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Urban Water Quality: Stereotypical Solutions May Not Always be the Answer

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Abstract

This paper discusses the outcomes of a research project which involved an in-depth investigation of pollutant wash-off by analysing the hydrological and water quality data from six areas having different land uses, in order to correlate urban form to water quality. The three main catchments selected were characterised by differing forms of land development and housing density; ranging from predominantly forested, to rural acreage-residential and forest to mixed urban development. Additionally, three smaller subcatchments within the urban catchment were identified for more detailed investigations into effects of increasing urban density on water quality. The data derived were initially analysed using univariate statistical methods to obtain an insight into the trends and patterns of variations in water quality. Subsequently multivariate 'chemometric' techniques were applied to identify linkages between various parameters and their correlation with land use.

The outcomes from the study bring into question a number of fundamental concepts routinely accepted in stormwater quality management. A significant fraction of the pollution was in dissolved form, hence it is more bio-available and is therefore more likely to cause pollution in receiving waters. It could well be that this condition is linked to the climatic and rainfall conditions experienced in the study region. This would mean that the effectiveness of structural measures would not be universal and stereotypical solutions will not always prove adequate.

These findings underline the need to move beyond the dependency on customary structural measures and end-of-pipe solutions and the key role that urban planning can play in safeguarding urban water environments. The univariate and multivariate statistical data analysis undertaken found that among the different urban forms, stormwater runoff from the area with detached housing in large suburban blocks exhibited the highest concentration and variability of pollutants. This was based on the concentration of various pollutants, their high variability and physico-chemical form. Rural residential on large blocks were only marginally better. It could be concluded that in terms of safeguarding water quality, high density residential development which results in a relatively smaller footprint should be the preferred option.

1. INTRODUCTION

Urban expansion transforms local environments and can dramatically alter local conditions. In the context of effective urban resource planning and management, the recognition of the impacts of urbanisation on the water environment is among the most crucial. The significance stems from the fact

that water environments are greatly valued in urban areas as environmental, aesthetic and recreational resources and hence are important community assets. Arguably it is the water environment which is most adversely affected by urbanisation. Any type of activity in a catchment that changes the existing land use will have a direct impact on its quantity and quality characteristics.
Land use modifications associated with urbanisation such as the removal of vegetation, replacement of previously pervious areas with impervious surfaces and drainage channel modifications invariably result in changes to the characteristics of the surface runoff hydrograph. Consequently, the hydrologic behaviour of a catchment and in turn the streamflow regime undergoes significant changes. The hydrologic changes that urban catchments commonly exhibit are, increased runoff peak, runoff volume and reduced time to peak (ASCE, 1975). However, urbanisation not only impacts on the hydrologic regime of catchments, but also has a profound influence on the quality of stormwater runoff. These consequences are due to the introduction of pollutants of physical, chemical and biological origin resulting from various anthropogenic activities common to urban areas. As Sartor and Boyd (1972) have identified, urban stormwater runoff constitutes the primary transport mechanism that introduces non-point source pollutants to receptor areas. These contaminants will detrimentally impact on aquatic organisms and alter the characteristics of the ecosystem. This results in a water body which is fundamentally changed from its natural state (Hall & Ellis, 1985; House *et al*, 1993).

The pollutant impact and 'shock load' associated with stormwater runoff can be significantly higher than secondary treated domestic sewage effluent (House *et al*, 1993; Novotny *et al*, 1985). In summary, the deterioration of water quality, degradation of stream habitats, and flooding, are among the most tangible of the resulting detrimental quality and quantity impacts of urbanisation. The true cost of these impacts extends beyond the immediate human or physical boundaries of the area and affects the function of surrounding ecosystems. Therefore the appropriate management of urban stormwater runoff and streamflow has significant socio-economic and environmental ramifications for urban areas.

The management of quantity impacts of stormwater runoff is relatively straight forward. The common approach is the provision of various structural or physical measures such as detention/retention basins or features such as porous pavements to retain part of the runoff volume and/or attenuate the runoff hydrograph. The primary objective of these measures is to replicate the pre-urbanisation runoff hydrograph. Under appropriate conditions, these structural measures have proven to be effective.

Unfortunately, the management of quality impacts due to urbanisation are far more complex. Though the sources and causes of stormwater pollution are widely known (Hall & Ellis, 1985; House *et al*, 1993), its control constitutes an intractable challenge in the drive towards sustainable human settlements. The current state of knowledge with regards to the process kinetics of pollutant build-up and wash-off is extremely limited. The inter-relationships between various factors and the build-up and wash-off processes of pollutants are complex and little understood. There is no question that the urban environment is adversely affected by a variety of anthropogenic activities which introduces numerous pollutants to the environment. However major uncertainties arise in efforts to articulate the process kinetics of pollutant generation, transmission and dispersion. Therefore in the absence of appropriate guidance and as a direct consequence of the fact that in the past, the major interest of regulatory authorities was quantity impact mitigation, current approaches to safeguard water quality are similarly guided by a primary focus on 'end-of-pipe' solutions.

