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Residential canal estates with water frontage are an obvious feature in many parts. While achieving human gain, the challenge for managers is also ensuring these novel ecosystems provide extended habitat opportunities for animals. Over time, these created waterways typically become degraded and require considerable management intervention. Increasing nutrient concentrations, summer time low oxygen concentrations and presence of algal blooms are commonly measured owing primarily to limited flushing capacity, but also proximate land use activities. Better waterway designs and planning are necessary, rather than expensive restoration programs.

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ARTICLE TYPE

Water and sediment quality, nutrient biochemistry and pollution loads in an urban freshwater lake: balancing human and ecological services

Nathan J. Waltham,[a,e] Amanda Reichelt-Brushett[b,c], Damian McCann[c], Bradley D. Eyre[d]

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Optimizing the utility of constructed waterways as residential development with water-frontage, along with productive and functional habitat for wildlife is of considerable interest to managers. This study examines Lake Hugh Muntz, a large (17ha) freshwater lake built in Gold Coast City, Australia. A ten year water quality monitoring programme shows that the lake has increasing nutrient concentrations, and together with summer algal blooms, the lake amenity as a popular recreational swimming and triathlon training location is at risk. A survey of fish and aquatic plant communities showed the lake supports a sub-set of species found in adjacent natural wetlands. Sediment contaminants were below the lower Australian trigger values, except As, Hg, Pb and Zn, probably a function of untreated and uncontrolled stormwater runoff from nearby urban roads. Sediment biogeochemistry showed early signs of oxygen depletion, and an increase in benthic organic matter decomposition and oxygen consumption will increase nitrogen recycling to the water column as NH_4+ (increasing intensity of summer algal blooms) and less nitrogen lost to the atmosphere as N_2 gas via denitrification. A series of catchment restoration initiatives were modeled and the optimal stormwater runoff restoration effort needed for lake protection will be costly, particularly retrospective, as is the case here. Overall, balancing the lifestyles and livelihoods of residents along with ecosystem protection are possible, but require considerable trade-offs between ecosystem services and human use.

Introduction

Expansion of coastal development for human gain continues to contribute to collateral damage of critical natural wetlands in estuaries and coastal areas in many locations.[1,2] The most obvious coastal development feature is construction of residential canal estates which achieve the purpose of increasing real estate with water frontage (global network of over 4,000km linear covering 270km^2).[3] The construction of residential canals requires large amounts of fill material to build over previously low lying coastal lands (e.g., mangroves, saltmarsh) or digging of terrestrial habitat to construct artificial urban waterway developments (canal estates). That this development is in close proximity to estuaries and waterways, where unobstructed water views can be sold for a premium, the maintenance or reintroduction of native vegetation that are critical for aquatic ecosystems and associated water quality are objected to and creates a planning challenge for managers of rivers and catchments. The challenge for coastal managers to continue approving coastal developments, at the loss of wetland habitat and conservation, is increasing in many places as human population increases.[4,5]

In Australia, construction of residential canal estates has proliferated since the early 1960s and was generally inspired by the first canal (Florida Gardens canal estate) completed in 1956. Since this time many more canals have joined directly to natural estuaries or to the end of existing canal systems.[6] Artificial urban waterways on the Nerang River estuary in Queensland alone have increased the original linear length of the estuary from 20km to over 150km.[3] A major consequence of this ongoing construction activity is hydraulic and erosion problems for downstream residential properties and bridge foundations. In response, waterway property developers altered the engineering to lake developments that are separated from the downstream waterway via a tidal control device (e.g., locks, weirs, gates, pipes).[7] The shift to lakes has allowed property developments to extend further landward with minimal consequences on the downstream tidal prism.[7] These lakes now occupy approximately 1,430ha in Australia, but are also an obvious feature elsewhere (Asia/Middle east 950ha, North America 460ha, Europe 138ha), representing approximately 5% of the total global extent of artificial urban waterways.[3]

Urban waterways differ vastly from natural coastal wetland habitats.[4] Not only do they lack aquatic vegetation such as mangroves and saltmarsh grass, or a gentle sloping muddy intertidal foreshore,[4] but they have a smooth, engineered, almost vertical shoreline and bare substratum as well as reduced water quality which is a consequence of greater depth, reduced circulation, high ramification (network of many narrow arms extending from a main channel) and high input loads of untreated urban stormwater which also impacts on habitat quality.[4,8] Poor water quality conditions create problems when considering community recreational values (swimming), aesthetic values and boating opportunities for landholders. In some constructed waterways, groundwater delivers freshwater water to adjacent tidal systems, diluting saltwater intrusion from downstream estuaries.[9]

This study examines long-term water quality data collected over 10 years, in combination a detailed field sediment contaminant and benthic biogeochemistry survey, and biological survey (fish and aquatic plants) in a large urban constructed freshwater lake. Pollutant loads were also modeled for the surrounding catchment entering the lake under current and mitigated urban development scenarios to determine the optimal extent of stormwater mitigation necessary to protect and enhance the lakes recreational and aesthetic values along with the ecosystem biodiversity. This study aims to assist managers balance the objective of lake amenity and ecosystem services.

