Dissolved Nitrogen – The Elephant in the Room?

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Abstract

Councils across Australia rely on the achievement of best management practice in stormwater quality to mitigate the impacts of new development. Along with removal of suspended solids and phosphorus this typically requires that 45% of total nitrogen be removed from the post development average annual pollutant load. A number of proprietary stormwater treatment devices (PSTDs) have been developed and largely following the Stormwater Australia, Draft SQID Evaluation Protocol have demonstrated compliance with this typical treatment target.

Based on a literature this paper:

- Provides a breakdown of the various components of nitrogen in stormwater.
- Shows the composition of stormwater varies by location and by study.
- Questions the difference between vegetated and non-vegetated media filtration systems in terms of assimilation of NOx-N and questions if proprietary stormwater quality improvement devices achieve "best practice" by removing particulate nitrogen without removal of the most bioavailable components, i.e. the dissolved fractions.

This paper also explores the case for revising stormwater management policy, discusses the approaches taken by some Councils to intrinsically address this issue when evaluating SQIDS and includes a discussion on the impacts of load based versus concentration based policies on the size of treatment devices.

Introduction

Best management practice (BMP) is the dominant design paradigm adopted by stormwater industries across Australia, the US, New Zealand and the UK (Liebman et al, 2009). Early pioneering documents like Thomas Schueller's *Controlling urban runoff: a practical manual for planning and designing urban BMPs* (Schueller 1987) laid down the BMP based framework for the planning and management of stormwater. These practices are still I use today and Schueller's seminal BMP design manual formed the basis for many important future guidelines such as Stormwater Treatment Techniques (NSW EPA, 1997).

Since 1987 the approach to managing stormwater has evolved considerably from single, end of line solutions to designing complex treatment trains linked through both the universal stormwater treatment model (USTM) (Wong et al, 2001) and simple pollutant removal relationships based on the concentration reduction efficiency (CRE). In Australia this practice now occurs through the use of the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) (eWaterCRC, 2003) which has in effect become two models – one for modelling vegetated BMPs using the relatively sophisticated USTM and a second simpler CRE based model used to model the performance of non-vegetated proprietary treatment devices.

In 2016 the dominant design paradigm, largely driven by various State and Council policies, remains a BMP approach with localised variations of the same targets. These targets include removal of at least 80- 85% of total suspended solids (TSS) 40- 65% of total phosphorus (TP), and 40- 45% of total nitrogen (TN). A multinational review of policy targets by Liebman et al, 2009 showed most countries focus solely on removal of TSS and that Australia is the only country to adopt removal targets which include TSS, TP and TN. Removal of TSS is relatively easy and current non-blocking filtering technology is well proven within the industry and removal targets are easily met. TP, mostly particulate in nature (IEAust, 2005) is also relatively easy to remove, as it too can be mostly screened or finely filtered. Orthophosphate, a dissolved form of Phosphorus (P) is readily exchanged and adsorbed by various types of filter media making it easy to target for removal.

This paper focuses on the removal of TN as it is the most intractable pollutant. As noted previously, typical stormwater policies require the removal of 45% of TN and do not discriminate between dissolved or particulate nitrogen.

This is reflected in the stormwater policies of many local government authorities in NSW, for example Blacktown City Council, and by the States of Victoria and Queensland which require 45% removal of the post development average annual load of TN. However this policy does not discrimate between particulate and dissolved forms.

To not address dissolved nitrogen is over looking the potential ecosystem altering processes that these substances cause to aquatic ecosystems which include ecotoxicity and eutrophication (IEAust, 2005).

The most widely used proprietary stormwater quality improvement devices (SQIDS) include media filtration systems and membrane filters. The current, approved and more widely adopted suite of SQIDS does not include the use of vegetation however with the advent of floating wetlands and proprietary bioretention systems, this space is changing rapidly.

This paper however focuses on non-vegetated proprietary products and their capacity to remove the bioavailable, i.e. the most harmful, component of TN while noting that it appears that the SQIDs can remove particulate nitrogen which leads substantially to the proprietor's claim that they can comply with the 45% TN removal target.

