

Ecosystem Guidelines for the Conservation of Aquatic Ecosystems of the Georges River Catchment: A Method Applicable to the Sydney Basin.

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Abstract: For waterway managers the conservation of freshwater streams in Australia is commonly underpinned by comparing water quality data with default ANZECC water quality guidelines. However distinctive conditions found within many streams of the Sydney basin render a number of the default guidelines not suitable and prone to misinterpretation. In this study we draw on a three year monitoring program and follow the framework recommended by the ANZECC guideline to develop a catchment specific approach for the conservation of aquatic ecosystems for the Georges River catchment. In addition to the 'common' set of water quality guidelines we include values for a selection of ionic parameters and guideline values for aquatic macroinvertebrate communities, riparian vegetation condition and catchment imperviousness. The study revealed three distinct patterns of ecosystem disturbance and water quality characteristics that corresponded to the level of development across the catchment from reference forested areas through to highly urbanised centres. When compared to non-urban reference sites streams with greater than 5% impervious surfaces showed emergent signs of ecosystem degradation while those with >19% imperviousness had highly degraded water quality, macroinvertebrate communities and riparian vegetation. Based on the results of this study, we recommend two sets of regionally relevant ecosystem and water quality guidelines, one for the conservation of streams with high ecological value that would apply to waterways with minimally disturbed catchments and the other to apply to urban streams and stream restoration projects. Although the focus of this paper is the Georges River catchment, the approach developed in this study can be easily applied to other urban catchments within the Sydney Basin.

Introduction

Water quality guidelines or trigger values are commonly used by waterway managers to assess the condition or 'health' of a stream. The Australia and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC Guidelines) (ANZECC 2000) is the national standard used to assess water quality. The guideline has evolved over the past 25 years (Moss *et al* 2005) and provides a comprehensive framework for the development of waterway management strategies.

The most recent edition of the ANZECC guidelines (ANZECC 2000) includes default water quality parameters for a wide range of pollutants. The common water quality guidelines which include total nitrogen, ammonia, oxides of nitrogen, total phosphorous, filterable reactive phosphate, pH, conductivity, dissolved oxygen, turbidity and chlorophyll-a were developed for slightly to moderately disturbed ecosystems across broad geographical regions. Parameters relevant to the Sydney region are included in the guidelines within the descriptors for south-east Australia. Concentrations for additional pollutants such as metals and other chemicals have been determined based on acceptable levels for ecosystem protection (that equates to 99% - 80% protection of all species).

In NSW, the ANZECC guidelines (2000) are widely used for environmental assessment and reporting by a variety of organisations including the NSW Environment and Protection Authority for State of Environment reporting (NSWEPA 2012), NSW Department of Environment and Climate Change for assessment of water quality in drinking water catchments (DECC 2009) and local councils to assess waterway condition (e.g. Ku-ring-gai Council 2013; Hornsby Shire Council 2012). They are also used by a range of organisations to assess the condition of waterways as part of local and regional aquatic monitoring programs (e.g. Ryder *et al* 2011).

For some waterways, however, the default ANZECC guidelines do not reflect typical background water quality and chemistry. In these situations, an assessment of water quality monitoring data against these default values can suggest the condition of the waterway is outside the normal range, or polluted, when in fact it is 'clean.' An example of how default guidelines may be misinterpreted is often seen with low pH values reported for many Sydney streams in undisturbed catchments that rise on Hawkesbury sandstone. These naturally acidic streams frequently report pH below the default ANZECC guideline of 6.50. For example, Tippler *et al* (2012) reported pH in reference streams of the Georges River catchment as low as 4.07, Wright (2011) reported pH of 5.40 in naturally vegetated Blue Mountains streams and both Davies *et al* (2010) and Wright *et al* (2007) reported pH of 5.50 and 5.30 respectively in reference streams in northern Sydney. In these cases determining what is a 'healthy' pH against the guideline would provide an incorrect assessment and may drive catchment investigations or management interventions contrary to the natural waterway condition.

Another limitation is that the regions within the ANZECC guidelines are geographically very large and geologically complex. The default guideline for south-east Australia applies to the Murray Darling Basin through to the small coastal tributaries of the Sydney Basin, despite major differences in water geochemistry across this vast area (Hart & McKelvie, 1986). This requires the default water quality values to be sufficiently flexible to incorporate a wide range of biological or geophysical difference.

To counter these problems, the ANZECC framework encourages the development of region/catchment specific guidelines to better reflect local conditions. The ANZECC guidelines (2000) outline the approach necessary to develop locally derived water quality guidelines and also to incorporate biological assessment of waterways into monitoring programs.

Urban streams and urban water quality

The impact of urbanisation on freshwater streams has been well documented. Degraded water quality, habitat fragmentation, loss of species diversity and altered hydrological regimes are impacts common to urban streams (e.g. Paul and Meyer 2001; Walsh *et al* 2005; Marchetti *et al* 2006). One element that has been identified as a key contributing factor to the decline of urban streams is the percentage of a catchment which is covered by impermeable surfaces, such as roads, buildings and car parks (Paul and Meyer 2001). Australian studies have shown that the onset of stream degradation occurs once a catchment is covered by between 3% and 5% impermeable surfaces (Walsh 2007; Davies *et al* 2010; Tippler *et al* 2012). Critical to stream degradation is the connection of impervious surfaces to local waterways via the urban stormwater drainage system. This connected imperviousness has a significant impact on stream hydrology (Dunne and Leopold 1978; Booth *et al*. 2004; Roy *et al*. 2005) and water chemistry (Hatt *et al*. 2004).