Methods

Study area

Lake Hugh Muntz is approximately 17ha in size, has a surface area of 148,462m^2, a maximum depth of 12m, and a total volume of 704,472m^3. It has an urban catchment (43ha) which drains rainfall runoff directly, unprocessed and untreated, into the lake via 16 constructed stormwater outlet pipes (Fig. 1). The shape of the lake maximizes residential real estate with water-frontage. Water discharges from the lake via overflow pipes, located at the southern end of the lake, into the tidal Nerang River canal network, an extensive urban residential canal estate.[3] The overflow design permits the occasional exchange of tidal waters from the adjacent canal estate.[10]

The lake historically formed part of an extensive coastal inland Melaleuca wetland and floodplain complex. The lake is a freshwater refuge for plants and animals in the centre of the urbanized Gold Coast (population approx. 0.6 million people).[11] It is the only primary contact (swimming) recreational freshwater lake in the coastal section of the Gold Coast. A range of recreational activities occur in the lake including fishing, swimming, canoeing, kayaking, and paddle boarding.

Fig.1 Nerang River estuary and adjoining canal network in southern Broadwater. Inset shows location map of Lake Hugh Muntz. O; Long term council water quality monitoring site (2 and 5); ● (A to G) sediment sites in this study: A, B and C were fish survey sites; A is also the location of sediment nutrient processes. ⇳ tidal flow under bridges. − underground pipe (90 cm diameter) permitting floodwaters to escape from Lake Hugh Muntz during high rainfall, but also allowing minimal tidal water to flow into the lake from the Nerang River canals.

Community use and expectations

A public meeting and workshop was held in September 2007 to discuss the lake. Additionally during the meeting 97 surveys were completed by community members including residents within and around the Lake Hugh Muntz catchment as well as people who come to the lake area and use it for various recreational and sporting activities. The community surveys and participation were designed to develop a vision for the lake. As part of this, environmental values, level of protection, aspired management goals, and level of importance of the lake as an aquatic ecosystem were explored, consistent with approaches described to support the Australian National Water Quality Management Strategy.[12]

Sediment sampling

Sediments were collected from seven locations in the lake on 22nd January 2008 (Fig. 1). Samples were collected using a van Veen sediment grab sampler, with samples immediately stored in snap seal bags and transferred on ice to the NATA accredited Environmental Analysis Laboratory at Southern Cross University. Sediments were digested in aqua regia and Ag, As, Pb, Cd, Cr, Cu, Mn, Ni, Se, Zn and Hg were determined by Inductively Coupled Plasma Mass Spectrometry (ICP MS), and Fe and Al were determined by Inductively Coupled Plasma Optical Emissions Spectrometry (ICP OES). Total phosphorus was determined by ICPMS after hot block digestion and according to the US EPA method 3050. Total carbon, total nitrogen, and total sulphur were determined using a LECO CNS2000 analyser. Additional samples from each site were collected in ethanol washed glass jars for oil and grease analysis via hexane extraction (APHA 5520-D). Organochlorine and organophosphate pesticides, and hydrocarbons were determined at the NATA accredited LabMark laboratory by solvent extraction and analyses by Gas Chromatography–Flame Ionisation Detector (GC–FID).

Triplicate sediment cores were also collected at one site (sediment collection site C which is likely to be an area of deposition; Fig 1) by a surface operated hand-corer in pre-soaked 95mm x 500mm long clear plexiglas tubes, retaining approximately 200mm sediment and 300mm (2.5L) overlying water. Care was taken to retain cores only with an undisturbed sediment surface. Cores were transported at in situ temperature and light to the laboratory within six hours of collection where they were placed uncapped into an incubator with 150L of recirculated and aerated site water at collection temperature. The in situ diurnal light-dark climate was maintained throughout the incubation, and PAR irradiance was set at the daily mean at the sediment surface at the site of collection. Cores were equipped with self-stirrers set at 0.1m above the sediment surface and stirring rates set to just below resuspension. A 24-hour equilibration period was observed, and flux incubations started approximately two hours after sunset the following evening. Cores were capped and sampled for the analysis of alkalinity, nitrogen gas (N_2), argon (Ar), ammonium (NH_4^+), nitrate (NO_3^-), dissolved organic nitrogen (DON), dissolved inorganic phosphorus (DIP), dissolved organic phosphorus (DOP) were taken every six hours. Dissolved oxygen concentrations (± 0.01 mg L-1) and pH (± 0.001) were also measured electro-chemically. Dissolved oxygen concentration typically decreased only about 20% during the dark incubation. All analyses were followed accepted methods.[12] Fluxes across the sediment-water interface were calculated by linear regression of the concentration data, corrected for the addition of replacement water and changes in the blank, as a function of incubation time, core water volume and surface area. Only the linear portions of the concentration versus incubation time curve were used in the flux calculations. Dark flux rates were calculated using concentration data from the first 10 hours of the incubation and light flux rates were calculated using concentration data from the second 14 hours of the incubation. Net flux rates are calculated from the dark flux*dark hours plus the light flux*light hours divided by 24 hours.

Aquatic biological communities

Fish were sampled during the day at three random locations across the lake, using three sampling techniques: seine net, gill net and bait traps. The gill net (soak time 45 mins) was set perpendicular to the bank at the southern corner of the lake. The seine net was launched and retrieved over three selected sandy beach sites, while 5 bait traps were also set at each site for 30 mins. Collected fish were identified and returned to the water alive. Aquatic plants were identified to species level (where possible) while walking the lake fringe and at deeper sites during sediment and fish sampling.