A number of SQIDS have been approved by Blacktown Council over the years, some well before SQIDEP (Stormwater Australia, 2016) was conceived however a number of newer products have more or less followed the DRAFT SQIDEP and have been recently evaluated on the basis of independently verified, Australian field performance. This behavior is indicative of a maturing industry and the industry should be congratulated for its efforts to scientifically validate performance claims.

We conclude this paper by questioning if there is a need to revisit the best practice management policies that we have had for nearly 20 years and to potentially replace them, with catchment specific, concentration based trigger values as is intended in the ANZECC Guidelines for Fresh and Marine Waters (NWQMS, 2000).

A Review of Nitrogen in Urban Stormwater

Review of available literature shows the quality of urban stormwater varies from location and by season and the components of nitrogen include both organic and inorganic, dissolved and particulate fractions (Figure 1)

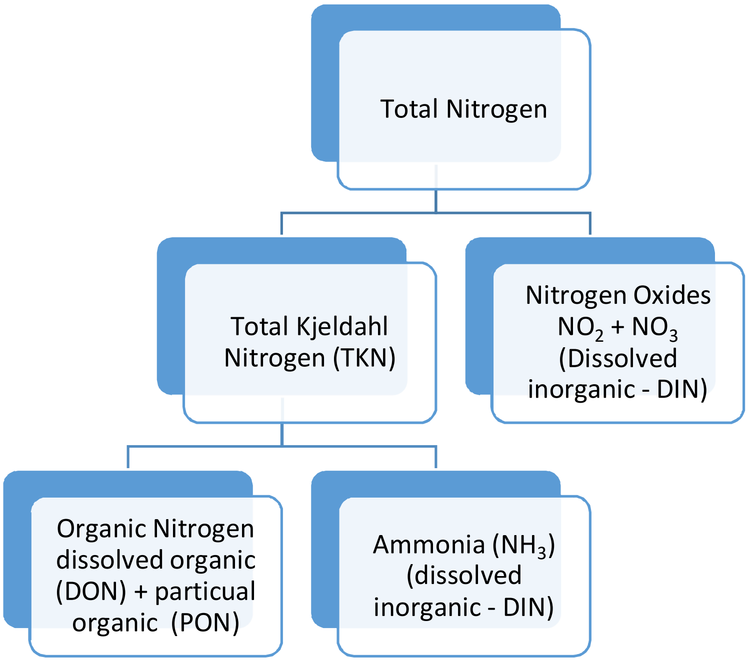

Figure 1. Components of nitrogen in stormwater

Several studies ave characterised the various fractions of nitrogen in stormwater and an approximate breakdown, described by Australian Runoff Quality (IEAust, 2005) is shown in Figure 2.

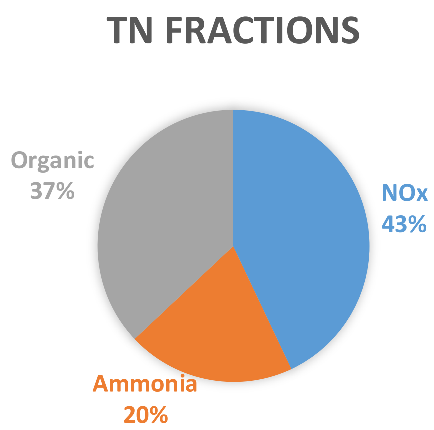

Figure 2. Australian Runoff Quality breakdown of TN (IEAust, 2005)

While it is not possible to calculate the dissolved fraction from Figure 2 it is possible to conclude that organic to inorganic ratios are approximately 1:2 and the dissolved fraction is at least 63% plus the undefined dissolved organic nitrogen fraction. Based on Figure 2, the particulate fraction of nitrogen must be less than 37%.

It must be appreciated that ammonia, oxides of nitrogen (NOx-N) and dissolved organic nitrogen (DON) are bioavailable while the particulate fraction is considered unavailable (under healthy aerobic conditions). From a regulatory perspective, regulators therefore need to concentrate on the bioavailable fraction, i.e. the 63% of dissolved nitrogen.