Stream restoration and catchment management projects have been implemented in an attempt to improve the ecological function and water quality within urban streams. This has usually involved various treatments including the rehabilitation of riparian zones, re-instatement of woody debris and the introduction of various Water Sensitive Urban Design (WSUD)¹ techniques within the catchment such as swales, bio-retention systems and artificial wetlands (Larsen *et al* 2001; Richardson *et al* 2011). While there can be short-term ecological and water quality improvements, the longer-term benefits of urban stream restoration requires on-going evaluation (e.g. University of Melbourne 2008 and Walsh *et al* 2005), particularly in catchments that are already urbanised and often increasing in density (further increasing the proportion of impervious surfaces) as well as catchments targeted for urban expansion in greenfield areas.

The performance of catchment and stream improvement projects are often determined against the change in water quality and ecological indicators, from pre-intervention to post intervention and using the ANZECC guidelines. Both approaches are fraught with problems in highly urban catchments due to the significance of the degradation and multiple causative factors contributing to poor water and ecological health (Paul and Meyer 2001; Walsh *et al* 2005). Further the default parameters used in the ANZECC guidelines are designed to reflect natural to slightly disturbed ecosystem conditions and are often unrealistic as a guideline to measure against the poor and highly variable water quality experienced by urban streams (eg. Tippler *et al* 2012; Wright *et al* 2007; Blakely and Harding 2005). Given these challenges urban creek restoration projects can be set up to fail from the outset due to unrealistic expectations and benchmark targets. Catchment specific guidelines and targets that reflect local conditions can overcome this problem (Ryder and Miller 2005) and a framework for developing such targets is outlined in chapter 3 of the ANZECC guidelines (ANZECC 2000).

¹ also referred to in the literature as Sustainable Urban Design (SUDS), Low Impact Development (LID) and more broadly environmental engineering

The research presented in this paper presents an approach for the development of localised aquatic ecosystem guidelines for the Georges River catchment in south west Sydney. Two guidelines are presented reflecting the variable level of disturbance (as defined by the of % impervious surfaces) and the pragmatic capacity for recovery. Measurements incorporate water quality, including anions/cations, in-stream freshwater macroinvertebrates (determined at Order and Family level) and riparian condition. The first guideline is designed to protect waterways of conservation significance, akin to the default ANZECC guidelines, but specific to the Georges River catchment. The second is aimed at more urbanised catchments to provide targets that are more achievable and realistic reflecting the inherent challenges of the urban stream syndrome. This method is transferrable to other regions and can be used by non-specialist personal to provide a more region-specific approach to waterway management.

Method

Study catchment

The Georges River catchment is located in south west Sydney with a population of over 1 million and an area of 960km². There are 12 local councils in the catchment (Rockdale, Kogarah, Hurstville, Canterbury, Bankstown, Holroyd, Fairfield, Liverpool, Campbelltown, Wollondilly, Wollongong and Sutherland) and it falls within the boundaries of two metropolitan planning sub-regions (South and South West) (NSW Government 2013) and for the purpose of on-ground catchment management is within the now combined Sydney Metro and Hawkesbury-Nepean Catchment Management Committee (CMA). Development and population within the catchment will increase significantly over the next 20 years (Table 1) driven by the targets within the South and South West subregional plans for Sydney (NSW Government 2013). Informing the development across the catchment are five environmental priorities within the subregional plans (NSW Government 2013) that include to:

- Protect the health and resilience of environmental assets, including internationally significant wetlands, national parks and the drinking water supply catchment
- Protect metropolitan-significant infrastructure including freight corridors, intermodal terminals and Sydney's drinking water supply catchment, key water storages and the Upper Canal corridor (a canal that transports bulk water from the metropolitan water supply dams to Prospect reservoir)
- Continue to provide extensive environmental, recreation and tourism opportunities in the Blue Mountains and Nattai National Park
- Recognise the subregion's agriculture and the extensive resource deposits valuable to employment and the economy
- Protect land to serve Sydney's future transport needs, including sites and associated corridors.

The spectrum of urban development across the catchment has resulted in a gradient of waterway disturbance which ranges from streams in 'near pristine' condition to highly disturbed and degraded urban streams. The condition of the streams generally corresponds to catchment development typologies ranging from minimally developed naturally vegetated catchments to highly developed urbanised catchments (Tippler et al 2012). Approximately 45 % of the catchment remains covered by large tracts of natural bushland (SMCMA 2012). These relatively undeveloped areas are managed and regulated by a variety of state and federal agencies including NSW National Parks and Wildlife Service, Sydney Catchment Authority (for the purpose of potable water supply) and The Australian Defence Force.

The dominant geological formations are Hawkesbury Sandstone in the east and south, Wianamatta Shale in the west and Hawkesbury Sandstone with Wianamatta Shale capping in the north (NSW Department of Mineral Resources 1983). Quaternary alluvium underlies much of the Wianamatta Shale and in some areas has been exposed by erosional processes (LCC 2002). Soils reflect the underlying geological formations (NSWDIPN 2004) (Figure 1).

