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Water for a Healthy Country

Towards an understanding of the filter function of tropical wetlands

Lessons from temperate locations, development of a conceptual model and design of a field monitoring strategy

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CSIRO

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1. Introduction

The ability of natural wetland systems to retain, remove and process sediment and nutrients has long been recognised as a means by which to improve the quality of water. Because of this ability, wetlands are sometimes referred to as the 'kidneys' of the catchment. The recognition of these filtering processes has led to the proliferation of artificial wetlands as a means to treat diffuse and point source pollutants from a range of agricultural, industrial and urban land uses.

In north Queensland, Australia, evidence exists that terrestrial sources of pollutants are degrading corals and the near shore aquatic ecosystems of the Great Barrier Reef (GBR) lagoon (e.g. Brodie and Mitchell 2005; Fabricius et al. 2005; Furnas 2003). This region has exceptional environmental value (Weston and Goosem 2004) and high economic importance (Access Economics 2005; Driml and Common 1995), therefore, efforts to mitigate and prevent any further degradation are increasing. One of the potential means by which to reduce the delivery of agricultural pollutants (sediment, nutrients and pesticides) to the GBR is through the use of wetland systems. However, the effectiveness of wetlands in tropical environments is largely unknown because of a lack of research in these regions. Research in temperate locations has been extensive and generally supports the role of wetlands as filters but the tropics represent a different set of conditions to which temperate findings may not apply. For example, the wet tropics are characterised by distinct wet and dry seasons with extreme rainfall events which result from cyclonic and monsoonal activity, such events result in rapid transport of large loads of sediment and nutrients which could have the potential to overwhelm the filtering capacity of wetland systems.

The ability of wetland systems to contribute towards the protection of the GBR is also restricted by the area of natural wetland remaining in catchments. Large areas of the wetland that originally existed in the region have been drained and degraded (Finlayson and Lukacs 2001) therefore, if wetlands are shown to be effective features in the tropics, it is likely that a reliance on artificial systems will be necessary. Artificial wetlands will need to be designed to capitalise on the features that contribute to make natural wetlands effective filters, but to understand this we need to design monitoring programs to identify these processes.

Uncertainty with regards to the filter function of tropical wetland systems is not widely acknowledged due to perceptions adopted from research in temperate areas. Funding for restoration and construction of artificial wetlands has increased greatly in the GBR catchments in recent years and natural resource managers are increasingly interested in finding out how best to spend the available funds in order to get best value for money. From a scientific research point of view there are a number of key questions that need to be answered before such advice can be given with any certainty. Within the tropical environment of north Queensland the following questions need to be answered:

1. Can natural wetlands in tropical systems provide valuable filtering services?

If this answer to this question is 'yes' then the following question need to be answered:

2. What are the biogeochemical, ecosystem and hydrological processes that take place in wetland systems which help them to retain and remove sediment and nutrients?
3. What are the most desirable characteristics for a tropical wetland?
4. Where are the best locations for wetlands?
5. What area of wetland is required for significant environmental benefits?

Although valuable lessons can be learnt from temperate wetland studies the best means by which to begin to answer these questions is to monitor the filter function of an existing wetland system. The aim of this report is review the current scientific understanding of the processes which contribute to wetland filtering and to incorporate this understanding into the design of a wetland monitoring study in the Wet Tropics of north Queensland.

In this document the types and diversity of wetland systems will be discussed and a brief review of the existing literature on the filtering capability of wetlands will be presented. Based on the current understanding of the key processes driving the filtering ability of wetlands a conceptual model of the filtering characteristics of a tropical floodplain wetland will be presented. From this conceptual model, the development of a field based water quality monitoring system will be described and development of an automated sampling strategy will be outlined.

It should be noted that this report discusses only the filtering capability of wetlands. It should be remembered that wetlands systems provide many other ecosystems services. Amongst other things, wetlands provide important breeding grounds for birds and fish and are often culturally significant sites. The full range of services provided by wetlands should to be considered in natural resource management decisions.

2. The Diversity of Wetland Systems

Many different classification systems for wetland environments have been developed around the world. The basis of all of these wetland classification systems is recognition of specific identifying characteristics which are generally related to a few key factors. For inland wetland systems these factors generally include geomorphological setting, hydrological characteristics and climatic conditions.

2.1. Geomorphological Setting

The configuration and functioning of a wetland system will be largely controlled by the local landforms or landscape relief. The local morphology will influence wetland depth, frequency and duration of flooding, and surface and groundwater inter-connections. Based on the landscape position DeBusk (1999a) grouped wetlands into three broad groups; depressional wetlands, fringe wetlands, and riparian wetlands. Depressional wetlands are formed in depression in the landscape not directly associated with rivers and lakes. Such wetlands are often isolated from the regional hydrology and in many cases the water balance of such wetlands is controlled largely by rainfall and evapotranspiration. Fringe wetlands are found adjacent to lakes and estuaries. While such systems are connected to the regional hydrology their influence on hydrology and water quality is limited by the throughput of water relative to riparian areas. Riparian wetlands are generally located around rivers and on the floodplain in regions subjected to periodic overbank flooding. These wetlands are hydrologically connected to the river and surrounding catchment and are often important to regional hydrology. Riparian wetlands often intercept surface and subsurface water and as such can act as buffers for streams. Riparian wetlands offer the greatest potential for water quality benefits (DeBusk 1999a) and as such these wetlands types will be the focus of the remainder of this report.

