CHELSEA PONDS – THE COMPLEXITY OF WATER QUALITY MANAGEMENT OF *DE FACTO* STORMWATER PONDS

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ABSTRACT

The Chelsea Ponds were created to provide a reliable fresh water supply for the Chelsea Sugar Refinery on Auckland's North Shore. The freshwater habitat that they provide has historically supported numerous fish and bird species, as well as providing for various recreational human activities. With the increasing urbanisation within the catchment, these ponds have increasingly become *de facto* stormwater treatment ponds, leading to accumulation of sediment and associated pollutants.

This paper reviews the various water quality and ecological issues present at Chelsea Ponds, including eutrophication and avian botulism. The potentially complex aetiology of these issues is addressed, considering past and present land use, including the role of accumulated sediment, air discharges and, potentially landfill leachate in these processes. The ongoing environmental management of the ponds is discussed, with reference to the amenity value that the ponds potentially provide. In this respect, this paper touches upon the wider issue of providing increased public amenity from ponds that perform a stormwater treatment function.

KEYWORDS

Stormwater Pond, Eutrophication, Avian Botulism, Public Amenity, Asset Management

PRESENTER PROFILE

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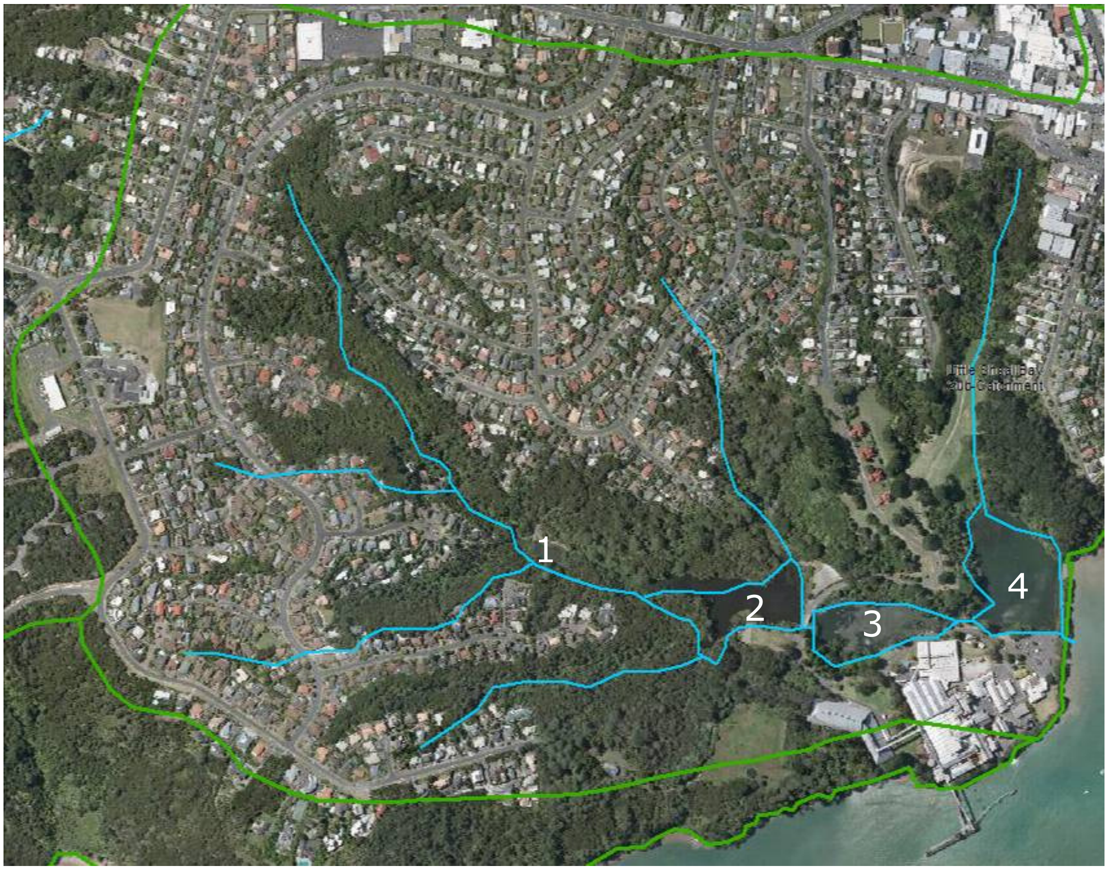
1 INTRODUCTION

The Chelsea Ponds are located in Birkenhead, Auckland, adjacent to the New Zealand Sugar Company Ltd sugar refinery (NZSC), established in 1884. The system consists of four relatively shallow ponds of varying size, in series, with water retention times during low flows in summer estimated between 2 days and 7-14 days for surface and bottom water, respectively, based on water quality sampling data (pers. comm. Auckland Council staff, 2012). Photograph 1 is provided for context. In summer the pond system is poorly flushed due to high evaporative losses and low flow rates, which reduce the outflow of nutrients from the ponds; this is exacerbated by water abstraction in Ponds 3 and 4.

Photograph 1: The Chelsea Ponds impoundment system



The ponds were constructed across a freshwater – saline gradient, with the majority likely located within historic saltmarsh, tidal creek and mangrove areas. Ponds 1, 2, 3 and 4 were established in 1884, 1884, 1901, and 1917, respectively (NZSC, 2003, cited in Al-Saleem, 2005). There is no exchange of freshwater with saltwater in the ponds. A number of stream tributaries feed into the pond system. The pond is regularly eutrophic in summer, with associated algal and cyanobacterial blooms, and incidences of avian botulism.

The ponds are of significant heritage value, as are most of the refinery and associated infrastructure and equipment. The estate has consequently been designated as a heritage park. The ponds are situated at the bottom of an urban catchment (approx. 191 hectares), including approx. 42 hectares of natural vegetation and a closed landfill site. The Chelsea Park Trust Board purchased Chelsea Estate land in 2008, and handed over the responsibilities to North Shore City Council (now part of Auckland Council). The natural areas are managed by the Parks Department, the landfill areas by Land and Coastal Processes Management, and the ponds currently managed by Stormwater Operations. At the same time, NZSC has the benefit of a consented water abstraction from the ponds. On June 2009, the heritage value of the site was officially recognized through establishment of the Chelsea Heritage Park (Category 1) by the New Zealand Historic Places Trust. The estate consequently performs multiple functions, and management of the ponds must also take into account recreational activities and public amenity.

The ponds suffer from high nutrient levels, low dissolved oxygen (DO), high temperatures, and sedimentation, with associated ecological implications, reduced public amenity, and health concerns. Whilst the issues associated with Chelsea Ponds are not uncommon in stormwater ponds, including avian botulism, eutrophication and ecological impacts, the complex aetiology is unique, and historic and present land uses have an influence on management of Chelsea Estate and its ponds.

