HOW SUSTAINABLE ARE STORMWATER MANAGEMENT PRACTICES WITH RESPECT TO HEAVY METALS? A MULTINATIONAL PERSPECTIVE.

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Introduction

The purpose of this paper is to explore stormwater management targets or policies and to question aspects of their sustainability.

A multinational review of stormwater management targets in Australia, New Zealand, USA and UK has shown that stormwater management approaches vary considerably amongst these countries.

The different approaches used can be defined as:

- No performance targets.
- Concentration based targets, e.g. total suspended solids must have a yearly average concentration of less than 35 mg/L.
- Load based targets, e.g. retain 80% of the average annual load of total suspended solids.
- Or a combination of the above.

We found the most common approach to the management of stormwater pollution is to adopt load based targets which apply to the development in question.

Specifically we wish to test the hypothesis that stormwater management policies in the Australia, New Zealand and the USA (ANZUS) tend to focus on long term or chronic impacts while potentially ignoring short term or acute impacts. We compare typical ANZUS policies against the UK Highways Agency approach where chronic or long term impacts are ignored and management focuses on acute stormwater toxicity.

The multinational review of stormwater management policies shows that where targets are adopted, they are predominantly load based and focus on the management of suspended solids and to a lesser extent on the removal of nutrients. We suggest that the dominant paradigm is to consider that suspended solids (usually measured as total suspended solids (TSS) and nutrients (usually measured as total nitrogen (TN) or total phosphorus (TP)) are the major pollutants of concern and serve as surrogates to indicate the presence of “other” pollutants that are also to be removed. An exception to the dominant paradigm is the UK.

The review of international water quality standards found that the UK is the only country within the study sample where water quality targets exist to assess the impact of acute toxicity on receiving waters. Research in the UK has shown that it is the presence of the heavy metals, Zinc (Zn) and Copper (Cu) in stormwater runoff which make it toxic (Crabtree et al, 2008) and this has been supported by similar findings in Australia (Kumar et al, 2002).

Relative to suspended solids and nutrients very little information is known about the treatment and removal processes of metals. This is also true in the UK despite mandatory assessment of dissolved metal loadings in highway runoff.

Through a literature review, we aim to determine if the use of suspended solids and nutrients are acceptable surrogates on which to base an assessment of the likely removal of heavy metals. This is important to know because if it is found that suspended solids and nutrients are a viable surrogate for toxic heavy metals then it justifies the current dominant paradigm. It could also mean that water quality modelling programmes such as the Model for Stormwater Improvement Conceptualisation (MUSIC) which have developed algorithms to model the decay of TSS, TN and TP can also be relied upon to provide an assessment of the removal of heavy metals despite the fact that these parameters are not implicitly modelled.

Conversely if suspended solids and nutrients are not adequate surrogates then it means that acute impacts (from Zn and Cu) are being ignored and that despite significant expenditure on the construction of stormwater treatment devices they could still be failing to deliver a sustainable outcome, i.e. the loss of macroinvertebrate communities in creeks receiving urban or highway runoff containing toxic levels of Zn and Cu is by definition considered to be unsustainable.

This paper also aims to highlight some of the problems and issues associated with the assessment of acute stormwater impacts.

Method

International Practice

Stormwater management targets from ANZUS and the UK where reviewed to identify their key performance criteria. The findings are summarised below.

United States of America

Of the 50 States and one District in the USA, 18 States explicitly require removal of total suspended solids. This is generally expressed as removal of a fraction of the average annual load. This is typically 80% removal but varies from 70% to 95%. Alaska requires removal down to 0.2mm diameter particle size for a given storm event. Neutral or beneficial effect policies are also adopted in some States.

In addition to sediment removal, nutrient removal is also explicitly required by 7 states, with the State of Maine being the only known case where phosphorus budgets have been developed for lake watersheds and which limit the export of phosphorus on new developments according to a phosphorus budget calculated for the new development. Elsewhere typically the average annual load of TP to be removed is in the range of 20% to 65% for new developments. Total Nitrogen removal is less commonly specified at 40% removal.

In conclusion 80% TSS removal is the most typical water quality requirement. No examples could be found where the removal of heavy metals is explicitly required.