Catchment export pollutant modeling

The catchment draining to the lake was divided into sixteen sub-catchments based on the existing urban drainage network, for the assessment of pollutant export modeling. Using GIS imagery (2006), the area of different land uses (urban, commercial, industrial, rural residential, forest) were calculated for each sub-catchment (km^2). The MUSIC (Model for Urban Stormwater Improvement Conceptualisation, developed by the Cooperative Research Centre for Catchment Hydrology, http://www.catchment.crc.org.au or http://www.toolkit.net.au) was used to determine pollutant generation for the different land uses. The model allows users to route catchment stormwater pollutants through a defined network of treatment measures to estimate the statistical distribution of pollutant loads and concentrations at any location within the network. All input data [i.e., rainfall, evapotranspiration, soil properties, pollutant generation parameters for TN, TP and total suspended solids (TSS)] were sourced from local guidelines[14], and were applied to the aerial percentage of land uses in each sub-catchment. After calibrating the model to local conditions using historical catchment water quality data total nitrogen, phosphorus and suspended sediment pollutant loads were determined for each sub-catchment and summed for total load.

Four catchment model scenarios were run including: 1) no change; 2) treatment with pit traps at all inlet points to the lake; 3) scenario 2+constructed wetlands within 7 sub-catchment areas; and 4) scenario 3+vegetated swales incorporated into streetscape in all sub-catchments. The intent of the different modeling scenarios was to progressively increase the level of stormwater treatment before discharging to the lake in order to determine optimal management (cost effectiveness) intervention. The efficacy of each engineered stormwater treatment device was based on literature values and model default values.

Long-term water quality monitoring

Gold Coast City Council (local government) has an ongoing water quality monitoring programme for all natural and constructed waterways within the City.[10] As part of this monitoring programme, two sites are located in Lake Hugh Muntz, with sampling occurring every 3 months since 1997. Surface water temperature (°C), electrical conductivity (mS/cm), dissolved oxygen (mg/L) and pH are recorded using a calibrated Hydrolab multi-probe, along with secchi disc depth (m) at each site. A composite water sample is taken from each site (50%

sample volume at each sample), stored on ice, and returned to a NATA certified laboratory for nutrient (total nitrogen (TNmg/L), total phosphorus (TP), nitrate (NO_3-), ammonia (NH_4^+), and orthophosphate-phosphorus (PO_4^{3-}), chlorophyll–*a* (µg/L), and turbidity (NTU) analysis using flow injection analysis (Sections 4500-NH3 H, 4500-NO_3- I and 4500-P G.[15,16] Samples were also collected every three months to determine faecal coliforms (CFU/100mL) and since December 2004 samples have been taken monthly in winter, fortnightly in spring and autumn, and weekly in summer. Since 2006 algae abundances have been investigated monthly with a focus on blue-green algae (Cyanophytes). The physico-chemical parameters from this data set were assessed against the trigger values for aquatic ecosystems and the microbiological samples were assessed again trigger values for recreational activities.[12] These data are included here to provide context for the period in which the lake investigation was completed.

Results

Human uses and community expectations

The community highly valued Lake Hugh Muntz as an aquatic ecosystem and there was specific community interest in the bird life using the lake and surrounds and passionate appreciation for the aesthetic value of the lake. Primary contact recreational activity and visual amenity were rated ‘highly’ by 77% and 65% of the survey respondents respectively. The desire for primary contact use has important implications for water quality management and encouraging bird life may conflict with maintaining such water quality. Further, 66% of the survey respondents rated Lake Hugh Muntz as ‘slightly to moderately disturbed’ and 13% rated it as ‘highly disturbed’. In group discussions there was also an important acknowledgement that the lake needs aquatic ecosystem and water quality management to ensure its long term quality and aesthetic value. The overall vision was to maintain and improve water quality to ensure continued use and enjoyment both for recreational and aesthetic purposes. Factors that contribute to declining water quality were recognized as not only a local government responsibility, but activities such as the discarding of lawn clipping in the water, pet waste management, and rubbish removal may also be managed and targeted in education programmes to enhance water quality.

Long term water quality

Long term water temperature showed a typical annual cycle ranging from 17°C during austral winter to 29°C during austral summer (Table 1). Despite the lake’s depth, there seemed to be little stratification, though this was not true during warmer summer months where there was evidence of thermal stratification. Salinity varied from 1 to 3 (salinity units), with the higher measurements probably associated with some saltwater intrusion from the downstream tidal Nerang River canal system. There was no evidence of salinity differences between lake bottom and surface waters. Dissolved oxygen concentrations were mostly within the guidelines,[12] except during 2002 and 2004 where concentrations were supersaturated. Dissolved oxygen concentrations were more depleted with increasing water depth, with concentrations approaching the minimum threshold for aquatic species. pH was generally within the range of the guidelines for the protection of aquatic ecosystems.[12] There was time periods when pH was elevated above the guidelines, approaching 9.0, however, it was consistently greater than 7.0.

Secchi depth was high in 1999/2000 (i.e., greater depth to visually inspect the disc), but then gradually became significantly lower (i.e., reduced depth to visually inspect the disc) over the monitoring period at both sites (Site 2 – R^2 = 0.42, P < 0.005; Site 5 – R^2 = 0.58, P < 0.005; Fig 2). Total nitrogen concentrations initially complied with guideline trigger values (1997 to 2005), thereafter steadily increased, and eventually consistently exceeded the guideline value (R^2 = 0.27, P < 0.005). Similarly, ammonium and nitrate concentrations, too, initially complied with the guidelines to approximately 2005, and then increased above the guidelines following 2005 (in the case of ammonium, the overall trend has been a significant increasing in concentrations; R^2 = 0.22, P < 0.001). Phosphorus concentrations between 1997 and 2005 were below the corresponding guideline, and similar to nitrogen, they gradually increased above the guidelines following 2005. While PO_4^{3-} concentrations were regularly above the guidelines during the initial few years of monitoring, concentrations increased significantly over time (R^2 = 0.16, P < 0.005). Total phosphorus concentrations occasionally exceeded the corresponding guideline, and there has been no overall trend in concentrations (P = 0.07).