2 THE EVOLUTION OF CHELSEA PONDS

Chelsea Ponds were originally constructed solely for supplying freshwater to the refinery, a function that the ponds still perform. As the urban component of the catchment developed, the ponds have assumed a more diverse role. Before the opening of Auckland's Harbour Bridge in 1959, access to the North Shore from Auckland City was restricted to transport by ferry, and consequently development of the area reflected local employment conditions. Before the establishment of the sugar works, the area consisted of farms and orchards, with a small village beside Birkenhead Wharf. Whilst the NZSC refinery was a catalyst for the growth of Birkenhead, very little development took place within the catchment of Chelsea Ponds. The ponds did not adopt a stormwater treatment function until the late 20th century. Development of the Chelsea Ponds catchment only took place after 1959, reaching its fully developed state by 1996, comprising residential, commercial and industrial areas. Photographs 2 and 3 illustrate the development of the catchment.

Photograph 2: The catchment in 1959

Photograph 3: The catchment in 1996

This development process took place almost entirely without consideration of the effect of stormwater discharges on the receiving freshwater and marine environments. Although impacts on the stream (Duck Creek) and its tributaries remain largely unmitigated, the ponds have served as an 'ambulance at the bottom of the cliff' to at least capture stormwater contaminants prior to discharge into the marine environment. This treatment of stormwater, although completely unintentional, serves an essential function within this urban catchment. The system is also influenced by a closed landfill site, containing waste from the NZSC sugar refinery.

Concomitantly, the site functions as an integral component of the urban landscape, affording the Birkenhead community with passive and active amenity, encompassing natural and heritage values.

3 ECOLOGICAL BASELINE

Habitats within the Duck Creek catchment have been assessed by Auckland Council (Brent, 2010). Significant areas of natural habitat have been transformed through construction of the ponds. Ponds 1 and 2 were constructed within what was likely freshwater stream habitat, and Ponds 3 and 4 were likely constructed with estuarine habitat. The dams present in the catchment have resulted in potential barriers to fish migration into and out of the catchment. This is of particular importance to native fish communities, the majority of which are diadromous (utilise both freshwater and marine habitats at distinct stages in their life cycles), travelling between the coastal and freshwater environments to complete their life cycle.

Nevertheless, the catchment still supports approximately 5 km of watercourse length of varying quality available to freshwater fish. Intact stream habitat is typically steep and punctuated by pools and chutes associated with the steep topography, within a forested canopy, which provides suitable habitat for native fish species which have excellent climbing ability. Natural fish passage barriers within the catchment may be as limiting for non-climbing species as artificial barriers posed by dam walls. Overall, the remaining stream reaches comprise aquatic habitat of high natural character, the majority of which is maintained by Auckland Council Parks as part of Chelsea Heritage Park. The pond environments comprise poor habitat for native fish species.

The Index of Biotic Integrity (IBI) score for native fish populations in the Duck Creek catchment is very good to excellent despite the impoundments and presence of potential fish passage barriers on the watercourses. A total of six different native fish species and koura have been found within the Duck Creek catchment; longfin (*Anguilla dieffenbachii*) and shortfin (*A. australis*) eels and the banded kokopu (*Galaxias fasciatus*) were the most common species recorded in the database, with banded kokopu present in all streams. All three species are known for their climbing ability, with longfin eels and banded kokopu in particular recognized for their strong climbing ability and having a preference for upper stream reach habitats. They are also all diadromous species which spend part of their life cycle in the sea, but are not reliant on significant estuarine habitat for reproduction.

Species linked closely to estuarine and tidal habitats (not present in the Duck Creek catchment), such as redfin bullies and inanga were absent; these species will continue to be excluded from the system as long as the ponds exist.

The catchment is therefore characterised by good quality upper catchment streams and modified lower reaches, which overall still maintain high natural value.

4 DESCRIPTION OF WATER QUALITY IN THE PONDS

4.1 CONTEXT

The quality of water in the Chelsea Ponds has been of concern to many different parties over the past few decades. The regular incidence of sick and dead ducks in summer, due to avian botulism, has led to public concerns regarding water quality.

Avian botulism is a paralytic, often fatal disease of birds resulting from the ingestion of a toxin produced by the bacterium *Clostridium botulinum*. The toxin thrives in still, shallow, anoxic, warm, nutrient-enriched water, with fluctuating water levels (Locke & Friend,

1953) - the occurrence of this disease is therefore symptomatic of the key water quality problems issues associated with the ponds.

The water quality status of the pond system is discussed below. Monitoring has been restricted to Ponds 2-4 as per the stormwater discharge consent requirements, and monitoring of all water quality parameters has not been consistent; sampling dates and timelines therefore do not necessarily coincide and may have variable sampling periods. Furthermore, real-time monitoring at varying depths in the water column has not taken place; this is an option that Auckland Council is currently investigating.

4.2 NUTRIENTS

High nutrient levels encourage the development of nuisance growth of aquatic plants (ANZECC, 2000) and increase microbial activity, with related impacts on DO.

Nutrient concentrations vary between the different ponds (Table 1), with Pond 4 consistently reporting the highest levels of between three to five times the concentrations found in Pond 3 based on 2009-10 data. Concentrations of the nutrient fraction are at levels where the ponds are eutrophic to supertrophic. The concentrations present in Pond 4 have potential to cause significant effects on pond physicochemical stability.

Table 1: Median nutrient concentrations in ponds 2, 3 and 4 for May 2009 to May 2010 compliance data

Pond	Chlorophyll a (mg/L)	Total Phosphorus (mg/m^3)	Total Nitrogen (mg/m^3)	Indicative Trophic State
2	0.0078	20	393	Eutrophic
3	0.0049	18	432	Mesotrophic-Eutrophic
4	0.0178	94	788	Supertrophic

The trophic state is further verified by review of the median concentrations of Chlorophyll a, also illustrated in Table 1. According to Quinn (1991) (cited in ANZECC, 2000) an annual mean of 0.005-0.015 mg/L and an annual maximum of 0.015-0.04 mg/L of Chlorophyll a indicate that a system is eutrophic. Pond 4 is reaching supertrophic levels. Nutrient levels in Ponds 2 - 4 all exceed the ANZECC trigger values for slightly to moderately disturbed ecosystems.

4.3 SUCROSE

Stormwater discharges, air emissions from NZSC, and landfill leachate (within groundwater and stormwater culverts) are contributing to sucrose levels within the ponds. Whilst sucrose has been detected at concentrations of 5-10 ppm in stormwater entering ponds (Simpson, 1997), the cumulative effect of potential leachate from the landfill and air emissions on sucrose concentration and distribution in the ponds has not been evaluated.