The fractions reported in Figure 2 are not absolute and ARQ provides a range of typical values for urban runoff. TN for example varies from 0.5 to 13 mg/L, NOx-N varies from 0.4 to 5 and so to conclude that every system should have a minimum of 43% NOx-N ignores the highly variable nature of nitrogen in urban runoff.

Although the amount of particulate N is not often quantified (Seitzinger 2002), studies show particulate N contributes a relatively small amount to TN in both freshwater and stormwater (approx. 20-30%) and that the majority of TN is made up of dissolved nitrogen (Cerda et al. 2000, Taylor et al 2005). These findings are broadly consistent with those in ARQ (it is understood the source of ARQ data is different to the studies by Seitzinger, Cerda and Taylor).

Dissolved nitrogen (DN) is found in both freshwaters ecosystems and urban stormwater in inorganic (DIN) and organic (DON) forms and although usually a limiting factor in freshwater ecosystems, elevated levels of dissolved nitrogen have been shown to have deleterious effects on aquatic ecosystems and become nuisance plant growth stimulators (IEAust, 2005).

Parker (2010), monitored the performance of a stormwater treatment train at Coomera Waters in Queensland. Parker found generally lower levels of all three target pollutants. Parker also quantified the nitrogen speciation on three subcatchments and found that dissolved nitrogen comprised between 66% and 82% of TN. This means particulate nitrogen ranged from 18% to 34%, results which are consistent with Figure 2.

In one of the most extensive southern hemisphere studies, Francey (2010) monitored stormwater in seven catchments across Melbourne and undertook a full speciation of nitrogen and reported both dissolved and particulate fractions as well as organic and inorganic.

This study found that particulate nitrogen accounted for between 21% to 43% of TN.. One of his catchments included a roof at Monash University and results indicate the very significant role that atmospheric deposition and consequently impervious area creation plays in the nitrogen cycle.

Francey's work clearly enables one to conclude that impervious surfaces, even relatively "clean" roofs allow for the conveyance of significant volumes of DIN.

Dissolved inorganic nitrogen (DIN) comprises of $NH^{4+,}$ NH_3, NO_2, HNO_2, NO_3 which in freshwater ecosystems is derived from atmospheric deposition, wastewater inflows, agricultural practices and urban stormwater (Comargo et al 2004). DIN is readily bioavailable to primary and secondary producers and when in excess can stimulate excessive growth leading to eutrophication, oxygen depletion and the formation of toxic reduced compounds such as SO_2. All of which have negative effects on freshwater biota (Comargo and Alonso, 2006). In addition, direct toxicity to aquatic biota caused by exposure to

DIN has been shown in many studies with unionized ammonia (NH_3) being most toxic and NOx-N the least toxic (Hickey and Martin 1998, Comargo and Alonso 2006, Comargo et al 2004).

Dissolved organic nitrogen is derived from the breakdown of organic material sourced from natural and anthropogenic sources and include fulvic and humic compounds, amino sugars, lignins, and tannins and peptides and has been shown to dominate the nitrogen pools of many freshwater ecosystems and typically represents up to 40 to 50% of total nitrogen (Willett et al, Fiedler et al 2015). However, in some cases this figure has been noted to be as high as 70-90% (Seitzinger and Sanders 1997, Stepanouskas et al 1999).

DON has been shown to be readily assimilated by macrophytes, algae and phytoplankton which will preference DON over NOx-N (Fiedler et al 2015, Alexdre et al 2015). This is important to note in terms of treatment system performance – it indicates DON can be removed more readily and in preference to NOx-N.

In aquatic systems DON is broken down in the nitrification process to form NOx-N (Taylor et al 2005) however when in excess DON has been shown to inhibit nitrification processes which results in extended retention times of NH_4^+-N and NOx-N (Xia et al 2013).

How Well Do SQIDS Remove Nitrogen From Stormwater?

