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RESEARCH ARTICLE

Impact of concrete and PVC pipes on urban water chemistry

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Waterways contain a chemical signature of catchment land use, climate and geology. This is increasingly being influenced by the urban landscape and particularly the composition of materials and activities that occur on impervious surfaces. This paper examines the degree and extent of two types of drainage materials, concrete and PVC, on urban water chemistry. This study found that water collected from a zinc and slate/tile roof and stored in a plastic rain tank (roof water) was acidic (pH 4.79) and had low bicarbonate concentrations (0.5 mg/l), water from an undeveloped catchment (reference creek) was mildly acidic (pH 5.5) with bicarbonate concentrations of 1.7 mg/l while water from a stream draining a residential catchment (urban creek) was mildly alkaline (pH 7.35) with bicarbonate concentrations of 36.3mg/l. The three types of water were then circulated through a concrete pipe or PVC pipe for 100 min and measured for a range of water chemical attributes. Roof water and water from the reference creek reported a significant increase across a range of analytes, most notably bicarbonate and calcium levels when passed through the concrete pipe, while water from the urban creek changed a lesser amount. When passed through the PVC pipe the changes in water chemistry were significantly less for roof water and urban creek water. The data suggests that in-transport processes from concrete drainage systems are having a significant influence on water chemistry, particularly where inflow is acidic. The major factor identified in this study could be attributed to the dissolution of calcium, bicarbonate and potassium ions from the concrete pipe. This could impact on receiving environments that are naturally acidic and low in bicarbonate, such as those in northern Sydney. The implications of this study point towards a need to consider the type of materials used in urban drainage networks if water chemistry and stream ecosystem health is to be protected.

Keywords: diffuse pollution; hydrogeology; integrated urban water management; stormwater quality; sustainable urban water management; water sensitive urban design

Introduction

The use of pipes and culverts to convey urban runoff has become a ubiquitous treatment used by drainage engineers around the world. This has come from the necessity to mitigate and manage the risk of flooding. More recently, water sensitive urban design (WSUD) or low impact development (LID) has entered the domain of the engineering, physical scientists and landscape architects such that urban runoff is no longer confined to the management of flood or overland flow prevention rather now takes a broader view of water within its catchment (Meyer *et al.* 2005).

As most of the world's population live in cities (Grimm *et al.* 2008), there is a growing concern about the degradation of urban waterways by urban and human activity (Aplin 2002). There have been numerous studies describing the generally poor quality of runoff from various urban surfaces such as roofs (Bridgman 1992, Garnaud *et al.* 1999), roads and other transport related surfaces (Sartor and Boyd 1972, Schuler 1987, Ball *et al.* 1998, Drapper *et al.* 2000, Shinya *et al.* 2000) and impervious surfaces generally (Ladson *et al.* 2006, Conway 2007). Many studies have sought to quantify the degree to which urban stormwater adversely influences waterway health (Dunne and Leopold 1978, Klein 1979, Hall and Ellis 1985, Walsh *et al.* 2001, Hatt *et al.* 2004, Walsh 2006).

Scientific studies, and waterway managers, have often focused their attention on diffuse pollutants in urban waterway including nutrients, hydrocarbons, metals, particulates, oxygen demanding substances and micro organisms (such as pathogens and indicator bacteria). This work has influenced regulatory standards or similar guidelines (e.g., McKay and Moeller

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2002) as issued by government for urban runoff (Austroads 2003) and other water sources (ANZECC and ARMCANZ 2000).

The challenge for those within the urban water profession is to protect both water quality and the ecological health of urban waterways (Aplin 2002). A number of researchers (e.g., Meyer *et al.* 2005, Lawrence and Breen 2003) have sought to encapsulate both perspectives and have identified a number of interrelated factors that influence waterway health. This has been aptly described by Meyer *et al.* (2005) as the ‘‘urban stream syndrome’’. This considers not only the quality of water but also factors such as stream hydrology and the degree of connection of the urban drainage network directly into waterways.

When describing the role of urban land use and its impact on urban water pollution, the processes that lead to changes in pollution loads have generally focused on build-up and subsequent wash off of contaminants (Lawrence and Breen 2003). Build-up is a combination of wet and dry deposition, point source and diffuse pollution, while the transportation process, such as wash off, has focused on surface flow processes or in-stream erosion.