There have been significant advances in the control of point sources of pollution such as sewage effluent outfalls. However, it is the non point-sources which are the most damaging, the least visible and the most difficult to control. Many factors affect the quality of stormwater runoff with land use being the most important. Though numerous research studies have attempted to relate land use to pollutant loadings, the outcomes reported can be conflicting (Hall & Anderson, 1986; Lopes *et al*, 1995; Parker *et al*, 2000; Sartor & Boyd, 1972). This can be attributed to the reliance on physical processes and the neglect of important chemical processes in describing various stormwater associated phenomena. These contradictory findings indicate that other catchment characteristics such as soil type may also play a significant role in influencing urban stormwater runoff quality and its impacts.

2. MATERIALS AND METHODS

2.1. Study Areas

The research project was located in The City of Gold Coast, Queensland, Australia. The primary focus of the project was to undertake an in-depth investigation of pollutant wash-off by analysing the hydrologic and water quality data from six areas having different land uses, in order to correlate urban form to water quality. The project commenced in July 1999 and encompassed three existing catchment study areas. Subsequently three additional subcatchments were included in December 2001. The data analysis undertaken included rainfall event based water quality data collected to end 2003.

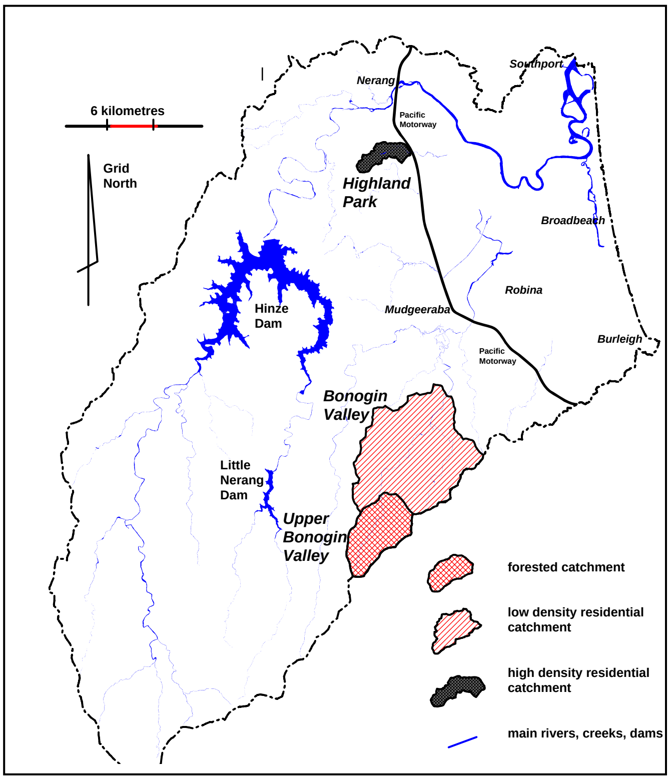

Figure 1 Locations of main catchments

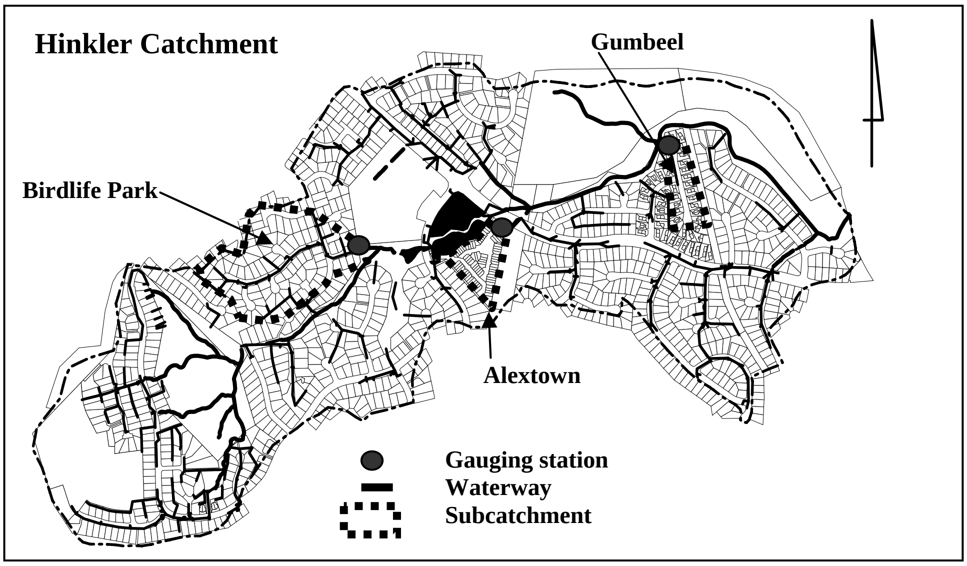

Figure 2 Locations of the urban subcatchments

The study areas were selected so as to ensure that there was uniformity in the geological, topographical and climatic variables, which could possibly influence the water quality characteristics. The three main catchments are characterised by the same geology based on the Neranleigh-Fernvale metasediments and similar predominant soil types mainly Kurosols (Isbell, 1996). However they have differing forms of land development and housing density; ranging from predominantly forested in the upper Bonogin Valley (or Bonogin), to rural acreage-residential (un-sewered) and forest in the lower Bonogin Valley (or Hardy), to mixed urban development (sewered) in Highland Park (or Hinkler) catchment. The study catchments have been mapped in detail, including detailed landuse, geology, soils, topography and stream morphology (GCCC, 2001).