The average annual rainfall across the catchment is approximately 900 mm per year (BOM 2013) with more rainfall nearer the coast. The sub-catchment closest to the coast (6km) has an average of 1427 mm/year compared to 871 mm/year in the sub-catchment furthest from the coast (36 km) (BOM 2013).

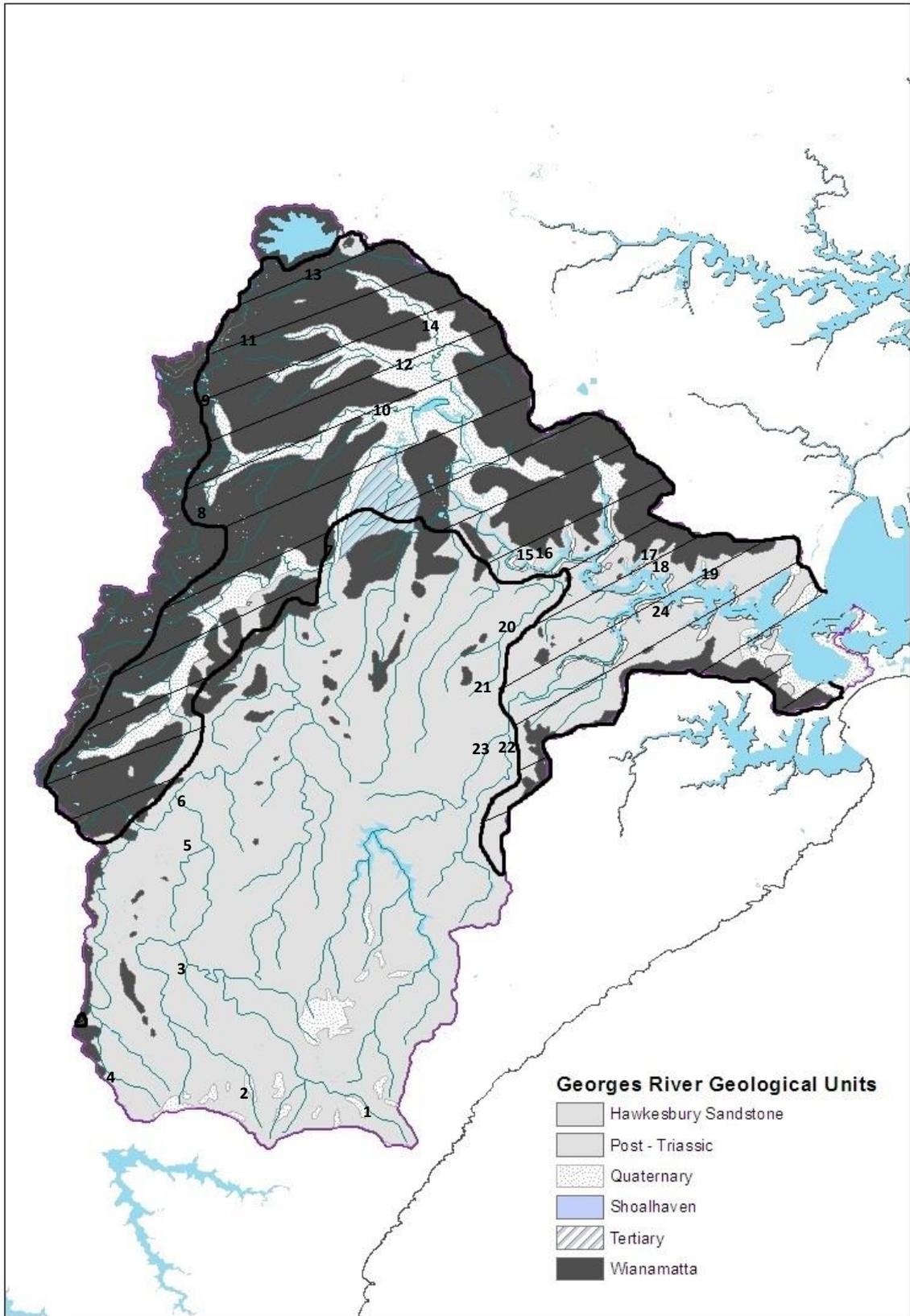


Figure 1. The Georges River catchment. Sample sites (numbered), catchment geology and urban area (black outline, diagonal lines)

Table 1. Current and growth targets for population, housing and employment that will impact on the Georges River Catchment as outlined by the draft Metropolitan Strategy for Sydney (NSW Government 2013)

Subregion		Current	Target for 2021	Target for 2031
South West	Population	829,000	1, 048,000	1,298,000
	Housing	286,000	346,000	427,000
	Employment	298,000	362,000	432,000
South	Population	609,000	655,000	685,000
	Housing	241,000	263,000	283,000
	Employment	183,000	207,000	226,000

Data collection

Catchment imperviousness upstream of each monitoring site was quantified using Environmental Systems Research Institute Arc-Map version 9.3.1 with sub-catchments delineated using 10 m contours. An impervious/pervious layer was developed using remote sensing of Satellite Pour l'Observation de la Terre imagery on a 10x10 m grid that was clipped by the digitised sub-catchment layer. Sub-catchment pervious/impervious areas were totalled, enabling the percentage of impervious surface to be calculated.