Missing in the discussion to date is the role of the drainage network itself with respect to contributing to the in-transport pollution load and also the natural ionic balance and how this may impact on ecological health.

While focusing on the hydrogeochemistry in Hong Kong, Leung and Jiao (2006), investigated the quality of water that came in contact with the basements and foundations of high-rise buildings that are periodically or permanently below the water table. Leung and Jiao (2006) concluded that the dissolution of concrete from the foundations was most likely to be responsible for the chemical signature reporting a high pH and high levels of bicarbonate, calcium and other ions associated with concrete. Whilst this could be seen as another source of diffuse pollution within the urban landscape it identifies a new area for investigation. Conway (2007) investigated changes in pH as related to catchment imperviousness, and while that study noted an increase in pH coupled with an increase in impervious surfaces, it did not identify the materials that comprise the drainage system as a possible causal factor.

Hart and McKelvie (1986) reviewed the chemical nature of Australian inland waters that focussed on the importance of the natural ionic balance of waterways. They discussed the importance of the composition and relative proportion of the major ions (Na, Ca, Mg, K, HCO_3, Cl, SO_4) which responded to the chemical nature of each waterway depending on atmospheric and/or catchment geological sources of ions.

Within the northern suburbs of Sydney, urban waterways have previously been found to have significantly different chemistry and ecology to that found in nearby non-urban waterways (Wright *et al.* 2007). Dry weather water quality was highly dissimilar with higher levels of alkalinity and electrical conductivity at urban streams. Urban waterways were generally circumneutral to slightly alkaline while undeveloped (natural) streams were acidic (Wright *et al.* 2007). As a result of these observations, this current study was developed with an objective to explore the existence of any causal link between the water chemistry in urban streams and the materials comprising the urban drainage system.

Methods

Study area

Research was undertaken within the Ku-ring-gai local government area (LGA), situated north of Sydney City at 33°45′20”S and 151°9′0”E. Development across the Ku-ring-gai LGA, is dominated by low density residential housing on block sizes around 940 m^2 with little commercial and no industrial development. The LGA is 84 km^2 with one-third bushland and has a population of 101,000 (ABS 2007).

The geology is characterised as Wianamatta Shale overlying Hawkesbury Sandstone on ridges with the deeply incised valleys and streambeds dominated by exposed Hawkesbury sandstone (NSW Department Mineral Resources 1983). The soil type is closely related to the underlying geology and is generally described as poor in both structure and geochemistry (Herbert and Helby 1980). A notable characteristic of the northern suburbs of Sydney is that development has occurred on the upper and flatter sections of the catchment while the steeper incised valleys contain remnant bushland and modified streams. The intermittent and ephemeral streams that would have existed in the upper reaches of the catchment have largely been replaced by concrete pipes that discharge to either the permanent or intermittent streams within the steeper sections of the landscape and narrow valley floors.

Study design

Three types of water were used in this study: roof water, urban stream water and non-urban reference stream water. Each type of water involved collection and mixing from two different sources within each category to help ensure that the sample used in the experiment was representative of water quality of that type in the study area. Rainwater was collected from two sources within the LGA: a 100% zincalume roof and the other had an 80% slate and 20% ceramic tile roof. Both rainwater samples were stored for approximately two weeks in an on-site plastic rainwater tank prior to sampling. Urban stream water was collected from two creeks within the Ku-ring-gai local government area (Falls Creek and Quarry Creek, Table 1). In each case samples were taken immediately downstream from the urban/bushland interface. Reference creek water was taken from two creeks draining predominantly naturally vegetated, non-urban catchments, within the Ku-ring-gai Chase National Park, Salvation Creek and McCarrs Creek (Table 1).

Water samples were collected from the rainwater tanks (roof water) and from the urban and non-urban creeks on the same day as the experiment. Samples were collected in clean 20 litre plastic jerry cans, and were stored in the shade prior to their use. The weather was overcast and dry and the flow in all waterways was typical of dry weather (low flow) conditions.

A polyvinylchloride (PVC) and steel-reinforced concrete pipe was fixed to a frame with a 6.5% and 7.5% grade respectively, the higher grade for concrete chosen to counteract the higher roughness of the pipe. Each pipe was previously unused and was 1.4 m in length. Equal portions of the same water type were mixed to make a composite sample. These were divided into two batches, each with a volume of 20 l. Each water type was manually circulated using buckets, with the water delivered to the pipes through an anti-scouring device at a rate of approximately 0.2 l/s for 100 min. Prior to the commencement of sampling, each pipe was flushed with surplus sample water of the type to be used in order to remove any residue chemical or particulate matter.