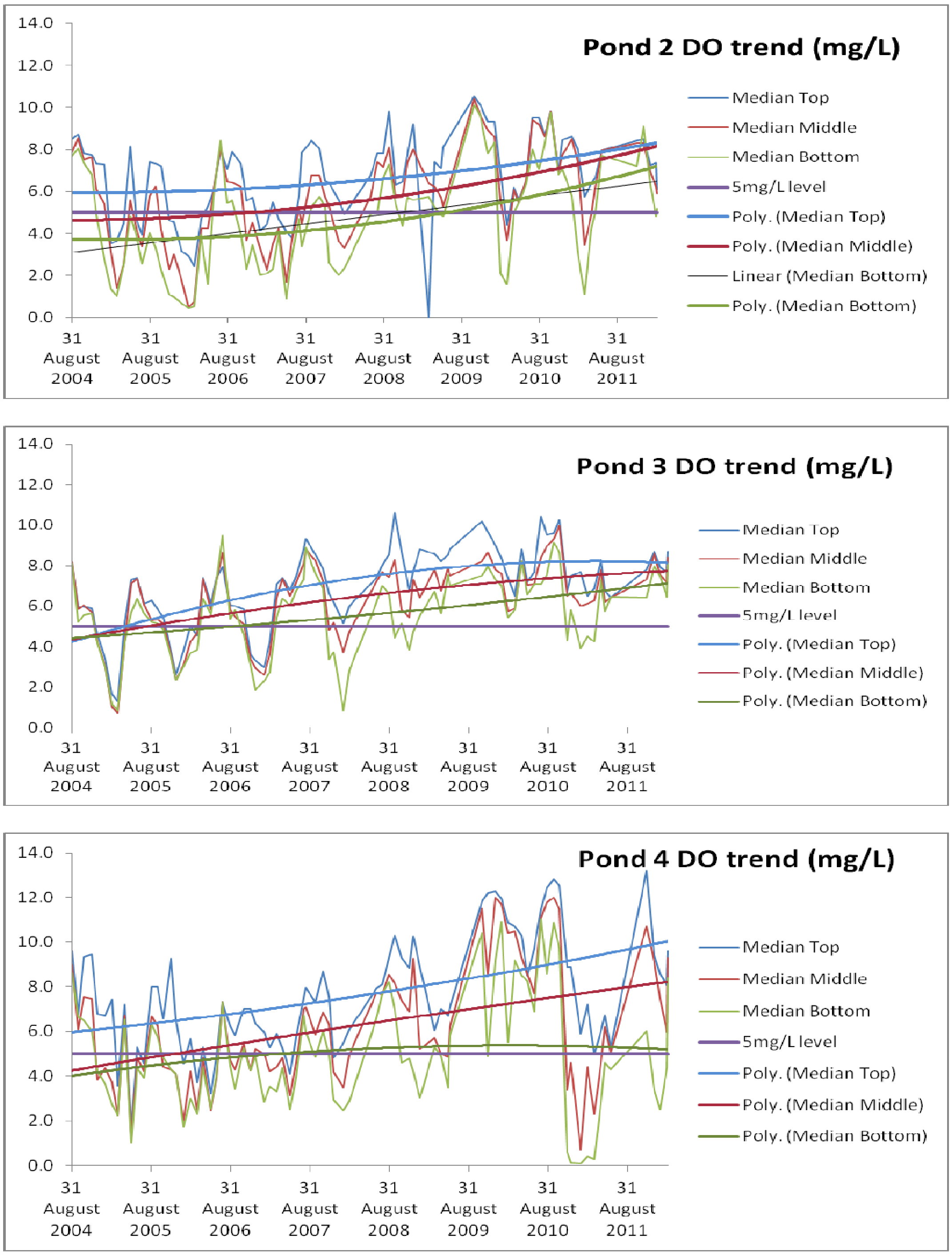
Further analyses would need to be carried out to confirm sucrose concentrations in the ponds.

4.4 DISSOLVED OXYGEN AND TEMPERATURE

Water physicochemistry issues within the Duck Creek catchment are generally associated with high water temperatures and low DO concentrations. The interactions between these two variables are strongly linked as solubility of oxygen is directly affected by temperature, declining as water temperatures increase. Their interaction with the surrounding aquatic environment is also highly complex, driven by seasonal changes in solar radiation and the physical, chemical and biological properties of individual waterbodies. Dissolved oxygen levels above 5 mg/L provide protection for most aquaculture species (Meade, 1989, cited in ANZECC, 2000).

Figure 1 illustrates trends in DO, including polynomial regressions.

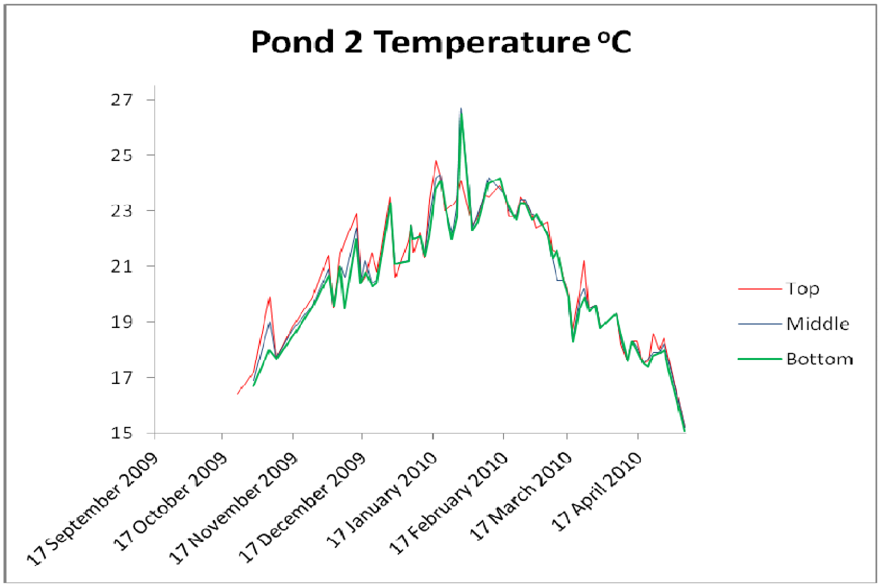
Figure 1: Dissolved Oxygen levels in Pond 2, 3 and 4

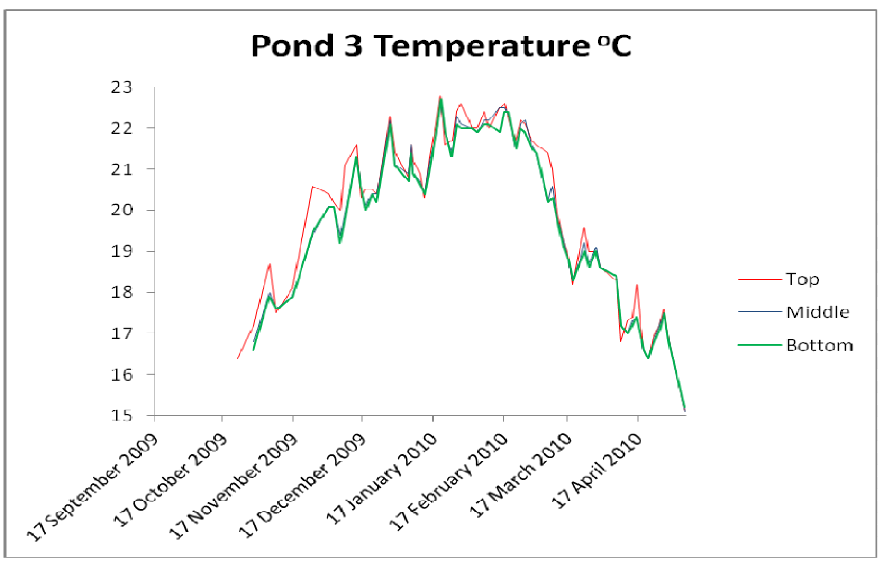


All three ponds regularly exceed the 5 mg/L ANZEC trigger value during summer. Dissolved oxygen levels fluctuate significantly throughout the year (being at their lowest in summer), and decrease rapidly with increasing depth in Ponds 2 – 4. Pond 4 has the highest and lowest DO levels, with the largest fluctuations. All 3 ponds appear to have improved in DO status from 2008 onwards. The improvement is most pronounced in Pond 3, whilst Ponds 2 and 4 still exhibit exceedences, although less frequently.

