact on lake turbidity levels during dredging. Turbidity values recorded before, during, and after dredging was completed did not differ from each other significantly. The

---

[e] 'Turbidity' as used in this reference appears to really mean suspended solids. Turbidity is caused by suspended material (plus some soluble compounds) but it is difficult to establish a direct correlation between the two parameters, and different units are used.

> background lake turbidity levels were relatively high (>50 NTU) and the operation of the SEDCUT® [f] unit did not significantly increase water column turbidity levels.
>
> "Occasional spikes were observed in the turbidity measurements, however, it could not be determined if the spikes were caused by movement of boats and/or equipment or the SEDCUT® operations. No turbidity plume was observed during the monitoring.
>
> "Review of the in- lake water quality monitoring data indicated no significant difference in water quality (selected nutrients and metals) between samples collected upstream and downstream of the dredging area, as compared to the samples collected within the active dredging zone."

Further discussion of this pilot operation may be found earlier in this report, in the section headed 'Lessons from other dredging operations.'

Detailed water quality data collected before, during and after the dredging operation is available in the EA report [39], which is available on line at:

(http://www.sfwmd.gov/org/wrp/wrp_okee/projects/pilotdredgingreport.pdf).

This data is in a format that does not transfer well to a Word document and is therefore not presented here.

In the end, the conclusion from the Lake Okeechobee trials was that dredging was not economically viable, mainly due to the size of the lake.

> "So what are the solutions that are being looked at? The biggest factor in the lake is all the sediments in the bottom carry a huge nutrient load – let's dredge those. This is a 1900 square kilometre lake! …..Well, $2.5 million dollars later some consultants came back and told the District, 'Yes it's not feasible'." (Dr Dell Bottcher 2003 [40]).

Three options were offered for the Lake Okeechobee Internal phosphorus Management Programme (LOIPMP) , namely:

- To dredge
- To treat sediments with aluminium sulphate or sodium aluminate (for P retention)
- To do nothing.

In the end, the 'do nothing' option was selected.

Other specific issues that dictated against dredging Lake Okeechobee were as listed below (Dr Dell Bottcher, Soil and Water Engineering Technology Inc., *pers.comm.*):

- The most active portion of our sediments, chemically, is a surface flocculent fluid layer, which is hard to do much with. Hydraulic dredging is the only method that will work, but even this method stirs up this layer making it hard to collect. (*It should be noted that this dredging work took place in a very*

---

[f] The SEDCUT unit was the proprietary dredge head used during the Okeechobee trials.

shallow lake, where even the movement of dredging equipment and attendant vessels caused disturbance to the bottom sediments. N.C.M.)

- The highly fluid nature of the sediments requires very large settling basins, which means the cost of obtaining such land for doing this is huge. Plus the distances to construct pipelines to these settling areas would be very high. (*A tentative option to use suitable land is already in place for the dredging of Lakes Rotorua and Rotoiti.* N.C.M.)
- The organic sediments are quite deep in many areas, so estimated sediment volumes were large, assuming that you wanted to remove them all. However, if you just removed the active surface layer, it meant that you would still have exposed organic sediments and the active flocculent layer would probably just reform. (*Generally this situation does not apply in Lake Rotorua or Lake Okaro, according to Dr Hendy's research.* N.C.M.)

Impacts on remaining sediment column

The concern is frequently expressed as to what happens after the upper nutrient-rich sediments are removed. Provided that periodic hypolimnetic anoxic episodes continue, it may be expected that concentration of phosphorus and various trace elements into the upper sediment layers, due to migration from lower in the sediments, will continue. This concentration process has been demonstrated in sediments of Lakes Tarawera and Rotorua by Dr Hendy of Waikato University. It is therefore very important that the cycle of high phytoplankton productivity, resulting in high hypolimnetic oxygen demand (and resulting hypolimnetic deoxygenation), be broken, by limiting nutrient inputs to the water column as much as possible. For this reason, all other possible measures to reduce nutrient inflows should be planned or underway before dredging is undertaken (see section on 'Preconditions for Dredging', earlier in this report.) It is essential that this anoxic nutrient release cycle is broken if lake water quality is to be restored.

Obviously some disturbance to the biota of the sediments will be caused by dredging. Providing the dredging is carefully carried out, with minimum resuspension of sediments, this disturbance may be expected to be limited for several reasons:

- Any major lake dredging will take place over a prolonged period, with only limited areas of lake bed being disturbed over any one time. This allows time for dredged areas to be colonised from nearby undredged areas.

- Lake bed areas subject to periodic anoxia (and these are the areas of a lake bed that are most likely to be dredged), will tend to support a benthic fauna of reduced biodiversity, due to the anoxic periods. Those benthic fauna which are able to migrate into shallower waters will do so during anoxic periods. This group includes kakahi, koura and bullies.

    Kakahi (*Hydridella menziesi*), also known as freshwater mussels, attain sizes over 100 mm and reported maximum ages ranging from 13 to 33 years. They are filter feeders, travelling around on lake beds and leaving distinctive tracks behind them in the lake sediments. They are abundant in some of the Rotorua lakes, including Rotorua and Rotoiti. Wells and Clayton [41] studied the impacts of diquat spraying of aquatic weed beds in Lake Rotorua and found that kakahi were abundant (at densities up to 550/m^2) in water depths of 0.5 to 9 metres. They hypothesised that hypolimnetic deoxygenation may exclude kakahi from the hypolimnion in summer.