Monitoring sites were grouped by the degree of catchment disturbance based on catchment imperviousness (a measure of the proportion of hard impermeable areas such as roads, roofs and footpaths). In previous studies of the Georges River catchment (Tippler et al 2012a, b) three disturbance categories were identified based on the level of sub-catchment imperviousness: <5 % impervious surfaces were classified as having low disturbance; 6-19 % impervious surfaces were classified as having moderate disturbance; and >19 % impervious surfaces were classified as being highly disturbed. This classification resulted in 7 sites with low disturbance, 4 sites with moderate disturbance and 11 sites with high disturbance.

Water quality, water chemistry and macro-invertebrate data were collected from 24 freshwater sites across 18 waterways within the Georges River catchment over a 44-month period. Water quality was monitored between October 2009 to May 2013 based on a seasonal (spring and autumn) sampling frequency. In addition, three sites (two low disturbance; one moderate disturbance) were monitored monthly between September 2011 and May 2013.

Physiochemical water quality parameters of pH, electrical conductivity (EC), dissolved oxygen (DO%) and turbidity (NTU) were measured in-situ using a calibrated TPS 90FLMV multi probe meter. Between October 2009 to May 2013 surface water grab samples were analysed at each site for total nitrogen (TN), total kehldahl nitrogen, NO-x nitrogen (NOx-N) and total phosphorus (TP).

Grab samples for major anions and cations and total suspended solids (TSS) were collected from 2010 and ammonia nitrogen (NH₃-N) collected from October 2012. These were collected in decontaminated sample containers (acid preserved for nutrients) provided by a commercial testing laboratory. Samples were chilled and delivered to the laboratory for analysis. All grab samples were analysed using standard methods (APHA 1998) by a National Associations of Testing Authorities (NATA) accredited laboratory.

Macroinvertebrate samples were collected according to the Australian National River Health Program protocols (DEST et al. 1994; Chessman 1995, 2003). This involved collection using a 'kick' net, with 250-µm mesh and square 30x30 cm net frame (Chessman 1995) to survey pool, edge and riffle habitat. Pool, edge and riffle sub-samples were combined into one homogenised sample to be

representative of each study site. A total of 10 m of stream habitat was sampled within a 100 m section of each site. Samples were live picked in the field on a sorting tray for 30 minutes using forceps and pipettes, and animals were identified in the field to Order level using x30 magnification hand lenses and the recommended Australian taxonomic keys of Hawking and Smith (1997) and Gooderham and Tsyrlin (2002). Samples were then preserved in ethanol and later identified in a laboratory to Family level under microscope with the recommended taxonomic keys (Hawking and Smith 1997).

The aim of the macroinvertebrate sampling was to maximise the diversity of animals identified at both Order and Family taxon using the rapid assessment SIGNAL2 approach (Chessman 1995). Freshwater macroinvertebrates identified to both Order and Family taxonomic levels have been widely used to detect the impacts of water pollution and environmental change to aquatic ecosystems (eg. Wright et al. 1995; Bowman and Bailey 1997; Tippler et al 2012). Four macroinvertebrate biotic indices were calculated for each macroinvertebrate sample:

- percentage of Ephemeroptera (mayfly), Plecoptera (stonefly) and Trichoptera (caddisfly) (EPT) (Cairns and Pratt 1993) - a biotic index based on the percentage of pollution sensitive taxa present at a site
- Order and Family taxonomic richness (Rosenberg and Resh 1993)
- Shannon index (Krebs 1989) - a biodiversity measure that reflects taxa richness and evenness of taxa distribution
- Order and Family level SIGNAL 2 scores (Chessman 2003b) - Biotic index based on the presence/absence of pollution tolerant/intolerant invertebrate taxa.

Riparian vegetation condition was surveyed at each site in spring 2009 and autumn 2013 using the 'Rapid Appraisal of Riparian Condition' (RARC) Version 2 (Jansen et al. 2004). This method uses a suite of 15 indicators of riparian condition that reflect the functional aspects of the physical vegetation community and landscape features of the riparian zone (Jansen et al. 2004). Due to the variability of access to survey sites a standardised approach where 100 m metres of stream bank was surveyed and survey transects were limited to 40 m (Tippler et al 2012 a, b).

Data Analysis

A one-factor analysis of variance (ANOVA) was used to investigate whether riparian condition, macroinvertebrate biotic indices (SIGNAL 2, percentage of EPT, taxonomic richness and Shannon index) and water quality parameters varied according to catchment disturbance (low, moderate and high).

Multivariate analysis was used to assess macroinvertebrate community response to waterway disturbance using the software package PRIMER version 5 (Clarke 1993). Non-metric multidimensional scaling (NMDS) was performed on a Bray-Curtis similarity matrix calculated with cube root-transformed macroinvertebrate data grouped by the degree of catchment disturbance (low, moderate and high) (Clarke 1993; Warwick 1993). Two-dimensional ordination plots were generated to give a representation of the dissimilarity among individual samples and disturbance categories. Two-way crossed analysis of similarity (ANOSIM) (Clarke 1993) was used to test for macroinvertebrate assemblage differences between disturbance categories and season of sampling.

