Management options for Modellers Pond, Tahunanui, Nelson

NIWA Client Report: HAM2011-001
November 2010

NIWA Project: ELF11216

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Executive Summary

Modellers Pond was constructed over 50 years ago and is a 0.8 ha pond less than 1 m deep. It is the focal area for the Nelson Society of Modellers Inc. for sail and powered model boats with model trains around the perimeter and the area is a significant attraction popular with families, enthusiasts and the general public. It is also used for storm water disposal pumped from Centennial Rd intersection area at times of heavy rainfall.

The Nelson City Council approached NIWA for advice on Modellers Pond Tahunanui, Nelson, (through the Envirolink Fund of the Foundation for Research, Science, and Technology) to review management options for weed and algal problems in the pond with considerations of pond design, its integrated storm water disposal function, and avoidance of contamination from herbicide use.

We reviewed information provided by Council and the Modellers Society on the pond use and past management and had an on site meeting with the parties identifying past problems and outcomes sought. We examined the biota in the pond and collected some of the plants for herbicide testing and algae for identification.

Ruppia megacarpa was the only macrophyte found growing in the pond and the algae were composed of a number of Chlorophyta (filamentous green algae). They included the genera *Cladophera*, *Ulothrix*, *Ulva* (syn. *Enteromorpha*) and *Spirogyra* (*Spirogyra* at one location only), all common algae well known for forming nuisance blooms.

The concerns identified were:

1. Excessive growths of water weed and algae detracting from the aesthetics of the pond, and entangling model boats.

2. Low water levels in the pond over summer, resulting from evaporation and percolation through the bottom sediments, that hinder model boats and detract from the aesthetics of the area.

3. Poor water quality in summer when the pond can go stagnant and appears black and unattractive.

4. Accumulations of rubbish (bottles, cans, wrappers etc.) and decaying organic detritus which in combination with duck faeces forms an undesirable organic sludge on the bottom of the pond.

5. Build up of copper residues from weed control in the past (resulting from copper sulphate over use).

6. Storm water pumped into the pond from a nearby intersection contains sediment and contaminants associated with road washings.

The options available range from do nothing, to lining and maintaining it to clean clear swimming pool standards, with both extremes being inappropriate for outcomes sought. The weed and algal control options considered included flushing, desiccation, glyphosate, diquat, copper, hydrothol, chlorine, dye, bottom lining and deepening.

Recommendations are:

- *In the interim* use regular flushing (~ every two months) in summer to reduce algal biomass and to help maintain water quality, and use glyphosate when empty for algae and *R. megacarpa* control. A dye treatment could be tried after filling to improve aesthetics and see if it reduces algal and *R. megacarpa* growth rates. If greater levels of control are needed then alkylamine endothall (Hydrothol 191) is likely the best options available. However weed control adding decaying organic matter will reduce oxygen levels in the pond water. Copper is not recommended for long term use as it will accumulate.

- *In the longer term* bottom lining the pond would greatly facilitate pond management by controlling the *R. megacarpa*, reducing sediment re-suspension, stop pond seepage and facilitate regular flushing and bottom cleaning. It would help deter macro-algal growth, and greatly reduce the oxygen demands of the pond system. The measurement of dissolved oxygen (via handheld meter) concentrations in the pond to monitor the extent and / or seasonality of anoxia would be beneficial for future pond management initiatives.

1. Introduction

The Nelson City Council approached NIWA for advice on Modellers Pond Tahananui, Nelson, (through the Envirolink Fund of the Foundation for Research, Science, and Technology; Contract 935-NLCC) to review management options for weed and algal problems in the pond with considerations of pond design, its integrated storm water disposal function, and management of contamination from herbicide use.

Modellers Pond is located in Tahunanui, Nelson (Fig. 1), at the top of a tidal estuary (Fig. 2). It was initially constructed pre-1945 and then re-formed in 1959 as noted on a photograph in the Modellers Society display room (Fig. 3). The pond is oval, shallow (<1.0 m) and on a sand base with no natural surface water inflow (Fig. 4), and insignificant ground water inflow. Modellers Pond is part of a recreational area with roading, parking and planting recently upgraded in the immediate vicinity. The pond is the focal area for the Nelson Society of Modellers Inc. for sail and powered model boats and society members have largely developed it and maintained it over the years. There is also a small model boat for children's rides and a network of model trains around the perimeter. The area is a significant attraction popular with families, enthusiasts and the general public.