Koura (*Paranephrops planifrons*) or freshwater crayfish, are abundant in some of the Rotorua Lakes, including Lake Rotoiti (although numbers are believed to be falling) and are common in Lake Rotorua. They are the largest bottom-living crustacean in these lakes, growing up to 70mm long (excluding antennae). They may shelter under rocks or in burrows (substrate permitting) during the day, emerging at night to feed. They are omnivores, feeding on small invertebrates, organic detritus and plant material [42, 43]. In Lake Rotoiti they have been shown to live at depths of 7 to 10 metres in the summer, but after the lake destratifies they become widely dispersed across the lake bottom at depths of up to at least 50 metres Lack of hypolimnetic oxygen is the cause of these summer migrations. They probably play a role in nutrient cycling, in that their feeding activities result in the breaking down of larger pieces of organic detritus and plant material [42].

The common bully (*Gobiomorphus cotidianus*) is abundant in most of the Rotorua Lakes, and is a bottom-dwelling species. Most specimens occurring in lakes reach a maximum length of 70-80mm. They are opportunistic carnivores, feeding on a variety of invertebrates, small fish etc [44]. They may be when present in large populations which may reach up to 500/m^2. They do occur in deep water, especially the large adults (they have been recorded at depths down to 70 m in some lakes [45]), but these will presumably migrate into shallower waters to avoid hypolimnetic deoxygenation during the warmer months.

- In the case of Lake Trummen, in Sweden, (discussed earlier in this report, in the section ‘Lessons learned from other dredging operations’) Peterson comments:

> “The effect of dredging on the benthic community of Lake Trummen was absolutely negligible. A year after dredging, tubificids oligochaetes and chironomids were more numerous than before dredging, but the total number of benthic organisms changed little.”

It would be useful to be able to view the biological data arising from this case. Should there be concern about particularly sensitive areas of lake bed in any lake, these areas could be dredged during the summer months, when many of the benthic denizens could be expected to be absent anyway.

RECOMMENDATIONS FOR FURTHER RESEARCH

During the preparation of this report, it became evident that a number of items require further investigation before firm proposals for major dredging operations could be produced. These include (in approximate order of priority in timing):

- Trials to determine whether the upper layer of very fluid sediments (the principal target for dredging) can be adequately detected by precision sonar methods

- Determination of arsenic speciation in sediments of geothermally influenced lakes. (it is probable that the majority of the arsenic present is in inorganic forms, but this needs confirmation; Assoc. Professor Chris Hendy, University of Waikato pers.comm.).
- Determination of the mobility of sediment arsenic during dewatering of dredged material.
- Laboratory and field trials on dewatering sediments and establishing the quickest, most cost effective methods that do not require excessive space.
- Trials of dredging equipment under lake conditions.
- Investigations as to the behavour of freshly exposed lower lake sediments following small-scale dredging trials (i.e. does a new active layer form rapidly)
- Trials of composting wood wastes with sediments to produce soil enhancing products. Trials on possible alternative uses for reclaimed sediments.

COST ESTIMATES FOR A LAKE DREDGING OPERATION

Large scale dredging costs

Obviously, any cost estimates at this stage are preliminary only.
An initial quotation for an appropriate modular dredging unit has been supplied by Ravenstein Container Pontoon B.V., of Dodewaard, Holland. The initial quoted price (2005) is approximately €2.500,000 (approximately $NZ4,400,000) plus taxes and shipping.

Mr Paul Hartley (Hartley Contracting Ltd) considers that an appropriate modular dredge could be built locally in Kawerau, which has the necessary heavy industrial capacity. Three smaller dredges with dredging capabilities up to 20 metres depth have already been built there. At this stage, it would be premature to give any detailed estimates of costs for a large project such as that required to dredge Lake Rotorua.

However, some indications may be taken from the cost estimates to dredge Lake Okeechobee, in Florida. Quoting from the EA 2002 report [39] on the pilot dredging project on Lake Okeechobee:

> "In 1999, the Lake Okeechobee Issue Team of the District developed an action plan for the rehabilitation of Lake Okeechobee. This Plan recommended the removal of all or part of the nutrient laden fluid mud sediments (i.e. upper layers of the lakebed sediment column) to the maximum extent practicable, in order to substantially reduce ecosystem internal phosphorus loading. If these sediments are removed, they must be processed and disposed of in a manner that will not re-contribute phosphorus to the lake or other regional water resources. These sediments in Lake Okeechobee cover more than 80,000 hectares of the lakebed; the approximate volume has been estimated at 200 million cubic meters1. This amount of material is of an order of magnitude greater than has ever been removed from any lake in the world."

Reports of the estimated cost of dredging Lake Okeechobee varied considerably. To quote from a statement on the LakeOkeechobee.org website:

> “Chemically treating sediment, which was anticipated to cost approximately US$493 million over 3 years, was rejected unless programs to reduce external phosphorus loads to the Lake fail to achieve the Lake's TMDL by 2015. The dredging alternative was also rejected despite the success of a May, 2002 in-Lake pilot dredging project (see discussion below). Not only would the cost of dredging be prohibitive (US$3 billion), but dredging would leave behind a small layer of phosphorus-laden target sediment that "would continue to release phosphorus into the water column."
> "Even if an optimistic P concentration is assumed, after 2060 the performance of the dredging alternative is essentially equivalent to the No In-Lake Action alternative."
> ”The rejection of sediment dredging as a viable management option is discouraging given the successful results of the Lake Okeechobee Pilot Dredging Project. This project, which was conducted on the eastern side of the Lake in May, 2002, concluded that the SEDCUT dredge head could effectively remove phosphorus-laden mud from the Lake without significantly impacting Lake water quality or increasing turbidity levels downstream of the dredging area [g]. Although the scale of the pilot project was not comparable to the scale of work needed to resolve loading problems in the Lake, the findings were nonetheless encouraging given the immense amounts of phosphorus-laden mud on the Lake's bottom, the emphasis placed on sediment removal by the Lake Okeechobee Issue Team, and the demonstrated inefficacy of external phosphorus loading control program. As noted above these programs have not reduced phosphorus inflows to the Lake since 1990. Rather, annual inflow rates of this nutrient have actually increased since 1990.” (from LakeOkeechobee.org website)

On the other hand, in a statement to a US Senate Subcommittee Mr Barry Hill (US General Accounting Office [46]) remarked:

> “Although no final decision has been made on what actions to take, a preliminary estimate prepared by an issue team of federal and state scientists showed that fully dredging the lake (Okeechobee) could cost at least US$1 billion.”