Three smaller subcatchments within the Hinkler catchment were identified for more detailed investigations into effects of increasing urban density on water quality. These subcatchments are a tenement townhouse development of around 60 properties (Alextown), a duplex housing development with around 20 dual occupancy residences (Gumbeel) and a high-socio-economic single detached dwelling area (Birdlife). The locations of the study areas are shown in Figures 1 and 2 whilst Table 1 provides a summary of relevant characteristics for each area.

Table 1. Characteristics of selected study areas

Study area	**Extent (ha)**	**Land cover**	
		Impervious area (buildings, roads)	**Pervious area (forest, grassland)**
Forested catchment – Upper Bonogin Valley (Bonogin)	647	2%	98%
Rural acreage residential catchment – Lower Bonogin Valley (Hardy)	2726	9%	91%
Urban Residential Catchment – Highland Park (Hinkler)	161	55%	45%
Town Houses – Alextown subcatchment	2	60%	40%
Duplex Housing – Gumbeel subcatchment	7.5	70%	30%
Detached housing – Birdlife subcatchment	8.5	60%	40%

2.2. Water Sample Collection and Testing

Automatic monitoring stations were established at the outlet of each area to record rainfall, stream-flow and a range of water quality parameters. Each station was equipped with an automatic event sampler to augment grab samples taken during low flow conditions. The automatic monitoring stations recorded rainfall, streamflow, pH, electrical conductivity (EC), temperature and dissolved oxygen concentration (DO). Event samples collected by the automatic sampling devices and the grab samples taken during low flow conditions were analysed for total organic carbon (TOC), suspended solids (SS) and total dissolved solids (TDS), total nitrogen (TN) and total phosphorus (TP).

2.3. ANALYTICAL METHODS

2.3.1. Univariate Statistical Analysis

Univariate statistical analysis was undertaken to determine the mean and standard deviation for the primary water quality parameters for the six study areas. It was anticipated that these values would provide an insight into the trends and patterns of variations in water quality with land use. This would provide further information to underpin the outcomes derived from more detailed data analysis. At the initial stages of the research project, using correlation matrices, Rahman et al. (2002) developed a set of preliminary predictive equations relating key pollutant parameters and rainfall characteristics. This was based on the data obtained from July 1999 to July 2001 for the three primary catchments. For

Bonogin, an equation was developed to predict TP from TSS. This equation had a high coefficient of determination (95%) and a relatively small standard error of estimate (25%). Unfortunately in the case of Hardy and Hinkler catchments, the various predictive equations developed did not reflect the same degree of statistical accuracy. However most importantly, the study by Rahman *et al* (2002) highlighted the importance of developing a deeper understanding of the interactions and linkages between influential parameters.

2.3.2. Multivariate Statistical Analysis

Subsequent to the univariate study, multivariate chemometric techniques were applied to identify linkages between various pollutant parameters and correlations with land use. The analytical technique used was Principal Component Analysis (PCA). Essentially, PCA is used for pattern recognition. PCA is a multivariate statistical data analysis technique which reduces a set of raw data into a number of principal components which retain the most variance within the original data in order to identify possible patterns or clusters between objects and variables. Detailed descriptions of PCA can be found elsewhere (Adams, 1995; Kokot *et al*, 1998; Massart *et al*, 1988). PCA has been used extensively for various applications related to water quality. As examples, Wunderlin *et al*, (2001) used PCA for the evaluation of spatial and temporal variations in river water quality and Marengo *et al* (1995) to characterise water collected from a lagoon as a function of seasonality and sampling site and for the identification of significant discriminatory factors.

In order to undertake PCA, the water quality concentration data (as mg/L) was arranged into a matrix for each study area. The columns defined the variables and the rows, the sample measurement. The raw data was initially subjected to pre-treatment to remove 'noise' which may interfere in the analysis (Adams, 1995, Kokot *et al*, 1998). Firstly, the data was log transformed to reduce data heterogeneity. Following this, the transformed data was column-centred (column-means subtracted from each element in their respective columns) and standardised (individual column values divided by the column standard deviations). PCA was undertaken on the transformed data for pattern recognition and for the identification of correlations between selected variables.