Table 1 Range (mean, SE) of water quality in Lake Hugh Muntz (1997 – 2007). (A) 0.3m below water surface; (B) 3m depth and (C) 6m depth.

	Site 2				Site 5			
	Temp (°C)	Salinity	pH	DO (mg/L)	Temp (°C)	Salinity	pH	DO (mg/L)
A	17.0 – 29.7 (23.2, 0.64)	1.1-22.4 (2.2,0.57)	7.2-9.0 (8.1, 0.14)	7.5-12.0 (8.9, 0.16)	16.8-29.8 (23.2, 2.17)	1.9-22.5 (3.7, 1.94)	7.3-9.0 (8.1, 0.34)	7.3-11.0 (8.9, 0.55)
B	17.1-29.4 (22.8, 0.33)	1.9-5.88 (3.1, 0.61)	7.3-9.1 (8.1, 0.12)	7.7-9.2 (8.6, 0.47)	16.8-29.7 (22.9, 2.17)	1.9-5.95 (3.2, 0.51)	7.4-9.0 (8.1, 0.21)	6.9-12.0 (8.8, 0.56)
C	19.1-24.7 (22.4, 1.68)	2.8-3.5 (3.2, 0.21)	7.6-8.1 (7.9, 0.12)	1.7-12.0 (8.7, 0.26)	16.8-29.4 (23.1, 2.09)	0.9-22.5 (3.9, 2.02)	7.4-8.9 (8.1, 0.31)	1.7-12.1 (8.5, 0.92)

DO, dissolved concentrations – national guidelines are 6.0 to 10.0 mg/L
pH, - national guidelines 6.0 to 9.0

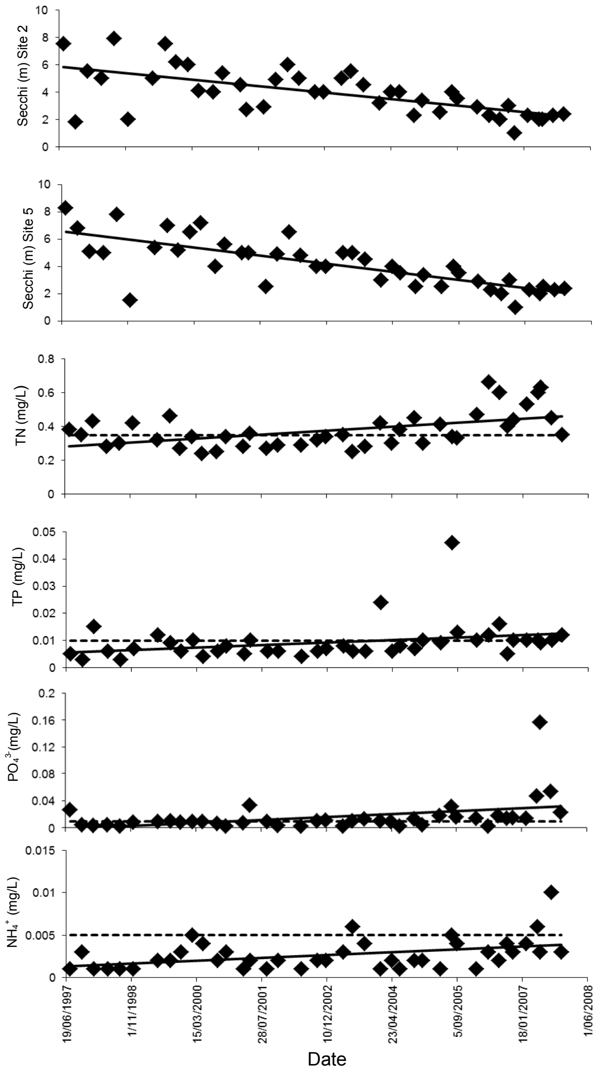

Fig. 2 Temporal plots for secchi depth and nutrients (particulate and dissolved forms) in Lake Hugh Muntz over 10 years of monitoring between 1997 and 2008. Solid lines show significant temporal trend, dashed line Environmental Protection Agency, Queensland (EPA) guideline for protection of aquatic ecosystems (Environmental Protection Agency, 2006).

Sediments

Organic carbon concentrations were highest at site Site A (A) (Table 2). This site also had the lowest sediment molar C:N ratio suggesting algae (which have a molar C:N ratio of 6.6), contributed significantly to the organic matter pool at this site. This site would accumulate organic matter from most of the north-east part of the lake during trade south-east winds. Site SF also had a low molar C:N ratio indicating that the deeper middle lake areas also accumulate algal detritus. The other sites had molar C:N ratios ranging from 12.8 to 15.3 indicating a higher proportion of organic matter derived from other sources such as macroalgae (C:N ~ 20) and terrestrial material (C:N > 30).

Sediments at location A, C, E and G were elevated in some contaminants and exceeded the ISQG – low trigger values in some instances (Table 2).[12] There were no sediment samples that exceeded any of the available ISQG – high trigger values. Site C exceeded the ISQG – low trigger values for As, Pb, Zn, and Hg, well above other sites.