Water temperatures increase dramatically over summer, however do not vary significantly between the top, middle and bottom of the water column – median temperature fluctuations between 0.2 and 0.3 (Figure 2, Table 2); this may be on account of the very shallow depths (average depths of 1 m, 2.7 m, and 2 m, for Ponds 2 - 3 respectively). This suggests that reduced DO trends with depth are primarily driven by decomposition in the hypolimnion (the water layer immediately above the sediments) and respiration, rather than temperature and maximum oxygen saturation.

Figure 2: Temperatures in Pond 2, 3 and 4





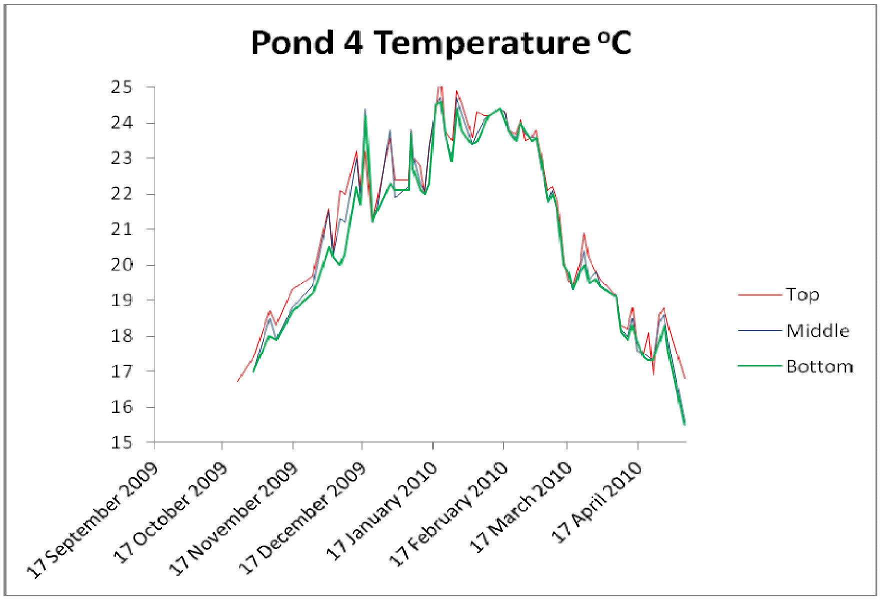


Table 2: Temperature Differences between top, middle and bottom pond depths

	Pond 2			Pond 3			Pond 4		
Temperature Difference	Max	Minimum	Median	Max	Minimum	Median	Max	Minimum	Median
Top - Middle	2.6	0	0.2	1.2	0	0.1	1.2	0	0.2
Middle - Bottom	1.1	0	0.1	0.7	0	0.1	1.5	0	0.1
Top - Bottom	2.4	0	0.3	1.4	0	0.2	2.1	0	0.3

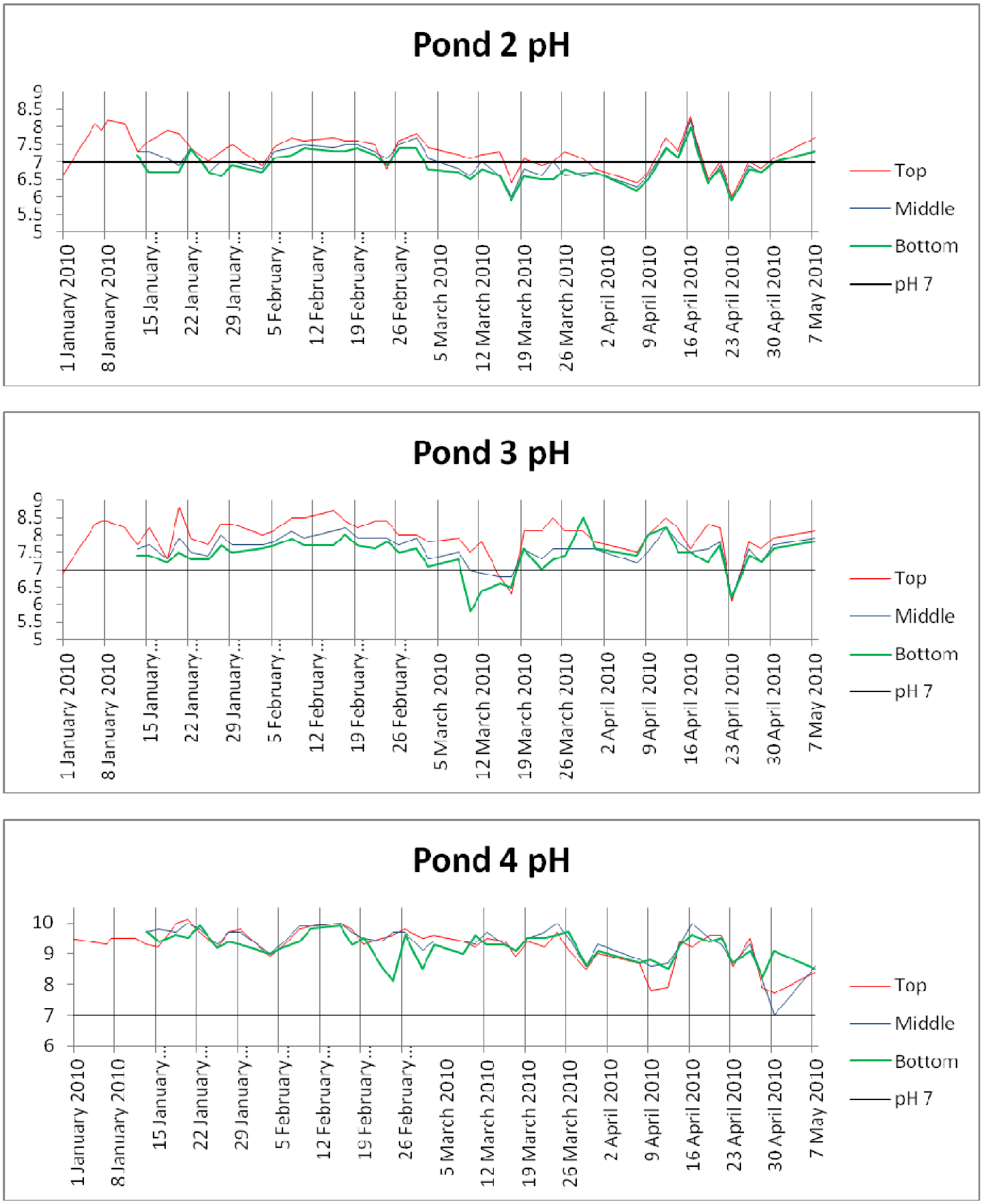
4.5 pH

Photosynthesis reduces the acidity of the water (increasing pH) by using up dissolved carbon dioxide (CO_2), which acts like carbonic acid (H_2CO_3) in water. Respiration of organic matter produces CO_2, which dissolves in water as carbonic acid, thereby increasing acidity (lowering pH). The pH may therefore be higher during daylight hours and in the upper levels of a pond, where light is readily available for photosynthesis.