The following table from the EA 2002 [39] report is of interest and is presumably responsible for the $1 billion figure being used:

Table 4
Cost Estimate for Full Scale operations (Lake Okeechobee).
After EA, 2002.

Task	**Units**	**Cost**	**Cost/yr**	**30 yr Total**
Dredging	6,666,667 yd^3	$3.02/ yd^3	$20.1M	$604 M
Land Disposal	3,333,333 yd^3	$1.73/ yd^3	$5.7 M	$173 M
Water Treatment	730 MGY	$1,695/MG	$1.2 M	
TOTAL			**$27 M**	**$813 M**

All costs in US$

---

[g] Although the movements of barges, dredging equipment etc in the very shallow environment of Lake Okeechobee did cause turbidity due to disturbance of the loose bottom sediments,

As discussed above, estimates of costs to dredge this large (1900 km^2) lake ranged from US$1 billion (or slightly less) to US$3 billion. On an areal basis, assuming that some 80,000 ha (800 km^2) needs to be dredged, this equates to approximately US$1.25M to US$3.75M per square kilometre.

Applying this to, for example, Lake Rotorua, the following may be calculated:

Table 5
Initial estimate of costs to dredge Lake Rotorua (Based on Lake Okeechobee costs)

Area of lake bed below 10 m depth		43.7 km^2
Approx cost/km^2 (in US$)	$1.25M to $3.75M	
Cost to dredge Rotorua (in US$)	$54.7M to $163.9M	
NZ cost to dredge Rotorua [1]	NZ$84M to NZ$252M [2]	

[1] With $NZ at US$0.65
[2] Rounded off to nearest NZ$1M

There are various factors which would cause variations in this comparison:

- Lake Okeechobee is very much shallower than Lake Rotorua. In practical terms this is not disadvantageous for Rotorua, as the shallow nature of Okeechobee caused considerable difficulties and disruptions to the dredging programme, and would render the use of a large dredge (such as that mentioned above) difficult or impractical. This makes for an inefficient, and costly, dredging project. The EA report notes that since the development of a preliminary conceptual cost estimate without a developed conceptual plan is premature from a good engineering practice perspective, the costs are based on the production rates observed during the pilot test and the historical data produced by the US Army Corps Of Engineers for conventional hydraulic dredging.

- The costs for Lake Okeechobee included an allowance of US$4,600/acre for the substantial areas of valuable land required for the disposal of sediments. In the case of (for example) Lakes Okaro or Rotoiti, it appears probable that such land could be made available at little or no cost, as landowners would benefit in other ways (use of wood wastes, soil enhancement).

- No allowance was made for the potential usefulness of nutrient-rich sediments once removed from the lake.

- Lake Rotorua sediments contain significant amounts of naturally-sourced arsenic, which would need to be removed or stabilised. It would be interesting to determine whether this arsenic could be extracted and put to some use.

Operating costs for a large scale dredging operation would include operator salaries, interest charges on capital, sundry costs and energy costs. It is probable that energy costs would make up a significant proportion of the operating costs. The use of methane, released from sediments during the dredging process, to run the diesel engines of the dredge and ancillary equipment, is worthy of investigation. The cost of dredging may well compare favourably with the costs of sealing or immobilising sediment nutrients.

Peterson [35] comments that the costs of lake rehabilitation works should be amortised over the effective life expectancy of a project in order to make a realistic comparison of the true costs of various lake remediation measures. He uses the example of Lake Trummen (Sweden), where the dredging costs per hectare were approximately US$5722 (1991 dollars), but when amortised over the then 25 years of benefits (now more) the cost per hectare was US$229. He also comments that nutrient inactivation (particularly for phosphorus) introduces potentially harmful materials to the lake, whereas dredging removes them, and this should be borne on mind when comparing the two techniques. To date dredging appears to show a potentially longer-lasting effect than does P inactivation, but the true situation is still unclear.

Smaller-scale dredging costs

Indicative estimates of the costs of smaller-scale trial dredging may be obtained by studying the recent (August 2006) contract awarded to a local dredging contractor for dredging an aeration and treatment pond at a North Island pulp and paper mill.

The dredge, an Ellicott 270 (modified to enable dredging to at least 15 metres depth), delivers sludge slurry to the dewatering ponds via a 200 mm HDPE pipeline at 5000 litres.minute^{-1} . For a 10.5 hour working day, this equated to approximately 3000 m^3.day $^{-1}$. This is equal to a dry solids output of 70 to 130 m^3 per day. Dredge tailings comprised up to 4% solids by volume of liquid.

Initial dredging carried out in 2002, using a similar suction dredge, removed approximately 30000 m^3 of sludge in 3 months i.e. a removal rate of 10,000 m^3 per month or (assuming a 48 hour week) 500 m^3 per day.

