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AN ECOSYSTEM HEALTH APPROACH TO ASSESSING STORMWATER IMPACTS ON CONSTRUCTED URBAN LAKES

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Abstract

Concrete channels and non-functional landscapes are abundant in many older urban settings. They exist as a legacy to traditional, outdated water management strategies that had, as their principal objective, the rapid transit of stormwater through catchments out to sea. The long-term economic, social and environmental costs associated with such strategies have been well documented. In contrast, urban catchments are now designed to meet multiple objectives, including the provision of healthy, diverse ecosystems and represent the goal of many researchers, planners and managers who have embraced the principles of water sensitive urban design (WSUD).

WSUD seeks to establish functional landscaping within urban settings that provides some level of treatment of pollutants that are typically associated with stormwater runoff while creating hydro-ecological conditions that are similar to the pre-development state. Functional landscaping within urban catchments is now required by many local authorities in greenfield developments. Developers too, have recognised that by adding a 'water-front' aspect to new urban developments, their value is increased through enhancing the aesthetic and liveability appeal. As a result, urban lakes have become popular components of functional landscaping within residential developments.

In many developments, urban lakes have been promoted as a means of stormwater treatment, even though the treatment capabilities of urban lakes were poorly understood. The current reality is that many urban lakes have significant water quality issues, stemming from problems in design, management and unrealistic treatment objectives. Lake conditions can degrade significantly in a relatively short period, eutrophication being highly prevalent in such systems. The remedial management requirements are becoming increasingly expensive as communities expect the water views and aesthetics they invested in to be maintained.

'Reactive' management strategies, which wait for problems to occur before assessment and remediation begins, usually result in short-term solutions that do not address the underlying causes of problems nor recognize the scope of their impact throughout the ecosystem. Furthermore, aesthetics are often the driver of remediation, rather than overall ecological health. The goal of contemporary urban landscaping should be to create diverse ecosystems, that are resilient to perturbations and the increasingly variable hydrological inputs expected under modelled climate change scenarios. A systems approach is needed to establish effective management strategies with the goal of maintaining long-term health.

The ecosystem health paradigm supports such a systems approach and utilises interdisciplinary perspectives to assess and manage the 'total health' of an ecosystem. Further, key biological, physical, chemical and social indicators are used to establish the organisation, resilience and vigour of urban lake systems, the critical components of ecosystem health. Such an approach is conducive to the formulation of adaptive management strategies, establishing a benchmark of urban lake ecosystem health and characterising the links between the range of factors that impact urban lake heath.

Research on sub-tropical urban lakes is limited and generally only considers physicochemical quality. As such, the Ecosystem Health paradigm has been applied to the assessment of a series of ten connected urban lakes on the Sunshine Coast in southeast Queensland. Results indicate that the direct input of unbuffered stormwater has led to biological, chemical and physical degradation in these urban lakes. In addition to poor biogeochemical outcomes, the community has expressed periodic dissatisfaction with lake conditions. Together, these results reflect relatively low levels of ecosystem health. The modelling of key biogeochemical and social indicators within this study will serve to illustrate a comprehensive understanding of the connectedness, and interactions between, these components of the total system. With further development and validation, this model may prove to be an effective tool for adaptive management of urban lake ecosystems.

This research highlights the value of the ecosystem health paradigm through its novel application to the management of stormwater in urban lakes. It provides an effective means of balancing biodiversity and amenity through functional landscaping and adaptive management.

Introduction

The traditional means of managing stormwater runoff was through rapid collection and conveyance into the receiving environment. Relatively little thought was given to storage and less so to the quality of runoff (Wong et al., 2008) and many older urban developments display the legacies of such management, examples of which include large concrete culverts and flows piped directly into receiving environments.

The impact of such traditional management strategies are now being felt on a number of levels. Such impacts are strongly observed on an environmental level, but are also becoming more apparent on social and economic scales. From an environmental perspective, there has been substantial degradation of waterways and water bodies due to urban runoff and traditional management styles (Walsh, 2000; Sonneman et al., 2001; Walsh et al 2004; Walsh et al 2005; Walsh et al., 2007; Likens et al., 2009). From a social perspective, this has impacted on the mental and physical well-being of the people and communities associated with degraded environments (Horwitz et al., 2001). Economically, the need and demand to repair and mitigate degradation has a high, but often necessary, associated cost (Likens et al., 2009).

However, there has been a pronounced shift away from the use of rapid conveyance of urban runoff in developed catchments. Urban stormwater has now been recognised as a major contributor to the degradation of downstream aquatic ecosystems and, as a consequence, significant changes to the design and management of urban runoff have developed (Walsh, 2000; Sonneman et al., 2001; Walsh et al 2004; Walsh et al 2005; Walsh et al., 2007). Part of the movement away from the traditional style of stormwater management and the development of new styles, has been through the use of Water Sensitive Urban Design (WSUD) and incorporating functional landscapes into urban developments, including filtration systems, constructed wetlands and urban lakes.

The shift to on-site management and to mimicking the properties of natural catchments represents a major improvement from simple conveyance. However, this shift has added new dimensions to catchment management, notably the need to manage and maintain functional landscapes with the aim of protecting receiving environments. Components of functional landscaping, such as constructed wetlands and urban lakes, act to mimic natural systems, including how they respond when exposed to unmitigated stormwater pollutants. So, as with the shift away from conveyance as a means of 'treatment', management of functional landscapes requires a shift from traditional paradigms, such as a dependence on physicochemical proxies as the sole indicator of health or quality. Physicochemical indicators are critical components of ecological quality, or health, but do not represent all the links and components of an ecosystem.

The Ecosystem Health Paradigm represents a framework for assessing the state of an environment from a systems perspective to establish ecological health, rather than just providing baseline physicochemical quality (Rapport et al., 1998; Gaudet et al., 2008). To truly characterise the health of an ecosystem, it is necessary to consider a range of indicator categories which reflect the system's organisation, vigour and resilience, such as those outlined in Figure 1 (Rapport et al., 1998; Gaudet et at., 2008). These three components are critical in identifying ecological health, as they quantify the diversity/abundance, ability to cope with stressors and the productivity of an ecosystem (Rapport et al., 1998).

