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A risk-based approach to the improved understanding and management of denitrification in urban stormwater treatment wetlands

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Abstract: Increased nitrogen loading of estuaries and coastal systems can lead to eutrophication and toxic effects. Considering the extent of urban development in coastal catchments, concerns about high concentrations of N, and in particular nitrate-N, in urban stormwater runoff are well justified.

Denitrification represents the major pathway of NO_3^- removal from aquatic systems. Wetlands provide an ideal environment for denitrification from surface runoff and are widely used to improve the quality of stormwater. However, the treatment capacity of wetlands remains largely unknown, and wetland treatment of stormwater is still considered to be an emerging technology.

Climatic and hydrological conditions and the geographical and biogeochemical variations between wetlands and associated catchments make it difficult to apply generic concepts of design and management. Wetlands are highly complex systems and are characterised by extreme variability, which leads to unpredictable outcomes and makes it difficult to translate results from one wetland to another.

In recent years, there has been a large research effort aimed at better understanding denitrification, at both the microbiological scale and the larger catchment or wetland scale. We are applying risk assessment techniques to make practical use of the existing and cumulative knowledge to further our understanding of ways to stimulate and maintain high rates of denitrification in urban wetlands. The application will assist with improving stormwater and urban wetland management.

The risk assessment methodology is based on determining the level of risk to denitrification posed by stressors within urban stormwater and wetland systems through consideration of the multiple factors in operation and their various interactions. A Bayesian Network (BN) is being used as the modelling environment.

This paper describes the iterative development of the BN, and provides examples of sources of data and information and the methods by which they have been incorporated into the model. Information has been obtained from multiple sources and at various scales, including expert literature, monitoring data, and domain experts. It will be demonstrated that one of the key advantages of using BNs as the modelling framework is that it readily allows information from a range of scales and sources to be incorporated.

During ongoing model development, sensitivity analysis (SA) has been used as an important model validation and assessment tool and has allowed structural and probabilistic errors to be identified and corrected. Through ranking the relative importance of network variables on the output, SA has enabled the identification of the key drivers of the system. The modelled variables found to be exerting the greatest influence over variations in the output (the removal of stormwater NO_3^- by constructed urban treatment wetlands or "Denitrification efficiency") are hydraulic retention time (time taken for the input stream to pass through the wetland), the input NO_3^- load, available organic carbon, and toxic inhibition by contaminants sequestered within wetland substrates (eg heavy metals). Identifying the primary driving factors within a system can assist with the prioritisation of management actions and research resources, thus fulfilling the intended use of the BN as a Decision Support Tool (DST).

Uncertainty in many of the processes being modelled is high but the BN represents our current knowledge of a highly complex system within an accessible framework, and where uncertainty is demonstrated explicitly. With continued research under an adaptive management framework, additional information will become available and the model can be further developed and updated, thus further satisfying the fundamental requirements of risk assessment.

Keywords: *urban wetlands; stormwater; denitrification; Bayesian Network; nitrate nitrogen; Ecological Risk Assessment (ERA); Sensitivity Analysis*

1. INTRODUCION

In coastal systems, primary production is usually nitrogen (N)-limited. Nonpoint source urban runoff tends to be N-rich because of increased traffic density (by increasing atmospheric N), leaking septic systems, residential practices such as fertilising and weeding gardens and lawns, and, in some urban environments, the use of combined sewer overflow systems. Consequently, eutrophication of estuaries and bays as a direct result of N pollution is of particular concern (eg Coulter *et al*., 2004). A number of coastal systems in the developed and industrialised world are currently experiencing the effects of eutrophication, the symptoms of which may include episodic or persistently low dissolved oxygen concentrations, algal blooms, declining shellfish populations, and periodic fish kills. (eg Galloway *et al*., 2003). The risk of estuaries and bays downstream of large urban centres developing some of these symptoms as a result of N enrichment has lead to an emphasis being placed on managing the transport of N by urban streams, and on maximising its attenuation prior to downstream receiving aquatic ecosystems (Mitsch *et al*., 2005).