The new contract provides for the contractor to carry out the following:

1. Supply, operation and maintenance of the dredge, plus all associated dredging equipment, including but not limited to excavators, anchors, pipelines, small plant and equipment.
2. Supply, operation and maintenance of booster pumps (along the slurry pipeline).
3. Supply, operation and maintenance of dewatering pumps and pipelines.
4. Installation and maintenance of sediment booms and chimney drains.
5. Hydrographic surveys, at 3-monthly intervals, during the course of dredging.
6. Supply, operation and maintenance of flocculant injection equipment.
7. ‘When not engaged in operating or… maintaining the dredge or dredge related equipment, the Contractor’s employees shall be available from time to time and as may be required… to carry out general maintenance works around the effluent treatment ponds, dams and general appurtenances…free of charge to (the client)’

In general, materials, staff facilities, storage facilities, fuel, flocculants, electricity and cranes were supplied by the client. The Contractor was required to have three operators in attendance at the dredge and its associated equipment (while dredging was underway), in the interests of system security.

The contract rates applicable (excluding GST) were as follows.

Service	**Hourly rate**
Dredging (at more or less 48 hours per week)	\$300
General (18 hours per week but providing unlimited use of a 20 tonne hydraulic excavator provided by the Contractor)	\$200
Booster pumps (one or more as required)	\$115

It may be seen that these rates cover a whole range of activities outside the core dredging and pumping of sediment.

For the purpose of this report these costs were applied to a trial dredging scheme, namely to dredge Lake Okaro.

Earlier in this report, the recent sediment survey carried out on Okaro by Hendy and Milicich [6] was discussed. They calculated that about 14.5 tonnes of phosphorus are found in the loose lake sediments, largely in the loose organic seston layer. They comment:

> "If this loose sediment were to be dredged, a layer 0.3 m thick off an area of $3x10^4$ m^2 would remove almost all of the mobile phosphorus**,** giving approximately 100,000 m^3 of sludge, which upon dewatering would yield approximately 25,000 tonnes of dried sediment. The phosphorus content of the then exposed sediment at the lake bottom would then be reduced to about 10% of that of the current lake/sediment interface."

If a dredging operation, similar in scale to that discussed in the pulp and paper mill pond (above) was carried out in Lake Okaro, an initial estimate of costs may be prepared. This estimate applies only to the physical costs of dredging, and does not cover the costs of consultation, obtaining resource Consents or acquiring land for sediment dewatering [h]. It also does not include any possible financial, or other, contributions that might be received from nearby wood processors for assistance with their wood waste problems.

The estimate of dredging costs is based on those in effect at the pulp and paper mill site, which cover a number of items unlikely to be required at the Lake Okaro site. For example, general site maintenance on areas unrelated to the dredging project, regular Hydrographic surveys etc. For this reason, this estimate is viewed as a 'worst case' scenario. It is based on August 2006 costs. The cost estimate is shown below in **Table 6**.

The seston layer of sediments in Lake Okaro are very fluid, with a water content of 90 to 95% by weight and a bulk density of 0.26 g cm^{-3} (Hendy and Milicich 2005 [6]). This is a similar density to that of the dredge tailings in the pulp mill dredging programme (up to 4% solids by volume) and it is likely that a properly set up dredge would remove this fluid seston layer without entraining very much additional lake water. It is claimed that the slurry from a cutter-suction dredge may have a solids

---

[h] Considering that the (agricultural) land used for dewatering would probably end up being more productive once the dredging project had been completed, it is unlikely that such land would need to be purchased.

content of between 30 and 40 percent (Duder and Venus 1991 [3]), so that there should be no problem in dredging and pumping such a fluid mixture.

Table 6
Estimated dredging costs for Lake Okaro

Item	Quantity	Rate	Result
Dredge sediment from lake bed	100,000 m^3	500 m^3 per day	200 days
Operate dredging @ 10 hours/day	200 days (2000 hours)	$300 per hour	$600,000
General services @ 3.6 hours/day [i]	200 days (720 hours)	$200 per hour	$144,000
Booster pump (one) [j]	200 days (2000 hours)	$115 per hour	$230,000
Total dredging costs [k]			**$974,000**

---

[i] At the pulp mill site used as an example, this item also covered a number of general maintenance tasks that would be unlikely to apply at Lake Okaro. It also included regular Hydrographic surveys.

[j] The dredging operations at the pulp and paper mill involved pumping 1 to 2 km against a considerable head. The land around Lake Okaro is generally of reasonably level contour and only a few metres above lake level. It is probable that booster pumps may not be needed, depending on the dewatering site chosen.

[k] This represents something of a ‘worst case’ scenario, given that general services and booster pump costs are likely to be significantly lower than at the pulp mill site used as an example.

OTHER MATTERS TO BE CONSIDERED

PRECONDITIONS FOR DREDGING

Dredging is an expensive option, and there is little point in carrying it out if any beneficial effects from it are likely to be undone in a short space of time. It is therefore suggested that any programme of dredging lakes is not carried out until the following pre-conditions have been satisfied:

- Lakeside settlements have been sewered or provided with efficient wastewater treatment system, or such work has been scheduled.
- Whatever land use changes, seen as necessary in the catchment, are underway or have been scheduled.
- All practical steps have been taken, or scheduled to be taken, to reduce other external nutrient loads, including those from both anthropogenic and natural sources.
- All possible steps have been taken, or scheduled to be taken, to reduce silt and sediment inflows.
- The lake should be one that is considered likely to benefit from dredging.
- There is a consensus of scientific opinion that water quality in the lake would benefit from dredging (as was the case, for example, with the Ohau Channel outlet diversion).