Australia and New Zealand

An assessment of 20 Councils and various State Agency requirements in Australia and New Zealand revealed that requirements for stormwater treatment for new developments vary greatly.

We estimate from our sample that 60% of coastal NSW Council's adopt the NSW Department of Environment and Climate Change recommendation of requiring new urban development (over a certain size) to achieve 85% removal/retention of TSS, 65% removal of TP and 45% removal of TN. These targets have also been adopted by the Growth Centres Commission which is responsible for much of the green field development in Sydney. Melbourne Water requires 80% removal of TSS and 45% removal of TP and TN. Brisbane City Council has similar requirements. Auckland Regional Council in New Zealand requires 75% retention of TSS.

The most common treatment requirements relate to Gross Pollutants (GPs), TSS, TP and TN with some requiring percent removal of Hydrocarbons (HC). The removal percentage required of the respective pollutants varies between Councils but is generally 70-90% for GPs, 80-85% for TSS, 45-65% for TP and 45% for TN. Councils that required removal of HC specified a 90% removal.

None of the Councils assessed had explicit treatment requirements for metals although reference to removal of metals were made by two Councils.

In conclusion, Australian and New Zealand requirements tend to be similar to those in the USA i.e. they explicitly require about 80% removal of TSS, but in Australia nutrients are more commonly required for removal. Requirements for the treatment and removal of heavy metals are rare and practically non-existent.

The United Kingdom

The Water Framework Directive (WFD) requires an improvement in waterways in all European Economic Community member countries by 2015. To date in the UK it is only the Highways Agency (HA) which has developed a response to the WFD while River Basin Management Plans are currently being developed by the remainder of government. This implies that it is only the HA which stipulates water quality treatment on new developments in the UK at this point in time.

The HA has included requirements for the assessment of water quality impacts from new highway developments in their Design Manual for Roads and Bridges (DMRB, 2008). The work underpinning the DMRB was based on ecotoxicological and highway water quality monitoring studies in the UK which identified that the greatest risks to water quality (from highways) occur from dissolved Zn and Cu. Not surprisingly the same findings have been reached in Australia using Australian data (Kumar et al, 2002). The UK data has recently been bolstered with what is likely to be the most extensive water quality monitoring programme of highway runoff ever undertaken (Crabtree et al, 2008).

The DMRB water quality impact assessment process aims to determine if a new development requires stormwater treatment. Initially the expected loads of dissolved Cu and Zn are calculated. The calculations then assess any likely dilution in the receiving water.

The calculations consider:

- Traffic volumes – greater traffic volumes are equated with greater loads of metals. The monitoring work by the HA has enabled them to confidently estimate expected loads of dissolved Cu and Zn (amongst others) according to traffic volumes.
- Water Hardness – water hardness is a critical factor affecting the bioavailability of heavy metals in receiving waters. As hardness increases dissolved metals tend to become less bioavailable. This fact is also recognised in the Australian and New Zealand Environment and Conservation Council (ANZECC) Aquatic Ecosystem Protection Guidelines (NWQMS, 2000) and yet few (if any) practitioners modify the ANZECC trigger values to account for the impacts of hardness.
- Background or receiving water concentrations (assumed concentration if no data is available) under typical wet weather conditions. This allows for dilution of the discharge flows to estimate the concentration in the receiving water by summing the highway metal load and receiving water metal load and dividing by the total flow (receiving water and stormwater discharge) to derive a combined concentration.

The DMRB calculations may be a little simplistic in that calculations do not consider mixing zones and simply assume that stormwater readily mixes with the receiving waters.

If the concentration of the metals in the receiving water is estimated to be higher than the runoff specific threshold for that pollutant then treatment is required. Despite the relatively sophisticated approach for highway impact assessment in the UK, if treatment is required, reliance is made on the use of the CIRIA SUDS Manual by Woods Ballad et al (2007) to determine how to treat the flow. The CIRIA SUDs Manual is a typical BMP manual. Here for example wetlands are still designed using a design storm approach rather than through the use of continuous simulation methods and treatment trains are modelled assuming pollutants decay infinitely. Finally the actual treatment techniques developed to remove the heavy metals may or may not achieve the required criteria.