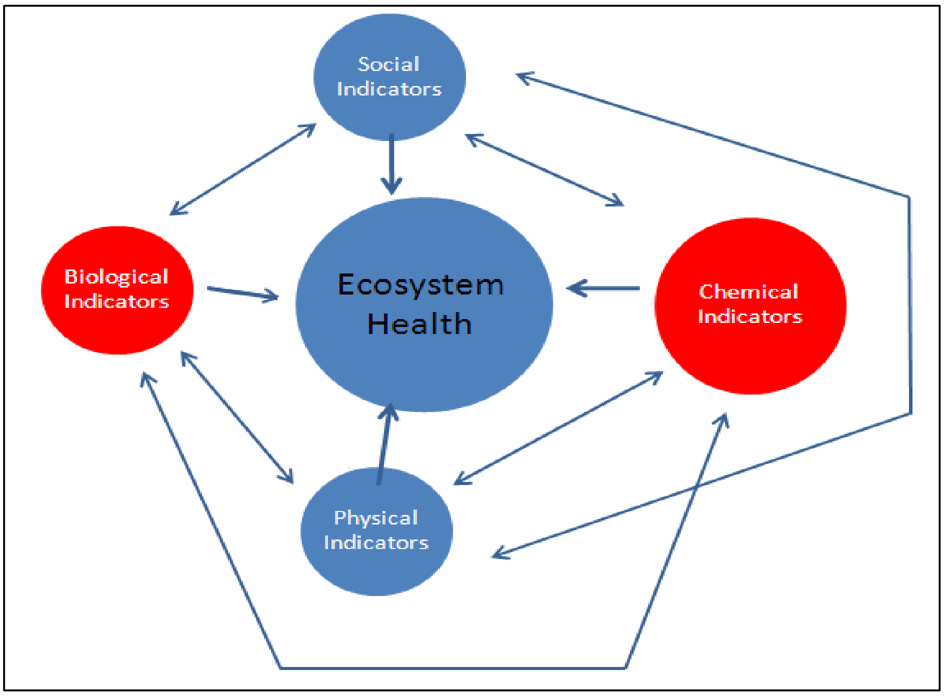

Figure 1 - Categories of Ecosystem Health which aid in establishing organisation, vigour and resilience

Urban lakes represent a significant challenge to catchment managers, as the impacts from surrounding development tend to cause a number of ecological problems, often resulting in a loss of appeal and dissatisfaction by the affected community (Bayley & Newton, 2007; Taylor et al., 2007). As indicated, management of urban lakes has often been limited to physicochemical water-quality monitoring. While valuable, such monitoring does not conceptualise the resilience, organisation or vigour of the ecosystem, but rather provides a static snapshot.

Current management trends are reactive, in which a problem/complaint must occur before action will be taken. Furthermore, management of urban lakes is often driven by unrealistic water quality objectives, such as those outlined in the ANZECC (2000) guidelines, as the combination of the impacts from urban development with current management trends have resulted in many urban lakes failing to achieve an acceptable state of health, based on current guideline values (Bayley & Newton, 2007). The reference criteria outlined in the ANZECC (2000) guidelines are appropriate for slightly - moderately disturbed ecosystems, where urban lakes are commonly found in highly impervious residential settings, which are likely past being considered simply 'moderately' disturbed. While the desire to achieve such stringent criteria is laudable, the application of such objectives seems to be the result of a lack of any substantial data on typical urban lake quality which can be used to establish realistic reference criteria for urban lakes.

Research on sub-tropical urban lakes has been limited and has yet to conceptualise these water bodies as aquatic ecosystems in detail (Kruk et al., 2009; Likens et al., 2009). To begin filling this knowledge gap, urban lakes require a more detailed assessment, such as presented in the Ecosystem Health Paradigm. The application of this paradigm to urban lakes facilitates the ability to conceptually model an urban lake as an aquatic ecosystem, identifying the components of an urban lake ecosystem and how they represent and influence organisation, vigour and resilience.

The aims of this paper are to demonstrate the utility of the Ecosystem Health Paradigm (EHP) in an urban lake context to:

- Characterise the range of factors that impact on the health of urban lakes
- Benchmark the ecological health of constructed urban lakes;
- Provide a basis for a management tool for existing and future urban lake developments

These aims are addressed by presenting the preliminary results of a detailed case study of urban lakes in south-east Queensland. A basic, conceptual model of linked, weighted indicators was used to illustrate how the Ecosystem Health attributes of organisation, vigour and resilience can be captured effectively.

It is proposed that the use of this type of ecosystem health model will facilitate more proactive and adaptive management of urban lakes, as it removes the limitations of considering the physicochemical indicators alone. The inclusion of the surrounding community as a part of an urban lake ecosystem, and therefore as an integral component of the model, provides an additional benefit, in that it allows residents to identify impacts they may have on an urban lake, which in turn fosters custodianship, and potentially long-term improvements.

The Shift towards Water Sensitive Urban Design

Water sensitive urban design (WSUD) has been defined as a philosophy which seeks to minimise the stormwater impacts from urbanisation through the integration of functional landscaping within the urban setting, designing urban areas to maximise water re-use and to promote amenity (Paramatta City Council, 2005). WSUD has been actively explored as a mean to change traditional management perspectives and practices since its widespread introduction to Australia in 2001 (Lloyd et al., 2001). In WSUD philosophy, functional landscaping serves to buffer potentially sensitive receiving environments from the impacts of development, allowing for infiltration or retention of runoff into pervious landscapes and/or constructed water bodies/waterways (Wong, 2001; Lloyd et al., 2002; Wong, 2006). Functional landscapes act to process/retain typical pollutants in urban runoff (Wong, 2006). Typical forms of functional landscaping, such as bioretention/ basins, constructed wetlands and urban lakes are used to remove pollutants typically associated with urban runoff, though the use of the latter remains contentious (Leinster, 2006).

From a developer's perspective, functional landscapes may help meet the requirements needed to achieve development approvals, but can also serve to generate profit and create a unique component of a planned estate. Urban lakes initially create settings of high aesthetic value, serve as a source of fill, and may act to reduce the quantity of runoff in conjunction with active stormwater harvesting. Other benefits include an increase in property values, which is linked to the aesthetic attributes of a newly established urban lake. Some urban lake systems have been promoted by developers as a means of improving water quality, generating further interest by consumers. These reported benefits have led to an increase in the number of urban lakes being incorporated into planned residential developments and have generated a high demand for property adjacent to them (Wong et al., 1999; Eves, 2007).

Problems with Urban Lakes

As stated earlier, well-designed urban lakes have a range of potential benefits and often are established to fulfil multiple objectives. Historically, urban lakes were established to serve an ornamental function, often in public parks or on private property as a sign of affluence (Birch & McCaskie, 1999). Contemporary urban lakes are still established to fulfil an aesthetic function, but often as a central feature of an urban development, rather than on an estate or public park. Furthermore, including treatment functions in relation to both runoff quantity and quality has been a recently added objective. However, establishing urban lakes to fulfil these multiple objectives, has often led to number of economic, social and environmental problems (Wong, et al., 1999; Taylor et al., 2007).