The pH in Ponds 2 and 3 clearly decreases with depth, as expected, whilst Pond 4 exhibits an unstable pH (Figure 3). The reasons for the latter are unknown at this stage, but may be an indicator of turnover within Pond 4.

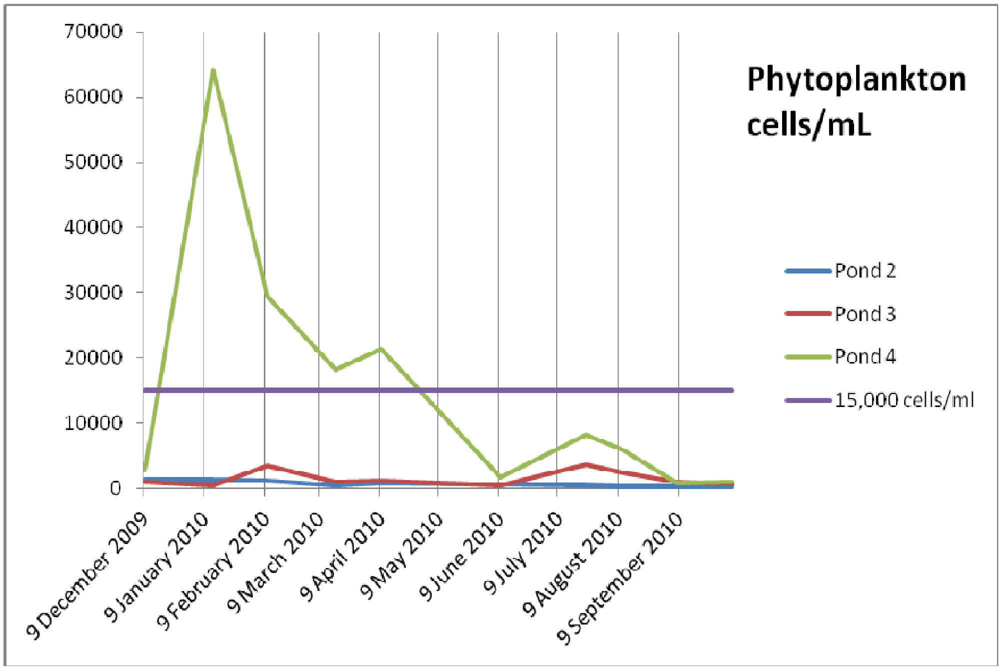
Overall, Ponds 2, 3 and 4 are neutral, slightly alkaline, and highly alkaline, respectively, suggesting high levels of photosynthesis, particularly in the middle and upper levels of the ponds. This increased alkalinity may also be linked to duck mortality at the ponds; Tonie and Michael (1999) reported an increase in the risk of botulism outbreaks when water pH was between 7.5 and 9.0.

Figure 3: pH in Pond 2, 3 and 4



The high pH across all depths of the water column may be evidence of regular phytoplankton blooms (and high rates of photosynthesis) occurring in summer in Pond 4 (Figure 4 – phytoplankton cell counts regularly exceed the 15,000 cells/mL water quality threshold during summer). The unusual pH approaching pH 10 within Pond 4 suggests there may be external factors increasing pH which have not yet been identified, such as alkaline landfill leachate. A pH above 9 is considered detrimental to fish and other aquatic fauna. The pH monitoring data for Chelsea Ponds is currently limited to daytime sampling, and additional monitoring is required to adequately describe pH dynamics in the ponds.

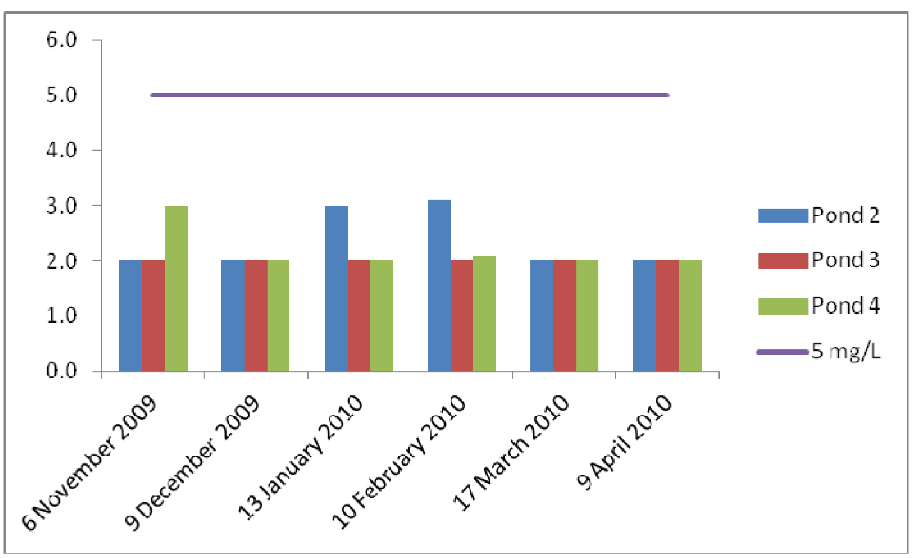
Figure 4: Phytoplankton cell counts in Pond 2, 3 and 4



4.6 BIOLOGICAL OXYGEN DEMAND (BOD)

BOD_5 levels within the ponds over the 2010/11 summer (Figure 5) were within the 5 mg/L water quality threshold, at face value inferring good water quality.

Figure 5: BOD_5 within Ponds 2, 3 and 4



However, insufficient information is available for accurate analysis of this water quality parameter; water samples are likely to have been collected at variable depths, favouring the upper and middle of the water column. Whilst this approach is adequate for well-mixed waters, this method would not necessarily have been appropriate for Chelsea

Ponds as the steep decline in DO with depth suggests that the majority of biological oxygen demanding substances are within the hypolimnion and sediments of the ponds. BOD_5 values in the bottom of the ponds are likely to significantly exceed the 5 mg/L water quality threshold, potentially elevating the overall BOD values well above 5 mg/L. Further investigation is required to accurately describe BOD in the ponds.

5 REASONS FOR POOR WATER QUALITY

5.1 URBAN STORMWATER INPUTS

Urban development proceeded in the absence of adequate stormwater attenuation and contaminant treatment. Consequently, stormwater volumes are significantly greater than pre-development levels, stream flow velocities are abnormally high, the stream bed has experienced high levels of erosion, and pollution is conveyed directly to the receiving environment. Prior to urban development in the upper catchment, water of the Chelsea Ponds was reported to have been extremely clear (Simpson, 1997). The high volumes of erosion and sedimentation in Chelsea Ponds can therefore largely be attributed to this urbanisation process.