In conclusion ANZUS countries have followed a similar path in specifying that typically 80% of TSS is to be removed on new developments. Australia and some parts of the USA go further and also specify that nutrients are to be removed. It is believed that this approach originally developed from an understanding of what levels of performance could be achieved by Best Management Practices (BMPs) rather than on the ability of the receiving water to tolerate the discharge. The UK assesses highway impacts on water quality by examining likely heavy metal concentrations in the receiving water. However where treatment is required in the UK, because a standard BMP approach is adopted, compliance with heavy metal based water quality objectives may or may not be achieved.

Characteristics and Ecotoxicity of Stormwater

Crabtree et al (2008) characterised highway runoff across 4 climactic regional areas of the UK with a range of traffic volumes. Initially 10 events at 4 sites were monitored for a full range of parameters and then a further 10 events at 24 sites were monitored for specific pollutants. The monitoring also included pollutograph monitoring or intra-event monitoring of 10 events to enable first flush or other characteristics to be determined.

Crabtree et al (2008) reported that extensive monitoring of highway runoff found the presence of polyaromatic hydrocarbons (PAHs) and Cadmium (Cd) but at levels which were not toxic to receiving waters however Zn and Cu were found at levels toxic to receiving waters. MTBE (a lead replacement in petrol) was detected above the limit of detection in one sample but cyanide was not. Most PAHs were not detected at limits above the limit of detection but Pyrene and Fluoranthene were detected but not at toxic levels. PAHs, Lead (Pb) and Chromium (Cr) were tested by both Kumar et al (2002) and Crabtree et al (2008) and in both cases found at levels which are not toxic to receiving waters.

In describing the toxic characteristics of stormwater we therefore focus on Cu and Zn as they have been shown to be the most toxic constituents of stormwater (Kumar et al, 2002), (Crabtree et al, 2008).

It is known that heavy metals exist in receiving waters in several forms. There is the particulate bound form which can be suspended in the water column (i.e. attached to suspended solids) or which forms parts of the benthic sediments (i.e. attached to sediments which have fallen out of solution) and the dissolved fraction which exists in ionic form. ANZECC (2000) suggests that in order to test the acute toxicity of stormwater one could first filter the water (to remove suspended solids) and then test for dissolved Zn or Cu. The logic here is that the particulate bound fraction of metals is thought to be biologically unavailable and therefore not toxic while the dissolved fraction is thought to be easily absorbed by fish and therefore to be bioavailable and potentially toxic. Kumar et al (2002) found that both particulate bound forms and dissolved forms of Zn and Cu bioaccumulate in fish and must therefore both be bioavailable. Bioaccumulation is associated with chronic toxicity or long term risks. The finding by Kumar et al (2002) therefore supports the long term need to treat stormwater to remove suspended solids *and* particulate bound metals. The findings by Crabtree et al (2008) and Kumar et al (2002) support the need to remove the dissolved fraction of Zn and Cu in stormwater to protect receiving waters from acute toxicity.

With respect to Zn and Cu Crabtree et al (2008) found that dissolved event mean concentration (EMC) values for both Cu and Zn were about one third of the total Cu and Zn EMC values. In terms of the total loading Crabtree et al (2008) found that the dissolved fraction of Cu was about 25% of the total Cu load and dissolved Zn comprised about 20% of the total Zn load. Through typical extraction methods, Dierkes and Geiger (1999) determined that about 40% to 45% of Cu and Zn are bioavailable in highway runoff.

Crabtree et al (2008) found that there was no visible first flush of dissolved metals and concentrations of dissolved metals appeared to increase toward the end of the storm event. Kumar et al (2002) found that the first flush of stormwater contained elevated levels of dissolved metals.

Barry et al (2004) through synthesizing rainfall established that there is a first flush of suspended solids. However Crabtree et al (2008) through examination of 10 pollutographs found that there is no correlation between suspended solids and total or dissolved metals and suspended solids can't be used as a surrogate for predicting the presence of heavy metals. This conflicts with the findings of Kumar et al (2002).