Water samples were collected at five instances over the 100-min period. The first were prior to commencement of flow through the water pipes, and then every 25 min. Three replicates were collected on each occasion. These samples were analysed at a commercial quality-assured laboratory for total alkalinity (bicarbonate, hydroxide and carbonate) and other major dissolved major anions and cations (calcium, sodium, magnesium, potassium, chloride and sulfate) and all were reported with a lower detection limit of 1 mg/l. Ionic balance (total anions and total cations) was reported to a lower detection limit 0.01 meq/l. In addition to the laboratory analyses, electrical conductivity (EC), pH and temperature readings were collected every 5 min (starting prior to experiment commencement and concluding at 100 min) using a hand-held water chemistry meter (TPS Model Aqua CP, TPS Pty. Ltd. Springwood, Queensland). On each occasion three replicate readings were obtained.

Results were compared by analysis of variance (ANOVA) to determine if any varied temporarily. Results below detection limits were set at half the detection limit to enable parametric data analysis (Clarke 1998).

Results

Initial water chemistry

Major differences were reported between the water chemistry of the three water types (Table 2). Roof water was strongly acidic (pH 4.8) and had a low concentration of dissolved salts (EC 26 μS/cm). The concentrations of chloride (5.9 mg/l) and sodium (2.0 mg/l) was elevated, reflecting the high levels of atmospheric salt fall-out being 16–19 km from the coast (e.g., Hart and McKelvie 1986). Reference creek water was similarly mildly acidic (pH 5.2). Conductivity of non-urban reference creeks was higher than roof water (152.6 μS/cm) and levels of dissolved minerals were generally low. Sodium and chloride concentrations of reference creeks (17.7 and 42.1 mg/l) similarly reflected their coastal proximity (16–18 km from the ocean). Water from the urban creeks was mildly alkaline (pH 7.4) with a conductivity of 355.7 μS/cm.

The alkalinity (bicarbonate) concentrations varied significantly according to type of water ($F_{2,6} = 844.7$, $P < 0.001$). Urban creek water was 2135% higher than reference creek water and 7260% higher than roof water (Table 2). Similarly concentrations of dissolved calcium were also significantly higher, 533 and 3200%, respectively ($F_{2,6} = 65535$, $P < 0.0001$).

Table 1. Catchment characteristics for urban and reference streams sampled this study.

	Urban creeks		Reference creeks	
	Falls Ck	Quarry Ck	Salvation Ck	McCarrs Ck
Catchment area (ha)	90.8	87.4	71.1	458.7
Roofs and hardstand (%)	19.7	20.2	0.0	0.7
Roads (%)	6.1	9.5	0.7	0.7
Other hard surfaces (%) (eg carparks, office buildings)	4.0	4.3	0.0	0.4
Connected impervious area (%)	29.8	34.1	0.0	0.0
Total impervious (%)	29.8	34.1	0.7	1.8

Table 2. Mean concentration of water chemistry attributes before and after 100 min of recirculation through either a PVC or concrete pipe. The resulting level is bolded where a statistical increase was detected after the 100-min test.

	Roof water			Reference creek			Urban creek		
		After 100 min.			After 100 min.			After 100 min.	
Units	Before	PVC pipe	Con. pipe	Before	PVC pipe	Con. pipe	Before	PVC pipe	Con. pipe
K (mg/l)	0.5	0.5	**4.0**^{3}	1.3	1.0 ns	**4.0**^{3}	3.0	3.0	**6.0**^{3}
Total alkalinity (bicarbonate) (mg/l)	0.5	**4.0**^{1}	**17.3**^{3}	1.7	3.0 ns	**14.3**^{3}	36.3	**40.0**^{3}	**41.7**^{3}
Ca (mg/l)	0.5	**1.0**^{2}	**3.7**^{3}	3.0	3.0	**6.0**^{3}	16.0	**17.7**^{2}	**18.3**^{2}
Na (mg/l)	2.0	2.0	**4.0**^{3}	17.7	18.7 ns	**19.0**^{1}	36.3	**38.0**^{1}	37.0 ns
EC (μS/cm)	26.0	**27.1**^{3}	**56.2**^{3}	152.6	151.7	**177.0**^{3}	355.7	**358.0**^{3}	**353.0**^{3}
pH (pH units)	4.8	**6.4**^{3}	**7.9**^{3}	5.2	**7.1**^{3}	**7.7**^{3}	7.4	**7.9**^{3}	**8.0**^{3}
Cl (mg/l)	5.9	6.6 ns	7.4 ns	42.1	43.3 ns	42.8 ns	74.0	75.7 ns	**76.3**^{1}
SO_4 (mg/l)	1.0	1.7 ns	**2.0**^{3}	8.0	8.0	8.0	19.7	20.0 ns	**21.0**^{3}
Mg (mg/l)	0.5	0.5	0.5	3.0	2.7	2.0	6.0	6	6
Total anions (meq/l)	0.2	0.3^{2}	0.6^{3}	1.4	1.4	1.6^{3}	3.2	3.4^{3}	3.4^{3}
Total cations (meq/l)	0.1	0.2^{3}	0.5^{3}	1.2	1.2	1.4^{3}	2.9	3.1^{3}	3.1^{3}