The Chelsea Ponds system is exceptionally effective at removal of sediment in stormwater; the *de facto* water quality volume is approximately 3 times that required for a catchment of this size (Atkinson et al., 1995). Present sediment volumes within the ponds are estimated at 54,865 m^3, based on bathymetric data and sediment analyses (Banks, 2009; Maunsell, 2005). Pond 2, 3 and 4 each contribute 20,000 m^3, 11,855 m^3, and 23,010 m^3 of sediment, respectively (SKM, 2010). Taking into account the 3,000 m^3 of sediment removed from Pond 1 in 1989, a total sediment load of approximately 57,865 m^3 can in majority be attributed to stormwater inputs. In addition to standard sediment inputs from stormwater, significant volumes of silt were deposited in the ponds as a consequence of earthworks undertaken in this catchment (e.g. the development of individual sites within the Chatswood development). Ongoing rates of siltation of the fully-developed (mature) catchment should be much reduced when compared to the development phase.

Elevated nutrient concentrations may be attributed to urban stormwater flows, although nutrient contributions of stormwater relative to the landfill, effluent inputs and the refinery have not been empirically determined.

5.2 DISSOLVED OXYGEN AND NUTRIENT CYCLING

The DO concentration in the epilimnion (surface layer of water) remains high throughout the summer because of photosynthesis and diffusion from the atmosphere. However, conditions in the hypolimnion vary with trophic status. In eutrophic water bodies such as Chelsea Ponds, hypolimnetic DO declines during the summer because it is cut-off from all sources of oxygen, while organisms continue to respire and consume oxygen. Anaerobic conditions above the sediments further increase the solubility of phosphorus in the sediment, releasing it into the water column.

Eutrophic to supertrophic conditions in the ponds are primarily attributed to accumulated nutrient-rich sediments in Chelsea Ponds. A rich organic layer, possibly buried macrophytes, is found within sediments in Ponds 3 and 4 (Water Quality Centre, 1989). Analysis of 2 composite samples of sediment from the bottom of Pond 3 and Pond 4 revealed BOD levels an order of magnitude higher than that characteristic of stormwater, levels closer to that of untreated domestic sewage (Tong, 1998). Bioresearches (2003) concluded that the water quality in the ponds is greatly determined by the urban runoff that continues to accumulate sediment and other contaminants in the ponds, and sediment is the principle cause for the deteriorated water quality in the ponds. Banks (2009) identified a sediment layer in Pond 4, which is characteristic of effluent; further investigation is required to verify this. Potential historic effluent discharges may therefore also be a factor. Laboratory analyses have confirmed the high nutrient status of the sediments.

Shallow eutrophic ponds such as Chelsea Ponds are predisposed to higher nutrient cycling than deeper ponds due to low volume to area ratios, which promote shorter water turnover times and more primary production per volume water. Nutrient transformations are dynamic in shallow, eutrophic ecosystems, and nutrient uptake rates relate to Chlorophyll concentrations. The high levels of Chlorophyll a in Chelsea Ponds (corresponding with high phytoplankton counts) are an indication of the high nutrient turnover in the system. Disturbances to nutrient-rich sediments drive the system further towards a phytoplankton dominated community; sediment disturbance and re-suspension by pest fish and waterfowl, and the mixing effect of the aerators in Pond 3, may be amplifying nutrient cycling at Chelsea Ponds. Intense phytoplankton blooms evidenced at Chelsea Ponds have the added effect of blocking light, driving down DO levels at lower depths by preventing photosynthesis and promoting decomposition.

Metabolism of sucrose by microorganisms would further deplete DO, whilst sucrose uptake in plants may also reduce photosynthesis. The influence of sucrose on oxygen depletion in Chelsea Ponds merits further investigation.

The key driver in the system appears to be the high oxygen demand of highly organic nutrient-enriched sediment, which results in a number of knock-on oxygen-depleting processes.

5.3 CONTAMINANTS ASSOCIATED WITH THE REFINERY

A number of contaminants associated with the operation of sugar refineries are also relevant to the NZSC refinery. Sucrose from the refinery may be entering surface and groundwater through entrainment in stormwater discharges, air emissions, leaks in the wastewater network, collection sumps, and associated drainage systems, and consequent leaching of contaminated soils (Williamson & Bremford, 2003). Whilst groundwater is unlikely to become contaminated as a result of operations within the refinery (SKM, 2003), and leakages within refinery pipelines and sumps can be repaired through infrastructural upgrades, air emissions and stormwater discharges are taking place and will continue in perpetuity. Sucrose, which has a biological oxygen demand, has an indirect effect on aquatic toxicity by reducing DO levels to below the critical ecological threshold; most aquatic organisms require DO levels higher than 5 mg/L to survive. Sucrose is decomposed by microorganisms, which use oxygen in the process.

Worst-case air discharges from the refinery have been modeled as part of the consent application for an Industrial or Trade Process permit for the site. It is modeled that 4 kg/h of total suspended particulate (TSP) would potentially have settled within 100 to 150 m from the refinery, historically. Since 2010 upgrades to equipment are likely to have reduced TSP to approximately 2.69 kg/h, approximately 65 kg per day (23.5 tons per annum); more detailed modeling would be required for definitive conclusions. Sucrose therefore settles directly onto the ponds or on hard surfaces, and would be entrained in stormwater. Simpson (1997) detected sucrose in stormwater flowing from the site, although this study concluded that volumes of sugar in stormwater would be low. Further investigations are required to verify actual sucrose deposition into the ponds.

Significant quantities of contaminants are contained within refinery waste deposited in the landfill located to the north of the site (including boiler ash, bone char, molasses, and filter muds). The unique nature of this landfill, which includes products high in sucrose and nutrients, may be responsible for some of the water quality issues in Pond 4. Monitoring results of groundwater wells within the landfill (Thorburn, 2011) show high levels of nutrients, including Ammonia and Phosphorous; this groundwater is also high in arsenic, cobalt and iron. These pollutants may be leaching into Pond 4; further investigations need to be conducted to verify this, and the quantum of leachate. Subsurface landfill stormwater drains have been inspected, and visible signs of sucrose leaching into these pipes have been noted.

Historically Pond 3 received wastewater discharges from NZSC until 2003 (SKM, 2010). Other sources include an accidental spill of approximately 4,000kg of sucrose into Pond 3 in 2002 (Williamson & Bremford, 2003) which caused a sucrose concentration of 49 g/L in Pond 3 while Pond 4 consequently turned anoxic (Bioresearches, 2003).

5.4 AQUATIC VEGETATION ISSUES

The creation of the Chelsea pond reservoirs has resulted in relatively large, shallow ponds which in an urban catchment provide ideal conditions for the growth of aquatic macrophytes. While plant growth in these systems is a natural process, vegetation is a problem when it becomes very prolific.

Aquatic vegetation effects in shallow water bodies are highly complex, with the balance between positive and negative effects often being very fine. Positive effects in shallow water bodies are associated with stabilization of processes including water circulation, water physicochemistry, nutrient and contaminant control and stabilization of benthic processes and the sediment-water interface. Negative effects can be associated with both too much weed or too little, particularly if the switch between either of the above states occurs too rapidly.