Formulation of region specific guidelines

To formulate region specific guidelines for the Georges River catchment we applied the rationale set out in chapter 3 'Aquatic Ecosystems' of the ANZECC guidelines (ANZECC 2000). This process involved defining guidelines for water quality, macroinvertebrate indices and riparian vegetation condition by applying the 80th and/or 20th percentile values of data obtained from the six reference streams in the Georges River catchment. Reference streams in this study were defined as having < 5% impervious surfaces. For stressors that cause problems at high concentrations (e.g. nutrients, pH and conductivity and major ions) the 80th percentile of reference stream data was used as the guideline. For stressors that caused problems at low levels (e.g. dissolved oxygen) the 20th percentile of reference data was used.

In addition to the development of a region specific guideline for streams with conservation significance, the ANZECC approach was applied to derive region specific guidelines for application to urban streams. Urban streams of the Georges River catchment are generally impaired beyond the 'slight to moderate' category spectrum that the ANZECC guidelines have been designed to be applied

against (Tippler et al 2012 a, b). To develop this guideline, data from moderately disturbed streams, which were defined as having between 6 – 19% impervious surfaces, was used. This guideline is based on data collected from peri urban streams with a lower degree of urbanisation that have retained a higher amount of ecological integrity when compared with highly urbanised streams (Tippler et al 2012 a, b). This 'peri-urban' guideline should provide waterway managers with more appropriate and realistic targets to use when assessing urban streams and evaluating the efficacy of urban stream restoration projects.

Results

Mean values for most water quality parameters across three levels of catchment disturbance generally complied with ANZECC upland and lowland river water quality guidelines for south east Australia (Table 2). The notable exceptions were: mean DO across all catchment disturbance categories was found to be lower than the minimal ANZECC guideline; mean NOx-N was in excess of both lowland and upland river ANZECC guidelines for all catchment disturbance categories; and mean NH₄₊ and TN exceeded ANZECC guideline limits for moderately and highly disturbed catchments.

Mean pH of minimally disturbed catchments fell below the ANZECC guideline range however mean pH at moderately and highly disturbed catchments were compliant with the ANZECC guideline. Mean EC of highly disturbed catchments was excessive of the lowland ANZECC guideline yet compliant with the lowland guideline. However this result was excessive of the 200-300 µS/cm recommended by ANZECC for NSW coastal rivers as defined in the ANZECC (2000) guideline table for south east NSW fine print.

Table 2. Mean water quality results across the three catchment groups compared against the ANZECC Guidelines for upland and lowland rivers

	Level of catchment disturbance based on % Impervious Surface				
	ANZECC guideline		Low (< 5%)	Moderate (6-19%)	High (> 19%)
Water Quality Parameters	<i>Upland river</i> ¹	<i>Lowland river</i> ¹	Mean	Mean	Mean
pH	6.5-8.0	6.5-8.5	5.93	7.18	7.25
Electrical Conductivity (µS/cm)	30-350	125-2200 [^]	124	333	789
Dissolved Oxygen (% saturation)	90-110	85-110	81	82	52
Turbidity (NTU)	2-25	6-50	2.7	10.7	25.8
TSS (mg/L)	NA	NA	3.5	9	17
NOx-N (mg/L)	0.015	0.04	0.03	0.08	0.34
NH ₄₊ (mg/L)	0.013	0.02	0.01	0.07	0.09
TKN (mg/L)	NA	NA	0.20	0.30	0.90
TN (mg/L)	0.25	0.35	0.20	0.40	1.20
TP (mg/L)	0.02	0.05	0.03	0.04	0.12
Total Alkalinity (as CaCO ₃) (mg/L)	NA	NA	5	38	100
HCO ₃ (as CaCO ₃) (mg/L)	NA	NA	5	38	100
SO ₄ (mg/L)	NA	NA	5	9	35
Cl (mg/L)	NA	NA	32	54	173
Ca (mg/L)	NA	NA	2	7	28
Mg mg/L	NA	NA	3	5	15
Na (mg/L)	NA	NA	18	38	110
K (mg/L)	NA	NA	1	2	5

Notes: [^] NSW coastal rivers are typically in the range 200–300 µS/cm (ANZECC 2000) *Bold = not compliant with one or both ANZECC water quality guidelines. ¹ Upland streams are defined as those >150m and lowland <150m

The one-way ANOVA test reported all water quality parameters that were tested had a significant variation across each of the catchment disturbance categories (Table 3). The level of significance for most parameters was $p = <0.0001$ indicating a very strong relationship with higher the level of development the poorer the water quality. The exceptions were TSS and NH_4^+ that reported a significance of $p = <0.001$ and $p = <0.01$ respectively (Table 3).

Mean values for all water quality parameters except DO were lowest in streams with low disturbance catchments and highest in streams in highly disturbed catchments (Table 3). Mean pH increased from 5.93 in streams in low disturbed catchments to 7.25 in streams in highly disturbed catchments. Mean EC in moderately disturbed catchments was more than double that of streams in low disturbed catchments. Additionally mean EC in highly disturbed catchments was more than six times higher than that of streams in low disturbed catchments. A similar pattern of increase was also reported for nutrients, TSS, turbidity and cations and anions (Table 3).

Mean DO in highly disturbed catchments was lowest (52%) while moderately and low disturbed catchments reported similar results with 82% and 81% respectively.

Table 3. Range, mean and results of ANOVA analysis water quality parameters across catchment disturbance categories based on percentage of impervious surface. Level of significance = * $p < 0.05$; ** $p < 0.001$; *** $p < 0.0001$.