One major issue identified is the widespread degradation of urban lakes as a result of urban runoff (Bayley & Newton, 2007). Many urban lakes experience significant ecosystem shifts, becoming eutrophic or hyper-eutrophic in a relatively short period after their establishment, in some cases as little as two years (Scheffer, 2004; Taylor et al., 2007).

The design of many urban lakes built prior to around 2005, and in some cases after that, exhibit a number of flaws that have contributed to a loss of ecological health. Urban lakes which receive runoff from directly piped inputs have highly concentrated stormwater flows, with increasing flow velocity and sediment loads (Walsh et al., 2004). Short circuiting (e.g. stormwater inputs found close to the lake output), a lack of pre-treatment and poor physical design (e.g. > 3 m deep) are some of the other contributions to a deteriorating urban lake (Bayley & Newton, 2007; Taylor et al., 2007). As the impacts from directly piped inputs and the lack of pre-treatment on urban streams have been well documented in Australia since approximately 2002, it is interesting to contemplate why such considerations are missing from many urban lake designs since that time (Walsh et al., 2004). It may be made that designers believed an urban lake would serve to initially retain or uptake stormwater pollutants, obviating the need for mitigate the above impacts, which may indeed be the case. However, this fails to consider the numerous physicochemical, biological and social impacts resulting from pollutant accumulation in the lakes, particularly in terms of nutrient species (Helfield & Diamond, 1997). Furthermore, applying a treatment objective within the water body inherently diminishes its ecological values, such as biodiversity, because sensitive species are unlikely to tolerate the irregular, variable and potentially high pollutant loads associated with urban runoff (Helfield & Diamond, 1997).

The degradation of urban lakes does not go unnoticed, as these lakes are in urban settings and, as adjacent property is at a premium, residents expect a significant aesthetic benefit and its loss often triggers complaint and dissatisfaction. Horwitz et al. (2001) and Ogunseitan (2005) have investigated the impacts of the degradation of one's home and environment on physical and mental well-being. Ogunseitan (2005) describes the bond between people their environment as 'Topophilia'. For example, when residents purchase property next to a newly constructed urban lake, it can be assumed there is a certain level of pride and affection for the environment, establishing a bond. When and if the lake degrades to an unhealthy state, this bond is affected and there is a sense of loss, or 'Solastalgia'. 'Solastalgia' is defined as 'the distress that is produced by environmental change impacting on people while they are directly connected to their home environment' (Albrecht et al., 2007, pg S95).

As a result of degradation in many urban lake and significant stakeholder dissatisfaction, many management authorities have begun to investigate the health of such lakes. While laudable, management is still triggered by complaint rather than driven to establish proactive and adaptable strategies, and often utilises singular approaches to assessing quality (Taylor et al., 2007; Likens et al., 2009). What may be more appropriate and effective in the longer term is an interdisciplinary approach to assess the environment from a systems perspective, identifying and assessing the key biogeochemical and social indicators of an urban lake ecosystem, which could allow managers to establish strategies for long-term health and realistic outcomes.

Current Management Trends and Mentality

As previously discussed, current urban lake management is driven by complaint and/or the presence of an actual problem (e.g. floating macrophytes or algal blooms), and aesthetics. This is a reactive style of management and often fails to address long-term issues by implementing temporary, specific problem solutions, rather than underlying causes. An example of which are the macrophyte harvesting regimes, a feature of many such lakes, where aquatic plants are regularly removed, but the causative nutrient inputs are not addressed.

Furthermore, while the health of many urban lakes is being monitored, these observations are often limited to the measurements of the physicochemical state of a lake and while arguably relatively efficient, do not provide an indication of its actual health from an ecosystem perspective. An additional limitation of current management is that such systems are often only monitored in a static or 'average' state. This does little to conceptualise the temporal variability of pollutant loads, and fails to assess the resilience of an urban lake to episodic events. Knowing the average state of a system is necessary, but so is establishing the recovery time from episodic events of different magnitudes, and this is often lacking.

Another trend in the management of urban lakes is the establishment of requirements to achieve certain water quality criteria, although again, generally limited to physicochemical indicators. Such requirements stem from documents such as the ANZECC (2000) guidelines. These guidelines state categorically that they should not be used as a basis for mandatory standards, 'because there is significant uncertainty associated with the derivation and application of water quality guidelines' (ANZECC, 2000, pg 1-1). Yet, they have been applied routinely as required criteria by state and local governments, presumably due to their simplistic nature, broad application and a lack of relevant reference criteria. This is a style of equilibrium-based management, which assumes that many aquatic ecosystems are generally in a static state and revert back to this situation relatively quickly after a disturbance (Reeves & Duncan, 2009). Furthermore, equilibrium-based management assumes a once pristine condition and many of the management criteria are based upon achieving this former state, if it ever existed, and generally only in terms of water quality (Reeves & Duncan, 2009). This management style has been applied to aquatic ecosystems in the past and has led to a view of such systems that perhaps limits the tendancy to conceptualise them as dynamic, complex ecosystems. One such example of this was the initial requirement by an Australian local authority for a proposed urban lake to achieve the ANZECC (2000) criteria for freshwater lakes in slightly - moderately disturbed environments. This requirement was stipulated as recently as 2009, despite the fact that the ANZECC (2000) guidelines preclude such use of the identified criteria. Upon further discussion between the lake developer and Council, this requirement was rescinded and more realistic criteria were established.

Applying such management criterion to urban lakes may therefore create unrealistic objectives and fail to achieve a true state of overall ecological health, in terms of resilience, organisation and vigour. For example, when an urban lake is first established, lake clarity is often high, something many people associate with being healthy, natural and pristine. In reality, while such a lake may be considered 'healthy' from a physicochemical perspective alone, it likely has limited organisation and vigour, in an ecological sense. This brings to light another concern, which is the suitability of urban lakes designed for stormwater treatment to provide necessary or desirable ecological services. Helfield and Diamond (1997) argue that stormwater treatment systems, such as lakes and wetlands, are not able to fulfil an ecological enhancement objective while acting as means to treat urban runoff, as the two are largely mutually exclusive.