Of the possible N removal and transformation processes, respiratory denitrification is considered to be the major pathway of N loss from aquatic sediments to the atmosphere (eg Spieles and Mitsch, 2000). Denitrification is mediated by certain genera of heterotrophic bacteria that are able to convert nitrate (NO_3^-) to gases, which then escape to the atmosphere (Figure 1).

Given the concerns about high levels of N in urban runoff, the incorporation of areas with high denitrification potential (eg wetlands) has potential as a useful component of a cost-effective stormwater management regime, and may reduce the loads of nonpoint source N delivered to coastal zones (eg Mitsch *et al*., 2005). For stormwater treatment, constructed urban wetlands can be effective, plus inexpensive with respect to both their construction and operation, provided that land costs are reasonable. Indirect benefits can include the provision of green space in the urban landscape, habitat for wildlife close to where many people live, and facility for recreation and education.

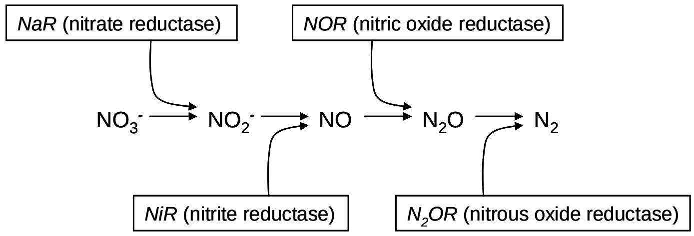

Figure 1. The denitrification pathway showing intermediates and enzymes for each stage (eg Zumft, 1997).

It is therefore not surprising that wetlands are a popular choice for the tertiary treatment of stormwater (Spieles and Mitsch, 2000). Despite this popularity, there are only sparse monitoring data on wetland efficacy for N treatment and there remain many gaps in our understanding of the biogeochemical processes contributing to water quality improvements. The monitoring data that do exist indicate that performance criteria for urban stormwater treatment wetlands are not consistently being met, and significant variability in treatment performance occurs during both high and low flows (data not shown).

In many respects constructed wetlands are still often considered to be an emerging technology for urban stormwater treatment and there is significant scope for investigating potential improvements in their application. To assist with this objective, our approach has been to generate a predictive model to facilitate decision-making in terms of predicting the effect of alternative wetland designs or management actions. The modelling approach has been based on a risk analysis aimed at furthering our understanding of the hydrological and biogeochemical processes involved and the roles they play in wetland treatment efficiency.

2. ECOLOGICAL RISK ASSESSMENT

Ecological Risk Assessment (ERA) is used to quantify the level of risk posed by hazards, threats and stressors to the structure and function of an ecological system or its assets. ERA considers the complexity of interactions between a variety of factors operating within a system and recognises a range of possible outcomes. The relative likelihood of each potential outcome is determined through the integration of information gathered from various sources, and incorporates data within a single predictive modelling framework.

An appropriate ERA modelling environment can combine knowledge from all available sources and scales: basic scientific knowledge, specialised and detailed literature, relevant models that characterise specific aspects of the system; monitoring data, and expert knowledge. Bayesian networks (BNs) provide a model structure whereby knowledge relevant to different scales and information from multiple sources can be incorporated (Borsuk *et al*., 2004) and thus are highly applicable for ERA.

Within an adaptive management framework, ERA acknowledges that complex ecological systems may be poorly understood and as a consequence have high uncertainty, but with ongoing monitoring and review those uncertainties can be reduced (Pollino *et al*., 2007). The process of BN development is iterative, which allows changes to the system being modelled and updated knowledge to be readily incorporated (Eleye-Datubo *et al*., 2006). Therefore BNs are ideal for use in an adaptive management framework, and satisfy the requirements of ERA.

3. BAYESIAN NETWORKS

A BN is a causal web whereby the conditions of variables can predict the outcomes of some other variables. A BN consists of a qualitative (graphical) component composed of a series of 'nodes' which represent specific variables operating within a system. The nodes interact through unidirectional linkages or 'edges' that define their relationships (Figure 2). The relationships are quantified probabilistically within a set of conditional probability tables (CPTs). Each node's CPT indicates the likelihood that it will be in a particular state, given the states of the nodes that exert influence upon it.

