R.I.P.arian vegetation and its capacity to bring streams back from the dead. Findings from a study investigating effective impervious and stream health in northern Sydney/Hornsby LGA.

David Knights, Equatica 02 8094 9703
David Beharrell, Hornsby Shire Council

Topics: Ecology of Urban Streams, Effective impervious, riparian zones

Abstract

In the late 1990s international research identified effective imperviousness (EI) as a good predictor of urban stream health. EI was defined as impermeable surfaces that are directly connected to streams by pipes, or similar drainage systems.

Empirical research was also undertaken in Melbourne in the 2000s. Fifteen streams in Melbourne were monitored for indicators of stream health including water quality parameters, macro-invertebrates, diatom indicators and algal biomass. It was found that EI was able to explain stream health better than any other indicator.

Based on this research Walsh et al. (2004) postulated that the greatest impact on stream health is due to small to moderate storms (runoff less than 15mm). In forested or rural catchments these events generate little or no surface flow runoff. In urban catchments with conventional drainage system these events produce runoff and high concentrations of nutrients and toxicants in streams.

A study was undertaken to apply the theory and processes associated with EI to Hornsby Council's existing extensive monitoring data. It is an extensive data set and contains varying catchment types ranging from bushland reference streams with an EI of zero, to streams with minor rural development and relatively low EIs, to heavily urbanised streams with very high EI. The study primarily reviewed data including monthly water quality grab sampling from 2000/01 to 2008/09, macro-invertebrate and diatom monitoring reports from 2005/06 to 2006/07.

EI was, in general, a relatively good predictor of the rapid deterioration of stream health as EI increases from 0 to 5% and from 5% to 80% EI. However two of the key findings of the study was that a range of streams did not follow the classic model of deterioration with increasing EI and these streams had a stream health similar to the reference streams. One of the key explanations for the difference between these streams and degraded streams was the role that the channel geomorphology and their associated riparian zones were having in recovering the health of these streams. This study found that the distance from the last significant stormwater source is an important factor in stream health indicators.

Introduction

Historically the common metric for urban density in urban stream catchments has been total impervious (TI). TI is the proportion of a catchment's area covered by impervious surfaces (surfaces such as roofs and roads). Many researchers (for example see Beach 2001) had shown that the health of urban streams broadly declined with increasing TI.

Empirical research consistently found that urbanisation had major impacts on stream ecosystems. These changes included elevated concentrations of pollutants, hydrologic changes including larger more frequent events and reduced baseflows, altered channel morphology including increasing channel width and increases scouring and reduced biotic richness (Walsh *et. al.* 2005a). Meyer (2005) has referred to this ecological degradation of urban streams as the *urban stream syndrome.*

In the late 1990s researchers (for example see Booth and Jackson, 1997) investigated *effective impervious* (EI) as a predictor of urban stream health. EI was defined as the areas of impermeable surfaces that are directly connected to streams by pipes, channels or equivalent drainage systems.

Significant research was also undertaken in Melbourne in the 2000s by the CRC for Freshwater Ecology (CRCFE). The researchers were investigating the relationship between waterway ecosystem health in Melbourne streams to the relatively simple catchment metric of EI.

The focus of the research undertaken by Walsh *et al*. (2004) was on *empirical* studies rather than causal relations. Fifteen streams in Melbourne were monitored. Monitoring of stream health included indicators such as water quality parameters, macro-invertebrates, diatom indicators and algal biomass. It was found that EI was able to explain stream health better than other indicators such as total impervious, unsealed road density, septic tank density or catchment area (see for example Hatt *et. al*. 2004, Taylor et. al. 2004; Walsh et. al. 2004; and Newall and Walsh 2005).

The basic principle of EI being a predictor of stream health is that those areas which are directly connected to streams by pipes or sealed drains are likely to be having the greatest direct impact on ecosystem health (see Walsh *et al.* 2004). This research led to the development of a model of urban stream health (Walsh, 2005b). This model suggests that stream health declines linearly with increases in EI from 0% to 5% at which point all stream health is impacted, as shown in Figure 1.

The CRCFE results showed that algal biomass and diatom assemblage composition reached a threshold of degradation at a low level of EI (1–5%), as did the water quality variables. Macroinvertebrate assemblage composition appeared less sensitive to degradation, reaching a threshold at a higher level of EI (6–15%) (Walsh 2004).

Based on these results the conclusion that only a very small part of a catchment needs to be developed *and* conventionally drained before an urban stream is severely degraded.