Both organochlorine and organophosphate pesticides were below the analytical detection limits of <0.5 mg/kg at all sites. Further studies with lower levels of detection could be completed for a more thorough investigation. Hydrocarbons were detected in sediments at all sites except SB. Site SG had the highest sediment concentrations of hydrocarbons C10-C36 of 860mg/kg, though were still well below the ISQG–Low trigger value of 4000mg/kg.[12] Total oils and grease were higher in sediments from site SA (0.62%) and SC (0.16%) than other sites, which were all below 0.4%.

Benthic fluxes for the study site are summarized in Table 4. The average dark CO_2 efflux and average sediment oxygen demand were below 1000µmol m^2 h^1, which is typical for an oligiotrophic system with low carbon loadings. However, the average dark denitrification efficiency (DE) was quite low, highlighting the fact that the percentage of total inorganic nitrogen released from sediments as di-nitrogen gas (N_2) ((N_2-N/(DIN+N_2-N)) x 100% was small.[18] Importantly, the low DE shows that nitrogen effluxes from the sediment, rather than being lost from the system as N_2, are effluxing as dissolved organic nitrogen (DIN; mostly NH_4^+), which can stimulate algae production and lead to greater loads of organic matter, having a bottom up flow on effect. The phosphorus fluxes were also low, well below what would be expected from the amount of organic matter being decomposed. It seems that due to the well oxygenated surface sediments with high iron content, most of the phosphorus will be trapped and bound to Fe III.

Aquatic biological communities

The aquatic plant communities are dominated by *Zostera muelleri* (formerly *capricornia*) (eelgrass), *Phragmites australis* (native reed), *Typha* spp. (cumbungi), *Cyperus* spp. (sedges) and *Juncus usitatus* (common rush) and occur around the shoreline, particularly in the very small bays located in the south west area of the lake. *Chara fibrosa*, a native submerged alga, was common in parts of the lake and encountered during sediment sampling. *Charah fibrosa* forms dense mats in the lake and has been reported to play an important role in nutrient removal.[19]

In all, 213 fish were caught, comprising 6 species (Table 3). The most common fish species was the barred grunter (*Amniataba percoides*). Of the species recorded, the River garfish (*Hyporhamphus ardelio*) is of economic importance.

Catchment export pollutant loads

The modeling demonstrated that under the current land use mosaic, for each mega-litre of flow entering the lake under rainfall runoff, approximately 220kg, 0.42kg and 2.03kg of total suspended sediments, total phosphorus and total nitrogen respectively are mobilized from the catchment and washed into the lake (Table 5). Annually this amounts to approximately 91,000kg, 176kg and 849kg of total suspended solids, total phosphorus and total nitrogen respectively being deposited in Lake Hugh Muntz. The results of the 4 scenarios modeled suggested that with each infrastructure investment in stormwater management further gains are made in reducing loads of suspended solids, total phosphorus and total nitrogen.

Table 2. Sediment contaminant concentrations for each site and corresponding national trigger values.[12]

		Site								
		A	B	C	D	E	F	G	LOD	Trigger values ISQG Low-ISQG High
Sediment Characteristics	Grain Size (%<63um)	-	-	-	2.5	19.6	4.4	18.6	-	-
	Moisture (%w/w)	67	21	22	21	79	69	66	-	-
	TOC (%)	11.94	0.34	8.09	0.12	11.02	6.69	7.04	<0.01	-
Metal (mg/kg DW)	Al	34 949	2 734	22 208	983	20 125	18 625	20 688	<50	-
	As	**29.1**	2.7	**33.3**	1.5	1.9	**20.1**	14.8	<0.5	20-70
	Cd	0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	1.5-10
	Cr	0.1	<0.1	0.2	2.0	24.0	13.0	18.0	<0.1	80-370
	Cu	31	10	41	<1.0	42	20	24	<1.0	65-270
	Fe	125 163	4 751	56 488	1 606	30 125	50 063	49 063	<50	-
	Hg	**0.29**	0.08	**0.39**	0.04	**0.19**	**0.15**	**0.16**	<0.01	0.15-1.0
	Mn	230	26	175	14	99	134	127	<1.0	-
	Ni	11.8	2.0	14.1	<1.0	13.0	9.0	9.0	<1.0	21-52
	Ag	0.5	0.3	0.9	0.1	0.1	0.9	0.9	<0.1	1.0-3.7
	Pb	**53.9**	4.6	**100.9**	2.0	**88.0**	43.0	**67.0**	<0.5	50-220
	Se	1.6	<0.1	0.9	0.1	1.9	0.7	1.3	<0.1	-
	Zn	184	20	**250**	5	186	124	123	<1.0	200-410
Nutrients	TN (%)	1.4	<0.01	0.73	0.01	1.02	0.79	0.70	0.01	-
	TP (ppm)	808	29	731	808	29	731	731	<10	-
	TC (%)	12.12	0.35	8.09	0.15	11.68	6.79	7.31	<0.01	-
	Molar C:N ratio	10.70	-	14.10	15.30	13.80	10.80	12.80	-	-

(LOR) Limits of Reporting; numbers in bold exceed national guidelines; (-) no information; (DW) dry weight

Table 3 Relative abundance (%), total species and total number of fish caught in Lake Hugh Muntz for the three different survey techniques.