Obviously, dredging would only be a practical option for certain of the Rotorua lakes. Such lakes would be those that are experiencing severe water quality problems and which undergo considerable nutrient recycling from the sediments during anoxic periods, or those which seem likely to do so in the near future. Potential candidates include:

- Lake Okaro (severe cyanobacterial blooms, enriched sediments with releasable phosphorus, small lake, sediment survey carried out).
- Lake Rotorua (severe cyanobacterial blooms, enriched sediments with releasable phosphorus, sediment survey carried out).
- Lake Rotoiti (severe cyanobacterial blooms, enriched sediments with releasable phosphorus, detailed sediment survey not yet carried out).
- Lake Rotoehu (severe cyanobacterial blooms, enriched sediments with releasable phosphorus, sediment survey not yet carried out).
- Lake Okareka (no major water quality problems as yet, some minor cyanobacterial blooms, but the cause of some concern for the future).
- Lake Tarawera (no major water quality problems as yet, some minor cyanobacterial blooms, but the cause of some concern for the future. Recent research shows that large quantities of nutrients are stored in its sediments).

COMPARISON OF SOME NUTRIENT LIMITING MEASURES

Recent work has shown the pronounced influence of the release of nutrients from sediments on some of the Rotorua lakes. This phenomenon occurs during periods of hypolimnetic anoxia. As discussed earlier, it is essential to break this self-perpetuating cycle of anoxia accompanied by nutrient release. This could be carried out by preventing lake stratification or by resupplying oxygen to the hypolimnion during stratification. Both of these options may be expected to be difficult and expensive in the case of a large lake. Research is also being carried out on a variety of means of immobilising sediment nutrients or ‘capping’ sediments, using such materials as modified bentonites or zeolites, allophane clays etc, or through oxidising sediments by a variety of techniques.

The following table compares the cost, life expectancy, advantages and disadvantages of some of these techniques, using known examples where possible.
There is a difficulty in compiling such a table, in that many discussions on lake treatments do not discuss the costs involved. In addition, some projects (particularly dredging projects) are poorly documented.

Table 7
A comparison of some lakes rehabilitation measures

Technique Example & year	**Scale***	**Cost**	**Life expectancy** years	**Cost/year**	**Advantages/disadvantages**	**Reference**
Oxygenate hypolimnion					No residues / May not be self sustaining solution	
Amisk Lake North (Canada)1990-1993	230 ha/ 10.8 m	C$30,000 (capital)	While operated	C$49,000	Decreased hypolimnetic N and P Diatoms favoured over cyanobacteria / Increased HOD	Prepas and Burke 1997 [47]
Lake Sempach (Switzerland) 1986-1996	1350 ha/ 90 m		While operated	CHF 80,000 **	Increased hypolimnetic [oxygen] / No significant reduction in sediment P release. No improvement in fish popn.	Gächter and Wehrli 1998 [48]
Lake Rotoiti (proposed)		$NZ1.5 M (capital)	While operated	NZ$ 1.2 M	No residues / Western end of lake not treated. Uncertain environmental impacts	Mistry et al (2003 [49])
Destratification/ aeration						
Myponga Reservoir (Aust) from 1994	280 ha/ 15 m	Capital cost not known		A$30,000	Shorter *Anabaena* season Reduced nutrient fluxes	Brooks (2005 [50])
Aluminium treatment						
Lake Okaro						
Three Mile Pond (USA) 1988	266	$US 170,000				
Phoslock						
Lake Okareka		~$300,000	Unknown		Possible reductions in water column P / Uncertain environmental impacts	McIntosh (2006 [51])

Technique	Scale*	Cost	Life expectancy	Cost/year	Advantages/disadvantages	Reference
Sediment oxidation (Riplox)					Potential alternative to alum, dredging / Lack of documented success	
Lake Trekanten (Sweden) 1980	49 ha/ >3m	US$340,000 (1990 cost)	Low		Some reduction in P release Few toxicity problems High external loading not addressed	Peterson 1993 [35]
Dredging of sediments						
Lake Trummen (Sweden) 1970-71	100 ha/ 1.75 m	$US 572,000	30 yrs plus	$19,000	Nutrient concentrations declined, SD increased, cyanobacterial biomass decreased substantially	Peterson 1993 [35]

*Scale is Lake Area Treated(ha)/ mean Depth (m)
** Assuming oxygenation for 3 months/year in Lake Sempach

ACKNOWLEDGMENTS

Thanks are due to the following for assistance in preparing this report:

Paul Dell, Environment BOP
John McIntosh, Environment BOP
Associate Professor Chris Hendy, University of Waikato
Professor David Hamilton, University of Waikato
Olivia Drake, University of Waikato
Paul Hartley, Hartley Contracting Ltd.
Alison Slade, Scion
Dr Dell Bottcher, Soil and Water Engineering Technology Inc., Florida
Elizabeth Miller, for proofreading

REFERENCES

---

[1] Cooke, D.G., Welch, E.B., Peterson, S.A. and P.R. Newroth. 1993. *Restoration and Management of Lakes and Reservoirs*. CRC Press LLC, Boca Raton, Florida. 548 pp.

[2] Rotorua Conservation Society. 1971: Proceedings of the seminar 'Top Dressing - Bottom Dredging' held at Rotorua August 14th & 15th, 1971. Rotorua Conservation Society. Rotorua. 34 pp.

[3] Duder, J.N and G.C. Venus. 1991. Lake Rotorua dredging and Reclamation Feasibility study. *Report prepared for Rotorua District Council* by *Tonkin and Taylor Ltd., Brian Coffey and Associates Ltd., Barnett Consultants Ltd., McCabe and Associates Ltd. and Barry Rae Consultants Ltd.* November 1991.