This question can be answered in two ways. Firstly, by analyzing the SQID's ability to reduce TN, as is required by typical Australian, BMP based stormwater policies or by analysing the ability of SQIDs to remove the different species of nitrogen so that you can identify if the SQID is removing just the unavailable particulate fraction, i.e. the least harmful component of nitrogen or if it is removing any of the bioavailable, dissolved fraction (i.e. NH_3, NOx-N and DON).

Payne et al (2014) undertook a tracer analysis to determine the fate of nitrogen inside a bioretention mesocosm. Payne found that there was virtually no denitrification (and consequently no justification for a carbon source) within the bioretention system and the principle pathway for removal of NOx-N from the system was via absorption by plants. This experiment was undertaken on submerged systems and therefore provided an opportunity for both aerobic and anaerobic processes to occur if they were going to. Payne also studied non-vegetated control mesocosms and found an increase in the export of NOx-N, the same occurrence has been measured during the evaluation of some (but not all) non-vegetated proprietary SQIDs.

This finding is important because it shows that non-vegetated systems, are unlikely to achieve removal of NOx-N from influent. Contrary to this research, the Humes Jellyfish, which can be described as a membrane SQID has repeatedly demonstrated removal of NOx-N (Kelly et al, 2015). However thethe mechanism for NOx-N removal is not yet entirely understood nor is the statistical significance of the NOx-N removal (pers comm, Dr Charles Kelly, Humes).

One potential mechanism for denitrification in the Humes system is via biofilm growth and development along the porous membrane which alludes to the denitrifying process being linked with a biochemical reaction and not just being dependent on the presence vegetation as was suggested by Payne.

The approval by Blacktown Council of a proprietary SQID for use in the LGA is based on a particular SQID's ability to meet the 45% TN reduction criteria. However, this provides no guarantee that the SQID in question removes any dissolved nitrogen. There can be two reasons for this, firstly because the SQID in question has no means of reducing dissolved nitrogen concentrations, consider for example a Gross Pollutant Trap (GPT) which is analogous to a "tea strainer" which can remove particles but not any dissolved substances and secondly because the test site, i.e. the site at which the SQID was evaluated may not have been a representative site and may have had unusually high levels of particulate nitrogen.

For example one approved media filtration system reported NOx-N concentrations in the influent as 7% of TN. This indicates TKN comprised 93% of TN. In this case the proprietor was able to demonstrate that their SQID was able to remove 48% of the TKN and therefore get very close to the requisite 45% TN removal. This happens because the device is very capable of filtering out particulates and thus removes a large proportion (if not close to all) of the particulate nitrogen without removal of any dissolved fraction.

While this approach is not incorrect the test site can't be considered to be representative of potential future installations sites in other areas such as Melbourne (based on Francey's work) or Queensland. The very low fraction of NOx-N found in the validation study differs markedly from the work by Taylor, Duncan and Melbourne Water in ARQ, Parker and Francey and others all of whom found that NOx-N should comprise about one third of TN (as opposed to 7%) and if this was the case the relative proportion of particulate nitrogen in stormwater would be considerably lower (probably closer to 20% to 30%) and it is unlikely that the SQID in question would get close to meeting the 45% target even when paired with a "tea strainer" like GPT pretreatment device.

There is no suggestion here that this outcome was planned by the proprietor, indeed the SQID in question was validated many years before the DRAFT SQIDEP was published.

This particular SQID demonstrates a feature of many non-vegetated proprietary SQIDS and one that Payne observed in her lab experiments on non-vegetated mesocosms – that of nitrification, i.e. the conversion of NH_3 into NOx-N resulting in a net export of NOx-N while reducing NH_3. This behaviour was also observed by Pham et al. (2012), who tested the performance of both media filtration (non-vegetated) and vegetated bioretention columns in a laboratory.

Gold Coast City Council has found that obtaining SQID evaluation data from a suitably representative site is considered to be a significant issue. Council initially stipulated that in order for a SQID evaluation test result to be acceptable the influent stormwater would need to have a minimum of 60% dissolved fraction of nitrogen. This initial work was subsequently peer reviewed and reduced to a minimum dissolved fraction of 40% (City of Gold Coast, 2015).