ANOVA results: df = 10 (EC and pH; df = 42), ns, $P > 0.05$; $^{1}0.01 < P < 0.05$; $^{2}0.001 < P < 0.01$; $^{3}P < 0.001$.

The ionic proportions of roof water were very similar to that found in non-urban reference creek water. Urban water was dominated by sodium and chloride ions, but calcium and bicarbonate were the sub-dominant anion and cation. Reference creek water, when exposed to concrete pipe in the experiment for 100 min, had similar ionic proportions to urban water with sub-dominance of calcium and bicarbonate ions.

Impact of the pipes

During the experiment, the pH in all water types and both pipe materials increased highly significantly over the 100-min period (Table 2, Figure 1). This rise in pH was largest for roof water and reference creek water.

The concrete pipe was associated with the largest changes in pH (Figure 1). It was greatest for the samples of rainwater and reference creek water. Although the pH of each water-type was different at the outset of the experiment (4.8–7.4), it was similar after 100 min circulation through the concrete pipe (7.7–8.0).

Total alkalinity (bicarbonate) levels also increased after the experiment with the concrete pipe: roof water (3360% increase), reference creek (741% increase) and urban water (14% increase) (Figure 2). Calcium concentrations also displayed large and highly significant increases for all water types exposed to concrete: roof water (640% increase), reference creek (100% increase) samples and urban (15% increase) (Table 2, Figure 3). The increase in potassium concentrations was also highly significant, increasing between 100 and 700%, in all water types exposed to the concrete pipe (Figure 4). PVC pipes did not result in an increase in potassium (Table 2).

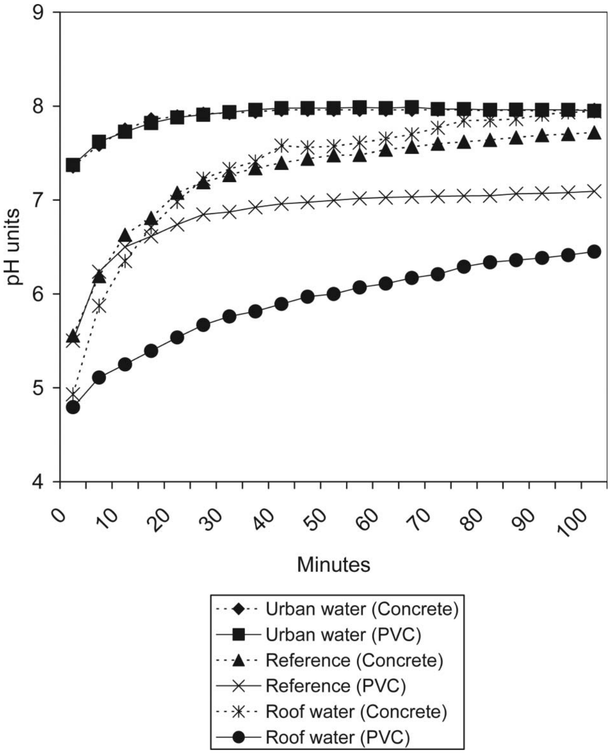

Figure 1. Mean pH levels of water samples measured every 5 min over 100 min.