The pond water is usually 'super' saline being filled with sea water during spring high tides above 4.3 m. Water is held and released by operating manual metal gates with rubber seals (Fig. 5) and is lost through evaporation and percolation through the bottom sediment at a rate of up to 11 mm day^{-1} (John Caldwell, Modellers Society, pers. comm.). Supplementary water can be added from the city water supply, but its use is now limited by Council to maintaining a maximum depth of 150 mm below full at times when there are no water restrictions and not within one week of a high spring tide.

Modellers Pond is also used by Nelson City Council for storm water disposal pumped from Centennial Rd intersection area at times of heavy rainfall. Such discharges can be potentially toxic but using the pond as a sediment trap is a cost effective option of dealing with the discharge.

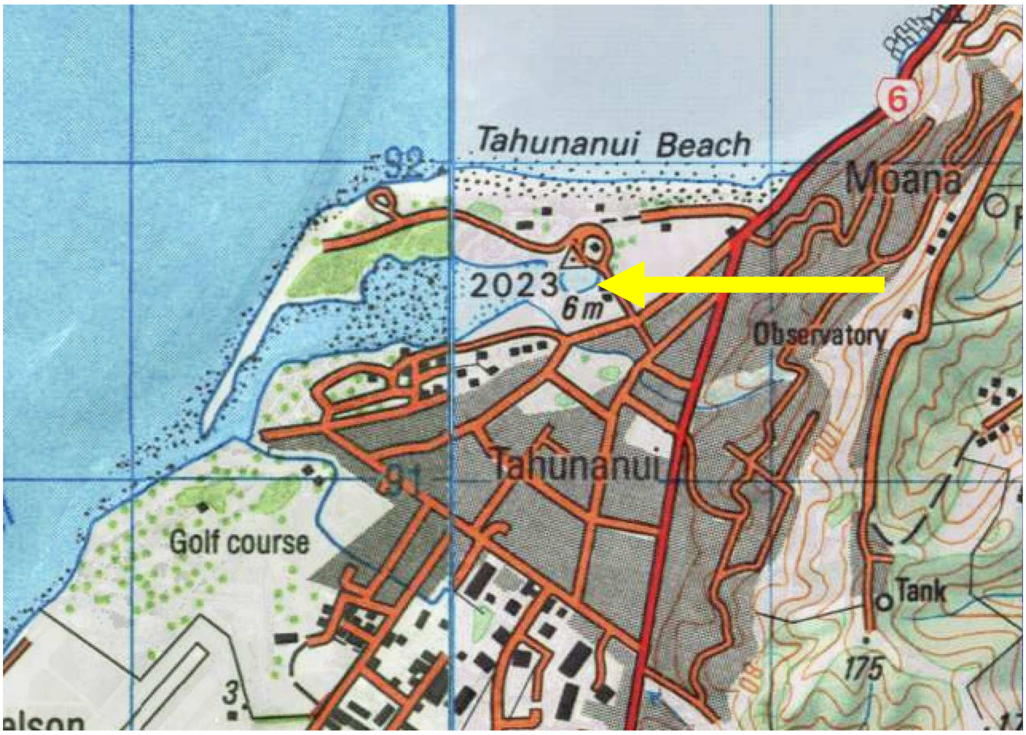

Figure 1: Arrow shows location of Modellers Pond at Tahunanui, Nelson.

Figure 2: Tahunanui tidal estuary viewed from the outlet of Modellers Pond.

Figure 3: Modellers Pond was re-constructed in 1959 (photo courtesy of Nelson Society of Modellers Inc).

Figure 4: Modellers Pond showing part of the enclosed area (foreground) for radio controlled boats, and the remainder of the pond (some 0.8 ha) for larger boats with a raised stone storm water inlet structure (far end).

Figure 5: Outlet gates at Modellers Pond, Tahunanui, bolted shut to retain water.

A literature search for ponds of similar size and nature was conducted and to our best knowledge there are no other similar systems in New Zealand or overseas. Natural saline ones such as Waituna lagoon, Bluff, and Lake Ellesmere, Christchurch are managed primarily as natural ecosystems, whereas a range of concrete lined saline ornamental ponds exist, but they are completely artificial and are managed more like a swimming pool for contact recreation.