Family/Species Name	Common name	Gill net	Seine Net	Bait Trap
Terapontidae				
Amnilata percoides	Banded grunter	78.5	47.1	91.5
Clupeidae				
Nematolosa erebi	Bony bream	21.6	-	-
Gobiidae				
Mugilogobius paludis	unknown	-	17.6	-
Hemiramphidae				
Hyporhamphus ardelio	River garfish[a]	-	35.3	-
Eleotridae				
Hypseleotris galii	Firetail gudgeon	-	-	7.5
Anguillidae				
Anguilla reinardtii	Long-finned eel	-	-	<0.1
	Total Species	2	3	3
	Total Number	14	17	213

[a] Economic species; (-) no data

Table 4 Measured benthic flux rates in the lake.

PARAMETER	FLUX TYPE	RATE (µM m-2 h-1).
NH_4^+	Dark Areal Flux	48.7 ± 44.8
	Light Areal Flux	26.4 ± 23.4
	Net Areal Flux	36.6 ± 33.1
NO_3^-	Dark Areal Flux	7.7 ± 3.9
	Light Areal Flux	-3.0 ± 17.5
	Net Areal Flux	1.9 ± 8.5
PO_4^{3-}	Dark Areal Flux	0.5 ± 0.6
	Light Areal Flux	0.2 ± 0.3
	Net Areal Flux	0.3 ± 0.4
DO	Dark Areal Flux	-898.9 ± 72.6
	Light Areal Flux	-392.6 ± 3.6
	Net Areal Flux	-624.7 ± 31.7
	Productivity	506.2 ± 75.5
CO_2	Dark Areal Flux	549.2 ± 371.0
	Light Areal Flux	384.5 ± 813.1
	Net Areal Flux	460.0 ± 298.1
	Productivity	-164.7 ± 1157.1
DON	Dark Areal Flux	-16.1 ± 61.7
	Light Areal Flux	80.2 ±131.5
	Net Areal Flux	36.1 ± 92.6
DOP	Dark Areal Flux	-0.5 ± 0.6
	Light Areal Flux	9.9 ± 17.4
	Net Areal Flux	5.1 ± 9.4
N_2	Dark Areal Flux	4.0 ± 2.1
	Light Areal Flux	8.6 ± 8.4
	Net Areal Flux	7.0 ± 4.8
Denitrification Efficiency		15.7 ± 10.1

Table 5 Nutrient loading reductions based on 4 urban stormwater retrofit scenarios: 1) Present land use; 2) Pit inserts; 3) Pit insets and wetlands; and 4) Pit inserts wetlands and swales. The percentage (%) reduction for each retrofit scenario has been calculated based on the median (kg/yr) loads under the current (2006) catchment land use.

Parameter	Scenario 1 (kg/yr) (median)	Scenario 2	Scenario 3	Scenario 4
Total Suspended solids	91280- 91480 (91380)	54866 (60%)	65886 (72%)	81934 (90%)
Total Phosphorus	169.4-176.8 (173.1)	49.1 (28%)	81.0 (47%)	127.7 (74%)
Total Nitrogen	815.1-849.3 (832.2)	124.5 (15%)	204.4 (25%)	252.3 (30%)

Discussion

Sediment and water quality

Water quality in Lake Hugh Muntz is declining with most parameters above the Australian water quality guidelines for the protection of aquatic ecosystems.[12] This outcome seems consistent with constructed freshwater lake systems elsewhere which commonly experience elevated nutrient concentrations, stratification and reduction in dissolved oxygen concentrations that are critical for survival of aquatic organisms.[5,20] A possible reason for such depauperate conditions is accumulated excessive nutrient loads, and a lack of flushing capacity of the built wetland.[21] In the case for Lake Hugh Muntz, both NH_4^+ and PO_4^{3-} concentrations have increased over time, along with secchi depth, which has slowly decreased over the past decade, (presumably due to shading caused by increased algal biomass associated with the increased nutrients). While the water quality in Lake Hugh Muntz is declining it has not yet interfered greatly with recreational uses. Though, the apparent trajectory if it continues, may contributed to reduced human use and amenity.

The significant increase in NH_4^+ and PO_4^{3-} concentrations from over the 10 years of water quality monitoring is most likely due to the continual nutrient load from urban runoff and atmospheric deposition. Lake Hugh Muntz is essentially a closed system with exchange with the Nerang River canal estate limited through the pipe. Therefore once nutrients (and other contaminants) are washed in they become trapped and are continually recycled. In addition, the increase in maximum temperature over a similar period may also have enhanced sediment respiration and the release of nutrients from the bottom sediments (internal recycling). Although this is inconsistent with the low benthic fluxes, only one site was sampled and it is therefore unknown whether the measured rate is true more broadly across the lake. It is considered plausible that benthic fluxes would be higher at sites SA and SE because of the higher organic carbon concentrations and lower sediment C:N ratios. With a trend of increasing algae biomass, further benthic flux research is warranted to examine both spatial and temporal heterogeneity.[13]

Continuing increases in algal production will likely result in more organic matter being deposited to the sediments, and when this organic matter decomposes it will consume water column oxygen, which can lead to hypoxia and anoxia in the overlying water column.[22] The lake has minor signs of oxygen depletion with dissolved oxygen concentrations dropping to 80%, particularly during the summer months, when ambient air temperature and rainfall is highest.[9] An increase in benthic organic matter decomposition and oxygen consumption will also result in more nitrogen recycled to the water column as NH_4 and less nitrogen lost to the atmosphere as N_2 gas via denitrification. In addition, if the sediment surface becomes anoxic, it is expected that PO_4^{3-} will be released as iron III is converted to iron II. Although the one site studied showed no signs of sediment anoxia, the water column derived organic matter may be deposited elsewhere in the lake (e.g., sediment quality site A). In addition, if the water column algal biomass continues its apparent trajectory, sediment organic matter loadings will increase and the enhanced efflux of NH_4^+ and PO_4^{3-} from the sediments would stimulate even more production in the water column. This would in-turn lead to greater organic matter deposition, decomposition and oxygen consumption. These bottom-up changes have been known to have flow-on effects, which alter the structure of higher trophic levels, such as fish communities.[24] In addition, declines in water quality may reduce the utility of the water body for primary contact recreational activities, which is an important expectation held by the community.