3. RESULTS AND DISCUSSION

3.1. Univariate Statistical Analysis

Table 2 gives the mean and standard deviation for the measured parameters for all the study areas for the monitored rainfall events from July 1999 to December 2003.

Table 2 Mean and Standard Deviations of the measured parameters

Parameter		**Bonogin** (Forest)	**Hardy** (Park living)	**Hinkler** (Urban)	**Alextown** (Town Houses)	**Gumbeel** (Duplex)	**Birdlife** (Detached Houses)
pH	Mean	6.49	6.67	6.78	6.73	6.69	7.04
	S. D.	0.20	1.28	0.33	0.25	0.38	0.39
EC μS/cm	Mean	91.44	151.99	222.45	74.78	103.11	161.74
	S. D.	56.74	73.77	138.77	28.48	46.26	84.48
SS mg/L	Mean	80.71	149.41	171.52	130.91	58.49	181.70
	S. D.	112.27	209.52	111.43	253.95	59.48	238.16
TN mg/L	Mean	2.34	2.66	6.77	2.06	3.31	2.01
	S. D.	0.47	3.18	14.08	1.11	3.79	1.96
TP mg/L	Mean	0.27	0.23	0.48	0.45	0.75	0.73
	S. D.	0.15	0.39	0.80	0.27	0.72	0.96
TOC mg/L	Mean	13.94	21.50	102.75	11.35	10.37	11.52
	S. D.	6.28	27.51	466.28	4.16	5.76	6.23

TN= Total Nitrogen, TP=Total Phosphorus, SS=Suspended Solids, TOC=Total Organic Carbon, EC= Electrical Conductivity

3.1.1. The primary catchment areas; Bonogin, Hardy, Hinkler

Based on the data given in Table 2, the following conclusions can be derived:

- There was no significant change in pH values obtained for individual catchments and values between catchments. This could be related back to the soil conditions prevalent in the study areas which are of similar characteristics.
- Considering the other primary water quality parameters measured, EC, TN, TP, SS and TOC, the mean values and the standard deviations obtained increase with increasing urbanisation. The increase in mean values can be attributed to the increase in the pollutant load in stormwater runoff due to urbanisation. The increase in standard deviations is even more significant. It indicates a high variability in stormwater runoff quality. This underlies the difficulties in predicting the quality of urban runoff and the large margins error usually associated with predictive modelling.
- The trend of increasing standard deviation with urbanisation does not apply only in the case of SS for Hardy and Hinkler catchments. It is postulated that this is due to the fact that the Hardy catchment does not have kerb and channelling and that this leads to relatively higher erosion along its roadways.
- It is also significant that despite the high canopy cover in the Bonogin catchment, the Hinkler catchment comparatively, still exhibits the highest TOC concentration.

3.1.2. The subcatchment areas; Alextown, Gumbeel, Birdlife

Based on the data given in Table 2, the following conclusions can be derived:

- Once again the pH values are relatively stable and there is no significant difference between the three study areas.
- In terms of the other primary pollutants, the trend in changes in data values is not very clear as in the case of the primary catchment areas. However other than for TN and SS, Birdlife subcatchment shows the highest variability in pollutant concentrations. In terms of the other two study areas, it is difficult to distinguish between Alextown and Gumbeel.
- It was not possible to determine the reasons for the higher standard deviation for SS for Alextown which is only marginally higher than for Birdlife. However it is important to note that the average SS concentration for Birdlife is higher when compared to Alextown.

3.2. Principal components analysis (PCA).

The PCA of the physico-chemical data resulted in most of the data variance being contained in the first two components, PC1 and PC2. PC1 is the orthogonal combination variables that explains the largest variance and PC2 the next largest. Biplots of data points against PC1 and PC2 for the individual study areas are shown in Figures 3 – 8. The angle between vectors shown in the biplots is significant. The smaller the angle between the vectors, the greater the correlation between individual parameters. Vectors situated closely together represent variables that are highly correlated while vectors at right angles are uncorrelated.