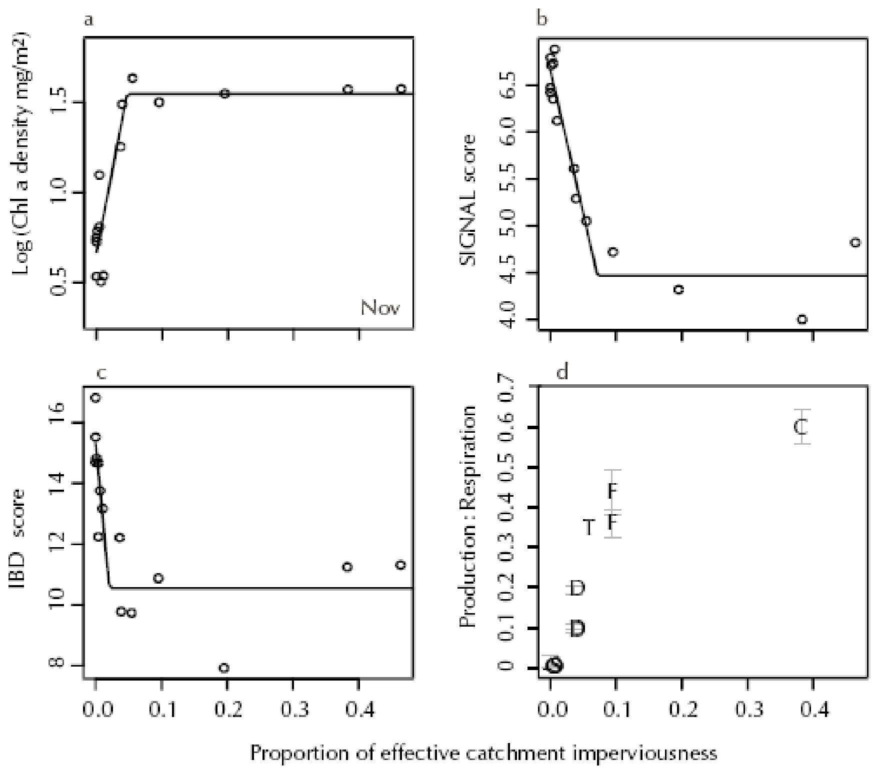

Figure 1 Model of Effective Impervious (from Walsh *et al.* 2004)

Methodology – Application of Effective Imperviousness to Hornsby Shire LGA

The key component of the study was to apply the theory and processes of EI to Council's existing monitoring data. This key data included in the study were:

- Water quality reports from 2000/01 to 2008/09
- Macro-invertebrate and diatom monitoring reports from 2005/06 and 2006/07

Hornsby Shire Council monitors a range of freshwater and estuarine waterways. The locations of these monitoring sites are shown in **Figure 2**. Monitoring in Hornsby LGA is taken for a wide range of purposes including stream health, impact of single point sources (e.g. sewage treatment plants or landfills), performance of water quality improvement devices and the recreational health of receiving waters. Not all of these monitoring locations are suitable for use in this study. Stations were excluded which were affected by point sources such as STPs, landfill, or were tidal sites or were not included in the following study as they were not currently active monitoring sites and therefore did not have a sufficiently complete data set.

The remaining stations were included in this study for analysis (22 in total) of which 18 sites had monitoring data for macro-invertebrates and diatoms (so only 18 have been plotted). Of the 22 stations selected, 7 stations included areas of non-sewered communities (sites 42, 49, 62, 63, 64, 80, 118).

Methodology - Calculation of Effective Impervious

Effective impervious is precisely defined as

Effective impervious (EI) = Total impervious (TI) x Drainage connection

While the definition and measurement of TI is relatively clear, the definition of drainage connection is not. The main issue is in defining the degree to which impervious surfaces are directly connected to a stream. When an impervious surface is immediately connected to a stream by a stormwater pipe the 'connection' is defined as 1 (EI is equal to TI). This is fairly straight forward. However, impervious surfaces can have varying degrees of disconnection and the value of this is not well defined (e.g. discharge through a small buffer, or via roadside swales common in rural areas).

Walsh et.al. (2004) in their research predominantly used a binary approach such that they defined unconnected (such that EI = 0) as impervious area that drained either to surrounding pervious surfaces, or to vegetated or earthen swales and then to streams.

In reality the binary classification of impervious surfaces as 0 or 1, is an oversimplification. The connectedness of drainage to streams ranges from 0 to 1 with varying degrees of connectedness depending on the intervening structure (e.g. earthen drain) or vegetation. For example consider a large roof area that drains to a very small vegetated garden bed which then overflows directly to a drainage pipe. The roof area is not directly connected but due to the large roof area and small garden area is likely to overflow relatively frequently and is unlikely to be considered completely disconnected from the drainage system.

In this study the binary approach to connection was adopted for the same practical reasons that it was adopted by the CRCFE researchers.

Total impervious areas in the catchments were determined by

- assessing the Hornsby LGA aerial for each relevant catchment and tracing around the developed/pervious area.
- An eyeball estimate was made of the impervious percentage within the urban residential developed area.
- This approach was repeated within a catchment for any rural, industrial and/or commercial areas.

To determine if an area was directly connected two key approaches were used. The first was to

- review Council's drainage layer to determine if drainage existed in the catchment and
- if it existed for all of the catchment or only a part of the catchment and
- assess whether the drainage pipe discharges directly to the receiving water and if so assume that the catchment area is effective impervious