Although the sediment concentrations of contaminants were not of serious cause for concern, any activities that disturb the sediments can potentially mobilize the contaminants into the water column and redistribute them in the environment.[23] Therefore, disturbance of the sediments should be avoided. Sediment phosphorus concentrations were high at all the muddy sites (A, C, D, F, G) and are within the range of concentrations recorded in river and estuarine sediments within the region[25], and more broadly in other major metropolitan areas.[26] Phosphorus associated with urban runoff or rainfall may be incorporated into the bottom sediments in the lake through a number of processes including coagulation or sorption onto particulate material which is subsequently removed through sedimentation, biological uptake and sedimentation, flocculation and precipitation reactions with iron and humic material. This benthic removal of phosphorus plays an important role in determining the system's ability to buffer changes in external phosphorus inputs. However, accumulating phosphorus may have reached concentrations that will cause the bottom sediments to act as a secondary pollution source that significantly impacts on the overlying water column.[27] Although the measured benthic fluxes of phosphorus were quite low due to oxic surface sediments, there is potential for a large phosphorus release if the surface sediments become anoxic. Phosphorus may also be released from the sediments by re-suspension during wind events.[28]

Hydrocarbons are deposited into water bodies as a result of stormwater runoff from roads and atmospheric deposition. All motorized water craft are banned from use on Lake Hugh Muntz which would eliminate them as a potential source of hydrocarbons, and also Pb, which has been found in elevated concentrations in the tidal reaches of the Nerang River canals where water craft vessels are numerous.[8] The elevated Pb result may be related to the use of Pb sinkers for recreational fishing or it could be from general roadway runoff, where hydrocarbons and other metals can be easily washed into the lake untreated and unprocessed. The elevated concentrations of As at some sites are probably due to the localized use of garden pesticides and leaching of Copper Chromium Arsenic (CCA) treated timber products, although at sites A and B Cr level are low. Detection of some sediment-bound metals elevated above the lower trigger values may pose some toxicological risk to local aquatic fauna. Examination of the metal content in tissues of aquatic fauna, namely fish, is necessary to establish whether there is uptake of contaminants, particularly given the strong community focus on the lake for fishing. Care should be given to the uptake pathway of contaminants by fish, as accumulation can occur via direct consumption of sediment or indirectly via prey intermediates.[8]

Aquatic communities

Fish assemblage occupying Lake Hugh Muntz included only a small number of freshwater fish species owing probably to the freshwater nature of the system, restricted access through the tidal pipes, or possibly the sampling methodologies (i.e., lack of night sampling, electrofishing, and net size limitations). Notwithstanding, however, two of the recorded species are found widely in local estuaries, including *Nematalosa erebi* (Bony bream) and *Hyporhamphus ardelio* (River garfish).[29,30] An important finding here was the absence of noxious fish species, including *Orechromis mossambicus* (Tilapia) and *Gambusia holbrooki* (mosquito fish) which have both been previously recorded in this lake (P. Kind pers. comm., Department of Primary Industries and Fisheries, Queensland). Both of these fish species are highly aggressive and have been shown in laboratory tank experiments to display high piscivory on native fish species.[31]

The community of aquatic plants in Lake Hugh Muntz plays an important role in the maintenance of water quality and habitat opportunities for local fauna. The presence of *Zostera muelleri* (Eelgrass) is particularly important for the overall health and ecology of fish and crustacean species in the lake. Numerous seagrass species in the coastal zone have been lost due to poor water quality, dredging, and fishing/trawling.[32] There has been pressure on Gold Coast City Council to harvest submerged water plants since they interfere with swimming and kayaking activities,[33,34] however, removal of these plants would substantially increase the risk of an algal bloom as the lake's ability to assimilate nutrients would be significantly diminished.[35] Along the lake fringes, the presences of *Phragmites australis* (native reed), *Juncus usitatus* (common rush), and *Cyperus* spp. (Sedges) provide important habitat for many land based animals (e.g., birds, frogs, lizards). The presence of *Typha* spp. (Cumbungi) is of some concern given it is a declared species under Queensland legislation and should be removed before it becomes too widespread. During the community workshops, some participants indicated that the presence of this fringing vegetation was unsightly owing to the accumulation of domestic rubbish trapped by this vegetation, particularly following stormwater discharge. While this trapping is effective in accumulating rubbish to localized areas, a more effective means of removal would be via the installation of rubbish trash racks installed to stormwater outlets, before entering the lake. Such forms of stormwater treatment are regularly used in protection of downstream sensitive waterway areas, though this infrastructure requires an active maintenance programme to ensure devices do not become blocked and increase localized flooding and property damage.[11,14] Prevention of rubbish entering stormwater from the direct source (local community) is the best form of intervention.[36]