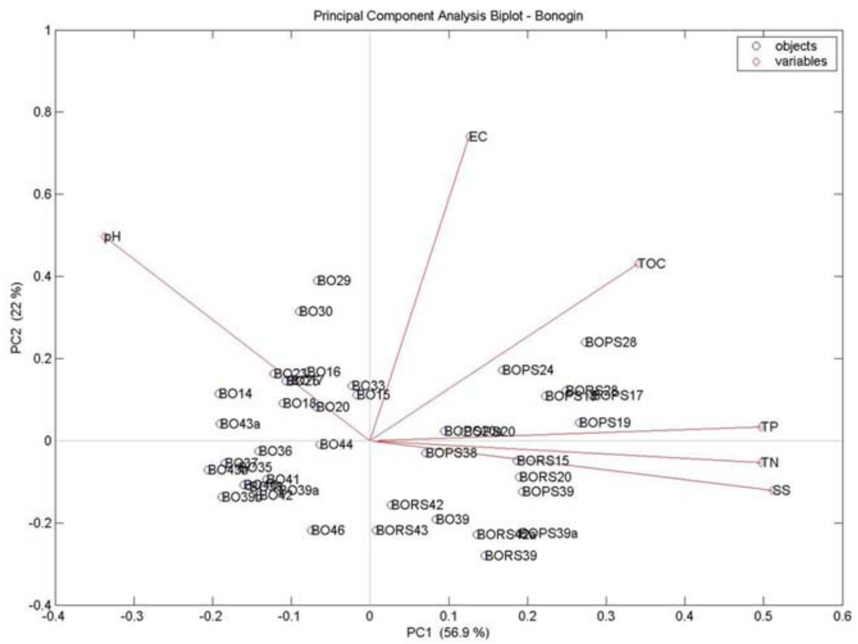

Figure 3. Bonogin Catchment: Biplot of data against two main Principal Components

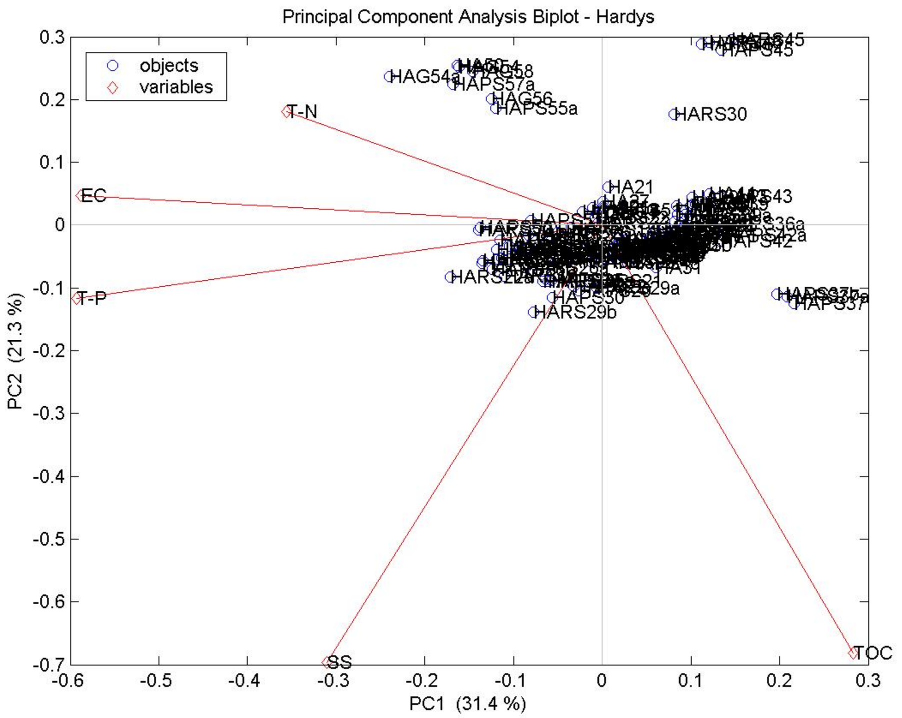

Figure 4. Hardy Catchment: Biplot of data against two main Principal Components

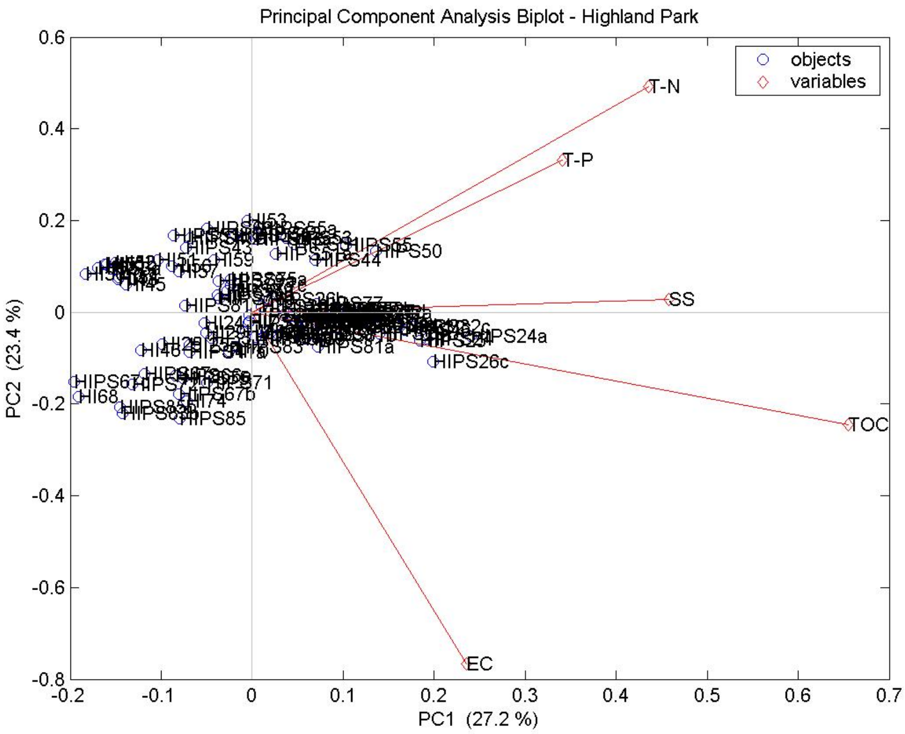

Figure 5. Hinkler Sub-catchment: Biplot of data against two main Principal Components