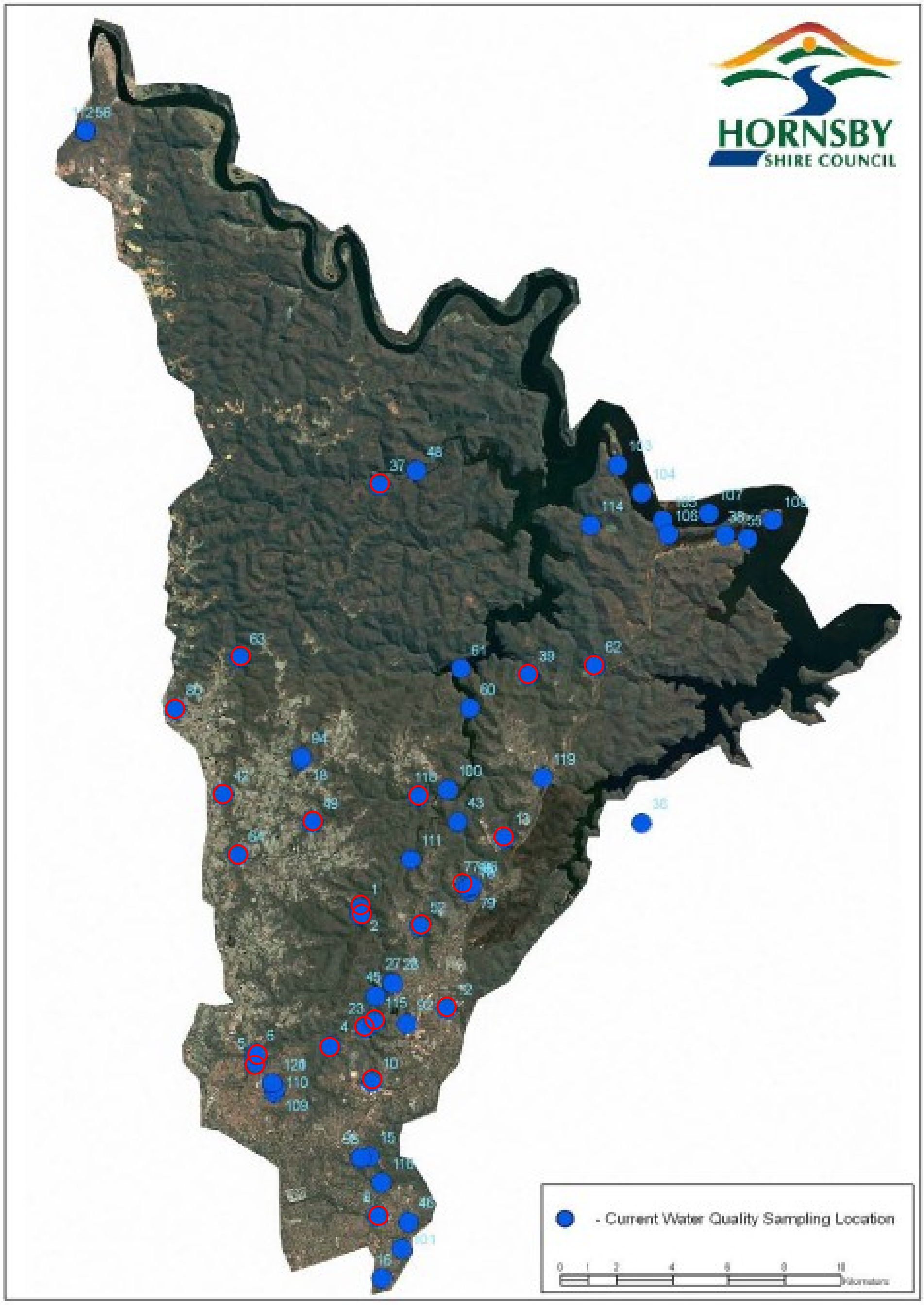

Figure 2 Location of Water Quality Monitoring Sites with red outlines indicating sites included in this study (modified from Hornsby Shire Council, 2009)

For catchments where no drainage layer existed in Council's GIS, Google Maps Streetview was used to assess the drainage connection. An example of this is shown in Site 2 catchment which had both directly connected drainage and indirectly connected drainage. A summary of the results is shown in Table 1.

Table 1 Catchment Summary

Site	Creek	Type	Sewered	Drainage	Suburb	Catchment (Has)	TI	EI
2	Tunks	Rural/NP	Partially	No	Galston	1688	2.7%	0.5%
4	Berowra	Res/Np	Yes	No	Cherry/Thorn	1235	33.4%	33.4%
5	Pyes	Residential	Yes	Yes	Dural	377.9	44.5%	44.5%
6	Georges	Rural/Res	Yes	Res - Yes	Dural/Glenhaven	443.1	21.2%	19.2%
8	Devlins	Res	Yes	Yes	Various	825	41.3%	41.3%
10	Larool	Res	Yes	Yes	Thornleigh	38.1	62.7%	62.7%
12	Hornsby	Res	Yes	Yes	Various	305.6	67.2%	67.2%
13	Sams	Ind	Yes	Yes	Mt KRG	18.6	80.7%	80.7%
23	Waitara (US STP)	Res/NP	Yes	Yes	Various	912.2	43.3%	43.3%
37	Smugglers	NP	No	No	-	532.8	0.0%	0.0%
39	Joes Craft	Res/NP	Yes	Yes	Berowra Hts	688	10.4%	10.4%
42	Colah	Rural	No	Res - Yes	Galston Village	1537	4.6%	4.6%
49	Still	Rural	No	No	Galston	439.4	0.0%	0.0%
52	Calna	Res/NP	Yes	Yes	Various	281.4	32.0%	32.0%
62	Cowan/Kimmerikong	Res/NP	No	Yes	Cowan	11	24.4%	24.4%
63	Colah	Rural	No	Res - Yes	Galston Village	1310	0.2%	0.2%
64	Trib Colah	Rural/Res	No	Res - Yes	Galston Village	145	15.9%	12.8%
77	Gleeson	Res/NP	Yes	Yes	Mt Colah	45.9	26.9%	26.9%
80	Glenorie	Rural/Res	No	Res - Yes	Glenorie	105.1	2.3%	2.3%
113	Dog Pound	Res/Np	Yes	Yes	Westleigh	24.8	16.1%	16.1%
117	Byles	Res/NP	Yes	Yes	Beecroft	316.1	29.0%	29.0%
118	Still	Rural/NP	No	No	Galston	1553.1	0.0%	0.0%

Results - Water quality

Hornsby Shire Council undertook water sampling for various water quality parameters from 2000/01 to 2008/09 including EC, Temp, Turbidity, TSS, TP, TN and faecal coliforms.