The total anion and cation levels in all three water types increased after each 100-min experiment in PVC and concrete pipes (Table 2). Urban water resulted in the lowest increases (anions: 4.3% PVC and 6.2% concrete; cations: 5.4% PVC and 6.5% concrete). Reference creek water had moderate increases (anions: 5.1% PVC and 11.5% concrete; cations: 5% PVC and

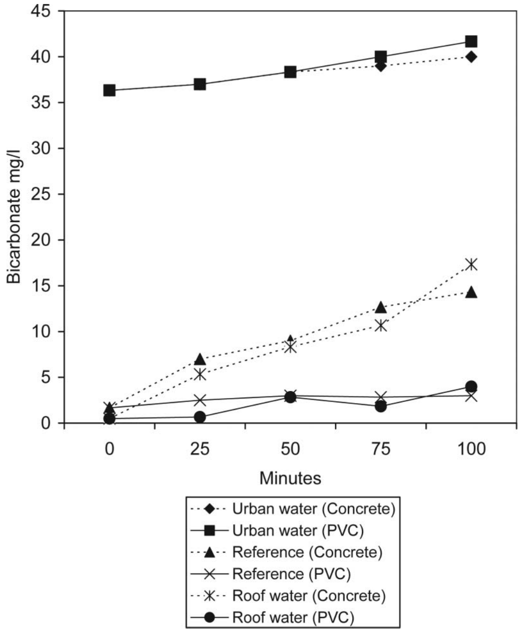

Figure 2. Mean total alkalinity (bicarbonate) levels of water samples measured every 25 min over 100 min.

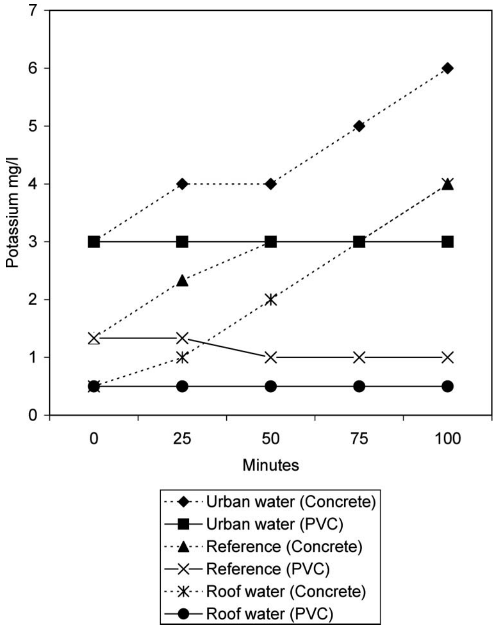

Figure 3. Mean potassium levels of water samples measured every 25 min over 100 min.

15.2% concrete). The largest increases were recorded in roof water (anions: 158% PVC and 337% concrete; cations 170% PVC and concrete 460%).

Discussion

Results from the current study provide support for the idea that concrete drainage materials and their widespread use as construction materials, has an influence on the water chemistry of urban streams. The largest rises in pH, EC and several major anions and cation concentrations was recorded when acidic and mineral-poor water was circulated through a concrete pipe. The increase was greatest for rainwater, lowest for urban creek water and was intermediate for reference creek water.

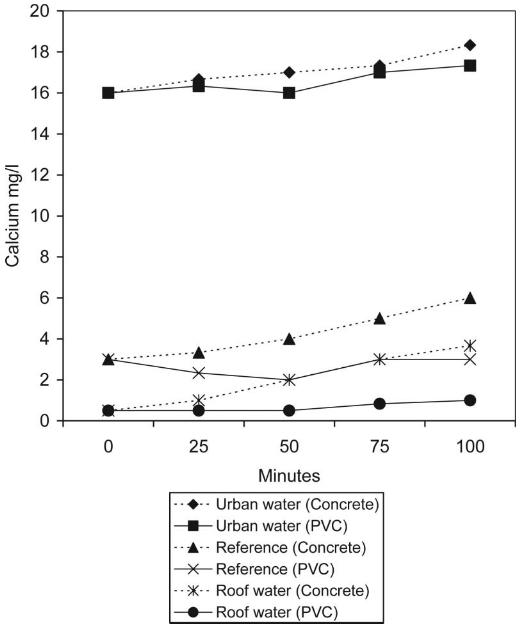

Figure 4. Mean calcium levels of water samples measured every 25 min over 100 min.