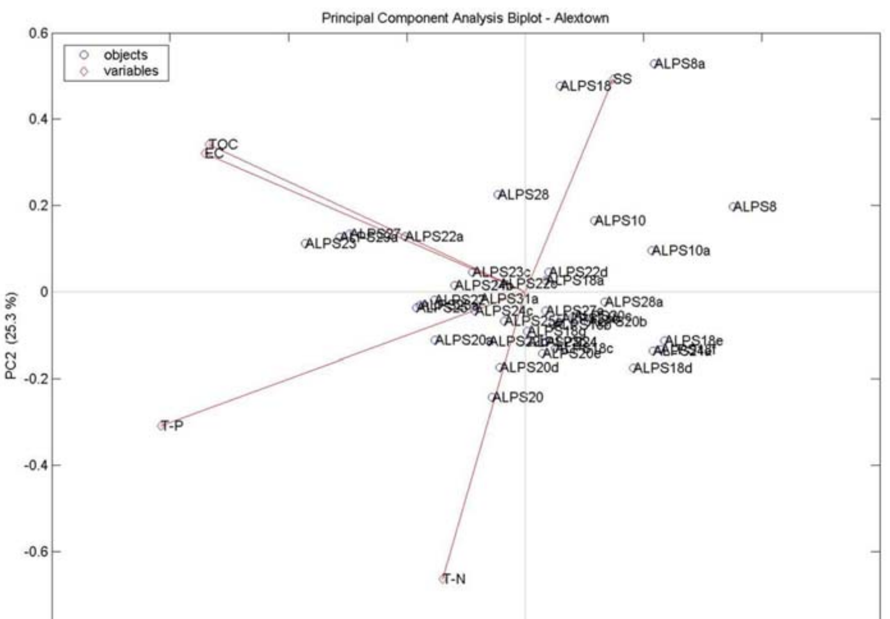

Figure 6. Alextown Sub-catchment: Biplot of data against two main Principal Components

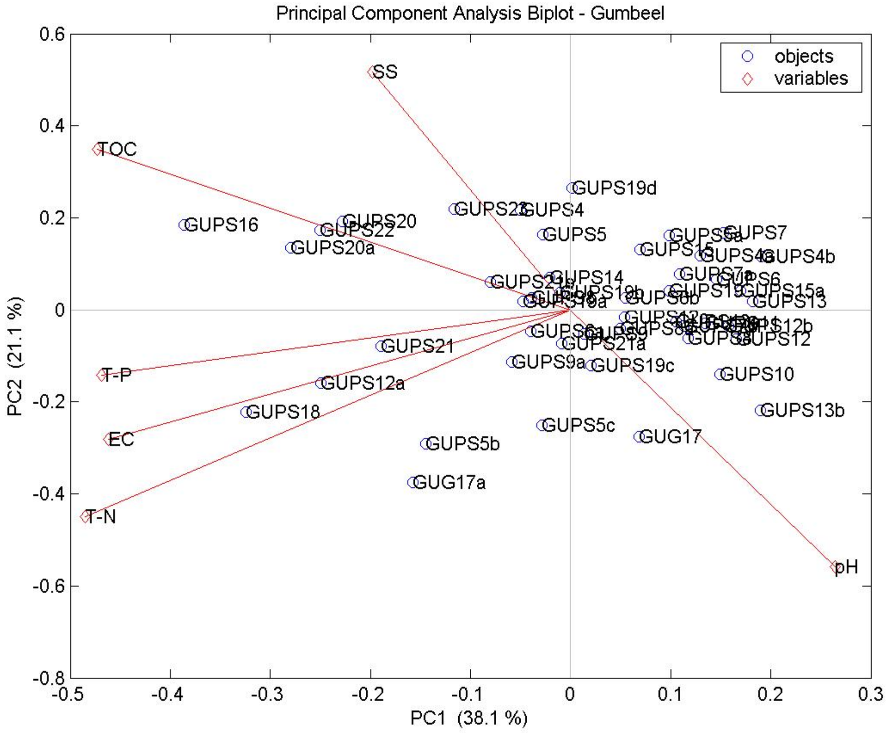

Figure 7. Gumbeel Sub-catchment: Biplot of data against two main Principal Components