2. Site visit

On 24th November 2010 we met with Nelson City Council and John Caldwell representing the Modellers Society on site. They explained the workings of the pond and the problems encountered, and we waded across the pond to examine the resident biota. The pond was less than 0.7 m deep at the time, had turbid water (about 0.4 m visibility), and soft flocculent sediment up to ~ 0.1 m thick.

No invertebrates or fish were seen but wildfowl, particularly ducks were present.

Ruppia megacarpa was the only macrophyte present (Fig. 6). *R. megacarpa* (sometimes called horse's mane) is a native (though not endemic) coastal species growing in brackish water or saline ponds and lagoons. Much of its habitat has been modified and lost in New Zealand so it is now uncommon though abundant at some sites such as Waituna Lagoon, Bluff. *R. megacarpa* was present throughout the pond but was of low abundance due to the pond being drained and treated with glyphosate just three weeks prior to our visit (Fig. 7). Less than 1% of the pond had surface-reaching *R. megacarpa* and algae at the time. The surface algal accumulations were present in downwind areas and were comprised of Chlorophyta or filamentous green algae (Fig. 8). They included the genera *Cladophera*, *Ulothrix*, *Ulva* (syn. *Enteromorpha*) and *Spirogyra* (*Spirogyra* at one location only), all common algae well known for forming nuisance blooms.

R. megacarpa was collected and tested for susceptibility to diquat and glyphosate. In the un-replicated test *R. megacarpa* shoots were subject to a 2 week treatment of 1 ppm diquat, 1% glyphosate and a control which had no herbicides. Both the diquat and glyphosate were confirmed to have herbicidal effects on *R. megacarpa* with fragmentation and loss of plant biomass (Fig. 9).

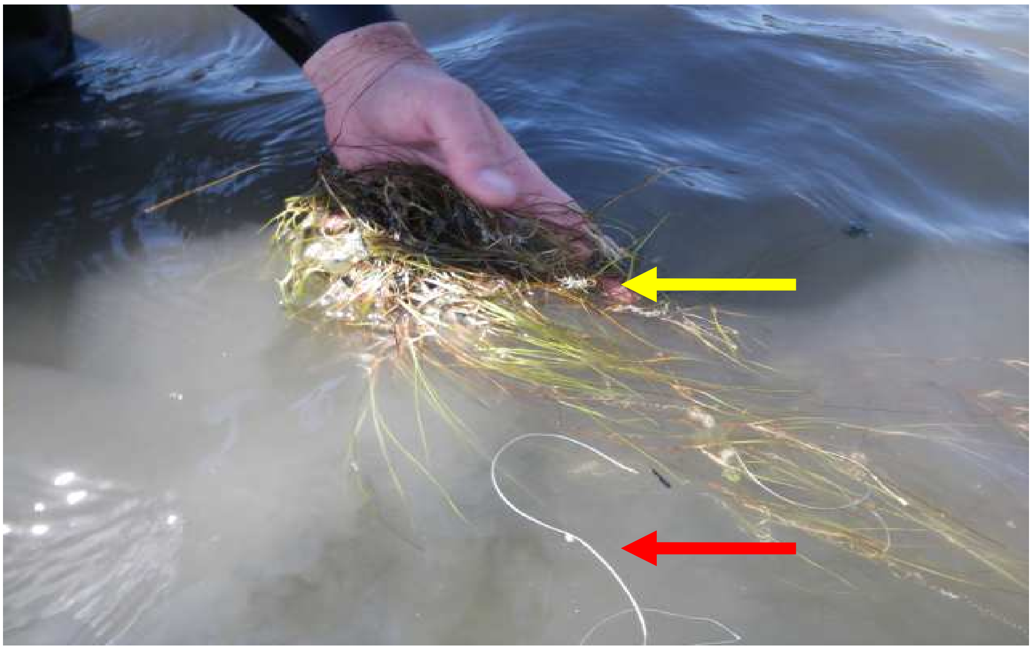

Figure 6: *Ruppia megacarpa* was the only macrophyte present in Modellers Pond. The plant has small flowers that are terminal on white stalks (red arrow) which reach the water surface. Following pollination the flower stalk retracts in a characteristic coil with the maturing fruit (achenes) as shown (yellow arrow).