Heavy Metal Removal by BMPs

Dunphy et al (2008) analysed the effectiveness of two different types of stormwater filters, one at Kiama in NSW and the other in Hornsby, NSW. Both systems used HydroCon pipes embedded in a filter media to treat stormwater runoff. The Hornsby filter which is sub-surface loaded relied on HydroCon pipes which were deliberately modified through the addition of iron oxides to assist with the removal of Cu. The Kiama site which is both a subsurface and surface loaded system used unmodified HydroCon pipes. Kiama is a busy rural town with a 6.5 hectare tourist dominated CBD catchment while Hornsby had a 0.16 hectare car park catchment. Results of the monitoring showed significant removal of Zn at both sites. The average concentration of Zn in the treated stormwater at Kiama was found to be 0.0256 mg/L and this equated to a 90% effective removal rate. It is strongly suspected that stormwater which is piped in concrete pipes is much harder than receiving waters where hardness may be typically less than 100. Without knowing the hardness of the stormwater at Kiama or Hornsby it is impossible to assess how toxic the stormwater was and benchmarking against unmodified ANZECC criteria which assumes a hardness of 30 will normally produce overly conservative results.

It is interesting to note that neither Kumar et al (2002) nor Dunphy et al (2008) modified the ANZECC toxicity data to account for hardness. Research by Hatt et al (2007) did not report if hardness was measured but it appears that hardness is not one of the parameters of their investigations and yet if one is measuring metal removal by bioretention systems hardness may well be one of the parameters which affects performance. Moreover the hardness of the semi-synthetic stormwater used by Hatt et al (2007) may account for changes in the speciation of metals.

The Kiama filter has also been shown to reduce TSS by almost 80% and TN and TP by 45% (Dunphy et al, 2005).

We highlight this example because:

1. The monitoring undertaken was extensive (Dunphy et al, 2005)
2. It shows that bioretention systems which can remove 80% of TSS and 45% of TN are also likely to remove significant quantities of toxic heavy metals with the discharge likely to deliver at least an 80% level of protection against heavy metal toxicity (based on overly conservative assumptions). In this case TSS and TN at retention rates that are typical of regulations in the countries we surveyed appear to be viable surrogates with which to also estimate the removal of toxic heavy metals.

Elsewhere laboratory tests of the treatment effectiveness of sand filters and bioretention systems has concluded that high levels of metal removal can be achieved using such systems (Hatt et al 2007), with removal rates close to 100% reported. These filters are especially efficient in removing the particle bound fraction of metals, as these are mainly removed through physical processes such as mechanical straining. It has been reported that metals found in stormwater are largely particulate bound (Muthukamaran et al, 2002 in Fletcher et al, 2004), so it should be expected that metal removal would follow that of TSS removal.

Many studies on the effectiveness of bioretention systems and sand filters do not make any distinction between the particulate bound fraction and the dissolved fraction of metals in stormwater. Where such a distinction has been made the removal rates of dissolved metals vary considerably (Hatt et al, 2007). The removal rates in bioretention systems of the dissolved fraction are consistently reported as being lower than that of the particulate bound metals (Fletcher et al, 2004). Dissolved Cu is particularly difficult to remove due to organic complexing (Dierkes and Geiger, 1999) but Dunphy et al (2008) has shown that treatment systems can be designed to enhance Cu removal.

Yousef et al (1987) found high rates of Zn removal (90% of the dissolved fraction) but in that study infiltration was an important part of the treatment in the Florida highway swales tested.

We do note that swales alone are unlikely to achieve an 80% reduction in TSS or a 45% reduction in TN and should be considered as part of a treatment train.

Constructed wetland and ponds are also commonly adopted BMPs in the countries sampled. Wet basins are the preferred treatment measure of the NSW Road and Traffic Authority for treatment of highway runoff though this preference is driven by maintenance costs rather than water quality objectives. Fletcher et al (2004) reports on the expected range of treatment of ponds, wetlands and sediment basins and shows that metal removal can be high but removal is likely to be greatest where biological process can occur. Wetlands, ponds and sediment basins are ranked in decreasing order of metal removal:

1. wetlands (with large areas of macrophytes),
2. ponds (with only fringing vegetation) and
3. sediment basins (without any vegetation or biological uptake).