BNs rely on the use of Bayes' theorem which outlines the relationship between given events or outcomes. Bayes' theorem allows probabilities of variables whose state is unknown to be updated given some set of new observations. BNs enable this process, and permit reasoning to proceed in any direction across the network of variables, not necessarily limited to the direction of the linkages.

This paper describes the development of a Decision Support Tool (DST) using Bayesian analysis. The BN is focused on determining whether changes in wetland management, or wetland design, or changing the way stormwater is managed is likely to ultimately lead to improvements in denitrification efficiency, with the primary goal of maximising the removal of nitrate from stormwater.

3.1. Development of the Graphical Structure

After problem formulation, the first step in BN development is construction of the graphical component (Borsuk *et al.*, 2004). Initially all relevant variables are identified and the relationships between them indicated using directed edges. Development of the graphical structure for the Denitrification in Urban Wetlands BN was based around the variable Denitrification Efficiency, with all other relevant variables positioned causally, either directly (parents) or indirectly (ancestral). A comprehensive review of the literature assisted with the initial stages of graphical structure (Conceptual Model) development. The draft Conceptual Model was then introduced as the basis by which the network could be refined through stakeholder elicitation. This was conducted at a workshop, during which stakeholders, each with specific interest, experience and knowledge in stormwater management, wetland design, or a specific understanding of catchment processes, were asked to critique and refine the Conceptual Model. At the workshop particular attention was paid to ensuring that all relevant variables had been identified and indeed whether potentially irrelevant factors could be ignored. Stakeholders were also asked to contribute to a discussion where key knowledge gaps and sources of knowledge were identified, and where possible attributes (specific measurable indices) were assigned to each factor. These discussion points were aimed at assisting with the development of a feasible model structure, which is considered to be critical in the modelling process as it forms the framework upon which the entire network is based.

The expert elicitation workshop allowed feedback on the draft version of the Conceptual Model such that a workable network structure could be generated. Subsequent modifications of the structure were required during later stages of model development and as new information became available. A final working graphical structure has now been defined and this constitutes the foundation of the BN (Figure 2).

3.2. Description of the Network

The basic requirements for efficient denitrification are well understood: an outcome of the numerous research initiatives that have been devoted to investigating specific aspects of denitrification at various temporal and spatial scales over the past 50 years. Pivotal to denitrification is a low oxygen environment, and adequate available nitrate and organic carbon. As denitrification is biologically-mediated, an environment at an optimum temperature for biological processes and free of potentially toxic material, such as heavy metals and other bacteriocides, is also necessary. Each of the aforementioned variables has been included in the network as parents (direct determiners) of the model's final output: "Denitrification efficiency".

Specific catchment activities (Landuse) can alter the quality and flow characteristics of stormwater, and thus play a significant role in the delivery of both toxic substances (potential inhibition of denitrification) and dissolved nitrogen (potentially enhancing the rate of denitrification) to wetlands. The developed network specifies a causal relationship from the node "Landuse" to "Toxic inhibition" (via "XOCs" and "Heavy metals") (refer Figure 2). Concentrations and loads of total N in urban stormwater are also dependent on landuse, but a generic relationship is complicated by aspects of hydrology (determining overall flow and the relative contributions of surface and ground waters); and the proximity of various sinks (eg. buffer zones) and sources (drains etc) (Coulter *et al*., 2004). Attempts to definitively model the relationship between Landuse and the delivery of nitrate via stormwater runoff have been largely unsuccessful. For this reason the network does not include a direct linkage between the nodes "Landuse" and "Stormwater NOx", which at this stage needs to be specified on a case-by-case basis, by the model end-user.