Figure 7: Under water photograph of *Ruppia magacarpa* (covered in flocculent sediment) and hard hit by glyphosate applied when the pond was drained about 3 weeks previously.

Figure 8: Algae at the pond outlet. The large green one is *Ulva intestinalis*, a smaller *Ulva* species is below and *Cladophora* is the main species present in the top of the picture.

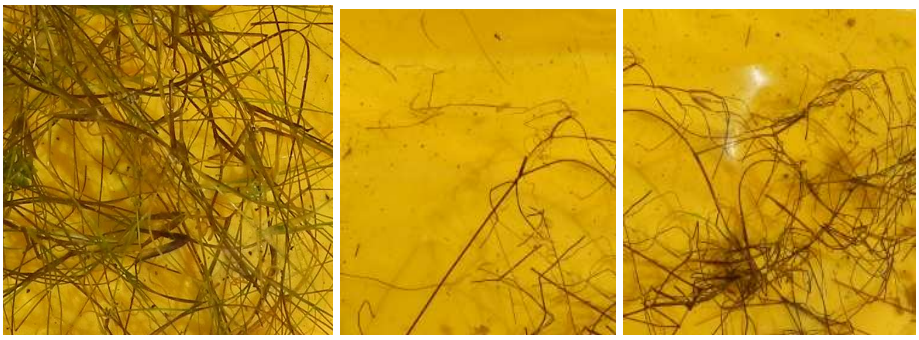

Figure 9: *R. megacarpa* herbicide treatment test results after 2 weeks: left untreated control, middle diquat 1ppm, right glyphosate 1%. What little remained in the two herbicide treatments was flaccid and mostly dead.

3. Pond management

Water quality has been managed by flushing the pond; draining and later re-filling on a spring high tide greater than 4.3 m. This needs to be done at intervals of less than 3 months over summer before the water goes anoxic (stagnant) and appears black. When drained the opportunity is also taken to remove accumulated debris and rubbish by hand.

On four occasions to date when the pond has been emptied, bottom sediments have been scraped out using earthmoving machinery to remove the build up of sludge. This also removed much of the weed and algae for a month in summer but within 2 months it returned to nuisance proportions. Sediment removal deepened the pond below the level of the outlet so required pumping to drain it. The pond was later lined with clay and road construction material to raise the bottom. This also alleviated the weed and algal problem for about 2 years.

Algae control has been achieved by adding 50 kg per treatment of copper sulphate to the pond (John Caldwell, Modellers Society, pers. comm.) giving a calculated dose of 6.3 ppm of copper if dispersed throughout the pond. The use of copper sulphate has now been prohibited in Modellers Pond as copper had built up in the sediment to levels exceeding ANZECC guideline values for copper (Conwell and Barter 2009). The contaminated sediment was removed in April 2010 with 100 mm of sediment removed across the whole surface.

Glyphosate (Roundup®) was used when the pond was drained at the beginning of November 2010, and when inspected on 24th November this treatment had apparently controlled the *R. megacarpa* and algae to a high level (Fig. 7) and to the satisfaction of the Modellers Society and the Council.

4. Issues/problems

Excessive growths of water weed and algae. A number of filamentous green algae and *R. megacarpa* grow excessively in summer forming surface growths that entangle model boats. Surface accumulations of weed and algae detract from the aesthetics of the pond, and contribute to a build up of flocculent organic matter in the pond.

Water levels. Model boats require up to 0.6 m water depth (for the large ones). Water levels in the pond drop in summer on average 11 mm per day through evaporation and percolation through the bottom sediments to levels that hinder the boats. During November 2010 following sediment removal operations, the pond was losing 16 mm per day, most likely attributable to the pond leaking. Without access to significant amounts of water to top the pond up, falling water levels are an ongoing issue.

Water quality. Over summer the water in the pond can go anoxic (stagnant). This would be caused by warm temperatures increasing the decay rates of excessive amounts of organic matter in the pond increasing oxygen demand. The stagnant water appears black and unattractive.

Detritus and rubbish. Overtime the pond accumulates a lot of rubbish (such as bottles, cans, wrappers) from visitors activities in the area and detritus from allochthonous inputs (such as from trees around the pond). Rubbish and debris need to be removed periodically.