Too much weed, prolific growths of introduced aquatic macrophytes can result in:

- dramatic diurnal shifts in water physicochemistry (in particular DO and pH);
- an increase water temperatures by absorbing more energy;
- restriction of water circulation;
- daily stratification and turnover of the water column;
- inhibition of other species and reductions in pond community diversity;
- clogging of inlets/outlets;
- unpleasant odours; and
- reductions in visual amenity values

A crash in aquatic macrophyte beds can result in:

- initial water quality effects caused by rotting vegetation;
- destabilization of the sediment-water interface at the bottom of the pond;
- re-suspension of sediment and increased turbidity;
- a switch to a microalgal dominated system which can result in algal blooms, cyanobacterial blooms, growth of toxic algae;
- reductions in nutrient and contaminant uptake and changes in trophic state of the pond;
- decreases in pond community diversity;
- unpleasant odours; and
- reductions in visual amenity values

The macrophyte community at Chelsea pond is unstable. Dense mats of pest plants, particularly *Lagarosiphon major*, dominate at most times of the year, experiencing seasonal dieback in response to light attenuation by phytoplankton blooms and die-back in winter. Whilst both macrophyte and algal blooms negatively affect amenity value, the primary ecological effect is the accumulation and cycling of nutrients in the water column, and the oxygen depletion due to increased temperatures and decomposition processes.

5.5 TEMPERATURE EFFECTS

All four ponds are naturally very shallow, with average depths of 0.4 m, 1 m, 2.7 m, and 2 m, for Ponds 1 to 4 respectively. The ponds are therefore subject to solar heating, which promotes algal and macrophyte growth, reduces DO (maximum DO concentrations vary with temperature), and promotes stratification. Temperatures between 22 and 25^{o}C (characteristic of water temperatures in summer in the ponds) render 100% DO saturation at between 9 and 8.4 mg/L; the maximum concentration of oxygen in the ponds is therefore severely constrained through temperature, rendering management difficult.

Temperature plays a critical role in avian botulism outbreaks. Outbreaks typically occur during summer months when ambient temperatures are at their highest, creating conditions optimal for microbial growth. With the bacterium being an anaerobe intolerant of oxygen, high temperatures in water also prove beneficial for growth by lowering DO concentrations.

5.6 FLUCTUATIONS IN WATER LEVEL

Water levels in Chelsea Ponds regularly fluctuate due to water abstraction from Pond 3 and 4; a consent authorises NZSC to abstract up to 1,500 m^3 of water per day (and up to 8,400 m^3 of water over a 7 day period). These fluctuations are most pronounced when baseflows are low in summer, which coincides with avian botulism outbreaks at the ponds. Fluctuations are amplified in summer due to large evaporative losses as a result of the high surface area to volume ratios in the ponds.

These fluctuations contribute to increases in temperature, turbidity, turnover, and the prevalence of avian botulism, which is promoted by regular changes in water level (Locke & Friend, 1953). Water abstraction from Pond 3 and 4, in conjunction with evaporative losses, also regularly exceed natural freshwater inflows during summer, preventing flow over the final dam wall into the coastal environment, exacerbating barriers to fish passage; this takes place during a critical time of the year when native diadromous species need to migrate to fulfill their life cycle requirements.

5.7 PEST FISH SPECIES AND WATERFOWL

A number of pest fish have been recorded in the ponds, including koi carp, silver carp, rudd, goldfish and tench. While the introductions of grass carp (*Ctenopharyngodon idella*) and silver carp (*Hypothalmichthys molitrix*) were intentional as a management tool to control aquatic weeds and algae, the remaining fish have likely been illegally introduced. All of these fish can have significant effects on water quality. Koi carp in particular continually mobilise sediments through their feeding action, potentially increasing nutrient re-suspension and affecting water clarity (thus temperature).

Waterfowl in large numbers, such as at Chelsea Ponds, are reported to contribute significantly to low water quality in ponds and lakes, particularly in respect of nitrogen and phosphorous inputs (Manny et al., 1994; Palmer et al. 2000). Higher nutrients drive the system to a state conducive for *Clostridium botulinum* production; the prevalence of avian botulism consequently rises with increasing duck numbers. Waterfowl diving within shallow pond environments is likely to re-mobilise sediments in the ponds.

6 ONGOING MANAGEMENT MEASURES

6.1 INTRODUCTION

Auckland Council is in the process of producing an updated Environmental Management Plan to guide future management of Chelsea Ponds. This will build on past successes, and is likely to include new management measures to address persistent issues.

6.2 AVIAN BOTULISM

The use of Chelsea Heritage Park for recreational purposes, and public concern over the regular incidence of sick and dead ducks (particularly in Pond 4), has focused management on preventing avian botulism.

Options associated with reducing or eliminating the presence of the *Clostridium botulinum* bacteria are unlikely to be feasible due to the bacterium being a ubiquitous member of the natural flora in the soils. Management of avian botulism outbreaks therefore focuses on controlling environmental conditions that promote the likelihood of outbreaks. Measures to combat avian botulism address the underlying water quality within the ponds.

6.3 MANAGEMENT OF AFFECTED DUCKS AND DUCK NUMBERS

An inspection, recovery and action plan for sick water fowl was implemented at the beginning of October 2009. Apart from the obvious public concern that dead and sick ducks evoke, decomposing birds are important sources of protein for *Clostridium botulinum* production. Signage was installed around the Chelsea Ponds which reminds people to report any sick waterfowl to Auckland Council.

The presence and overall numbers of bird species, of which ducks appear to be one of the most susceptible to botulism, is in itself responsible for the spread of avian botulism, and consideration must be given to implementing a programme to reduce the duck population at Chelsea Ponds. Reductions of mown grass areas may reduce the attractiveness of habitat to ducks, and reduce bird and public access to the ponds. Feeding of ducks should also be discouraged in order to reduce population growth and faeces production; however this is unlikely to be enforceable or a realistic objective, as a key public activity at Chelsea Ponds is feeding the ducks.

6.4 BARLEY BALES

Barley straw bales have been placed in Pond 3 and 4 in late September annually since 2008. Bales are equally spaced and adequately secured to avoid drift. Barley straw bales have been used in New Zealand, including elsewhere within Auckland, with some success to mitigate algal blooms, and indirectly avian botulism. Inhibition of freshwater algae by application of barley straw has been reported in a number of studies (Caffrey & Monahan, 1999; Ferrier et al., 2003). The spread of botulism and algae is marginally better controlled if barley straw bales are placed in a pond a few weeks before the summer season (pers. comm. Auckland Council staff, 2012). Reductions in algal growth are associated with improvements in DO, accumulation of organic materials in sediments, stabilisation of sediments, reduced nutrient cycling, reductions in temperature, and reductions in pH – all of these improvements reduce the likelihood of avian botulism.

6.5 AERATORS

Aerators were installed in Pond 3 in summer 2003. These aerators are activated when the pond water temperature rises to more than 20°C or the levels of DO drop significantly; the aerators stabilised DO levels between 2003 and 2005, with less or no tendency for anoxic events to take place (Stevenson, 2003, cited in Al Saleem, 2005). The aerators have however significantly improved DO levels in Pond 3 since 2006, when the aerators were serviced, set on automatic control over summer periods, and regular servicing and maintenance of the aerators was implemented.