Although the mechanisms controlling the kinetics of denitrification are often disputed, adequate water residence time in the wetland needs to be allowed for this process to be completed. Factors affecting the hydraulic retention time (length of time for inflowing water to pass through the wetland) will in turn influence the degree of contact between the nitrate and the denitrifying bacteria in sediments and biofilms. This will have a direct effect on the wetland's efficiency to

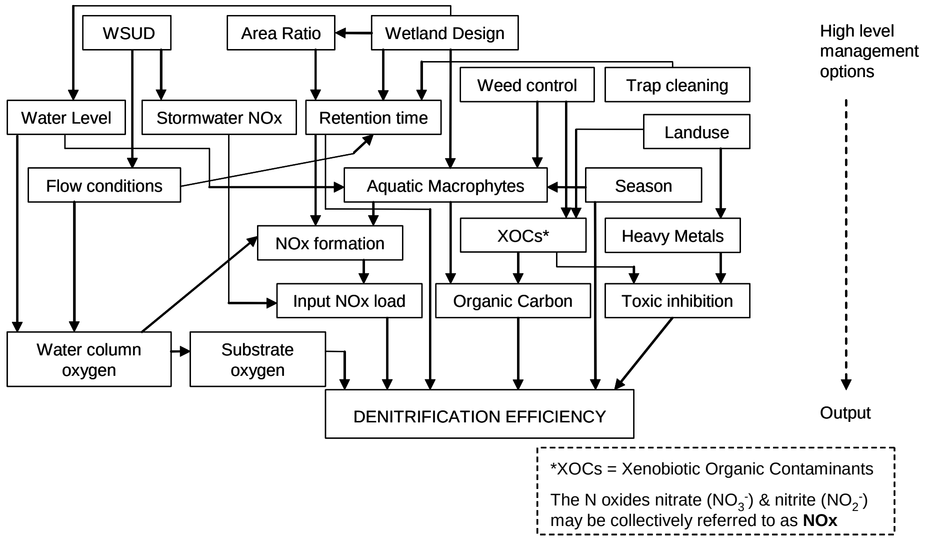

Figure 2. Graphical representation (Conceptual model) of the Denitrification in Urban Wetlands BN

remove nitrate from the input stream. There are a number of wetland design and management variables controlling retention time, including the size of the wetland in proportion to the contributing catchment (area ratio); flow conditions (compare flow during storm events with baseflow), wetland maintenance (unblocking drains and traps as required), certain aspects of wetland design, and water sensitive urban design (WSUD) initiatives, in particular those that are aimed at moderating the flow regime (Figure 2).

Aquatic macrophytes growing in a wetland are the primary source of organic carbon (required by denitrifying bacteria, which are heterotrophic). However, the decomposition of plant material can also be a source of nitrogen, which may be of detriment to overall treatment performance. Another role of aquatic macrophytes in wetland treatment is the filtration and removal of suspended particulate matter. They are also pivotal in wetland hydrology as they can disperse and moderate flow and by this may affect retention time. A direct linkage between “Aquatic macrophytes” and “Retention time” has not been included in the BN but instead has been incorporated within the node “Wetland design” which includes factors such as the compactness or hydraulic index, position of inlets and outlets, and macrophyte zonation. The relationship of “Aquatic macrophytes” with “Organic carbon” and “NOx formation” is defined in the BN structure as has the influence of “Season” and “Weed control” on macrophyte species and density.

3.3. Quantification of Conditional Relationships

Following specification of the qualitative network structure, the next stage in BN development is to discretise the variables and fully quantify the network with conditional probabilities that define each relationship. The size and complexity of CPTs is determined by the number of parent nodes upon which it is dependent. CPTs for root nodes (those without parents) are degenerate, containing just a single row which represents its prior probabilities (Korb and Nicholson, 2004). Prior probabilities are generally selected as likelihood based on knowledge of population statistics and are not conditional upon any evidence. Based on a causal understanding of BN structure, root nodes represent original causes (Korb and Nicholson, 2004) and in general, represent the “high level management options” shown in Figure 2.

Various methods can be used to estimate parameters and assign CPTs for each node. The source of information relied upon will depend on which is available or which most appropriately defines the combined effect of the controlling processes. The CPTs in the Denitrification in Urban Wetlands BN were quantified with probabilities elicited directly from scientific experts (i.e. expert opinion), obtained from expert literature, or from long-term monitoring data used to define relationships between variables or to statistically predict outcomes. CPTs for some of the variables (eg Toxic Inhibition from XOCs and/or heavy metals) were learned from collated data, using the automated learning function expectation-maximisation, which is embedded in the BN software. A combination of expert and data sources can provide good outcomes when the availability of certain data and information is low (Pollino *et al*., 2007). Inherent uncertainty comes with any of these information sources but by its probabilistic nature a BN allows uncertainty to be clearly represented. The software used to construct and implement the BN was Netica®, a commercially available package (Norsys Software Corp., 1990-2006).