As the water was circulating through the pipe gasses would have been expelled from the water influencing the chemistry. This was notable in the PVC pipe as reflected by an increase in pH, most likely attributed to a release of carbon dioxide. Such change would have also occurred in the concrete pipe, however the impact of the dissolution of concrete would seem to have had a greater influence.

Material degradation

The process of carbonation is a major factor in the degradation of concrete. It is the result of chemical reactions between carbon dioxide and concrete hydrates, such as calcium hydroxide ($Ca(OH)_2$ or portlandite) and calcium silicate hydrates (CSH) producing calcium carbonate ($CaCO_3$) and water. The mechanism is well described and understood in material science literature (Clifton 1993). A number of factors have been classified affecting the chemical attack of concrete including: acidic attack, alkaline attack, carbonation, chloride attach, leaching and sulphate attack (ACI 1982). In urban areas and where cementatious pipes are used to convey stormwater, it is likely that the acidic attack associated with the lower pH of rainfall is reacting with the alkaline hydration products of cement resulting in calcium salts (Zivica and Bajza 2001) as well as other changes to water chemistry. This process is evident in this experiment as demonstrated by the rise in pH and the elevation of alkalinity (bicarbonate), calcium and potassium concentrations (Figure 4).

In transport processes

A change in water chemistry can in part be attributed to the circulation of water resulting in aeration and a slight increase in temperature. This processes results in the release of CO_2 from solution in the water in turn shifting the pH towards neutral (pH 7). Figure 1 shows the pH increases for all samples, for both the PVC and concrete pipes. Roof water recirculating through the PVC pipe was the only treatment not to reach pH 7. When these water types were exposed through the concrete pipe, the pH continues to increase towards 8. This additional change is most likely attributed to a high amount of dissolved calcium and bicarbonate ions in the sample as it previously was subject to the chemical changes from the urban drainage system and environs. Changes in water chemistry from the urban water sample through the concrete pipes were minimal. It is suggested that the water has already been modified by contact with concrete materials that are typically from the pipe drainage network as well as from urban concrete surface materials such as kerb and gutters, driveways and carparks.

The experimental exposure of roof water and reference creek water to the concrete pipe led to a change in water chemistry that exceeded the pH and potassium levels recorded in urban creeks (prior to pipe exposure) (Table 2). The ionic proportions of reference creek water, after 100 min exposure to concrete, were similar to those found in urban water samples. The reference creek samples (following concrete exposure) had higher relative concentrations of Ca and HCO_3 ions than were found in roof water or reference creek samples.

Base line water chemistry

Ku-ring-gai's urban waterways are known to be of average to poor ecosystem health with degraded macroinvertebrate communities and elevated pH, alkalinity and EC levels (Wright *et al.* 2007, Davies *et al.* 2010). The current study also observed that pH, EC and major ionic constituents (major anions and cations) were clearly different at urban streams compared to non-urban reference streams. Within the study area natural or reference streams were mildly to strongly acidic while urban sites ranged from mildly acidic to slightly alkaline. The reference streams had a much lower level of dissolved salts and minerals, with much lower EC (mean 180–230 μS/cm) and lower levels of many major anions and cations, such as total alkalinity (bicarbonate) levels of 1–8 mg/l in reference streams compared to 30 –125 in urban streams (Table 2 and Figure 1). The major ionic proportions of roof water and reference creek water were relatively impoverished in calcium and bicarbonate compared to urban creeks. After roof and reference creek water were exposure to a concrete pipe, the relative proportions of calcium and bicarbonate rose, and became similar to that found in urban streams.

Implications

At a catchment scale the results suggest that concrete pipes, as a conduit for stormwater, have a greater effect on water chemistry than PVC pipes for certain chemical attributes. The concrete pipe that was used in the experiment was new and therefore had a greater exposure to concrete when compared to an older pipe where the aggregates are visible. This suggests that as the pipe is degraded over time the extent of change may be less.

A relationship was also evident between time of contact and changes to water chemistry for some attributes, particularly for the rainwater sample. This points towards differing rates of change as a function of the chemistry of water either through its contact with the pipe and or the concentration of dissolved gases.

The sampling design used in this study (20 l of water at 0.2 l/s over 1.4 m of pipe for 100 min) represents flow lengths of approximately 84 m. This is 17% of the average flow length within a typical catchment in the Ku-ring-gai Council LGA. As such, the study results may be viewed as conservative. As water from the urban creeks had been conveyed through concrete pipes and gutters prior to collection, it is of little surprise that the chemistry of this water did not change a lot during the pipe experiments as it had previously been subject to the influence of concrete and associated dissolution of calcium ions.