Stormwater contaminants. Stormwater from roads is a major source of, copper, zinc, and polycyclic aromatic hydrocarbons (PAHs). These contaminants can be toxic, and are mostly associated with the sediment contained in the storm water. The pond acts as a detention basin (i.e., sediment trap) for these sediments as they settle out on the bottom.

5. Management options

Options range from do nothing to maintaining the pond to clean clear swimming pool standards. Clearly the do nothing option is not acceptable as the pond is an important asset to the community and better management of the weed and algal problems, water levels and water quality is what is being sought. Lining the pond, filtering the water and maintaining it to swimming pool standards (Fig. 10) is not compatible with storm water disposal and people in the pond are not compatible with use of model boats. These options do however illustrate that there is a wide range of intervention levels from which to choose.

The literature on algal and macrophyte control is large. We recently reviewed the literature on algal control alone and read the abstracts of 1,200 relevant scientific papers. The aquatic Plant Group at NIWA is the foremost group in New Zealand working in the area of macrophyte and algal control and is the driver of new product research and registrations (through ERMA) in New Zealand. We are familiar with the literature and have an international profile. The following is our summary of the current range of useful options that could be considered for Modellers Pond.

Figure 10: At the other end of the spectrum from do nothing, the pond could be lined, and the water filtered and chlorinated to swimming pool standards. An example is the Hervey Bay water park, Australia and is typical of many in coastal Australian towns.

5.1 Weed and algal control options

5.1.1 Desiccation

R. megacarpa control has been undertaken on an annual basis by draining the pond to expose the *R. megacarpa* (and algae) during dry weather to cause desiccation. This process can take more than a week however, as moisture is retained by the soft bottom sediments and where there is a thick layer of plants and algae, just the surface layer is desiccated protecting that underneath. Inevitably the underground portions of the *R. megacarpa* remain intact and recovery occurs within several months after the pond is re-filled. One of the benefits of draining the pond is water flushed from the pond takes some of the algae with it and rubbish (broken bottles etc.) are also exposed which can be accessed and removed. At present however the floor of the pond is below the level of the outlet and pumping is required to empty it.

5.1.2 Glyphosate

The herbicide Roundup® (active ingredient glyphosate) was tried in November 2010 when the pond was empty and plants exposed. The treatment was apparently effective on both the weed and algae when inspected on the 24th November, 3 weeks later. Testing of *R. megacarpa* in 1% glyphosate confirmed it is susceptible (Fig. 9). The use of glyphosate over and near water ways is a permitted activity as glyphosate residues are virtually non-toxic to most aquatic life and do not accumulate. Glyphosate is not registered as an aquatic herbicide anywhere as it needs to be at high concentrations to work so would not be suitable for controlling *R. megacarpa* when the pond had water in it. In water, glyphosate is strongly adsorbed to suspended organic and mineral matter and is broken down primarily by microorganisms. Its half-life in pond water ranges from 12 days to 10 weeks.

5.1.3 Copper

Copper (II), the cupric ion, or Cu^{2+} (all synonymous) is one of coppers reactive states commonly used as an herbicide and algaecide. Copper applied as copper sulphate (it dissociates to Cu^{2+} and SO_4^{2-} ions) has a long history of use in Modellers Pond and has proven to be effective in controlling the algae but not the *R. megacarpa*. However, excessive copper dosing has resulted in high levels of copper accumulating in the sediments of the pond (which have since been removed by excavation). Copper sulphate is less effective in hard, alkaline waters because the copper rapidly precipitates out of solution. As such the amount of copper required increases with total alkalinity. In waters with a total alkalinity greater than about 300 ppm as $CaCO_3$, copper from copper sulphate precipitates out of solution so rapidly that it is difficult to achieve an effective treatment. Presumably this phenomenon accounts for the high dosing rates used previously in Modellers Pond to achieve effective weed control.

Chelated copper is more effective than copper sulphate as the Cu^{2+} ion lasts longer when used in a chelated formulation. Komeen marketed by Sepro in the USA is one such product (http://www.sepro.com/default.php?page=komeen). NIWA is registering Gemex, a copper chelate for use in water (developed for didymo control) in early 2011 and it is currently available through Select Chemicals Ltd, Hamilton. Copper is not a recommended option based on the potential for copper accumulation in pond sediments and mobilisation of copper-contaminated sediments to the estuarine receiving environment when the pond is drained periodically.