3.4. Sensitivity Analysis

An important stage in BN development and model validation is sensitivity analysis (SA), which assesses the reliability and robustness of the network and its output. SA effectively measures the degree of influence that one variable has over another (query) variable (Korb and Nicholson, 2004) and can be used to rank the importance of each variable on the model outcome, indicate potential structural problems in the network, and identify whether more accurate quantification of any of the variables is required. Ranking the relative importance of model variables can be pivotal in prioritising management actions and identifying where resources (eg monitoring and research) could be directed for greater efficiency. In this regard SA is a powerful tool in ERA, where knowledge of the major drivers of the system is of critical importance.

Evidence sensitivity analysis (sensitivity to findings) determines how sensitive the results of a belief update (propagation of evidence) are to variations in the set of evidence (observations, likelihood, etc.). It determines the change in variation between the range of lowest and highest possible values that each relevant node as well as any combination of these nodes can take (Eleye-Datubo *et al*., 2006). Sensitivity to findings is calculated as the degree of reduction of either entropy or variance (depending on whether a continuous or discrete variable is being examined) at one node relative to the information represented in the other nodes, effectively determining how much of the variation is explained by the other nodes (Amstrup *et al*., 2007). All tests were conducted using the Bayesian network modelling software package Netica® (Norsys Software Corp., 1990-2006). In Netica® entropy reduction is also termed mutual information (Amstrup *et al*., 2007) (see Table 1).

Sensitivity to findings was analysed for individual variables in the network to further explore the relationships that had been defined, and on the model as a whole (by undertaking SA on the output node – "Denitrification efficiency"). SA performed during model development on earlier versions of the network assisted with identifying and correcting structural and probabilistic errors. For example "Toxic inhibition" was found to exert an influence on "Denitrification efficiency" that was out of proportion with the certainty that was able to be placed in our knowledge of the toxicity of both trace organic compounds and heavy metals (see discussion that follows in the next section). SA assisted with model review during iterative stages of BN development.

Table 1. Sensitivity analysis for posterior network showing sensitivity of 'Denitrification_efficiency' based on findings at other nodes

Node	Mutual information
Denitrification_efficiency	1.48522
Retention_time	0.03692
Input_NOx_load	0.02996
Organic_carbon	0.02153
Toxic_inhibition	0.02114
Nitrate_in	0.01173
NOx_formation	0.01155
Metals_submodel	0.01144
Season	0.00826
Aquatic_macrophytes	0.00681
Water_level	0.00609
Wetland_design	0.00584
Water_Column_DO	0.00308
Flow_conditions	0.00249
Area_ratio	0.00175
Landuse	0.00150
Trap_cleaning	0.00063
Substrate_DO	0.00014
XOCs	0.00001
Weed_control	0.00000
WSUD	0.00000

Results of SA are presented for the model endpoint "Denitrification efficiency" in Table 1. Output from this SA indicates that hydraulic retention time, the input NO_3^- (NOx) load, and available organic carbon exert the strongest influence on variations in model output, and are therefore identified as being the three primary driving factors for the removal of stormwater nitrate by a constructed urban treatment wetland. In general, outcomes of sensitivity to findings are supported by findings reported in the literature and expert understanding (Table 1).

Toxic inhibition = f(heavy metals, xenobiotic organic contaminants)

In the Denitrification in Urban Wetlands BN, the variable "Toxic inhibition" is a function of the type and degree of accumulation of heavy metals and xenobiotic organic contaminants (XOCs) within the wetland. There is increasing evidence that XOCs are widespread in urban environments and can be detrimental to ecological systems. However, our current understanding of their fate is poor, and monitoring of the environmental levels of these substances and their degradation products is inadequate for complete understanding (Battaglin and Kolpin, 2009). Although, the effect of heavy metals on denitrification is better understood and significantly more monitoring data defining the levels of metals in urban environments is available than for XOCs, the biological availability of metals sequestered in wetlands varies significantly and is still largely unknown. Furthermore, the degree of heterogeneity within wetland sediments (where metals and organic compounds are likely to accumulate) is so significant that toxic effects are unlikely to extend uniformly across the entire wetland and it is expected that there will be at least some pockets where denitrification would be largely unaffected by toxicity.