Sampling was undertaken by grab sampling once a month including during both dry weather and wet weather. The sampling program on average sampled nine dry weather events and 3 wet weather events annually. The mean values for the water quality parameters were summarised into one value for all years.

The results are shown for TSS, TP and TN in **Figure 3** to **Figure 5**. A suggested line of best fit (red line) of the standard theory of EI is included in each of the figures. From these figures it is clear that the relationship between EI and various water quality indicators of stream health shows significant scatter. There is no obvious rapid deterioration of stream health with increasing small amounts of EI followed by a flat line of no further deterioration with larger increases in EI similar to that shown in **Figure 1**. It should also be noted that the pattern of results was similar for <u>all</u> parameters outlined above.

Further investigation of the pattern of the results, however, showed a relatively consistent pattern in the data based on the sites and catchments. The data was therefore further classified into four groups to attempt to explain the data. These groups were relatively consistent in the following factors; catchment development, location of monitoring site in relation to outfall and water quality results.

The identified groups are:

- Group 1: Heavily urbanised catchments (sites 10, 12 and 13) which have higher values of all water quality parameters than any other sites
- Group 2A: Moderately urbanised catchment (sites 5, 8 and 23) which have average values of water quality for degraded sites
- Group 2B: Low urbanised catchments with little or no riparian restoring opportunity as there is a significant directly connected drainage outlet in close proximity to the

monitoring location (6, *62* and *64*) which have average values of water quality for degraded sites

- Group 3:Riparian restoring catchments where the monitoring location is located a reasonable distance downstream from the last significant directly connected drainage outlet (site 4 and 52) which have better than average values of water quality for degraded sites

- Group 4: Riparian restored catchment where the monitoring location is located a reasonable distance downstream from the last significant directly connected drainage outlet (site 39) which has water quality approaching that of the reference site (which has no development)

Note that six of the sites with low EI (from 0 to 5%) have not been included in this grouping as they generally fit the model developed of rapid deterioration with increasing EI, although there are some notable outliers which are discussed further below.

A summary of the groupings and the distance from the monitoring location from the last directly connected stormwater outfall is shown in the summary table below.

Group	Description	Sites	Monitoring distance from last stormwater connection
1	Heavily urbanised	10,12, 13	less than 100m
2a	Moderately Urbanised no riparian restoring	5, 8, 23	less than 100m
2b	Lowly Urbanised no riparian restoring	6, 62 and 64	50 to 400m
3	Riparian Restoring	4, 52	750 to 1000m
4	Riparian Restored	39	More than 2000m