5.1.4 Endothall

Alkylamine endothall (Hydrothol 191) is a fast acting contact algaecide and herbicide with US EPA registration and over a 40 year history of use there. As little as 0.2 ppm is recommended as a label rate to control green filamentous algae when an entire pond is treated. The *R. megacarpa* will likely require an application of 0.5 to 2.5 ppm, though this species has not been tested (we did not have any on hand to test). Treated water is approved for human contact recreation (US EPA) immediately after application, though some states in the USA have imposed a 24 hour withholding period as an added precaution. Endothall does not accumulate in sediments and breaks down by microbial action rapidly to innocuous components such as carbon, oxygen and water. Alkylamine endothall is toxic to fish above 0.3 ppm (as opposed to other formulations of endothall) so if used in Modellers Pond, treated water should be retained for 25 days before being discharged to the estuary to ensure no fish toxicity.

5.1.5 Diquat

Diquat is registered for use in New Zealand as an aquatic herbicide and can be added while the pond is full (60L per hectare) or sprayed (diluted 1:200) onto the weed when the pond is empty. Our test confirmed that *R. megacarpa* is a susceptible species to diquat at 1ppm, but diquat is known to be rapidly de-activated in turbid water (Hofstra et al. 2001) and is not algaecidal. Diquat is a strong cation and binds so strongly to negatively charged clay micelles that it becomes biologically unavailable. Diquat may also be de-activated by salt water which has abundant anions. Diquat is therefore not likely to be of use in Modellers Pond.

5.1.6 Chlorine

Other chemicals such as chlorine could be used to kill the algae and *R. megacarpa* and would be especially effective if the pond is near empty. Chlorine is a commonly used product in general use available in a range of forms and will dissipate rapidly. Chlorine can be neutralised with sodium sulphite if it persists. Clearwater et al. (2008) described the use of chlorine products as a biocide in natural systems.

5.1.7 Dyes

Ponds can be treated with various non-toxic dyes to colour the water deep blue and do not accumulate in sediments. The colour reduces light penetration to the extent that algae and plant growth is much reduced. This method is used widely in the USA particularly in ponds on golf courses. The blue colour is aesthetically pleasing and preferable to muddy water. The cost of product (for a pond treatment the size of Modellers Pond) would be about $65 and last about 2 months according to web published information at http://www.solarogen.com. We have seen it used in New Zealand but do not have first hand experience with it. It would be worth trying because if it reduced the rate at which the weed and algal problems develop, it would reduce the frequency that other mitigating actions are required.

5.1.8 Bottom lining and flushing

R. megacarpa needs sediment to grow in, so lining the pond would control it by providing an unsuitable habitat. If concrete was used it could be made strong enough to enable machine cleaning when drained. Other options such as using butyl rubber liners could also be considered as it would be cheaper. Bottom lining would also prevent water seepage through the bottom of the pond and so help maintain water levels. Bottom lining on its own would not prevent algal growths but regular flushing (possibly bimonthly in summer) and bottom cleaning (frequency would depend on sedimentation rate) will likely control it and keep the water clean and healthy.

Upgrading the gates would also permit safer and easier flushing.

5.1.9 Deepening

R. megacarpa growth is limited to about 2 – 3 m water depth in clear water, but in the murky water of Modellers Pond it would be probably less than 2 m. The pond depth could be increased to prevent plant growth and could be achieved by raising the water level or digging out the bottom. This is likely to be an expensive option and have implications for safety. Furthermore, if deepened below the level of the outlet the pond will need to be pumped out to drain it.

The modellers require about 0.6 m water depth to use the largest boats, so some deepening would be of benefit. However, if the pond was maintained full, and weeds controlled, the current water depth is sufficient. Maintaining water levels is a problem with high spring tides infrequent and tap water use now restricted. An additional source of water would be an advantage such as pumping in sea water or ground water. Some test wells have been tried but they have not been successful due to fine sediment filling in the wells.

6. Issues relating to stormwater function of Modellers Pond

6.1 Background

To mitigate the risk of surface flooding when high rainfall events coincide with high tides, a Centennial Park pumping station was constructed to pump high flows to the "Back Beach" area via a rising main. A discharge study (NCC, 1998) outlined three discharge options, one being Modellers Pond, which, after considering multiple potential impacts, was selected as the preferred option.