	ANOVA F-value, (p), df	Level of catchment disturbance based on % Impervious Surface					
		Low (< 5%)		Moderate (6-19%)		High (> 19%)	
		Range	Mean	Range	Mean	Range	Mean
Water Quality Parameters							
pH	77.8 (***) 2,249	4.07 - 8.04	5.93	5.57-9.57	7.18	5.00-8.34	7.25
Electrical Conductivity (uS/cm)	66.5 (***) 2,249	11-312	124	101-1916	333	108-3310	789
Dissolved Oxygen (% saturation)	48.1(***) 2,249	35-113	81	38-132	82	0-108	52
Turbidity (NTU)	11.1 (***) 2,249	<0.10-13.2	2.7	<0.10-161.2	10.7	<0.10-345	25.8
TSS (mg/L)	53.1 (***) 2,140	1-23	3.5	2.5 -97	9	<0.5- 153	17
NOx-N (mg/L)	29.8 (***) 2,236	<0.01 - 0.39	0.03	<0.01 - 0.90	0.08	<0.01 - 2.12	0.34
NH_4^+ (mg/L)	4.6 (*) 2,71	<0.01-0.04	0.01	<0.01-0.66	0.07	<0.01-0.48	0.09
TKN (mg/L)	44.7 (***) 2,235	< 0.10 - 0.70	0.20	<0.10 - 0.80	0.30	< 0.10 - 6.90	0.90
TN (mg/L)	75.6 (***) 2,248	<0.10 - 0.90	0.20	<0.10 -1.20	0.40	0.30 - 6.90	1.20
TP (mg/L)	26.3 (***) 2,448	<0.01 - 0.32	0.03	<0.01 - 0.44	0.04	<0.01 - 0.94	0.12
Total Alkalinity (as CaCO_3) (mg/L)	139.1 (***) 2,210	< 1 - 33	5	10 -108	38	2 - 326	100
HCO_3^- (as CaCO_3) (mg/L)	139.1 (***) 2,210	< 1 - 33	5	10 -108	38	2 - 326	100
SO_4 (mg/L)	43.1 (***) 2,187	<1 - 19	5	<1-16	9	<1 -190	35
Cl (mg/L)	42.2 (***) 2,187	13 -67	32	24 - 100	54	14 - 699	173
Ca (mg/L)	126.4 (***) 2,187	< 1 - 12	2	3 -21	7	8 -104	28
Mg mg/L	53.1 (***) 2,187	<1 -6	3	2 -9	5	1 -58	15
Na (mg/L)	47.0 (***) 2,187	7-40	18	15-70	38	9 - 465	110
K (mg/L)	104.2 (***) 2,187	< 1 - 3	1	1 -6	2	1- 12	5

Analysis by one-way ANOVA of RARC score (riparian vegetation index) and macroinvertebrate indices showed variation across the catchment disturbance categories was significant for all parameters tested ($p = <0.0001$) (Table 4). Mean RARC scores (riparian vegetation index) were highest in low disturbance catchment streams (38.3/50) followed by moderately disturbed catchment streams (35/50) then highly disturbed catchment streams (22.7/50) (Table 4).

All macroinvertebrate indices at both order and family level showed a similar pattern of decline as the level of catchment disturbance increased. Mean Richness, mean SIGNAL scores, mean Shannon

Indices and mean %EPT were highest in streams in low disturbance catchments and lowest in streams in highly disturbed catchments (Table 4).

Table 4. Range, mean and results of ANOVA analysis for riparian condition and macroinvertebrate indices across catchment disturbance categories based on percentage of impervious surface. Level of significance = * $p < 0.05$; ** $p < 0.001$; *** $p < 0.0001$.

	ANOVA F-value, (p), df	Level of catchment disturbance based on % Impervious Surface					
		Low (< 5%)		Moderate (6-19%)		High (> 19%)	
		Range	Mean	Range	Mean	Range	Mean
Riparian Vegetation Condition							
RARC score (x/50)	54.9 (***) 2,60	32.5 - 44.0	38.3	29.7 - 40.5	35.8	14.5 -36.2	22.7
Invertebrate Indices							
Order Richness	74.1 (***) 2,172	7-14	11	8 -14	11	2 -13	7
Family Richness	28.2 (***) 2,45	13 - 31	21	8 - 27	18	4 - 16	10
Order SIGNAL	500.7 (***) 2,172	4.25-6.46	5.23	3.04 - 5.21	4.21	1.70 - 4.03	2.54
Family SIGNAL	70.6 (***) 2,45	3.92-4.94	4.39	3.12-4.94	3.76	1.83-3.43	2.83
Order Shannon Index (H)	59.0 (***) 2,172	1.10 - 2.34	1.96	0.93 - 2.16	1.81	0.36 - 2.13	1.43
Family Shannon Index (H)	139.8 (***) 2,45	2.14 - 2.94	2.51	1.70 - 2.80	2.34	0.85 - 2.24	1.6
%EPT	380.0 (***) 2,172	7 - 63	36	0- 40	16	0 - 26	1.0

Discussion

Based on analysis of water quality, riparian vegetation condition and macroinvertebrate data we have recommended the application of two guidelines for the Georges River catchment (Table 5). The first applies to the conservation of streams with high ecological value (such as Nature Reserve or National Park) and would apply to waterways with minimally disturbed catchments (i.e. < 5% impervious surfaces). The second applies to urban streams and stream restoration projects and is based on data collected from moderately disturbed urban catchments (<19% impervious surfaces). Guidelines developed specifically for application to urban streams and urban stream restoration projects provide more realistic targets and should encourage performance and environmental monitoring (Bash and Ryan 2002; Kondolf and Micheli 1995; Blakely and Harding 2005). While the ANZECC (2000) Water Quality Guidelines for Aquatic Ecosystems provides a useful background to undertaking water quality and stream ecosystem studies, greater utility can be derived from the approach developed here as the site specific data is able to provide more relevant standards and where necessary define upper limits within otherwise large ranges (such as for electrical conductivity).