It is unlikely that the aerators are having a significant impact beyond the confines of Pond 3. Furthermore, the indirect negative effects of re-suspension of sediment and associated nutrient cycling due to the physical action of the aerators have not been determined.

6.6 POLLUTION MANAGEMENT

Very long water retention times through the pond system, high evaporation rates, and consistent water abstraction by the refinery mean that accumulated contaminants are not readily flushed from the system. Eutrophic conditions in the ponds, on account of nutrient accumulation, are therefore likely to persist; however, flows through the ponds may improve after 2023 when the NZSC water abstraction consent lapses, although the overall improvement has not been quantified and may not be significant.

Management efforts to reduce the quantity of contaminants entering the pond system are therefore vital. A key capital intervention to reduce pollution entering the downstream pond system was the addition of sediment forebays to Ponds 1 and 2 in 2004/5. Ongoing management in the form of regular maintenance of inlets and outlets supports their function. The majority of contaminated stormwater and sediment from the upstream catchment enters the pond system via Ponds 1 and 2. The quantum of contaminants entering the pond system has therefore been decreased. However, significant developed catchment areas flow unmitigated into Ponds 3 and 4.

Another key intervention is the remediation of the stormwater culverts through the closed landfill; this process is currently underway.

6.7 FISH PASSAGE

Any attempts to enhance freshwater biodiversity by introducing non-climbing fish species to above the dams may result in a complete loss of productivity from the transferred individuals, which will not be able to survive or reproduce and contribute to the overall sustainability of the population. Based on field investigations and Brent (2010), implementing a fish passage programme past the dam structures at Duck Creek for non-climbing fish species would be of limited value due to a lack of saline wedge and estuarine habitat. Management measures therefore as a first step consider improvement of *in situ* habitat for existing fish populations. Control of pest fish species within the reservoirs benefits native fish communities within the ponds and in the catchment above the dams themselves. Managing water quality to improve DO levels and reduce temperatures is also beneficial for resident fish populations.

Measures for improving climbing opportunities are being investigated, such as the installation of spat ropes. Management strategies to promote more consistent flows over dam structures over the summer months may be a key intervention, especially when water is abstracted by the refinery (Speed, 2010). This would be of most importance for Dam 4 to ensure fish are able to enter the freshwater environment during their migration from the coast.

6.8 PEST FISH

A number of different methods are available for managing pest fish, including chemical treatment, dewatering, and capture methods. Dewatering and chemical treatment are problematic whilst NZSC continues to hold a water abstraction consent, limiting options to capture methods. The most common capture methods employed include line fishing, electric fishing, and netting/trapping, or a combination of the above. This is an aspect of management which has not received a lot of attention to date, but will form part of a management plan currently being produced for the ponds.

6.9 VEGETATION MANAGEMENT

Careful management of aquatic macrophytes and maintaining balance within the pond environment is a critical component of the long term environmental stability of the Chelsea Ponds. Options available for control of aquatic macrophytes in the Chelsea Ponds are restricted primarily by the overall size of the areas available for macrophyte growth and multiple uses of the ponds as a water supply for the NZSC Refinery operation.

The most viable option to control aquatic macrophytes appears to be cutting and removal of weeds in conjunction with the stocking of sterile Grass carp (*Ctenopharyngodon idella*), shown to control aquatic macrophytes (Mitchell, 1980; van Dyke et al., 1984; Clayton, 1996). Grass carp have been introduced to the Chelsea Ponds on a number of occasions in an attempt to control aquatic weeds, with the first introduction to pond 3 taking place in 1992. These fish were believed to have all died in 1995 as a result of a large scale anoxic event in the pond. Grass carp, together with a small number of Silver carp (*Hypothalmichthys molitrix*) were most recently stocked in the ponds during 2010, with additional fish added in 2011. Overall numbers of fish released and indicative stocking rates for each pond from these latest transfers are provided in Table 3.

Table 3: Grass carp stocking rates

Pond	Pond Area (ha)	Grass carp	Silver carp	Stocking Density (carp/ha)
1	0.5	50	-	100
2	2.5	220	-	88
3	1.3	270	-	208
4	3.0	400	40	147

A stocking rate of around 100 fish per vegetated hectare is generally considered a target density to achieve total control of aquatic weed species. Whilst Grass carp were introduced to address macrophyte issues, Silver carp are considered to assist in controlling planktonic algae which they filter from the water column using highly modified gill structures. Its use is generally regarded as not being as valuable as hoped (McDowall 2000).

A weed cutter boat was deployed at Chelsea Ponds during the summer 2010/11 to control significant macrophyte growths and assist in restoring water circulation in Pond 4. This intervention, in association with higher carp stocking rate, appears to have been effective in controlling macrophyte growth over the 2011/12 summer period; however, lower rates of macrophyte growth may also be attributed to an exceptionally cool and wet summer. Long term monitoring is required to verify the effectiveness of grass carp in Chelsea Ponds.

Grass carp do not reproduce in ponds and periodic restocking is required; the lifespan of the grass carp is between 10 and 15 years, and triploid grass carp will provide effective vegetation control for 8-10 years (Lewis, 1998).

7 CONCLUSIONS

The wide range of potential contaminant inputs and complex pond dynamics of the system makes it difficult to provide conclusive answers to how the system functions. Confounding issues are the clear stratification of DO levels whilst temperature is relatively constant throughout the water column, and the exceptionally high pH in Pond 4. However, a number of general statements can be made based on current information.

A key driver in the system is the availability of excessive nutrients throughout the water column. This is likely to be as a result of highly organic sediments, nutrient-enriched stormwater, regular vertical turnover of water as a result of diurnal temperature fluctuations, and the influence of pest fish and high numbers of waterfowl in re-mobilising sediments. It is likely that daily water turnover as a result of diurnal temperature fluctuations takes place in all but the deepest parts of the ponds.

Eutrophic to supertrophic conditions in the ponds are conducive for phytoplankton blooms as well as high macrophyte production, resulting in stratification of DO in the water column as respiration and decomposition processes dominate within relatively stagnant bottom waters. Resultant anoxic conditions in the hypolimnion cause the further release of nutrients, reinforcing the cycle. This process is intensified as photosynthesis is reduced further down in the water column on account of decreased light penetration and a reduction in oxygen saturation capacity due to elevated water temperatures.

The above conclusions, based on a number of assumptions, will be tested by a real-time monitoring programme.

The management initiatives in operation assist in mitigating the water quality problems in the ponds, which serves to protect the amenity of the ponds, particularly minimising avian botulism and reducing public concern. These initiatives are can be undertaken on an ongoing basis to reduce the severity of environmental effects associated with the *in situ* water quality issues. However, exceedences of water quality thresholds still occur in summer, although less frequently, and will continue to do so until the underlying causes are identified and addressed. The same will apply to amenity, and the value of Chelsea Heritage Estate for the public can only be realized once the intrinsic water quality issues are resolved.

Water quality factors that are not within the control of stormwater are sucrose inputs into the ponds, drawdown of Pond 3 and 4 due to the water abstraction, and leachate arising from the landfill. Further investigations and monitoring are required to understand their significance.

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