As mentioned earlier, the concentrations of pollutants associated with urban runoff and the accumulation of such pollutants in lakes and wetland inherently limit the ability of the system to establish itself as a biologically diverse and stable ecosystem (Helfield & Diamond, 1997). As this impairs the vigour, resilience and organisation of an ecosystem, this lake could not reasonably be considered healthy in ecological terms, even though it may be perceived as such by residents and managers alike (Likens et al., 2009). One problem with this 'clarity equals quality' perception is that once urban lakes develop naturally to become more productive and complex, the reaction from residents is likely to be negative. Residents and other stakeholders often drive and influence management decisions, triggering responses that bring about short-term success - perhaps a return to a perceived healthy, clear-water status. This is illustrated by Marotta et al. (2009) with reference to dredging and harvesting of floating macrophytes, as the authors found that such practices served to exacerbate eutrophic conditions, as the removal of the aquatic plants reduced nutrient uptake, reduced water clarity and promoted algal dominance.

Ecosystem Health

In terms of assessing and managing the health of urban lakes, a novel approach is required. Current management and monitoring trends provide a limited dataset, establishing physicochemical urban lake behaviour in a static state. Such methods may appear to be more practical and cost-effective, but they fail to conceptualise a sufficient number of dimensions to determine whether an urban lake is healthy from an ecosystem perspective.

The underlying principles of Ecosystem Health seek to establish the condition of an ecosystem, its components and the links within. The concept of Ecosystem Health can be applied broadly and then defined more specifically, based upon the system it is being used to assess. Ecosystem Health, when defining the health of an aquatic environment, seeks to measure the organisation, resilience and vigour of an environment and to identify contributing factors and how they influence overall system health (Mageau et al., 1995; Rapport et al., eds., 1998). It requires an interdisciplinary assessment of an environment to establish the weight of critical biological, chemical, physical and social indicators on overall health.

Organisation is regularly defined through the biodiversity of and species abundance within an ecosystem. The vigour of an aquatic ecosystem is commonly determined through the primary production occurring, such as through concentrations of chlorophyll-a and nutrient concentrations, as they influence this productivity (Rapport et al., 1998). The resilience of a system can be assessed by assessing its capacity to return to a pre-disturbance state following a disturbance/perturbation (Walker & Salt, 2006).

When using the Ecosystem Health paradigm in the context of urban lakes, identifying biogeochemical and social links and relationships is more time consuming initially, but current management strategies that do not consider these are not likely to be sustainable. Physicochemical data is an intrinsic component of Ecosystem Health, but they need to be substantiated with biological indicators and the community needs to be considered as a contributing element of an urban lake ecosystem, not as a separate entity (Likens et al., 2009).

Similar applications of the Ecosystem Health concept have been used to weight ecological indicators of fresh and marine systems in south east Queensland, which in turn have been used to determine a grade ('A' – 'F') of ecological health (EHMP, 2010). As described in Figure 2, indicators were weighted by subtracting the value observed in the ecosystem ('x') from a guideline value, such as the ANZECC (2000) values, and divided by the worst case scenario (WCS) minus the guideline value. This value is then subtracted from 1.0 to determine a value, or score, of ecological health (EHMP, 2010).

$$\text{Score} = 1.0 - \left| \frac{(x - \text{Guideline})}{(\text{WCS} - \text{Guideline})} \right|$$

Figure 2: Ecosystem Health scoring method, modified from EHMP, 2010

Using an Ecosystem Health paradigm broadens the definition of health away from just water quality and aids in visualising a more complex system, which then helps to establish proactive and adaptable management strategies. Furthermore, the explicit inclusion of the community in the assessment allows for a clearer definition of what health is. The surrounding community is something that is traditionally overlooked in the management of aquatic ecosystems, at least in terms of anything other than a source of pollutants. Unlike many natural systems, urban lakes are an intrinsic component of many residential developments and to exclude the community from assessment fails to contextualise an urban lake as a socio-ecological system. While the idea of a community being a part of an urban ecosystem is becoming more accepted, there is still a reluctance to incorporate human attitudes, values and behaviours into aquatic ecosystem health assessments, despite some data that supports the concept (Horwitz et al., 2001).

In order to determine the viability of applying the ecosystem health paradigm on urban lakes, a PhD research programme was established using a series of established sub-tropical urban lakes as the basis for assessment.

Case Study: Chancellor Park

Chancellor Park is a planned residential estate located on the Sunshine Coast, Queensland. Within the estate are ten interconnected urban lakes, which receive runoff from the surrounding medium to high density development. (See Figure 3).

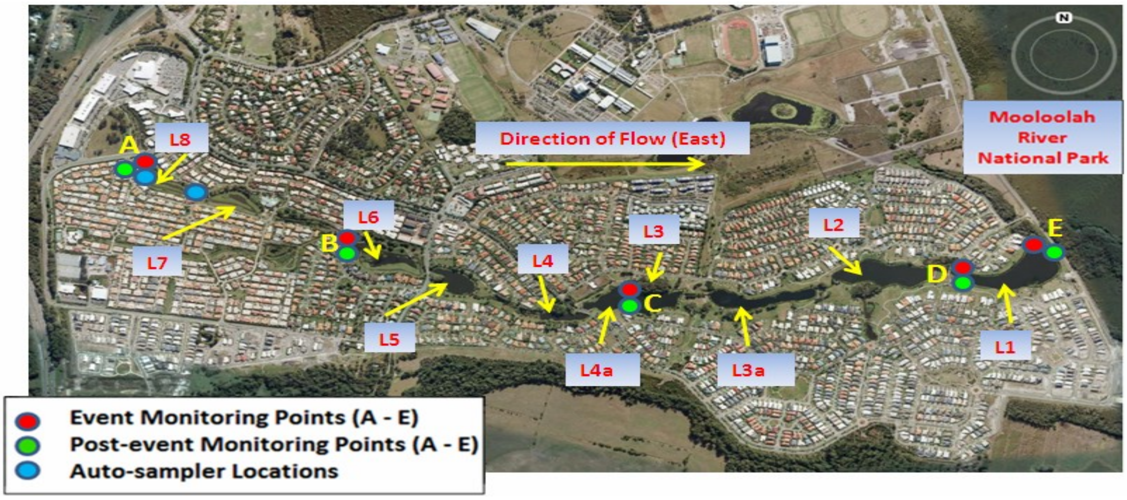

Figure 3 - Chancellor Park Lakes (L8 - L1) and Event & Post-Event Monitoring Locations. The catchment discharges into the Mooloolah River National Park (MRNP)

Construction of the Chancellor Park estate and the lakes began in 1993, with the final lake being constructed in 2003 (SCRC, 2009). Lake design varies, with the older lakes (8-4) being smaller and shallower than the younger lakes (4a -1). The lakes were built for multiple reasons; a source of fill in order to develop a low-lying area, to create a unique estate to improve sales, and to treat runoff. The developers stated that 'the primary function of the lakes is to collect and treat stormwater for the entire estate as well as acting as a filtration system for the adjoining Mooloolah River National Park' (Welcome to Chancellor Park, n.d).