Salinity, as measured via electrical conductivity, is one of the key water pollutants in the Georges River catchment. In this study, mean salinity rose from 125 uS/cm at low disturbance sites, to 333 uS/cm at moderately disturbed sites and 789 uS/cm at highly disturbed sites. The ANZECC default salinity guidelines for protection of ecosystems suggest a guideline of 125 to 2200 uS/cm for lowland rivers, and 30-350 uS/cm for upland rivers of south east Australia. The wide range of these default guidelines and lack of specificity as to their application makes it difficult to otherwise determine the extent to which EC can be considered as a pollutant across catchment disturbance gradients. Further ambiguity on applying this range is enhanced by the footnote in the ANZECC guideline which states that EC of NSW coastal rivers is generally in the range 200 to 300 uS/cm and therefore determining an upper limit to signify if the waterway is under stress is difficult. To counter this problem we recommend a guideline for minimally disturbed systems of <155 uS/cm and for urban stream ecosystems <371 uS/cm (Table 5). These maximum values avoid the need to determine if the stream's location is a lowland or upland river as streams in this study area include both and also considers the limited variability arising from distinct geological factors and proximity to the coast.

Another common water quality indicator used to assess stream condition is pH. The minimum default value for SE Australia is pH 6.50 for both lowland and upland freshwaters (ANZECC, 2000). This value does not take into consideration the background hydrogeology and biological activity that drives the naturally acidic processes within the aquatic ecosystem of Hawkesbury sandstone streams, such as the low disturbed streams in this study. To account for these naturally acidic conditions we followed the recommended approach in ANZECC to derive a locally specific pH guideline of < pH 6.76 for minimally disturbed systems. Following this same approach we also recommend a guideline for urban systems of < pH 7.80 (Table 5).

This study yielded further data that supports the theory that concrete stormwater infrastructure is modifying the chemistry in freshwater streams (Wright et al 2011, Davies et al 2010b, Nodvin et al 1986). In particular, the major mineral ions (bicarbonate and calcium) are much higher in moderate and highly urbanised streams when compared to the low disturbance sites (noting that the influence of alkaline concrete materials also raises the pH). Average bicarbonate concentrations were 7 times higher at moderately disturbed streams and 20 times higher at highly disturbed streams when compared to low disturbed streams. Such investigation of the ionic composition of water reveals that it is not only the strength of salt solution that is important, but also takes into account the mineral composition of salts (Hart & McKelvie, 1986). The extent to which the elevation of mineral ions affects stream ecology is still under investigation but applying a precautionary approach we would recommend that concrete stormwater infrastructure should be avoided in all high conservation values streams where protection of natural water quality and ecosystem health is a management priority. Given the clear difference in water chemistry across the urban development spectrum we recommend new guidelines be introduced (Table 5). The ANZECC (2000) water quality guidelines do not address ions such as calcium and bicarbonate.

In a previous study of the Georges River catchment multivariate analysis was used to isolate the most influential environmental variables affecting macroinvertebrate community structure (BIOENV procedure in Tippler et al 2012). This study revealed riparian habitat quality, catchment imperviousness, nitrogen and calcium were the most important attributes that correlate to stream health as indicated by macroinvertebrate community structure. The results of Tippler et al (2012) further emphasises that riparian habitat is highly important for aquatic ecosystem health (Shandas and Alberti 2009; Davies et al 2010; Miserendino et al 2011) and catchment works that only deal with water quality will not result in the full range of benefits that are needed for successful stream remediation projects (Walsh et al 2005).

The ANZECC guidelines (2000) do not recommend performance criteria for habitat quality. Given the importance of this variable to the ongoing health of a catchment we have recommended a regionally specific guideline for riparian habitat condition based on the RARC assessment scores. We also recognise that land and water managers may more readily improve stream and riparian habitat for the benefit of stream ecosystems.

A key aim of waterway management is to conserve and promote aquatic ecosystem health. Many studies (eg. Urban et al 2006; Wright et al 2007; Roy et al 2003; Walters et al 2009; Davies et al 2010a) have shown stream macroinvertebrates provide a highly relevant and direct measure of ecosystem 'health'. In this study macroinvertebrate communities in the most highly disturbed streams signalled a degraded ecosystem when compared to moderate or low disturbance catchment streams. For example the mean % EPT taxon (i.e. representing the more sensitive invertebrate groups) was only 1% at highly disturbed sites, when compared with 16% for moderately disturbed catchments and 36% at low disturbed catchment streams. A similar pattern applied for SIGNAL scores and other metrics used in the analysis. Following from this data we recommend new guidelines to assess the health of stream ecology through macroinvertebrate analysis for high conservation value streams and for urban stream assessment and restoration targets (Table 5).