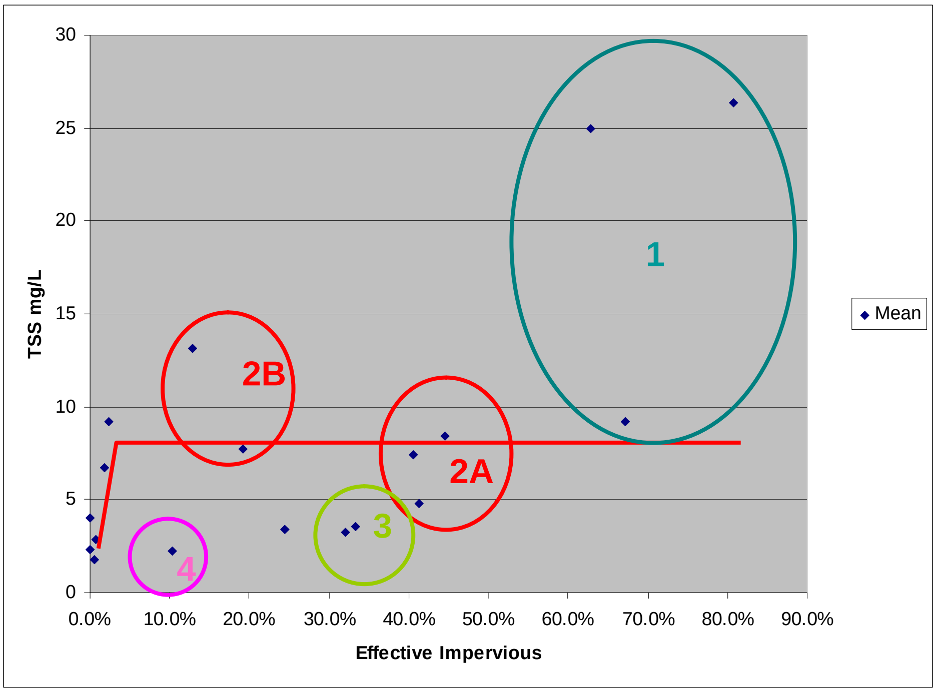

Figure 3 Effective Impervious vs TSS

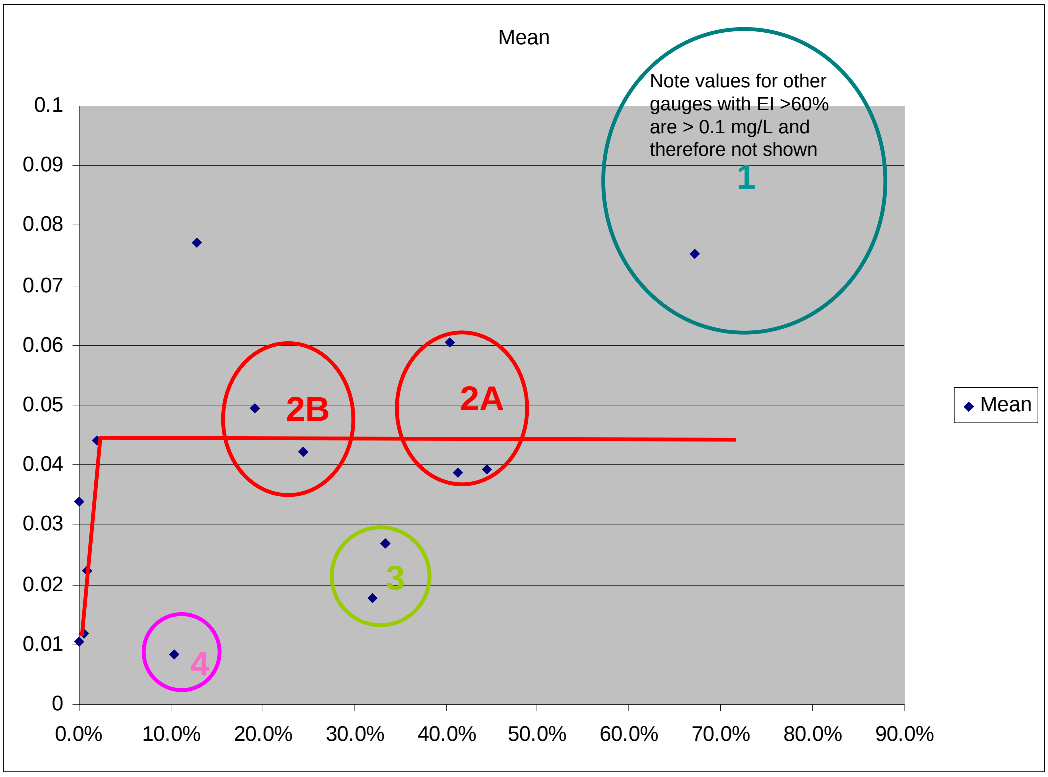

Figure 4 Effective Impervious vs TP

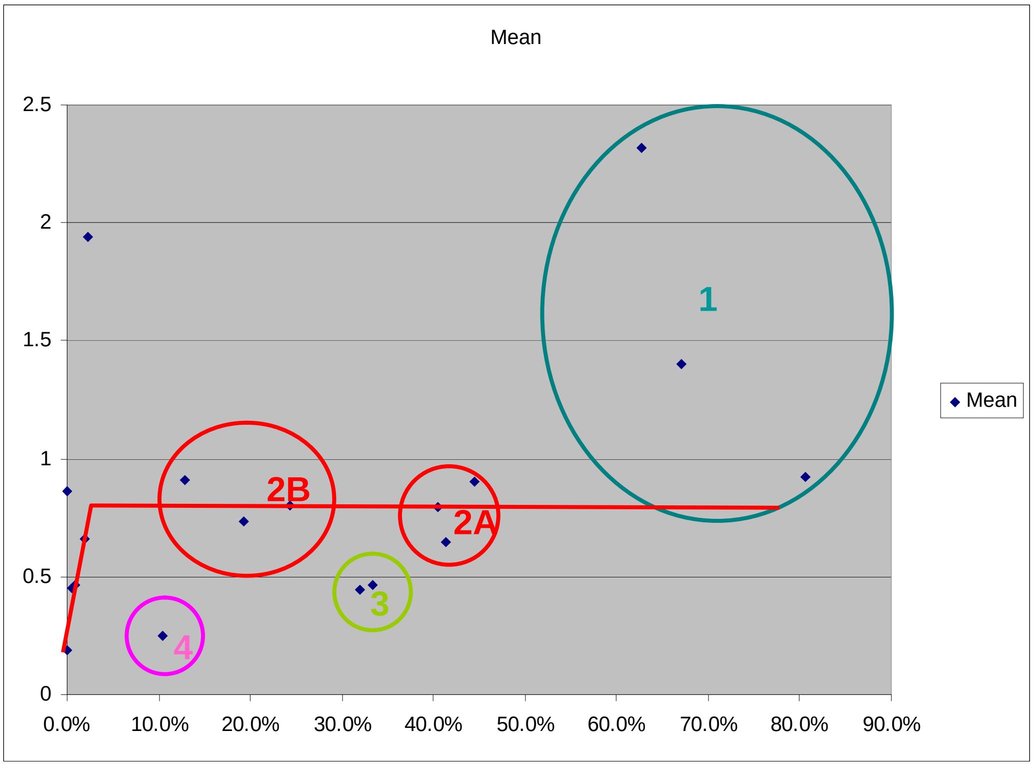

Figure 5 Effective Impervious vs TN

Discussion - Water Quality

In general EI is a relatively good predictor of the rapid deterioration of water quality as EI increases from 0 to 5%. As shown in the figures above; as EI increases water quality deteriorates in a linear relationship. By the time EI is greater than 2 to 5% the water quality exhibits somewhat similar water quality parameters to those of much higher EI catchments.

A key exception to this is site 49. This site has an EI of 0% and a TI of 5%. However it exhibits the characteristics of a catchment with an EI of much greater than 0%. It is not known why this is the case. Catchment 49 is not sewered, although this is unlikely to be the only explanation as the other low EI catchments (42, 63 and 80) are also un-sewered but show significantly better water quality.

It should also be noted that site 80 (with a low EI) shows *very* high TN and TP results. Its TN and TP results (note TP for this site is *greater than* 0.2 mg/L and therefore not shown in Figure 4) are more indicative of highly developed urban sites with an EI greater than 60%.