Presently, the lakes in Chancellor Park are in various states of degradation. The older lakes are eutrophic to hyper-eutrophic, routinely covered in floating macrophytes and thermally stratify in the summer, despite the lack of depth, which limits stratification. The younger lakes are prone to algal blooms and are persistently stratified. Residents of Chancellor Park have voiced strong complaints against the condition of the lakes and the Sunshine Coast Regional Council (SCRC) has invested significant time and capital towards the rehabilitation of the lakes, establishing pre-treatment and current best practice design. Although this remediation comes at a significant cost, if previous management styles are utilised, this may again prove to be a short-term solution. For this reason, the Council has invested in research which seeks to establish the health of the system on an interdisciplinary level with the aim of improving the management of this and similar urban lake systems.

Chancellor Park & Ecosystem Health

Chancellor Park presents an ideal system to assess urban lakes using the Ecosystem Health paradigm because the lakes in the development form the primary component of the functional landscape. As part of the assessment, Chancellor Park was evaluated using a range of indicators on physical, chemical, biological and social scales. Four of the ten lakes (lakes 8, 6, 3 & 1) were selected to be assessed as they represent the broad range of design as well as the input and output of the Chancellor Park catchment (lakes 8 & 1, respectively). (See Table 1).

Table 1 - Lake Attributes

Lake	Surface Area (Ha)	Catchment Area (Ha)	Surrounding Land Use	Mean Depth (m)	Max Depth (m)	Volume (ML)
8	0.63	82	Residential Retirement Village Commercial	1.82	3.04	11.4
6	1.67	67	Residential Retirement Village	1.57	3.32	26.2
3	1.28	14	Residential	5.03	6.5	64.3
1	2.83	31	Residential	6.07	8.5	171.6

In terms of the physicochemical assessment, typical water quality indicators were assessed monthly over a three and a half year monitoring period at the inlets, outlets and the epilimnions and hypolimnions of the selected lakes. (See Table 2)

Table 2 - Physicochemical parameters. *Note: 1 Chlorophyll - a is a biological indicator of vigour but has been included in this table as it was part of routine monitoring

Indicator	Unit of Measurement
Dissolved Oxygen (D.O.)	Percent saturated & milligrams per litre (% & mg/L)
Temperature	Degrees Celsius (°C)
Specific Conductivity	Micro Siemens per centimetre (µS/cm)
pH	Standard logarithmic scale (1 – 14)
Turbidity	Nephelometric Turbidity Units (NTU)
Salinity	Practical Salinity Scale (PSS)
Total Suspended Solids (TSS)	mg/L
Nitrite (NO_2)	µg/L
Nitrate (NO_3)	µg/L
Ammonia Nitrogen (NH_3-N)	µg/L
Total Nitrogen (TN)	µg/L
Phosphate (PO_4-P)	µg/L
Total Phosphorus (TP)	µg/L
Chlorophyll – a (Chl-a)*	µg/L

These parameters were also assessed during three storm events, which occurred in February, March and April of 2010 at locations specified in Figure 3. Such monitoring served to investigate these parameters along spatial and temporal dimensions, across different scales, to establish the resilience of the system to disturbance events and quantified incoming and outgoing pollutant load. Typical water quality criteria, as outlined in the ANZECC (2000) guideline, were used to establish whether or not the Chancellor Park lakes meet such criteria and based on analysis of the monitoring results, preliminary urban lake reference criteria will be established.

For a biological assessment, a floral and macroinvertebrate survey was conducted to establish the organisation, or species biodiversity and abundance, of the system. No previous data on the floral or macroinvertebrate composition of Chancellor Park existed and it was important to establish a baseline survey. The macro-invertebrate sampling survey was conducted using a standard method (DERM, 2009) and the results were assessed using both the SIGNAL2 (Stream Invertebrate Grade Number Average Level) Index and the SWAMPS (Swan Wetlands Aquatic Macroinvertebrate Pollution Score) Index. Both the indices were utilised and compared as urban lakes represent a novel application of both methods.

The social component of the study consisted of a screening level risk assessment to establish actual and perceived human health risks associated with the lakes and a community survey. The community survey aimed to characterise the attitudes and values the residents placed on the lakes and any behaviours which may impact lake health. It was necessary to establish the link between the surrounding community and the lakes to determine the dynamic of the relationship, i.e. how people utilise the lakes, what risks to health may exist and what impacting behaviours may be occurring. This was important to establishing the community as a linked component within an urban lake ecosystem.

Selected Results and Interpretations

Some representative results are presented to illustrate the varying states of the selected indicators used in the Ecosystem Health assessment of the Chancellor Park lakes. These results are a subset of a much larger study that is ongoing.

Basic physicochemical results establish that the lakes are persistently stratified throughout much of the year, although the strength and duration of the stratification is linked to the lake depth, as illustrated in Figure 4.

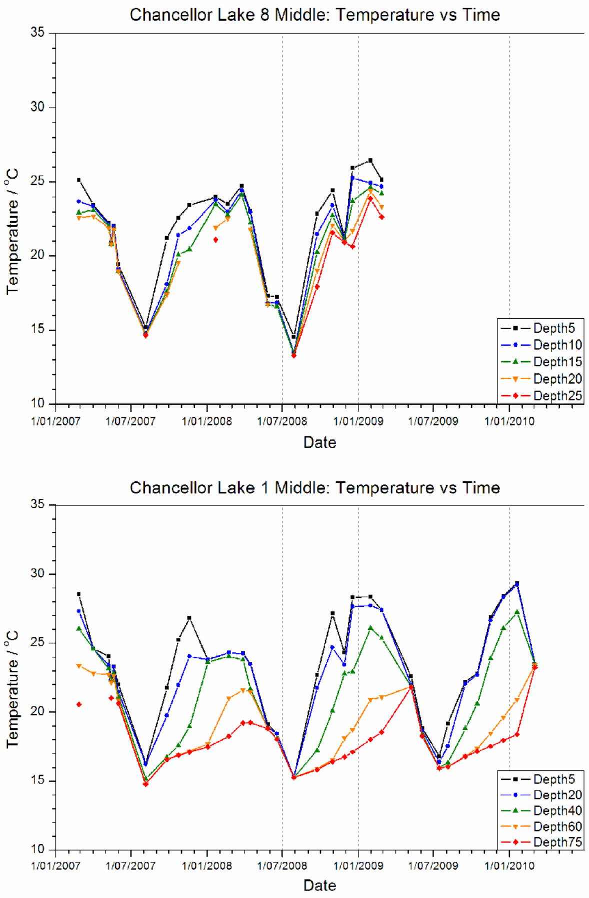

Figure 4 – Water column temperature (°C) of Lake 8 & Lake 1 over the duration of field work. Data collected at the deepest point (approximately the geographic middle) of each lake. Note that data collection ceased in Lake 8 in 2009 due to the reconstruction works.