The ANZECC guidelines are a very important guide to helping protect water quality in Australia and New Zealand aquatic systems. In the experience of the authors we have seen these be misused and misinterpreted. Very few studies actually follow the clear ANZECC process to determine either local relevant guidelines or management aims supported by appropriate data gathering and analysis. The advantage of this study is that there are multiple naturally vegetated waterways to offer excellent 'control' or 'reference' waterways that have only slight disturbance by current or historic human activities and accordingly it has not had to rely on proxy sites to established background reference conditions.

The impacts of urban development on stream health are well documented (eg. Walsh et al 2007; Walsh et al 2004; Walters et al 2009; Paul and Meyer 2001) and we contest that these should be considered a 'key threatening process' to environmentally valuable waterways and to sensitive ecological communities and species therein. In this study, the level of ecosystem degradation and water quality impairment reflected the proportional level of urban development with '% imperviousness' being a reliable surrogate for the extent of urban development. As many parts of this catchment will be urbanised in the coming decades (NSW Government 2013) there is a need for planners to consider the implications of where and how new estates and employment centres are built and managed. Accepting that governments wish to expand their economies and enable land for housing and development, we would recommend for this catchment that the naturally vegetated streams (with less than 5% imperviousness) be protected from major landuse change that removes vegetation or notably increases imperviousness. We would recommend that development be preferentially located in existing urban centres or in moderately disturbed catchments and include appropriate water and creek management systems and structures.

Table 5. Locally derived ecosystem guidelines for protection of clean freshwater streams and moderately disturbed streams in the Georges River catchment compared with default ANZECC guidelines for upland and lowland rivers.

	<i>Level of catchment disturbance based on % Impervious Surface</i>		<i>Upland River¹</i>	<i>Lowland River¹</i>
	Low (0-5%)	Moderate (6-19%)	ANZECC	ANZECC
	Guideline for the conservation of freshwater streams with ecological value	Guideline for urban stream assessment and restoration	Guideline	Guideline
Riparian Vegetation Condition				
RARC score (x/50)	>35.8	>33	NA	NA
Macroinvertebrate Indices				
Order Richness	>9	>10	NA	NA
Family Richness	>17	>13	NA	NA
Order SIGNAL	>4.85	>3.67	NA	NA
Family SIGNAL	>4.17	>3.24	NA	NA
Order Shannon Index (H)	>1.77	>1.62	NA	NA
Family Shannon Index (H)	>2.27	>2.01	NA	NA
%EPT	>28	>6	NA	NA
Water Quality				
pH	<6.76	<7.88	6.5-8.0	6.5-8.5
Electrical Conductivity (uS/cm)	<155	<371	30-350	125-2200
Dissolved Oxygen (% saturation)	>69	>65	90-110	85-110
Turbidity (NTU)	<4	<11	2-25	6-50
NOx-N (mg/L)	<0.04	<0.11	0.015	0.04
NH4+	<0.02	<0.04	0.013	0.02
TKN (mg/L)	<0.3	<0.5	NA	NA
TN (mg/L)	<0.3	<0.5	0.25	0.35
TP (mg/L)	<0.03	<0.05	0.02	0.05
Total Alkalinity (as CaCO3) (mg/L)	<6	<54	NA	NA
HCO3 (as CaCO3) (mg/L)	<6	<54	NA	NA
SO4 (mg/L)	<7	<12	NA	NA
Cl (mg/L)	<41	<73	NA	NA

Ca (mg/L)	<2	<9	NA	NA
Mg mg/L	<4	<6	NA	NA
Na (mg/L)	<21	<54	NA	NA
K (mg/L)	<1	<3	NA	NA
TSS (mg/L)	<2.5	<7	NA	NA

Notes: ¹ Upland streams are defined as those >150m and lowland <150m

Conclusions

The ANZECC guidelines are important to help inform how waterways should be managed. The generic values provided by ANZECC are not always applicable as local conditions will define the 'natural' state of the waterways. Undertaking robust water quality, ecosystem and physical assessments of streams enables a more thorough assessment of the condition of the aquatic systems and in turn should be used to develop locally or regionally relevant parameters on which to assess change. By relying on default values without appreciating the local context can lead to a misinterpretation of the health of the waterway and implementation of inappropriate water quality programs and policies.

The Georges River catchment is fortunate to have multiple naturally vegetated waterways that offer excellent 'control' or 'reference' waterways to enable comparison with the more disturbed lower reaches. From our study we would suggest some variation to the ANZECC guideline by allowing for the naturally acidic waterways and setting comparatively low salinity levels in the Sydney basin. The physical and vegetation condition of the creeks is again confirmed in this study as an important consideration emphasising the value of riparian habitat and an aspect that should be measured as part of a robust waterway program. Achieving protection for and assessing the health of aquatic ecosystems requires more commitment than simply collecting water quality data and checking compliance against the default parameters provided by ANZECC.

The success of urban restoration projects can rely on them meeting predetermined standards. We know that urban waterways are mostly represented in the highly degraded end of the water quality and ecosystem health spectrum. Being able to improve their condition to a near reference condition is arguably a technical challenge of not impossibility within the resources available to catchment managers. In this context setting more achievable standards based on intermediate conditions is pragmatic and preferable.

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