From a catchment perspective, the causal factors contributing to degradation in urban stream health are complex and have tended to focus on land use, with catchment imperviousness identified as one of the most influential factors affecting the degradation of urban streams and their biota (e.g., Arnold and Gibbons

1996). While other researchers, such as Ladson *et al.* (2006), have identified major factors that contribute to urban waterway health (including: biology; geology; in-stream habitat; hydrology; hydraulics; water quality; sediment quality; riparian habitat; and continuity and barriers), this work suggests that materials used as part of the drainage conveyance system should be given further consideration. In this context, it is necessary to not only consider build-up and subsequent wash-off pollutants within an urban setting but also to examine the impact of the deterioration of materials within the urban fabric. This incorporates the drainage network, roads, driveways, buildings and other structure. Such consideration would follow in the same way that geology and soil chemistry influence physical and chemical changes within the environment.

From a water quality perspective, the results clearly identify significant changes in aquatic chemistry. Hydraulically, stormwater pipes usually play the major role in urban areas for stormwater conveyance. The results of this study also point towards the use of concrete stormwater and drainage materials as a potentially important human modification of urban catchment geology and water chemistry. Concrete drainage materials provide an unnatural source of ionic compounds (particularly calcium and bicarbonate) that leach into urban waters. The ionic proportions of both non-urban reference creeks and rainfall (from roof water samples) in this study were ionically very similar and both reflect the importance of atmospheric derived ions, with sodium and chloride being the dominant ions. Both the roof water and reference creeks had very low relative concentrations of calcium and bicarbonate. Urban waters had a different ionic composition and although sodium and chloride were still the dominant anion and cation, calcium and bicarbonate were the next most dominant anions and cations. According to the review of Australian inland waters, the concrete drainage material has created an unnatural "urban geological" signature or source of ions (Hart and McKelvie 1986).

Such modification of water ionic proportions has major implications for the ecology of urban waterways. For example, an extensive continental-scale study of benthic diatoms of US rivers (Patapova and Charles 2003) revealed the importance of the chemical ionic proportions to freshwater diatom communities. Patapova and Charles identified that calcium and bicarbonate were the two of the most influential ions to species assemblages in diatom communities. Other literature also supports that pH, EC and major anions and cation levels can have a strong influence on the base levels of aquatic ecosystem food chains. For example, algal diatoms are a major source of food and energy in flowing waters and have been found to be strongly influenced by pH, salinity and other environmental factors (e.g., Lowe 1974, Hirst *et al.* 2004, Chessman *et al.* 2007). Changes in water chemistry that recorded in this study are likely to influence algal diatoms communities in urban streams, with flow-on effects to other elements of the aquatic ecosystem (such as; bacteria, fungi, invertebrates, zooplankton and fish).

While this study was based within the Ku-ring-gai LGA and its immediate surrounds, the results have broader implications. From the data it can be argued that in locations where the receiving environments are naturally acidic, they are more likely to experience significant changes to water chemistry if concrete materials are used conveyance of rainfall and runoff.

If protecting the environmental condition of waterways is a primary objective of an urban design or drainage program, greater consideration should be given to materials used in construction and operation of hydraulic systems and generally within the catchment. While this study has not sought to understand the implications of the ionic and chemistry difference that may arise from the use of concrete or PVC pipes, it is foreseeable that it would impact biota within an otherwise calcium and bicarbonate limited and acidic environment.

Conclusion

The results indicate that concrete pipes have a significant impact on water chemistry on rain water and water taken from a natural stream. This was most notable in terms of pH, EC, bicarbonate levels and concentrations of potassium and calcium. Aeration of water was also a factor that leads to a change in water chemistry. This was notable in the change to the water circulating through the PVC pipes and would have also been present in the concrete pipe though was overshadowed by other chemical changes from the concrete. Water from urban creeks reported the least change, though noting their cation, anion and pH levels were elevated from the outset from previous exposure. The research suggests that where creeks are naturally acidic and with naturally low calcium and bicarbonate levels, the use of concrete as part of the urban drainage system will impact on water chemistry. This points to yet another dimension for engineers and ecologists to consider when implementing water sensitive urban design or low impact developments.

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