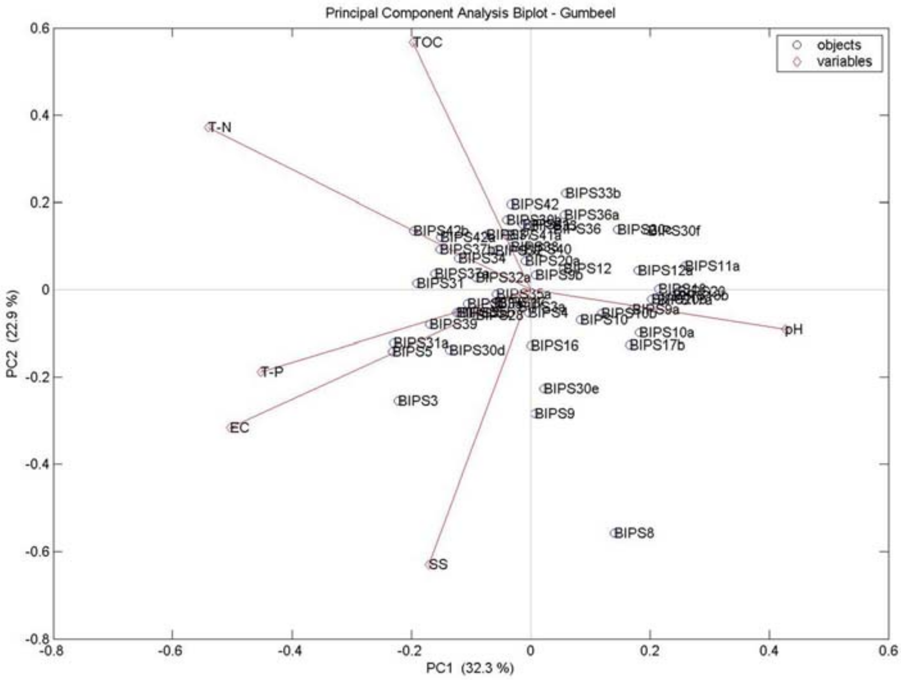

Figure 8. Birdlife Sub-catchment: Biplot of data against two main Principal Components

The multivariate analyses noted the following for each site.
Bonogin (forested)

- TP, TN and SS strongly correlated. Hence most nutrients are bound to particles.
- Some correlation between TOC and SS. Therefore TOC is in two forms, particulate organic matter probably from leaf litter, and as dissolved organic carbon (DOC).
- Hence a pollutant abatement measure such as a sediment basin would be effective.

Hardy (rural residential)

- TP is only weakly correlated, and TN not correlated, with SS or TOC. Hence TP and TN are primarily in solution.
- TOC is only weakly correlated with SS. Hence most TOC would also be in dissolved form primarily as DOC.
- Hence a pollutant abatement measure such as a sediment basin would be effective only in removing SS, but not TOC, TP and TN.

Hinkler (mixed use urban)

- TN and TP closely correlated and has some correlation with SS. Hence these nutrients could have originated from the same source and an appreciable proportion of the nutrients would be in particulate form.
- TOC is significantly correlated with SS. Hence an appreciable proportion of TOC would be in particulate form such as leaf litter or grass clippings.
- Hence a pollutant abatement measure such as a sediment basin would be effective.

Alextown (townhouse development)

- TN, TP, TOC and SS are not strongly correlated with each other. Hence TN, TP and TOC would be in dissolved form but independent of each other with TOC as dissolved organic carbon.
- Hence a pollutant abatement measure such as a sediment basin would be effective only in removing SS, but not TOC, TN and TP.

Gumbeel (duplex development)

- TN and TP are correlated with each other but not with SS. Hence both TN and TP would be in dissolved form.
- TOC is correlated with SS, but a fraction would be in the form of DOC.
- SS would be primarily in inorganic form.
- Hence a pollutant abatement measure such as a sediment basin would be effective in removing SS and most of TOC but not TN and TP.

Birdlife (detached houses in large blocks)

- TP is only weakly correlated, and TN and TOC not correlated, with SS. Hence, TN, TP and TOC would be primarily in dissolved form.
- Hence a pollutant abatement measure such as a sediment basin would be effective in removing SS but not TN or TOC and only weakly effective in removing TP.

3.3. Discussion

The results from the three primary catchments, Bonogin, Hardy and Hinkler demonstrate the accepted general trend of deteriorating water quality with increasing urbanisation. However, the results for each, particularly from the multivariate analysis, provide an insight into the relationships between the various and to highlight the significant role that urban planning and management can have.

In the forested Bonogin catchment, pollutant concentration was the lowest. However, correlations between SS, TP, TN and SS indicate that the nutrients are being transported as particulate matter probably associated with particulate organic matter and leaf litter from the surrounding forested landscape. In the Hinkler catchment, similar correlations were observed but the concentration of pollutants was higher.