[4] Hamilton, D.P., Alexander, W. and D. Burger. 2003. Nutrient Budget for Lakes Rotoiti and Rotorua; Part 1: Internal Nutrient Loads. *Report prepared for LakesWater quality Society by University of Waikato. December 2003.*

[5] Livingston, M.E., Biggs, B.J. and J.S. Gifford. 1986. Inventory of New Zealand Lakes: Part 1. North Island. Water and Soil Directorate, Ministry of Works and development for the National Soil and Water Conservation Authority. Wellington, 1986

[6] Hendy, C.H. and S. Milicich. November 2005. Sediments of Lake Okaro. *Report prepared for Environment BOP by Chemistry department, University of Waikato.*

[7] C. Hendy. 2006. Report on the Composition, Nature and Distribution of Sediments in Lake Rotorua. I *Report prepared for Hartley Contractors Ltd. by Department of Chemistry, University of Waikato. January 2006.*

[8] B. Love. 2004. Preliminary Investigation Report: Agricultural Residue Concentrations in the Bay of Plenty. *Report prepared by SEM New Zealand Ltd. for Environment Bay of Plenty.* September 2004.

[9] Mfe/MoH 1997. Health and Environmental Guidelines for Selected Timber Treatment Chemicals. Ministry for Environment and Ministry of Health, Wellington 1997.

[10] Ministry for the Environment, 2003. Contaminated Land Management Guidelines No. 2: Hierarchy and Application in New Zealand of Environmental Guideline Values. MfE, Wellington, November 2003.

[11] ANZECC/ARMCANZ 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Volume 2, Aquatic ecosystems. Australian and New Zealand Environment and Conservation Council; Agriculture and Resource Management Council of Australia and New Zealand. Canberra, 2000.

[12] Hawley, N. 2004. Response of the benthic nepheloid layer to near-inertial internal waves in southern Lake Michigan. *J. Geophys. Res.*Vol **109** CO4007, doi:10.1029/2003JC0021028.

[13] Blomkvist, D. and L. Lundstedt. 1995. Sediment Investigation of the Rotorua Lakes. *Environment B.O.P. Environmental report 95/23*. ISSN 1172 5850. November 1995.

---

[14] A. Sakamoto. 1998. Cement and soft mud mixing technique using compressed air-mixture pipeline: Efficient solidification at a disposal site. *Terra et Aqua* **73** December 1998 11-22.

[15] Macpherson, J., Ziemer, J. and M. LeMaster. 2003. Innovative crabshell extract used to treat Superfund cleanup site. *World Dredging and Construction.* July 2003. 6-7,26-29.

[16] Wichman, B.G.H.M., Sills, G.C. and R. Gonzalez. 2000. Experimental validation of a finite strain theory for gassy mud. *Canadian Geotech. J.* **37** (6) 1227-1240.

[17] M. Gentilomo. 1999. Mechanical treatment of dredged material. The Malcontenta Plant in the Lagoon of Venice. *Terra et Aqua* **76** September 1999 22-29

[18] Davenport, R. and A. Spacie. Acute phototoxicity of harbour and tributary sediments from lower Lake Michigan. 1991. *J. Great Lakes Res.* **17** (1) 51-56.

[19] N.C. Miller. 2003. An initial technical review of: Final Report, Waipa Sawmill Remediation Cost Estimates (A report prepared by URS New Zealand). *Review prepared by Analytical & Environmental Consultants for APR Consultants.* September 2003.

[20] Camp Scott Furphy. 1992. Pentachlorophenol Risk Assessment Pilot Study. *New Zealand National task group on Site Contamination from the Use of Timber Treatment Chemicals: National Task Group Study team report.* Prepared for the Ministry for the Environment and the Department of Health. July 1992.

[21] Minister of Supply and Services, Canada. 1989. ‘Chlorophenols and their Impurities: A Health Hazard Evaluation. Environmental Health Directorate, Health protection Branch. (Not seen.)

[22] H.P. Laboyrie. 2000. The handling and treatment of contaminated dredging material in the Netherlands. *Report from* Civil Engineering Division, Ministry of Transport, Public Works and Water Management of the Netherlands. www.kmi.re.kr/english/data/publication/9-1.pdf

[23] H. Hartnack. J.v. Steenwijk, P.C. Steenkamp. 1997. Recommendation for Environmental Impact Assessment on the disposal of Contaminated Dredged Material in Open and Semi-closed disposal Sites, *Preprints of the International Conference on Contaminated Sediments 1997.* (Not sighted)

[24] Laboyrie Hypolite P., Flach Bert. 1998. The Handling of Contaminated Dredged Material in The Netherlands. Proceedings 15th World Dredging Congress, Las Vegas, Neveda, USA, 1998.

[25] Ministry for the Environment. 2003. Contaminated Land Management Guidelines No. 2: Hierarchy and Application in New Zealand of Environmental Guideline Values. November 2003.

[26] Ministry of Health; Ministry for the Environment. 1997. Health and Environmental guidelines for Selected Timber Treatment Chemicals. Wellington, June 1997.

[27] NEPC. 1999. Schedule B(1); Guideline on the Investigation Levels for Soil and Groundwater. National Environment Protection Council. Australia. 1999.

---

[28] Investigation into the possible extraction of arsenic components from a liquid phase. *Report prepared by N.Z Steel Ltd. for Analytical & Environmental Consultants. October 2004.*

[29] N.C. Miller. 2005. Absorbing minerals, sediment sealing and flocculants for chemical remediation of lake water. *Report prepared for Environment Bay of Plenty by Analytical & Environmental Consultants*. August 2005.

[30] A. Kurata. 1994. Organic matter accumulation in the bottom sediments and its regulatory aspects in the southern basin of Lake Biwa. H*Journal of Aquatic Ecosystem Stress and Recovery (Formerly Journal of Aquatic Ecosystem Health)H.* **3** (3) 171-176

[31] Darmody, R.G. and J.C. Marlin. 2002. Sediments and Sediment-Derived Soils in Illinois: Pedological and Agronomic Assessment. *Environmental Monitoring and Assessment.* **77** (2) 209-227.