Stratification was more pronounced in Lake 1, though Lake 8 demonstrates stratification during the warmer months, despite being shallow. Lake 8 was routinely covered in floating macrophyte, which limited sunlight penetration of the water column, causing thermal stratification.

Figure 5 shows the relationship between dissolved oxygen (mg/L) and time. Lake 8 demonstrated low concentrations of DO during warmer months and was routinely hypoxic. The high availability of organic carbon in the form of decayed macrophytes likely contributed to low oxygen as a result of microbial activity. Lake 1 also demonstrated hypoxic conditions at the lake hypolimnion, as the lake depth limits submerged macrophyte colonisation.

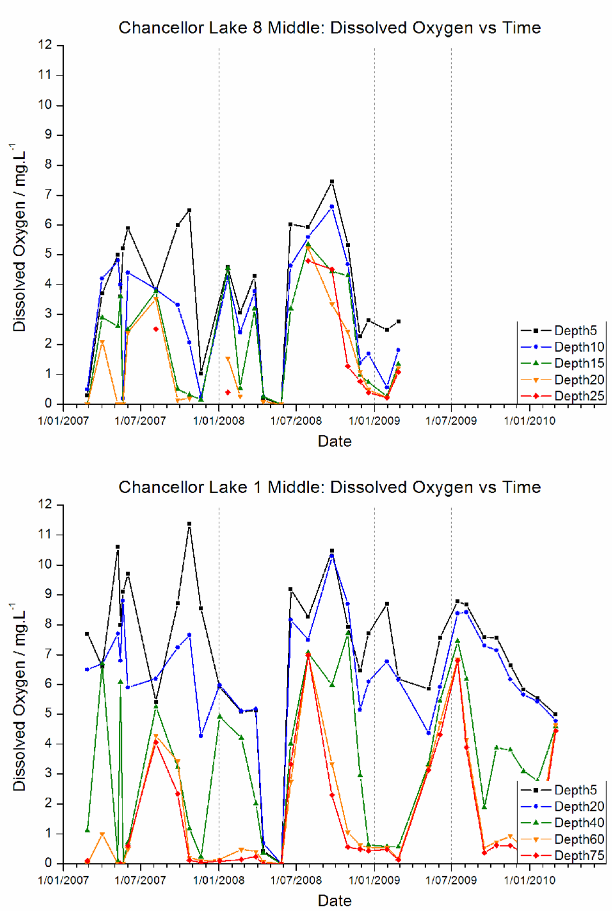

Figure 5 – Dissolved oxygen concentration (mg/L) in the water column of Lake 8 & Lake 1 over the duration of field work. Data collected at the deepest point (approximately the geographic middle) of each lake. Note that data collection ceased in Lake 8 in 2009 due to the reconstruction works.

The pre-event, event and post-event monitoring served to identify incoming/outgoing pollutant loads and characterises system resilience. Figure 6 shows both turbidity and total nitrogen increasing at location 'B', indicating possible point sources from lakes 8 & 7, as well as the sub-catchment that drains into Lake 6. Given the small retention capability of lakes 8 & 7, it can be argued that pollutants, particularly sediment (and the subsequent sediment bound nutrients) were flushed from the two lakes and may build up in Lake 6.

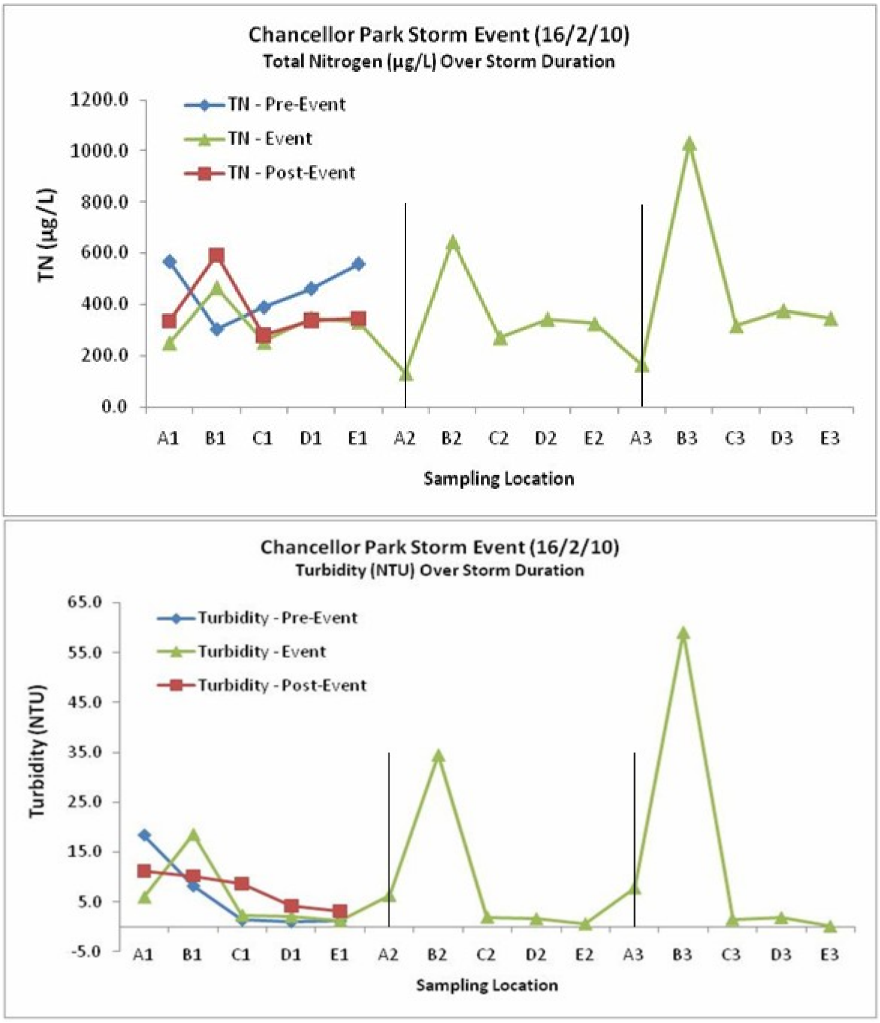

Figure 6 – Total Nitrogen (µg/L) and Turbidity (NTU) data collected over the duration of a storm on 16/2/10. The black lines indicate the start of a new round of sampling

The floral survey established floral diversity and identified a number of aquatic weeds present in the system, most noticeably *Salvina molesta, Nymphaea mexicana, and Azolla pinnata*. (See Figures 7 & 8). The dominance of these species limits resource availability for other species, and therefore reduces ecological organisation. Such species also serve to reduce light penetration, inhibiting growth of beneficial submerged macrophytes.