In summary while EI is able to generally predict the performance of water quality as an indicator of stream health in the Hornsby LGA, it is not able to explain

- the impact of the distance from connection on water quality and the suggested ability of creeks and their riparian zones to 'restore water quality'
- the increasing degradation of highly impervious catchments with minimal riparian zones as opposed to moderately developed catchments with larger intact riparian zones

- the poor performance of catchments with very low EI (site 49 and 80)

Results - Macro-invertebrates and Diatom

Results from 2005/06 to 2006/07 were collated for macro-invertebrates (SIGNAL) and diatoms (Trophic Diatom Indices). The following assessment was based on this data.

The mean values for SIGNAL2 and TDI parameters were summarised into one value for both years of sampling.

The results are shown in **Figure 6** and **Figure 7**. Similar to the results for water quality parameters a suggested line of best fit (red line) of the standard theory of EI is included in each of the figures. From these figures it is clear that the relation to EI and macro-invertebrate and diatom indicators of stream health shows significant scatter.

A detailed analysis of the results however shows a very similar pattern to the water quality data. The data was further classified into the same four groups (and sites) as the water quality data to attempt to explain the data. The only difference between the groups for water quality and macro-invertebrate and diatom data is that Group 3 did not contain site 52 as only water quality data was collected for this site.

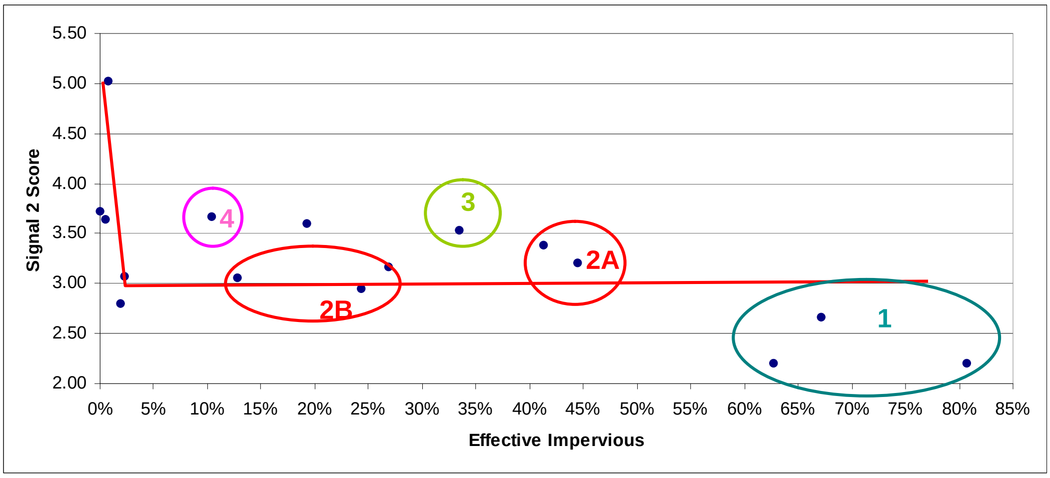

Figure 6 Effective Impervious vs SIGNAL2

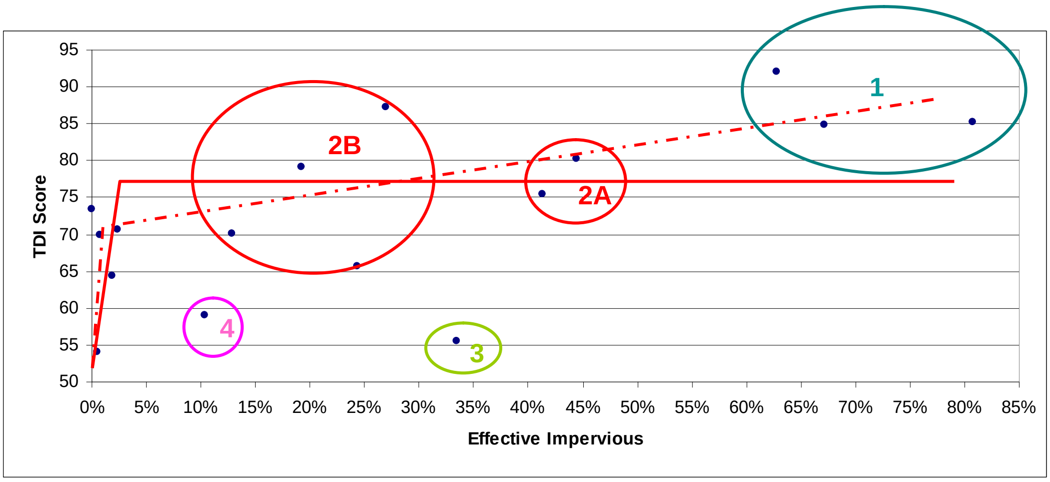

Figure 7 Effective Impervious vs Trophic Diatom Indices

Discussion - Macro-invertebrates and Diatom

There is a similar pattern for macro invertebrates and diatoms and the water quality data. There is more scatter in the macro and diatom data compared to the water quality data. This may be due to a number of factors such as:

- a smaller period of data collection
- macro-invertebrate data responds to habitat and stream form as well as water quality
- a number of sites have intact riparian zones and good habitat for macro-invertebrates
- Natural variability in macro-invertebrate and diatom assemblages. For example the reference site has relatively low scores for SIGNAL2 (3.6) and TDI (75)

Our observations indicate that EI is a much less useful predictor of the rapid deterioration of macro-invertebrate and diatom assemblages as EI increases from 0 to 5%. There is considerable scatter in the values of EI from 0 to 5%. In particular the reference site with no development (and therefore an EI of 0%) in the catchment (site 37) exhibits relatively low scores for SIGNAL 2 and TDI.