[32] E. Paipai. 2003. Beneficial Uses of Dredged Material: Yesterday, Today and

Tomorrow. *Terra et Aqua* **92** 3-12

[33] Arts, T. and B. Kappe. 1996. The Sweep Dredge: High accuracy dredging trials continue. *Terra et Aqua* **65** December 1996 18, 25

[34] S. Vandycke. 1996. New developments in Environmental dredging: from Scoop to Sweep dredge. *Terra et Aqua* **65** December 1996 19-25.

[35] S.A. Peterson. 1993. Sediment Removal. *In* Cooke, D.G., Welch, E.B., Peterson, S.A. and P.R. Newroth. 1993. *Restoration and Management of Lakes and reservoirs*. CRC Press LLC, Boca Raton, Florida. 548 pp.

[36] Van der Does,J., Verstraelen' P., Boers, P., Van Roestel J., Roijackers, R. and G. Moser. 1992. Lake restoration with and without dredging of phosphorus-enriched upper sediment layers. *Hydrobiologia* **233** (1-3) 197-210.

[37] Sven-Olof Ryding. 1992. Lake Trehörningen restoration project. Changes in water quality after sediment dredging. *Hydrobiologia*. **91-92** (1) 549-558.

[38] Arts, T., Borst, W. Elsman, R., Kappe, B., Mullie, T., Pennekamp. J., Rosenbrand, W. and K. Spelt. 1995. High accuracy Sanitation Dredging Trials. *Terra et Aqua* **61** December 1995 3-12.

[39] EA. 2002. Lake Okeechobee Pilot Dredging Project Report. *Report prepared for* South Florida water Management District *by* EA Engineering, Science and Technology Inc. (Authors not listed.) December 2002.

[40] A.B. Bottcher. 2004. Approaches for Nutrient Management in the Lake Okeechobee Watershed. *In* Proceedings, Rotorua Lakes 2003; Practical Management for Good Lake Water quality. 136-142. LakesWater Quality Society, Rotorua, March 2004.

[41] Wells, R.; Clayton, J. 1996. The impacts of weed beds and diquat spraying on the freshwater mussel, *Hydridella menziesi*. *NIWA Consultancy Report Project No. DOC 312*

---

[42] Chapman, M.A.; Lewis, M.H. 1976. *An Introduction to the Freshwater Crustacea of New Zealand.* William Collins (New Zealand) Ltd. Auckland.

[43] Devcich, A.A. 1979. Ecology of freshwater crayfish in Lake Rotoiti. *Unpublished PhD Thesis*, University of Waikato.

[44] McDowall, R.M. 1990. *New Zealand Freshwater Fishes: A Natural History and Guide*. Heinemann Reid, Auckland.

[45] Rowe, D.K. 2004. Lake Restoration. *In* Harding, J.S.; Mosley, M.P.; Pearson, C.P. and Sorrell, B.K. (editors) 2004. Freshwaters of New Zealand. New Zealand Hydrological Society Inc. and New Zealand Limnological Society Inc., Christchurch, New Zealand. 764 pp. ISBN 0-476-00708-9.

[46] Barry T. Hill, Associate Director, Energy, Resources and Science Issues, Community and Economic Development Division United States General Accounting Office. *Statement before the Subcommittee on Transportation and Infrastructure, Committee on Environment and Public Works, U.S. Senate.* September 20, 2000. http://epw.senate.gov/107th/hil_0920.htm

[47] Prepas, E.E. and J.M. Burke 1997. Effects of hypolimnetic oxygenation on water quality in Amisk Lake, Alberta, a deep eutrophic lake with high internal phosphorus loading rates. *Can. J. Fish. Aquatic. Sci.* **54** 2111-2120

[48] Gächter, R. and B. Wehrli 1998. Ten Years of Artificial Mixing and Oxygenation: No Effect on the Internal Phosphorus Loading of Two Eutrophic Lakes. *Environ. Sci. Technol.* **32** 3659-3665.

[49] Mistry, P.; Newsom, P. and M.Ogston. 1003. Rejuvenating Lake Rotoiti: BOC findings and recommendations for the oxygenation of Lake Rotoiti. *Report prepared by BOC Ltd. for Environment BOP.*

[50] Brooks, J. 2004. Detecting, predicting and managing cyanobacteria in source water *In* Proceedings, ROTORUA LAKES 2004: Restoring Lake Health - Nutrient Targets and Cyanobacteria. LakesWater Quality Society, October 2005.

[51] McIntosh, J. 2006. Phoslock Aplication – Lake Okareka. Environment BOP Environmental Publication 2006/06. May 2006.

Appendix A
OUTLINE ASSESSMENT OF ENVIRONMENTAL EFFECTS

This outline assessment is intended to form the basis for an Assessment of Environmental Effects for a lake dredging application. The example lake chosen is Okaro, as a potential candidate for trial dredging.

The document basically consists of a series of section headings, intended to indicate topics that would need attention in a full AEE. Explanatory notes, in italics, are provided where appropriate. At such an early stage of a project that is only under initial consideration, little detail is, as yet, available.