Figure 7 -*Nymphaea Mexicana*

Figure 8 - *Salvina molesta & Azolla pinnata*

The macroinvertebrate survey further characterised the organisation of the system. The SIGNAL2 Index was determined by the sensitivity grade of the family identified (1-10) multiplied by the weight factor determined by abundance. These scores were then combined and divided by the total combined weight factor to yield the SIGNAL2 Index score for the sampled area. The SWAMPS Index was determined by the combined sensitivity grade of the families present divided by the number of families.

The average SIGNAL2 Index score for Chancellor Park was 4.21 / 10, indicating moderate pollution is present, based on the species found and their abundance. The SWAMPS index yielded a score of 4.15 / 10, also indicating moderate pollution. Both scoring indexes indicate relatively low macroinvertebrate diversity and abundance. The SIGNAL2 index is characterised by species sensitivity and abundance, where SWAMPS is characterised by sensitivity and diversity. As such, the use of both scoring indexes may provide a better assessment of organisation in urban lakes. (See Table 3).

Table 3 - Macroinvertebrate survey results. Lake 8 was not included as reconstruction works had begun at the time of the survey.

Lake Sampling	Habitat	Families	SIGNAL2 SCORE	Score Indications	SWAMPS SCORE	Score Indications
Lake 6 - 1A	Floating Macrophyte	12	4.36	Moderate Pollution	3.42	Probable severe enrichment or pollution
Lake 6 - 1B	Emergent Macrophyte	10	4.35	Moderate Pollution	4.40	Probable moderate enrichment or pollution
Lake 6 - 2A	Floating Macrophyte	8	4.44	Moderate Pollution	4.50	Probable moderate enrichment or pollution
Lake 6 - 2B	Emergent Macrophyte	18	3.76	Severe Pollution	3.89	Probable severe enrichment or pollution
Lake 6 - 3A	Floating Macrophyte	7	3.78	Severe Pollution	4.00	Probable moderate enrichment or pollution
Lake 6 - 4A	Floating Macrophyte	10	4.28	Moderate Pollution	5.30	Probable minor enrichment or pollution
Lake 6 Average Score		**SIGNAL2 Score**	4.16	Moderate Pollution	**SWAMPS Score** 4.25	Probable moderate enrichment or pollution
Lake 3 - 1A	Floating Macrophyte	8	4.35	Moderate Pollution	4.75	Probable moderate enrichment or pollution
Lake 3 - 2A	Floating Macrophyte	5	4.92	Moderate Pollution	3.80	Probable severe enrichment or pollution
Lake 3 - 3A	Floating Macrophyte	13	4.11	Moderate Pollution	5.08	Probable minor enrichment or pollution
Lake 3 - 4A	Floating Macrophyte	9	4.24	Moderate Pollution	4.56	Probable moderate enrichment or pollution
Lake 3 - 4B	Emergent Macrophyte	11	4.17	Moderate Pollution	4.18	Probable moderate enrichment or pollution
Lake 3 Average Score		**SIGNAL2 Score**	4.36	Moderate Pollution	**SWAMPS Score** 4.47	Probable moderate enrichment or pollution
Lake 1 - 1A	Floating Macrophyte	8	4.57	Moderate Pollution	3.25	Probable severe enrichment or pollution
Lake 1 - 2A	Emergent Macrophyte	8	3.40	Severe Pollution	3.88	Probable severe enrichment or pollution
Lake 1 - 2B	Floating Macrophyte	7	4.33	Moderate Pollution	4.43	Probable moderate enrichment or pollution
Lake 1 - 3A	Emergent Macrophyte	9	4.35	Moderate Pollution	3.00	Probable severe enrichment or pollution
Lake 1 - 3B	Open Water	7	3.67	Severe Pollution	3.00	Probable severe enrichment or pollution
Lake 1 - 4A	Emergent Macrophyte	8	4.45	Moderate Pollution	4.63	Probable moderate enrichment or pollution
Lake 1 Average Score		**SIGNAL2 Score**	4.13	Moderate Pollution	**SWAMPS Score** 3.70	Probable severe enrichment or pollution
	SYSTEM AVG SCORE		**4.21**	**Moderate Pollution**	**4.15**	**Probable moderate enrichment or pollution**

A screening level risk assessment, as part of a separate, related project, assessed the actual and perceived risks within the lakes, using the methods outlined in the National Health and Medical Research Council's 'Guidelines for Managing Risks in Recreational Waters' (2008). The results found that microbial water quality was generally poor, but indicated only a slight health risk associated with primary contact (Lampard, 2010). Potentially toxic cyanobacteria were found at all the sampling locations in low cell counts, yet a moderate to high risk of cyanobacterial contamination exists, due to previous blooms and regular physicochemical conditions which favour algal growth (Lampard, 2010). Children were repeatedly observed swimming in the lakes and jumping off typical residential infrastructure (i.e. bridges, weirs), which characterised the presence of physical risks. Such anecdotal observations lend weight to the fact that despite not being established for primary recreation, the Chancellor Park lakes are still routinely utilised as such.

A self-administered questionnaire of the Chancellor Park residents was conducted, which helped to identify the attitudes and values the residents have towards the lakes, as well as to identify behaviours that might impact upon lake health. The cross-sectional survey was distributed to 466 residences chosen at random, with a response rate of 33% (n=145). In terms of basic attitudes and values placed upon the Chancellor Park lakes by the residents, a total of 54% of residents felt that the lakes greatly contributed to a sense of community. A total of 52% of residents felt that the influence of the lakes on property values was great (25%) or significant (27%) and 62% of residents claimed they received great (29%) or significant (33%) enjoyment from the Chancellor Park lakes. Such results indicate that a strong bond exists between many residents and the lakes and the lakes add significant value to the estate. In terms of impacting behaviours, 29% of residents sometimes washed cars at home with 11% often doing so and 15% always doing so and over a third of respondents (35%) stated they sometimes used fertilisers, 41% sometimes used herbicides, and 26%

sometimes used pesticides. These community behaviours have the potential to be detrimental to lake health, in addition to the impacts commonly related to urban development.