Sites with reasonable distances from the last significant outfall also show significant signs of recovery. Groups 3 and 4 have SIGNAL 2 and TDI scores similar or *better* than the reference site and equivalent to other catchments with much lower EI.

Discussion – How significant are Riparian Zones in protecting stream health?

It is generally accepted that riparian zones provide an important role in maintaining stream health. For example retention of riparian zones is now legally required in NSW (Water Management Act, 2000) when considering any land use change and riparian zone restoration is a key part of works when improving degraded streams.

A number of researchers and practitioners (e.g. Horner et. al. 2002, Stephens et. al. 2002) have argued for retention of catchment forest cover, and wide continuous riparian buffers to mitigate the impacts of urbanisation. Retention of catchment forest cover and riparian buffers provide a number of key roles:

- shading, which reduces in-stream algal production by reducing temperature and light
- supply of energy sources to the stream food web;
- habitat such as woody debris, rocky bedrock substrate
- interception of pollutants including sediments and the transformation of nitrate from shallow groundwater

However Walsh et. al. (2004) argue that while catchment vegetation can be an important determinant of the nature and condition of stream ecosystems this should not be the primary aim of stormwater management as “they divert attention away from the problem”. Their research found that catchment vegetation was not as important as EI. They concluded that while there are good reasons for aiming to maximise forested land in urbanised catchments, the beneficial effects this has on streams are likely to be substantially reduced by the impacts of conventional drainage design.

These impacts include:

- bypassing of riparian zones by stormwater drainage pipes, which removes or greatly reduces the capacity of riparian zones to intercept contaminants from the catchment
- dislodgement of habitat such as woody debris
- disconnection of the channel from its floodplain
- channel incision that reduces groundwater levels and thereby creates drier conditions for the surrounding riparian zone (and thus potentially leaching nitrate) (Groffman et al 2002).

The overall conclusion that was reached by Walsh et. al. (2004) was that dispersed stormwater treatment measures (which are able to reduce EI and disconnect the stream from its catchment) are the most effective means of achieving good stream health in urbanised catchments. This requires alternative drainage systems that promote retention and infiltration of stormwater.

The observations from this study do not support the conclusions of Walsh et. al. (2004). This study in fact provides a strong counter argument showing the significant role that riparian buffer zones and continuous catchment forest cover can play in preventing stream degradation and improving water quality. This study has shown that well vegetated riparian zones of approximately 1000 m stream length can significantly improve indicators of stream health while lengths greater than 2000 m of stream with good riparian buffer zones can restore indicators of stream health to levels similar to reference streams.

One potential factor that may work in the favour of streams in the Hornsby Shire is that the channel substrate is naturally eroded to bedrock in many streams. The bedrock substrate prevents incision of many channels (although it does not prevent channel widening). Shallow bedrock may also help maintain natural groundwater levels in the vicinity of Hornsby's streams, which in turn would help ensure that riparian zones continue to provide their important function as nitrogen "sinks" (Groffman et al 2002).

Furthermore, the maintenance of natural groundwater levels may also assist in recharging the surrounding riparian zone groundwater as interactions between groundwater and surface water are largely driven by the relative difference between the groundwater and surface water levels as shown in **Figure 8**.

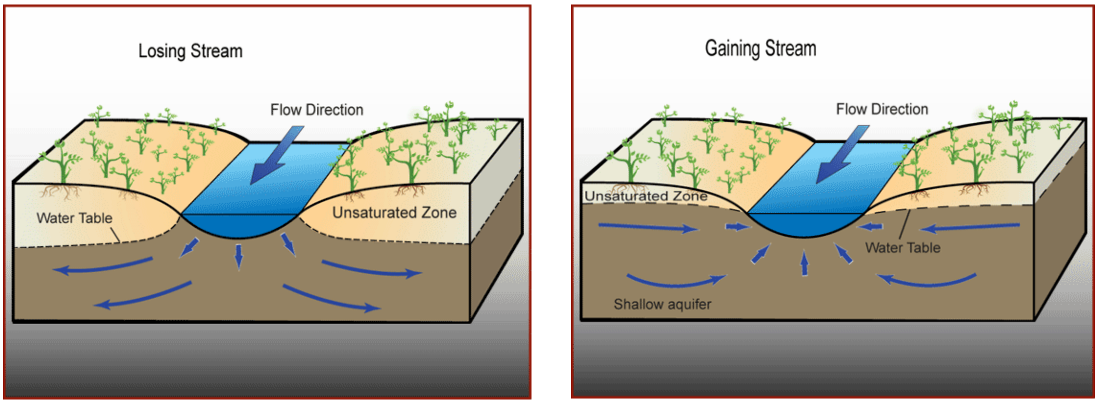

Figure 8 Concept Schematics for stream interactions with groundwater (Winter, 1998)

The natural bedrock channels also mean that the general habitat of streams may be less disturbed from pre-development conditions.