Removal processes for particulate bound metals will occur through sedimentation and removal of the dissolved fraction may be through uptake by plants or biofilms. It is reasonable to conclude that where removal of each of TSS, TN and TP are greatest, removal of metals will also be greatest. 80% removal of TSS while nutrient removal remains low (as in the case of a well sized sediment basin) is not to be used as a surrogate to estimate high rates of metal removal. It is likely that when removal of sediments and nutrients exceeds 80% and 45% respectively removal of metals will be high. Bioretention systems or wetlands should be preferred to both ponds and sediment basins for heavy metal removal in terms of removing the dissolved fraction of metals.

Discussion

Difficulties associated with assessing the toxicity of stormwater

This paper has highlighted how Australian industry researchers appear not to take account of water hardness when assessing the toxicity of stormwater while those in the UK and U.S appear to do so. This is also compounded by the fact that some researchers also fail to measure the bioavailable fraction of metals in stormwater and then benchmark performance using ANZECC toxicity guidelines. Use of unfiltered samples, i.e. measurements of total metals, can be made however this will significantly overestimate the toxicity of the stormwater.

Assessing the toxicity of the first flush of stormwater as Kumar et al (2002) did by immersing aquatic organisms (Water Flea and Rainbow Fish) in the first flush (which by definition implies that it is a short lived phenomenon) for 48 hours is questionable. The same principle applies to assessing acute impacts by immersing organisms in a composite stormwater runoff sample for 4 days. It is known that many of the practices developed to assess aquatic toxicity have been developed in response to waste water discharges which have a completely different loading or exposure pattern to stormwater. The HA in the UK has relied on 6 hour and 24 hour bioassays and these are likely to be much more representative of real world exposure patterns of aquatic organisms to stormwater.

Time Scale Effects of Stormwater Runoff

Hvitved-Jacobsen et al (1994) produced a figure which plots the time scale effect of various pollutants. This is reproduced in Figure 1.

Figure 1 shows that nutrients have an accumulative effect on receiving waters. This is also supported in the ANZECC Guidelines for Aquatic Ecosystem protection (NWQMS, 2000) where it is stated that although it is key nutrient concentrations that stimulate algal growth it is the load of nutrients that is responsible for the final biomass of aquatic plants.

Suspended solids also impact on ecosystems in a load based manner with smothering of benthic organisms being related to the total load of sediment on the receiving water (NWQMS, 2000). Bioaccumulation of particulate bound heavy metals may also occur as a result of sediment loading where additional input (over a threshold value) accumulates over time.

Figure 1 shows that heavy metals can have both acute and accumulative or chronic effects.

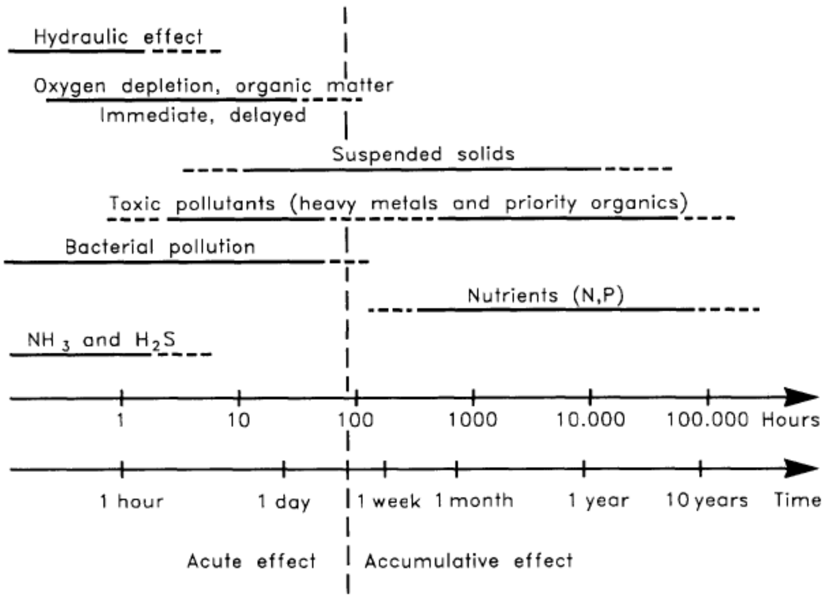

Figure 1 Time scale effects of water pollution (reproduced from Hvitved-Jacobsen et al (1994)).