Output of SA identified that excessive emphasis was unduly placed on the detrimental effects arising from the accumulation of potentially toxic compounds in the wetland. This arose from the experts' understanding of the definition of toxicity. Subsequent iterations of the BN were able to amend this error based on clarifying that the toxic inhibition CPT needed to have a higher degree of uncertainty embedded within it. By reviewing the sensitivity of the developing BN, and through consideration of a range of contributing factors, some of the potential errors in the network's construction have been identified, reviewed and amended.

Retention time = f(flow conditions, area ratio, trap cleaning, wetland design)

Hydraulic retention time is a measure of the average residence time of water in a wetland system and is basically the ratio of the total volume to flow rate of the input stream. Unlike most wastewater treatment wetlands, urban stormwater wetlands do not tend to operate as steady state systems and flow rates are strongly affected by antecedent rainfall conditions. It is for this reason that retention time is demonstrated to be influenced by a range of variables in the BN model (see Figure 2). Retention time is a function of flow conditions (itself a function of catchment permeability and rainfall patterns), area ratio (the ratio of the wetland and catchment areas), trap cleaning, and wetland design. Wetland design features aimed at maximising hydraulic effectiveness include the positioning of the outlet relative to the inlet, wetland shape, and the inclusion of berms and islands. Hydraulic inefficiency can be brought about by short-circuiting and the presence of preferential flow paths, which dictate the degree of mixing in a wetland, and tend to result in retention times much shorter than the nominal design.

Maximising retention time will effectively prolong the contact time between the substrate and the microbial populations within the sediment-water interface and in biofilms fixed to the stems of submerged vegetation. A suitably extended retention time will allow adequate time for the diffusion of NO_3^- within and between substrates, which will enhance biological transformation processes and ultimately maximise NO_3^- removal (eg Galloway *et al*., 2003). It is expected that although the presence of organic C and NO_3^- are critical to denitrification, permitting time for biological processes to proceed and diffusion to occur is likely to exert an even greater influence. The nominal retention time upon which the CPT has been parameterised is 48 h.

Organic carbon = f(aquatic macrophytes, xenobiotic organic contaminants)

The heterotrophic metabolism associated with denitrification means that an exogenous carbon source is required. Organic C endogenously derived through plant photosynthesis becomes available to denitrifying bacteria through a number of pathways, including death and decomposition of plant litter and secretion of root exudates. A variety of plant communities contribute to the organic detritus in wetlands, and so the quality and quantity of organic matter also varies. In addition, wetland systems and substrates are spatially heterogeneous. Therefore, a direct measurement of the total organic carbon (TOC) content of a wetland is neither a useful index nor a meaningful attribute for use in the DST being developed. Instead, the relationship between organic carbon and wetland macrophytes has been defined in the BN model. Pivotal to this is the view that plant debris from a "moderately dense wetland marsh" can provide enough carbon to denitrify approximately 300 g $N.m^{-2}.y^{-1}$ (Kadlec, 2004). Analysis of local (Melbourne) stormwater and catchment data indicates that the annual load of N that is likely to be delivered to an urban wetland via stormwater runoff is an order of magnitude less than 300g $N.m^{-2}.y^{-1}$. Therefore, it has been assumed that there is a high probability that mature stormwater treatment wetlands will have adequate carbon to support the majority of denitrification that is required.