Therefore if the dissolved fraction must be a minimum of 40% then the particulate fraction can be up to 60%. Thus if a GPT can remove 25% of the particulate load and that is followed in the treatment train by a non-vegetated filter media which can remove 65% of the particulate load then it is possible to demonstrate compliance with the 45% removal target without removing any dissolved fraction at all.

Other proprietors have sought to gain approval for SQIDS by proposing that regulators accept statistically insignificant performance results. For example, several proprietors now claim that GPTs remove a percentage of the total nitrogen load and are using SQIDEP as the basis for adoption of their claims.

Given that GPTs are high rate mechanical screening devices the only mechanism for TN removal in a GPT is by removal of the particulate fraction of TN – being unavailable this is not helpful in reducing pollution. In fact, trapping what is normally unavailable in an anaerobic sump may cause it to become available by converting the particulate nitrogen into NH_3 which is not only potentially ecotoxic but readily bioavailable.

To compound this, measured removal of TN by a GPT is typically marginal, i.e. less than 20% of TN (this equates to roughly removing the particulate load) and so it becomes almost impossible to verify the statistical significance of very low removal rates (at 95% confidence levels) without evaluating several hundred qualifying storm events which is of course cost prohibitive. One SQID proprietor is suggesting that because it is cost prohibitive regulators should simply ignore the lack of statistical significance demonstrated and simply adopt the insignificant relationships put forward. If the CRE or input/output relationships proposed are not statistically significant then put simply, there is no input output relationship because there is no relationship.

Is There A Case For Moving Toward Concentration Based Performance Targets?

The problems described above are not that proprietors are seeking to have Council adopt statistically insignificant relationships or related to finding representative sites, the problem lies with the regulators' reluctance to allow our stormwater policy practice to evolve.

Liebman et al (2004) questioned the sustainability of stormwater targets including the BMP targets which are now 30 years old and identified that one of the key problems with the load reduction approach that is so widely adopted is that it rewards the most polluting sites and makes it hard for the least polluting sites to comply. This was explained with an example which showed that it is relatively easy to remove 45% of a very high load rate and relatively hard to remove 45% of a very low load rate. This is consistent with the law of diminishing returns which is clearly demonstrated by the USTM (Wong et al, 2001) with its use of first order kinetic decay equations.

This problem is significantly compounded by several recent stormwater studies including those by Francey, Parker and a number of proprietary SQID suppliers. From the data presented in these studies, there is a discernible trend indicating that stormwater runoff from newly developed test sites is significantly cleaner than the widely adopted event mean concentration (EMC) values proposed by Fletcher et al (2004). Francey suggested that cleaner air quality may be one reason for this.

The problem of cleaner stormwater is significant, so much so, that several SQID evaluations are having to deal with influent and effluent values which are falling below detectable levels and where effluent values are compliant with the default ANZECC trigger values (pers comm, Mr Michael Wicks) (the default trigger values are not to be applied to point source discharges because they represent in-situ values which do not account for dilution of point source pollution. If they were to be applied directly to regulate point source pollution, they would be considered to be very conservative).

Very low influent values make it nearly impossible to demonstrate compliance with a policy which demands 45% reduction of the post development load.

It is therefore proposed that there is a clear and emerging case to revise treatment targets and to start to move toward concentration based approaches which would be much easier to regulate than any load based policy. This approach could be reminiscent of the EPA licencing approach which by way of example might stipulate that a particular site must keep the X percentile discharge concentration below certain level. A concentration based policy would also overcome the key problem of diminishing returns and start rewarding clean sites and clean production as opposed to more polluting sites.

Most importantly it would permit specification of a NOx-N based concentration limit and ensure that the most harmful fraction of stormwater is actually managed in reality rather than just on paper. The City of Gold Coast's attempt to address this issue (by specifying a minimum dissolved fraction of nitrogen on a test site), does not address the problem in the long term. The problem is not the test method, it is the load based policy approach which for too many years has had no ecological context. In 1987 it made sense to ask developers to build and design a BMP to protect their watershed without consideration of either catchment values or the assimilative capacity or condition of the catchment. Armed with powerful computers, powerful software and many more years of experience it no longer makes sense to simply ask developers to build and design a BMP. We need to start linking discharges from sites with receiving water ecological conditions and catchment specific objectives. It is suggested that this approach will support the business case for stormwater treatment significantly.