Australia is a very large and generally dry country. Water that falls as rain in some parts of Australia may not reach the sea for several months. The same applies to the U.S. The UK on the other hand is a small country with a relatively short hydrological turn over time and frequent rainfall. Water that falls as rain is likely to reach the sea within a day in most parts of the UK. In Australia and the USA where the hydrological regime is a long regime cumulative stormwater impacts from chronic pollutants are thought likely to predominate. In Australia and the USA flushing is often limited and nutrients and sediment may be the principal pollutants of concern.

The opposite is true in the UK where turnover is frequent and flushing of both sediment and nutrients within waterways is high and nutrient related pollution occurs mainly in artificial reservoirs but generally not in rivers or lakes. Therefore in the UK acute stormwater impacts such as heavy metal pollution are the dominant driver behind regulations. Conversely in Australia and the USA nutrients and suspended solids are regulated while heavy metal discharges aren’t.

We question if heavy metal pollution does not also pose a serious threat to waterway health in both Australia and the U.S. This effect is much less obvious than an algal bloom caused by excessive levels of nutrients however its consequences can be just as dramatic in terms of aquatic ecosystem health. Macroinvertebrates form the bottom of the food chain in aquatic ecosystems and as such their presence is essential to maintaining the biodiversity of a waterway.

We therefore question the relative importance given to the treatment of nutrients and suspended solids and aimed to establish if these are adequate surrogates for the treatment of stormwater and if they do also result in the effective removal of heavy metals. We ask if by specifying that suspended solids and nutrients are to be removed at say 85% for TSS and 45% for TN what level of protection will this deliver in terms of heavy metal toxicants?

Using the Kiama bioretention system as a case study we have shown that under typical conditions a bioretention system which achieves 80% removal of TSS and 45% removal of TP and TN will also remove 90% of the Zn load. At Kiama the total Cu load was fairly low and removal was therefore minor. At Kiama an 80% level of protection was estimated by Dunphy et al (2008). Testing for the bioavailable fraction of metals (as opposed to total metals) and measuring water hardness would have shown the level of protection to have increased significantly.

We suggest that accounting for dilution of stormwater in the receiving water is generally the main reason that concentration based targets are not widely adopted. The UK HA method assumes that the receiving water will be flowing under typical low flow conditions during the runoff event. This approach enables dilution to be accounted for. One then also needs to test the hardness and metal concentrations in the receiving water to establish background levels to assess the impact of the current (untreated) and proposed situations.

This method could be applied to ANZUS conditions to assess the potential impact of heavy metals on receiving waters however we question the need to do this. In ANZUS the purpose of this would not be to determine if treatment is required (as it is in the UK) – indeed treatment is required to manage the long term cumulative impacts of TSS and nutrients. Therefore treatment will be provided in any case. This method however may have application where development is proposed in sensitive ecological or pristine areas such as drinking water catchments, alpine areas, National Parks, above protected wetlands or rivers etc or wherever it is necessary to demonstrate the ability to treat stormwater runoff to achieve high levels of aquatic ecosystem protection.

Conclusion

A review of regulatory requirements in the ANZUS countries showed that these countries regulate stormwater runoff on new developments by requiring about 80% removal of the annual load of TSS. Australia and the some parts of the USA go further and require TP and TN to be treated too. The UK was the only country in the sample which assesses the potential impacts of a development against receiving water quality and ecosystem tolerance.

This paper questioned whether the typical regulatory requirements in ANZUS of 80% TSS removal and 45% nutrient removal were viable surrogates on which reliance could be made to conclude that high levels of retention of heavy metals would also occur. For well designed and constructed bioretention and artificial wetland systems this appears to be the case with Zn retention typically in the order of 85% to 95% removal and Cu less reliably removed. Ponds, swales and gross pollutant traps will need to be used as part of a treatment train if they are needed to remove heavy metals which will ideally include some form of bioretention or wetland in the treatment train.

This paper also questioned if the ANZUS country regulators are ignoring heavy metal impacts where others seem to focus on metals. We found that the different hydrological regimes that exist in those countries may explain why acute effects dominate regulation in the UK and why chronic or long term effects dominate in Australia and the USA. It is concluded that until designers have sufficient information to specifically design for acute toxicity that reliance on TSS and nutrients is an acceptable interim approach and one that is likely to provide reasonable levels of protection to aquatic ecosystems.

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