The model variable "Aquatic macrophytes" has been discretised thus (Figure 2):

<u>Sparse</u>: <20% mixed macrophyte coverage, or <40% single species; considered applicable for a newly constructed wetland (<10 y); will provide organic carbon to support a moderate amount (50%) of stormwater denitrification

<u>Moderate</u>: 20-40% mixed species, or >40% single species; mature constructed or natural wetland with pockets of deeper water; will provide organic carbon to support the majority (85%) of stormwater denitrification

<u>Dense</u>: >40% emergent & submergent species i.e. mixed; mature constructed or natural wetland; will provide adequate organic carbon to support most (90%) of the required stormwater denitrification

In addition to decomposing organic detritus, the accumulation of XOCs can contribute to the overall carbon budget in an aquatic system (eg Zumft, 1997). Sources of XOCs include oil and gas leaks (Macleod *et al*., 2001), pesticides (herbicides, fungicides, insecticides, and fumigants), and pharmaceuticals and personal care products (Costanzo *et al*., 2005). These types of substances are highly adsorptive and are readily retained by the organic rich soils in wetlands. Monitoring is generally not cost effective because of the large number of potential contaminants and their associated degradation products. However, available monitoring data indicates that most XOCs are present at trace levels. This, combined with their general recalcitrance means that they are likely to contribute only a small amount to the TOC content of an urban wetland (Macleod *et al*., 2001).

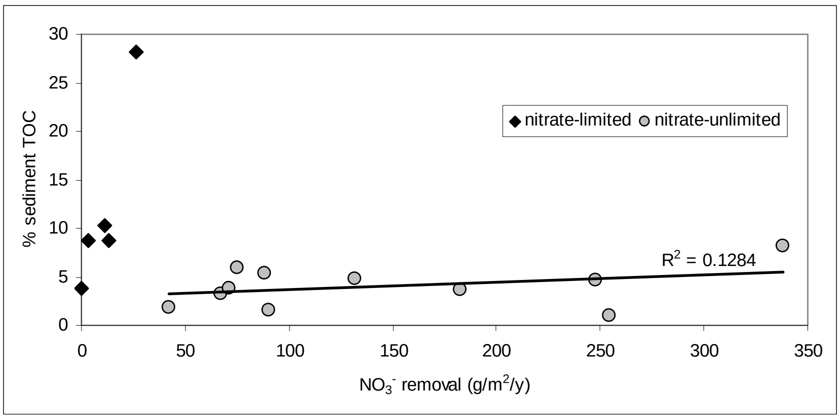

Figure 3. Relationship between NO_3^- removal and sediment organic carbon. Data compiled from the international literature. Each datapoint represents findings from a single wetland.

Input NOx load = f(stormwater N, NOx formation)

In their study of nitrate removal from 5 different wetlands, Whitmire and Hamilton (2005) found nitrate was removed by first-order reaction kinetics, "indicating that NO_3^- removal…was limited by NO_3^- availability and that increased

NO_3^- inputs would stimulate greater removal". Similar findings of increased denitrification and N-removal rates under conditions of N-enrichment have been consistently reported by numerous researchers. In effect, the role of nitrate levels in regulating denitrification is well established.

The presence of both TOC and NO_3^- are critical for denitrification to proceed. Given that most mature constructed wetlands are expected to contain adequate TOC for the majority of denitrification requirements, in such situations NO_3^- availability is likely to exert the stronger influence on denitrification (eg Figure 3). This is further supported by Hernandez and Mitsch (2007), who found denitrification to be NO_3^--limited, as opposed to C-limited, where an increase in denitrification rate would be expected with the addition of a carbon source.

4. CONCLUSION

Various types of model validation and testing are necessary during the iterative process of BN development. One of these is the analysis of sensitivity to findings. Such analysis offers an opportunity to assess and interpret the model, provides deeper insight into the likely outcomes of management change, and can assist with prioritising future research and focusing knowledge elicitation resources. The BN described in this paper models our current knowledge of a highly complex system. Uncertainty in many of the processes involved is high but the BN that has been developed has allowed the key drivers to be identified by providing a framework for transparent and structured decision-making under a risk assessment framework. As research into these particular areas continues and additional information becomes available, the model can be updated and reviewed. After the model has been evaluated it may be accepted for its intended use as a DST and is likely to be further developed through future iterations. BN models within an ERA framework are intended for ongoing assessment and continued development (Pollino *et al*., 2007).

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