Discussion

The results of this assessment will be used to benchmark the ecosystem health of the Chancellor Park lakes, characterising the vigour, resilience and organisation of the system. Preliminary results indicate that the lakes routinely exceed the physicochemical and biological criteria outlined in such guidelines as the ANZECC (2000). To this end, it is not considered appropriate to apply such guidelines, particularly when values are established for slightly - moderately disturbed ecosystems. Ongoing analysis of the results will be used to establish preliminary reference criteria for use in future urban lake monitoring programmes. The results of the monitoring will be analysed to establish a score of ecological health using both the ANZECC (2000) criteria and the Chancellor Park reference criteria as guideline values, using the EHMP (2010) method described in Figure 2. This will allow a comparison of Ecosystem Health scores based on slightly – moderately disturbed guideline criteria (ANZECC, 2000) to the scores derived from the Chancellor Park reference criteria.
Another objective of this research is to establish a model of urban lake ecosystems. Figure 8 provides a conceptual model of the Ecosystem Health assessment used for Chancellor Park, and represents the first step towards creating a more complex model, which will utilise the study results to characterise the links within an urban lake ecosystem, establish cause and effect scenarios, and integrates the results of the assessment to characterise the organisation, vigour and resilience of the lakes based upon national and derived reference criteria.

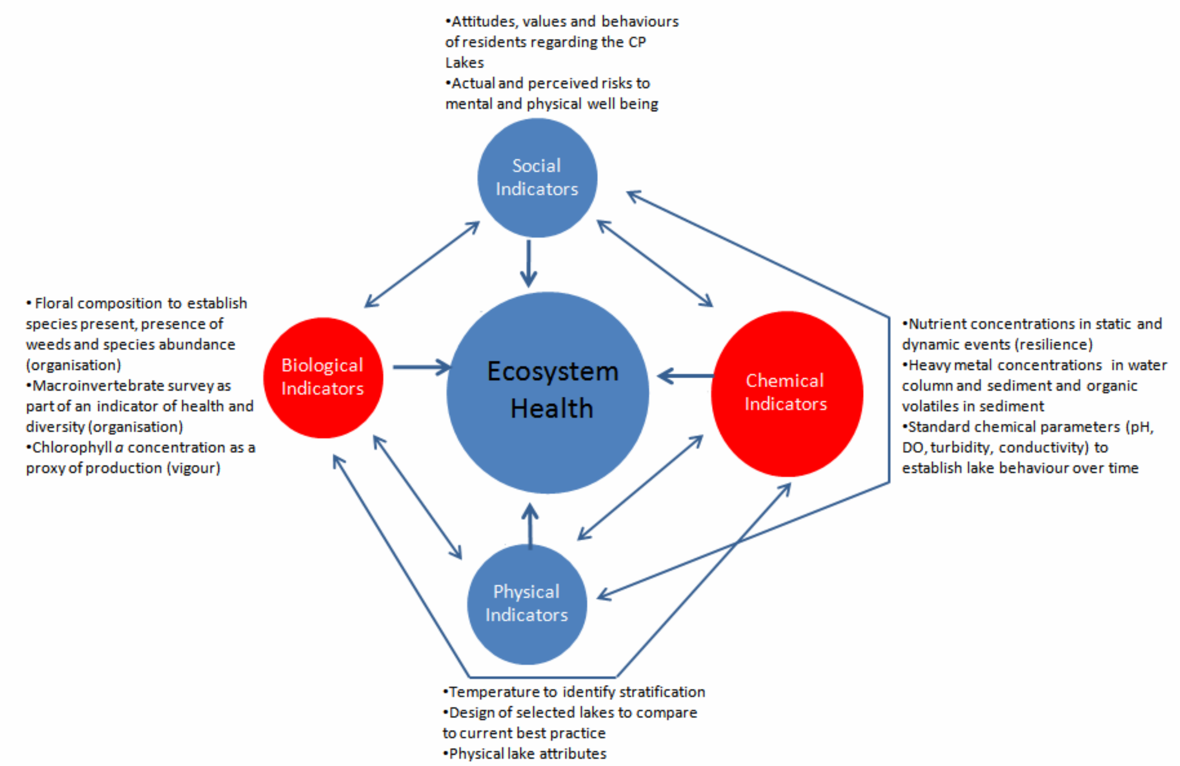

Figure 8 - Conceptual model of Ecosystem Health approach tailored to constructed urban lakes

Any model derived from this application of the Ecosystem Health Paradigm will require further validation and research, but the outcomes of this study will serve to establish the links and relationships between defined indicators of urban lake ecosystem health and to establish baseline urban lake reference criteria, both of which may be used to form future management tools.

Although assessing the ecological health of natural shallow lakes is not new, particularly in temperate climates, assessing a constructed system as part of an urban environment is a novel concept, as is the application of the Ecosystem Health Paradigm in this context. Ecosystems include functional urban landscapes and the inclusion of social indicators is paramount to truly assess ecosystem health and help to increase community understanding of urban lake ecosystems and to foster realistic objectives. As there are no current guidelines which provide reference criteria for the social indicators as derived from this Ecosystem Health assessment, the manner in which social indicators will be scored and modelled is to be determined in near-future research.

Conclusion

This novel application of the Ecosystem Health Paradigm on urban lakes, as described in this paper, illustrates the need to move beyond traditional means of assessing the health of urban water bodies. Ecosystem Health cannot be defined by physicochemical qualities alone, but must be assessed from a systems perspective. In addition, urban lakes should no longer be viewed solely as a means of treatment for urban runoff, as they are likely to continue to be features of functional landscapes. They should rather be considered as a receiving environment, designed to enhance ecological habitat and diversity. To this end, a realistic level of water quality must be achieved prior to discharge to an urban lake and management strategies which strive for long-term health must be in place (Likens et al., 2009). Pre-treatment measures, such as constructed wetlands, should be designed for pollutant removal/retention rather than aesthetics or for habitat, as the two objectives are mutually exclusive (Helfield & Diamond, 1997). Furthermore, urban lakes must be managed using a systems approach, inclusive of biogeochemical indicators and social indicators. Residents are an often over-looked source of information and expertise and managers should encourage an active community role to establish a sense of custodianship of urban lakes in the community.

The adoption of the Ecosystem Health Paradigm has allowed for a more in-depth assessment of the Chancellor Park lakes from a systems and interdisciplinary perspective. Arguably, it allows a much more substantial picture of health to be formed, assessing ecological resilience, vigour and organisation, rather than just monitoring physicochemical quality. This improved picture will certainly allow for more comprehensive functional landscape management.

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