Given the recreational and environmental value of the Back Beach estuary, an important issue associated with the discharge of stormwater to Modellers Pond was the potential for adverse impacts on receiving water quality in the estuary. Although stormwater can contain elevated concentrations of typical urban contaminants such as petroleum hydrocarbons (including polycyclic aromatic hydrocarbons or PAHs) and heavy metals (namely copper, zinc and sometimes lead), the NCC report (1998) outlined a number of reasons as to why the discharge of stormwater to Modellers Pond would have a minimal impact on water quality in the Tahunanui estuarine receiving environment. These included:

1) "The Tahunanui catchment is very small and contains little traffic and no heavy industry. In this context the impact on the receiving water from the runoff will be insignificant. It is important to emphasise that pumping stormwater to Modellers Pond has no significant effects".

Then in relation to diverting some of Tahunanui stormwater to Modellers Pond via the pumping station:

2) The volume of discharge pumped to Modellers Pond is relatively small. For most years, only 3% of the total stormwater volume from the catchment is pumped to Modellers Pond. Accordingly, the total loadings of contaminants that are pumped to the pond are relatively small.

3) In the absence of the pumping station, all the stormwater discharges to the Back Beach area. Hence discharging a proportion of the Tahunanui catchment stormwater via Modellers Pond simply means that the total discharge to the Back Beach receiving environment is similar, but occurs via two separate locations.

In addition to this third point, although only receiving 3% of the discharged stormwater volume, Modellers Pond presumably will be functioning as a stormwater treatment pond (i.e., slowing velocities and facilitating settlement of contaminated suspended sediment) and hence reducing contaminants loads in pumped stormwater that is ultimately discharged to the Back Beach area via Modellers Pond.

The report (NCC 1998) stated that it is "common and acceptable practice for catchments like Tahunanui to be discharged directly into the environment. Water quality will therefore not be a significant issue for any of the options."

6.2 Water quality

Although the input of stormwater to Modellers Pond has been identified as a potential concern, considering the non-contact recreational use of the pond, the relatively low volumes of stormwater pumped into the pond annually, and that the majority of road-derived contaminants are typically associated with the particulate phase (i.e., not dissolved), that 'water quality' impacts are not significant with respect to the social / recreational value of the pond.

6.3 Sediment

The majority of contaminants in stormwater are associated with (i.e., bound to) suspended sediment or the particulate phase. At the time of writing this report, there was very limited information relating to the hydrodynamics of Modellers Pond, however, in the scoping proposal (NCC, 1998) the pond was going to be capable of holding a 15 year average recurrence interval (ARI) flood event. Based on this proposed retention capacity, it is reasonable to assume that most of the suspended particulate material in the stormwater would be retained and deposited (settled) on the pond bed – as opposed to be discharged via the pond outlet to the estuarine receiving environment.

Although the amount of stormwater pumped to Modellers Pond represents only ca. 3% of the total volume of stormwater from the Tahunanui catchment, for all intents and purposes it is functioning as an off-line stormwater treatment pond, which over time will accumulate particulate material containing petroleum hydrocarbons and heavy metals. This presumably will have regulatory implications for the disposal of any sediment excavated as part of regular pond maintenance. Road-derived particulate material, including road sweepings, catchpit sediments and pond sediments, are general regarded as being mildly contaminated and as such require landfill disposal. New Zealand cleanfill guidelines (MfE, 2002) specifically exclude road sweepings and catchpit sediments on account of the potential for these materials to contain elevated contaminant concentrations.

6.4 General comments on relationship between pond sediment and water quality

Potential cost implications (with respect to sediment disposal) for the NCC of using Modellers Pond as an off-line stormwater pond was not considered in the initial scoping document (NCC 1998). Historic sediment management of sediment/sludge accumulation in the pond, namely accumulation rates, pond cleaning frequency, volume / weight of bed material removed and how this material was disposed of are not known, so it is unclear as to the possible ongoing costs to NCC of managing sediment / sludge accumulation in Modellers Pond. However, with landfill charges increasing to reflect the true 'whole of life' cost, landfill costs of >$100 per tonne are common place. Nelson landfill charges are currently $92 per tonne but are expected to be $117 by 2013 (Nelson Mail, 2010).