There are a wide range of other unknown factors which could impact on the observations made in this report including (but not limited to):

- The nature of surface flow runoff in both the pre-development and post-development conditions. Hornsby's catchments, with shallow sandy soils overlying sandstone bedrock, may naturally exhibit more frequent surface runoff than catchments that have been studied in Melbourne

- The shallow sandy soils may provide less attenuation of nutrients in the pre-developed condition (due to poor soil structure and limited nutrient retention capabilities)

- The role of in-stream pollutant uptake processes, including the ability of sandy, well-vegetated streams to filter and treat significant volumes of water within the stream itself and thereby provide a degree of treatment as water is conveyed within the stream

- Factors impacting on the relatively low values for macro-invertebrates and diatom assemblages in Hornsby's reference streams

Bledsoe and Watson (2001) noted that "the relationship between channel instability and imperviousness is complex and involves several factors and processes". They suggested that different stream types are likely to exhibit different levels of resilience and the key factors of stream resilience included:

- relative erodibility of bed and banks,
- riparian condition,
- mode of sediment transport (bedload versus suspended load), and
- proximity to geomorphic thresholds.

It is clear from this study that streams in Hornsby LGA have higher resilience than those streams studied in Melbourne and it is likely that a number of these factors outlined above are playing significant role in this stream resilience.

Conclusion - Use of EI as a management tool in Hornsby LGA

This study found that EI is particularly useful in identifying, relatively easily, *poorly* performing streams with low EI. This study found one very low EI catchment (approximately 2% EI) which exhibited poor water quality particularly for nitrogen and phosphorous. The nitrogen and phosphorous levels were similar to the most heavily urbanised catchments. While the exact causes of this poor water quality are not known at this stage, it is highly likely that there are significant sources of nutrients other than stormwater in this catchment. Anecdotal evidence suggests that poor on-site wastewater disposal practices within the catchment are likely to be the cause of poor stream water quality. In this catchment the key catchment management focus should be first identifying and then addressing the source of pollutants, prior to the adoption any stormwater management measures.

This study also found that streams in Hornsby LGA had a relatively high level of stream resilience. EI and the theory of frequent flow management is not *necessarily* applicable to streams in the Hornsby LGA. The streams in Hornsby LGA exhibit some key differences from the EI theory put forward by Walsh et. al. (2004) including:

- Highly urbanised catchments (greater than 60%) with very limited riparian zones show significant additional deterioration in all parameters monitored
- Distance from last significant source is an important factor in stream health indicators
- Biological data had significantly more scatter than water quality data, particularly for the reference site

A key message from this study is that catchment management techniques need to be related to the specific stream health processes within the catchment. Due to the resilience of Hornsby's streams, frequent flow management techniques may not necessarily be applicable to stream health in Hornsby LGA. For example, this study found that streams which are likely to have *high frequent flow disturbance* also have *high stream health*. The stream processes and appropriate catchment management techniques for Hornsby LGA are currently being further investigated to better understand the in-stream processes and the processes contributing to stream resilience in Hornsby LGA.

A key finding of this study is that riparian zones, in their broadest sense, have a significant role in improving water quality and in-stream biodiversity in Hornsby LGA. The riparian zones appear to be contributing significantly to natural stream resilience in the LGA. Hence, natural riparian ecosystems should feature prominently in catchment management techniques in Hornsby LGA.

References

Beach D. (2001). Coastal Sprawl. The Effects of Urban Design on Aquatic Ecosystems in the United States. Pews Ocean Commission (Arlington, Virginia.)

Bledsoe and Watson (2001), Effects of Urbanization on Channel Instability, Journal of the American Water Resources Association, Vol 37, No 2, 255-270.

Booth D. B. and Jackson C. R. (1997). Urbanization of aquatic systems — degradation thresholds, stormwater detention, and the limits of mitigation. *Journal of the American Water Resources Association* 33, 1077–1090.

Hatt et. Al. (2004), The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams, *Environmental Management*, Vol 34 (1), 112-124.

Horner R., May C. W., Livingston E., Blaha D., Scoggins M., Tims J. and Maxted J. (2001). Structural and non-structural BMPs for protecting streams. In *Linking Stormwater BMP designs and performance to receiving water impact mitigation - Engineering Research Foundation Conference*. (Ed. B. Urbonas) pp. 60–77. American Society of Civil Engineers, Colorado.

Hornsby Shire Council (2009), Annual Monitoring Report, 2008/09., Sydney.

Newall P. and Walsh C. J. (2005). Response of epilithic diatom assemblages to urbanization influences. *Hydrobiologia* 532, 53–67.

Stephens K. A., Graham P. G. and Reid D. (2002). *Stormwater planning: a guidebook for British Columbia*. BC Ministry of Water, Land and Air Protection, Vancouver.

Taylor S.L., Roberts S. C., Walsh C. J. and Hatt B. E. (2004). Catchment urbanisation and increased benthic algal biomass in streams: linking mechanisms to management. *Freshwater Biology* 49, 835–851.

Walsh C.J. (2004). 'Impacts of stormwater treatment wetlands on stream macroinvertebrates: a study of four wetlands constructed by Melbourne Water on streams in eastern Melbourne.' Water Studies Centre, Monash University, Report prepared for Melbourne Water (Melbourne.)

Walsh, C.J., Leonard, A.W., Ladson, A.R. and Fletcher, T.D. (2004), Urban Stormwater and the Ecology of Streams, CRC for Freshwater Ecology and CRC for Catchment Hydrology.

Walsh, C., Roy, A, Feminella, J., Cottingham, P., Groffman, P., and Morgan II, R (2005a)., The urban stream syndrome: current knowledge and the search for a cure. *Journal of North American Benthological Society*, 24(3):706-723.

Walsh, C.J., Fletcher, T.D., and Ladson, A.R. (2005b), Stream restoration in urban catchments through re-designing stormwater systems: looking to the catchment to save the stream. *Journal of the North American Benthological Society*, 24, 690-705.