PROPOSAL TO DREDGE SEDIMENTS FROM LAKE OKARO AND TO DISPOSE OF DREDGINGS ON TO LAND: ASSESSMENT OF EFFECTS

(Outline only)

EXECUTIVE SUMMARY

Too early to provide this

INTRODUCTION

Lake Okaro, which is of modest size yet reasonably deep, appears to be a suitable candidate for a trial of sediment dredging, using equipment that is currently available in the Bay of Plenty Region. The fact that much of the available phosphorus is concentrated in the top 30 cm of sediments renders dredging a promising approach towards reducing the regeneration of sediment nutrients. Estimates by Hendy and Milicich suggest that approximately 100,000 m^3 *of material would need to be removed, and this would yield about 25,000 tonnes of dried nutrient-rich sediment which appears to be suitable for application to farmland or forested areas. Much of the area of the lake is between 10m and 18m deep, which makes it a good candidate for trials on dredging larger lakes of similar depth, such as Lake Rotorua. It is recommended that this option be investigated further. The relatively flat, and rural, nature of the surrounding land means that a suitable dewatering site should not be difficult to find. A nearby saw milling operation provides a supply of wood wastes to be composted with reclaimed sediments if that option is shown to be worthwhile.*

DESCRIPTION OF PROPOSALS

Insufficient detail at this stage.

TECHNICAL DETAILS OF PROPOSALS

Dredging process

An Ellicott 270 dredge (modified to enable dredging to at least 19 metres depth), would be used to deliver sludge slurry to the dewatering ponds via a 200 mm HDPE pipeline at 5000 $\text{litres.minute}^{-1}$. *For a 10.5 hour working day, this equates to approximately 3000* $m^3.\text{day}^{-1}$. *This is equal to a dry solids output of 70 to 130* m^3 *per day. Dredge tailings comprise up to 4% solids by volume of liquid.*

*These would be dewatered at (*site yet to be identified).

Considerable further detail would be added as the proposal solidified.

Sediment pumping process

Insufficient detail at this stage.

Mixing dewatered sediment with other materials and depositing on land

Insufficient detail at this stage.

ADVANTAGES OF PROPOSALS

Discussion of rational for dredging, environmental advantages in terms of lake quality etc.

ALTERNATIVES TO PROPOSALS

Discussion of other options e.g. sediment capping, nutrient inactivation, prevention of stratification, hypolimnetic oxygenation etc.

PLANNING IMPLICATIONS OF PROPOSALS

Extensive discussion of RMA implications, Regional Soil and Water plan, RDC District Plan etc.

CULTURAL IMPLICATIONS OF PROPOSALS

Extensive discussion by appropriate authority.

ASSESSMENT OF ENVIRONMENTAL EFFECTS

IN-LAKE EFFECTS

Chronological sequence of dredging

Areas of sediments to be dredged

Depth of sediments to be dredged

Vertical distribution of nutrients down sediment profile

Vertical distribution of contaminants down sediment profile

Ability to discriminate between sediment levels while dredging

Impacts on water quality

Suspended sediments

Turbidity

Dissolved Oxygen

Water chemistry

Release of contaminants

Sites of hypolimnetic oxygen demand

Long-term effects on hypolimnion

Long-term effects on lake water quality

Short-term effects on lake water quality

Proposed dredging monitoring programme

All needing discussion – fairly self-evident limnological matters. Specialist input required.

IMPACTS ON BIOTA

Flora
Macrophyte flora
Algae and phytoplankton flora
Fauna
Pelagic fauna
Benthic fauna
Avifauna

All needing discussion – fairly self-evident. Specialist input required.

OTHER IMPACTS

Noise

Noise from dredge, ancillary craft and equipment, booster pumps, trucks, heavy machinery etc. Specialist input required.

Odour

Odours due to dewatering and composting of sediments. *Specialist input required.*

Visual effects

Visual effect of dredge, equipment, pipeline, sediment dewatering areas

Traffic

Additional light and heavy traffic, transporting dredge and associated equipment, pipeline etc. *Specialist input required.*

Effects on navigation

Mainly to do with effects of floating pipeline – need to be clearly marked, lit at night, some areas to be sunk to permit boat passage, etc. also lighting etc of dredge, posting of warning signs, possible speed or use restrictions while dredge operating etc.

Effects of pipelines

Mostly covered in previous section.

EFFECTS AT DISPOSAL SITE

Proposed future land use at site

Suitability for agriculture etc. *Specialist input required.*

Impacts on topography and ground stability
Geotechical input may be required

Impacts on fauna and flora
Specialist input may be required

Impacts on soil quality
Specialist input may be required

Selection of criteria for contaminant levels
Discussion regarding MfE Hierarchy, application of various standards etc.

CONTAMINANTS
Arsenic
Short discussion – not a problem in this lake.

Mercury
Data not yet available – unlikely to be a problem.

Nutrients
Discussion on agronomic effects of nutrients in dredged sediments, also potential to enter ground or surface waters etc.

Other contaminants
No data at present.

Wood wastes
No data at present.

Dioxins
No data at present.

Mitigation of contaminants
No data at present.

On-site treatment
No data at present.

Vegetation uptake and phytoremediation
No data at present.

Volatilisation
No data at present.

OTHER ENVIRONMENTAL IMPACTS
Erosion
Specialist input may be required

Impacts on stream flows
Specialist input may be required

Impacts on ground water
Specialist input may be required

Impacts on springs
Specialist input may be required

Impacts caused by retention dam construction and operation
Specialist input may be required

Retention dam engineering and safety issues
Specialist input may be required

Visual effects
Specialist input may be required

Roads and traffic
Specialist input may be required. Heavy traffic for transport of wood wastes or other amending materials, composted sediment etc.

Noise
Specialist input may be required

Odour, dust
Specialist input may be required

Safety
Specialist input may be required

PROPOSED MITIGATION MEASURES
Self evident

PROPOSED DISPOSAL MONITORING PROGRAMME
Self evident

CONCLUSIONS AND RECOMMENDATIONS
Will emerge as project evolves

PROPOSED CONSENT CONDITIONS
Will emerge as project evolves

REFERENCES
Self evident

APPENDICES
Various technical reports.