Strategic management planning

The water quality and environmental values of Lake Hugh Muntz are currently suitable for the protection of the diverse range of community activities undertaken in the lake. The community places a high value on the lake for primary contact recreation and for aesthetic purposes. To maintain these expectations, management intervention will need to focus on reducing nutrient loading through a programme of stormwater treatment. At the commencement of this study, no pollution reduction devices had been inserted in stormwater drains within the Lake Hugh Muntz catchment. The modeling demonstrated that reduction in nutrient loading will improve the long term health of Lake Hugh Muntz and several scenarios for retro-fitting infrastructure were identified that would achieve the reductions necessary. A reduction in sediment loading will also alleviate other pollutants including metals and organics that are known to bind strongly to sediment particles.[37] The level of intervention in infrastructure will depend on recourses available and refinement of the treatment options can be made with more detailed investigation specifically within the sub-catchments identified for potential wetlands and swales. Importantly, the community engagement activities showed there to be interest in active participation associated with maintaining the environmental values of the lake, and so education programmes and community based management activities would also play a role in reducing nutrient and contaminant loads from reaching the lake.

Without a clear plan of management intervention, the likelihood that the lake will continue towards a eutrophic state is high. Nutrient enrichment and urbanisation have already been linked to increased frequency, magnitude and persistence of the benthic filamentous cyanobacteria *Lyngbya majuscule* locally. Large scale outbreaks of *L. majuscule* in Moreton Bay has caused on-going, widespread public health problems, and have even been linked to observed reductions in fish production in the Bay.[38] The Gold Coast has not been affected by similar harmful algal blooms, though planned future land use changes and anticipated pollutant load increases may contribute to the prevalence of harmful algal blooms, particularly if the management strategies outlined here are left unturned. It seems the early signs of harmful algae in this lake system are apparent, after 10 years of monitoring, and deterioration of water quality would ultimately threaten recreational qualities of this lake system. The visual amenity of the lake may also have indirect implications, impacting on the economic value of waterfront properties boarding the lake. The only other comparable data available is from canals in Florida where on-going poor water quality and hypoxic conditions diminished the aesthetic amenity, which had economic implications particularly reduction in property values.[39] In response, the Florida state government implemented strategies to enhance and protect the socioeconomic and ecological benefits of these systems,[39] but the effectiveness does not appear to have been monitored.

Recent research in stormwater planning has revealed tangible benefits in addition to polishing water before delivery to nearby waterways. Moore and Hunt (2012)[40] provide a review of the biodiversity services for local wildlife, aesthetic amenity, cultural and education training, improvements in flood protection through greater water retention, carbon sequestration, and improvements in local air quality. A range of small scale stormwater management programmes have been completed over the past few years in Gold Coast City, including the construction of wetland ponds and treatment train (series of treatment devices engineered to progressively polish stormwater runoff. While many projects have successfully achieved improvements in stormwater quality runoff, the programme as a whole has been ad hoc with no systematic programme of delivery.[35]

There exists no stormwater management plan for the lower Nerang River catchment of which Lake Hugh Muntz is a part. This is typical of older residential areas within the Gold Coast, which were constructed generally prior to the widespread adoption of stormwater quality planning policies and the practice of water sensitive urban design. Retro-fitting of stormwater quality improvement devices and strategies in these established urban areas is typically constrained by cost and availability of suitable locations for the placement of devices.[35] A rule of thumb, commonly adopted in Australia is that between 1% and 3% of an urban catchment should be dedicated to stormwater treatment devices.[41] This is a major challenge in established residential areas particularly in the coastal zone where residential real estate attracts a premium price.

Protection and enhancement of remnant vegetation is also an important (significantly cheaper) consideration. A recent study in the Nerang River Estuary[42] revealed a positive relationship between remnant estuarine vegetation and water quality, however, there is often strong resistance for reinstatement of native vegetation in waterways since this often comes at the expense of water views and activities such as boating. This is a challenge that local government authorities must confront however since the Nerang River Estuary, like many estuaries in Australia, are experiencing a trending increase in dissolved organic nitrogen loadings and subsequent deleterious impacts associated with eutrophication.[43,44] A campaign targeting stormwater management is necessary, in order to achieve a balance between the lifestyles and livelihoods of residents and wildlife conservation. Success here in this coastal urban development waterway could become the blueprint for protection and enhancement of constructed waterways more broadly.

Conclusions

As more coastal areas becoming modified and replaced with human activities, managers will become under increasing pressures to approve further urban expansions, while at the same time ensure ecosystem services and resilience is maintained. This urban lake, many decades after construction, is now showing signs of rapid decline; it has potentially reached a tipping point. Computer modeling shows that large scale treatment devices for stormwater runoff are necessary, in order to achieve/protect the desired values and expectations. Here we advocate that longer term vision and expectations be considered up front during the planning and designing phases of these engineered waterways. For this lake system, implementation of stormwater management treatment of runoff prior to reaching the lake will serve greatest in improving water quality. Management of stormwater quality is expensive, but is far more challenging retrospective, as the case here shows.

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Notes and references

[a] Gold Coast City Council, PO Box 5042, GCMC, QLD, Australia 9729
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[d] Centre for Biogeochemistry, School of Environment, Science and Engineering, Southern Cross University, PO Box 157, Lismore, NSW, Australia 2480
[e] TropWATER, Centre for Tropical Water &Aquatic Ecosystem Research, James Cook University, Townsville, QLD, 4811

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