Discussion

The ANZECC Guidelines for Fresh and Marine Waters (NWQMS, 2000) has been ignored by stormwater regulators across Australia. That is, the approach proposed in the ANZECC guidelines requires the determination of catchment specific trigger values. The default trigger values included in the ANZECC guidelines are frequently confused by ignorant regulators as being akin to in-situ water quality values which could then form concentration discharge limits for a specific site.

In 2005 ARQ recognised that a mechanism for conversion of in-situ trigger values to a catchment based sustainable load rate should be developed and presumably then translated to site specific discharge limits. This approach has largely been ignored, perhaps because it requires significant resources and knowledge to implement. It also ignores the fact that most urban catchments in Australia probably exceeded their sustainable load rates once the level of imperviousness exceeds 10%.

It is suggested here that a new policy approach needs to be developed that is conscious of the limited resources available to most regulators and catchment managers in Australia, and yet should be a concentration based approach which would both protect the environment and remain economically affordable.

While this paper has focused on nitrogen and identifies the need for improved chemical regulations, it is observed that there is not one stormwater problem that can't be reduced by reducing the volume and frequency of runoff from a site. It is very clear that the creation of impervious surfaces is the root of all stormwater problems including dissolved nitrogen related problems. Any future policy development must be coupled with flow management objectives or they risk being as problematic to receiving waters as the current load based approaches.

If stormwater today is cleaner than the EMC values determined by Fletcher et al (2004), which are widely adopted, then this is further evidence to support moving toward a concentration based approach. Take the case of Blacktown Council for example which, as part of the north west growth centres work, is currently delivering over $400 million of stormwater treatment infrastructure to meet a 45% TN load reduction target. If EMC values have declined by just 1% over currently adopted values (the literature suggests the improvement is actually much greater than this), then using the same 45% load reduction policy with EMC values reduced by 1%, Council would need to increase (sic) the size of its proposed treatment measures at an additional cost of over $4 million. This is a politically unsavory position to be in. On the one hand stormwater is cleaner than we thought it was but on the other hand, due to diminishing returns and a 45% reduction of TN load based policy, Council would need to spend more money to deliver the same outcome – again showing the treatment targets we currently adopt are no longer serving us well.

Blacktown Council also recently adopted a stormwater offset scheme (Liebman et al, 2015). Through the planning of this scheme it became obvious that even well educated, experienced Town Planners and Developers do not understand the logic of the current load based approaches. With reference to Blacktown's old on-site, source control policy, stakeholders observed that "mixing clean water discharged from a site with dirty water in the gutter was a pointless exercise because the clean water would get dirty anyway". Whilst this statement reflects the fact that the broader community does not understand the concept of total load reduction it does show that the community is engaged with stormwater management and that we need to develop defendable, scientifically based, business cases to justify our stormwater treatment policies or we risk those policies being repealed. Simply being reliant on BMP treatment as a policy position is no longer good enough for the community.

Finally, despite the SQIDEP (Stormwater Australia, 2016) having sought to establish a level playing field between proprietary suppliers, the playing field between non-proprietary and proprietary products remains inequitable. This statement is based on the fact that bioretention modelling in MUSIC, unlike the performance of proprietary products, is not based solely on Australian field evaluation data but largely on laboratory experiments. It is suggested that all SQIDS, including bioretention should be field evaluated in accordance with the SQIDEP before Council's approve their use.

Conclusion and Recommendations

This paper has shown that the nitrogen cycle is a complex cycle and one that needs to be better appreciated by the stormwater industry and regulators in particular. This paper has also put forward an argument in favour of revising stormwater policy with a view to setting concentration based limits to stormwater discharges to overcome some of the key problems that are being experienced with SQID evaluation and the problems associated with the BMP based policy approach.

It is recommended that a new policy could drive better protection of our waterways and potentially at a lower economic cost.

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