Depending on the amount of pond sediment / sludge requiring disposal, the cost of implementing any management options that reduce sediment / sludge accumulation would be offset by reducing or eliminating ongoing maintenance costs associated with cleaning and disposal. For example, if lining the pond was an effective control option for weed growth (presumably a major source of sludge that accumulates in the pond), then the costs would be off set by reduced cleaning / disposal and biocide application.

Another sediment-related concern relating to the pond is the tendency for the pond water to stagnate and basically become anoxic resulting in unpleasant appearance and odour of the pond. This is the result of the large amounts of organic matter in the pond bed undergoing decomposition. This decomposition, or more accurately, oxidation of organic material removes oxygen from the overlying water resulting in stagnant anoxic water. This is process is more pronounced in summer with higher temperatures favouring more rapid bacterial-mediated reactions of the organic material. Anoxic conditions at the sediment-water interface results in high concentrations of hydrogen sulphide (H_2S – responsible for 'rotten eggs' odour) and ammonia (as ammonium) in overlying and pore water, which can be toxic to any resident biota. The quality of the water in the pond could be easily monitored using a hand held dissolved oxygen (DO) meter. Water quality monitoring of the pond would prove useful for developing effective management strategies to improve water quality.

With regard to management of the pond, the presence of organic-rich sludge on the pond bed (presumably of largely autochthonous origins) has an effect on the overlying water quality in the pond. This means that it will probably be difficult to address water quality concerns in the pond without adequate management of the pond bed material.

To maintain water quality in the pond it would be beneficial to reduce the biological oxygen demand of the bed sediment / sludge. This could be done by lining (butyl pond liner) and effectively removing the sediment compartment from the system. Alternatively, additional oxygen could be supplied to the overlying pond water to offset the oxygen consumption by the bed sediment / sludge. Possible ways to achieve this is via aeration (e.g., paddle wheels or pumping air) or higher turnover rate of water in the pond. The benefit of pond lining is that it would also address the issue of water loss via infiltration.

Interestingly, the ponds most similar to Modellers Pond could be the large (often >1 hectare) and relative shallow (ca. 1m) shrimp ponds, which suffer from anoxic conditions caused by organic rich wastes accumulating in the bed sediment. While the inputs of organic matter are far more excessive for prawn aquaculture, the management approaches to mitigate the effects of reduced sediment (i.e., anoxic sediment / water conditions) may have some broad applicability to Modellers Pond. Such options include aeration, circulation, chemical additions to control sediment anoxia (e.g., nitrate addition) and trench design in ponds beds to collect fine sediment for ease of cleaning (Avnimelech & Ritvo, 2003).

7. Recommendations

In the interim the recommended management regime is to drain the pond every two months in summer and use glyphosate on the exposed algae and *R. megacarpa*. Flushing has been found to help maintain water quality and reduce algal nuisance and glyphosate did a good job of controlling excessive algae and *R. megacarpa* in November 2010. The glyphosate will not accumulate or be a health hazard if used in this way. A dye treatment could be tried after filling to improve aesthetics and see if it reduces algal and *R. megacarpa* recovery rates. If greater levels of control are needed then alkylamine endothall (e.g., Hydrothol 191) is worth considering. However, as mentioned below, periodic 'kill offs' to control weed growth potentially exacerbate problems of water quality because it places a large amount of decomposing organic material in the pond bed, risking anoxia of the overlying pond water

In the longer term, lining the pond would greatly simplify pond management by eliminating the *R. megacarpa* and sediment re-suspension and would facilitate flushing and enable easier cleaning when drained. This would improve water quality because the biogeochemistry of pond sediments (oxygen consumption ⇒ anoxia ⇒ release of hydrogen sulfide and nutrients like ammonia) has a significant impact on the quality of the overlying water. Because autochthonous inputs (from weed growth and subsequent 'kill offs') are assumed to be a major input of organic material to pond sediments (or 'sludge'), improvements to water quality will require management of the oxygen demand (i.e., reduction) of the sediment, or oxygen supply (i.e., increase) of the overlying water in order to prevent formation of anoxic conditions which decrease the public amenity value of the pond. A lined bottom would help deter macroalgal growth, prevent water loss via seepage and greatly reduce the oxygen demands of the pond system. The measurement of dissolved oxygen (via handheld meter) concentrations in the pond to monitor the extent and / or seasonality of anoxia would be beneficial for future pond management initiatives.

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