In contrast, the Hardy catchment, with similar levels of pollution to Bonogin does not exhibit the same correlation with SS for these pollutants. The pollutants are in solution and more bio-available. The Hardy catchment is comprised of forest and grassland areas and extensive, un-sewered, low-density urban form. It is possible that these dissolved pollutants are originating from the on-site wastewater treatment systems in the catchment. Additionally, as most SS were not related to TOC, they are most likely inorganic particles such as silts and sands probably from the road edges which do not have kerb and channel. The three sub-catchments of Hinkler; Birdlife, Gumbeel and Alextown represent a trend in increasing urban density and in contrast to their parent catchment TN, TP and TOC are not correlated with SS.

The explanation for this apparent contradiction may lie in the different hydrologic processes operating at different scales. It should be noted that this mixed-use urban catchment has appreciable open space and vegetation cover with only 55% impervious cover. It is also important to note that the concentration of TOC is much higher (by 67%) than the SS concentration. At the sub-catchment scale the pipe network from which the samples were taken is significantly different from the open channel stream from which the whole catchment is sampled. Pipe networks are designed to prevent accumulation or growth of organic matter within them and all particulates originate from the surrounding land uses. There is virtually no entrainment of material from within the pipe. While such systems may generate relatively high SS, such as in Birdlife, these will be mainly inorganic particles such as silts and sands, and nutrients are more likely to be in dissolved form.

Over the whole of Hinkler the open stormwater drainage systems include a sedimentation basin and a wetland bird habitat. The retention time for the water in these systems combined with the input of dissolved and available nutrients will lead to increased algal growth and tie-up of dissolved pollutants into organic matter. In addition for much of its length, the open natural stream is highly vegetated with a closed canopy. This combination of reduced velocities, algal growth and accumulation of organic debris can explain the apparent contradicting correlations.

The fact that TOC is not commonly correlated with SS would mean that the organic carbon is primarily in dissolved form or as dissolved organic carbon (DOC). DOC is an important water quality parameter. DOC absorbs and reacts with sunlight energy, complexes metals, provides an energy source for microorganisms and associates with hydrophobic substances. Additionally, organic carbon adsorbed on suspended solid particles enhances their sorption capacity for combining with hydrocarbons and some heavy metals. Though some of these characteristics can be considered to be beneficial, the organic matter is liable to microbial decomposition, thereby returning the pollutants back into the dissolved phase (Parks & Baker 1997; Westerhoff & Anning 2000).

Comparing the three different sub- catchments in terms of impact or ‘footprint’, Birdlife with detached houses, has the highest impact on the water environment. This is based on the concentration of various pollutants, their high variability and physico-chemical form. Considering the nature of the different urban developments, it could be surmised that detached houses contribute a greater pollutant load than higher urban densities. It is probable that these pollutants are being generated from over-managed landscaped gardens, and from the larger total road surface-area in the sub-catchment.

Structural stormwater improvement measures such as detention basins or sediment traps could be partially effective in removing SS particularly larger silt and sand sized particles. Such devices will also remove TN, TP and TOC, but only when there is a strong correlation between them and SS.

4. CONCLUSIONS

The conclusions from this study bring into question a number of fundamental concepts routinely accepted in stormwater quality management. The fact that the pollutant characteristics are not consistent across all the study areas would mean that the land use characteristics or the urban form is the overriding factor influencing water quality. This not only relates to the concentration, but also to the chemical composition of stormwater pollutants. These conclusions would mean that the effectiveness of structural measures would not be universal and stereotypical solutions will prove inadequate. The common management technique of dealing with suspended materials as a primary treatment measure for urban stormwater quality may not always be successful as other pollutants are not necessarily in suspended form. It was repeatedly found that SS in most occasions is not correlated with TN, TP or TOC. Therefore as much of the pollution is moving in dissolved form, it is more bio-available and is therefore more likely to cause pollution in receiving waters. It could well be that this condition is linked to the climatic and rainfall conditions experienced in the study region which significantly influences pollutant composition, build-up and wash-off. Therefore it is important that predictive models developed have the versatility to take these characteristics into consideration.

The study confirmed that there is a general increase in pollutant concentrations with increasing urbanisation. However an increase in standard deviations was also observed, which is significant. It indicates a high variability in stormwater runoff quality with increasing urbanisation. This underlies the difficulties in predicting the quality of urban runoff and the large margins of error usually associated with predictive modelling.

The above findings underline the need to move beyond the dependency on customary structural measures and 'end-of-pipe' solutions and the key role that urban planning can play in safeguarding urban water environments. The univariate and multivariate statistical data analysis undertaken found that among the different urban forms, stormwater runoff from the area with detached housing in large suburban blocks exhibited the highest concentration and variability of pollutants. This is based on the concentration of various pollutants, their high variability and physico-chemical form. It is probable that these pollutants are being generated from the landscaped gardens and the relatively greater extent of road surface area. Rural residential on large blocks were only marginally better. It could be concluded that in terms of safeguarding water quality, high density residential development which results in a relatively smaller footprint should be the preferred option.

5. ACKNOWLEDGEMENTS

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