2.2. Hydrological Setting

The source of water for a wetland also greatly affects it's hydrological functioning and, hence, filtering capacity. Wetlands in which rainfall is the dominant water input are not considered to have a high filtering potential because such wetlands have very low nutrient inputs. Groundwater dominated wetlands can receive large amounts of dissolved nutrients from the surrounding landscape. This provides an opportunity for filtering nutrients before water either seeps back into the groundwater system or is flushed by periodic flooding of the area. Surface water dominated wetlands are considered 'open' systems with constant cycling of water into and out of the wetland. Such wetlands are often characterised by periodic influxes of water, sediment and nutrients providing the opportunity for filtering before water leaves the wetland system. Riparian wetlands are often fed by a combination of groundwater and surface water inputs (often seasonally controlled) which adds to the potential of such wetlands to influence regional hydrology and water quality.

2.3. Climatic Setting

Temperature and precipitation strongly control the functions of a wetland system. Temperature regimes control the rates of biological processes while precipitation characteristics control the amount and seasonality of flows into and out of the wetland. The combination of timing of inputs of sediments and nutrients relative to peak biological activity has great implications for filtering ability.

3. Wetland Processes

The filtering of a wetland system takes place as a result of biogeochemical processes. The term 'biogeochemical' refers to the partitioning and cycling of nutrients and other compounds between the biotic (living) and abiotic (non-living) ecosystems. These biogeochemical transformations include sediment deposition, nitrogen and phosphorus removal and transformation of inorganic nutrients to organic forms. As surface water flows into a wetland system its velocity is dramatically slowed as the cross sectional area of flow and the abundance of aquatic vegetation increases. This allows particulate matter and sediments to settle out of suspension. Wetlands provide ideal conditions for a range of chemical and microbial processes which promote nutrient removal and storage. Wetlands provide ideal conditions and a large surface area for microbial activity in the soil and detritus layer. Such conditions, combined with the increased residence times of water in wetlands when compared to streams, promotes microbial transformations. Within a wetland system, the presence of oxygen depleted (anaerobic) soils which interface with the aerobic inflowing water creates an ideal environment for the occurrence of unique chemical and microbiological reactions which enhance the removal of nutrients.

Despite the common notion that wetlands function as a sink for nutrients it is also possible for then to operate as a source. Whether the wetland acts as a sink or source depends on the biogeochemical characteristics within the wetland and the rate of nutrient input. Net export of nutrients can result from a high loading followed by a period of reduced loading. In such a case, the nutrients accumulated under high loading continue to be exported from the wetland at lower loading rates. Under such circumstances a wetland system can function as a sink or a source for nutrients over time. The net filtering ability will be reflected in the long term nutrient budget, however these shorter term fluctuations between sink and source provide valuable information about the rates of biogeochemical processes.

3.1. Hydrological Balance of Wetland Systems

In order to understand the hydrological functioning of a wetland system, it is necessary to determine a system water balance. This water balance describes the movement of water through the wetland for a given time period. The water balance of a riparian wetland with surface and subsurface water inputs can be described by Equation 1:

$$P + Q_{in} + G_{in} = E + Q_{out} + G_{out} \pm \Delta S \qquad \textbf{Equation 1}$$

Where P is precipitation falling on the wetland surface, Q_{in} and Q_{out} are surface water inflow and outflow, respectively, G_{in} and G_{out} are groundwater inflow and outflow, respectively, E is evaporation from the wetland surface and ΔS is change in wetland water storage.

3.2. Sediment and Nutrient Balance of Wetland Systems

Based on the hydrological balance of the wetland it is also possible to develop sediment and nutrient balances. This is demonstrated for nitrogen in Equation 2:

$$PN + QN_{in} + GN_{in} = DN + QN_{out} + GN_{out} \pm \Delta SN \qquad \textbf{Equation 2}$$

Where PN is nitrogen inputs in rainfall (usually very small), QN_{in} and QN_{out} are inputs and outputs of nitrogen in surface water, GN_{in} and GN_{out} are inflows and outflow of nitrogen in groundwater, DN is gaseous loss of nitrogen through denitrification and ΔSN is the change in nitrogen stored in the water body, plants, soil and detritus.

The nutrient balance for phosphorus is given by Equation 3:

$$PP + QP_{in} + GP_{in} = QP_{out} + GP_{out} \pm \Delta SP \qquad \textbf{Equation 3}$$

Where PP is phosphorus inputs in rainfall (usually very small), QP_{in} and QP_{out} are inputs and outputs of phosphorus in surface water, GP_{in} and GP_{out} are inflows and outflow of phosphorus in groundwater and ΔSP is the change in phosphorus stored in the water body, plants, soil and detritus. There are no atmospheric losses of phosphorus.

The balance for suspended sediment is given by Equation 4:

$$PS + QS_{in} + GS_{in} = QS_{out} + GS_{out} \pm \Delta SS \qquad \textbf{Equation 4}$$

Where PS is sediment input in rainfall (usually very small), QS_{in} and QS_{out} are inputs and outputs of suspended sediment in surface water, GS_{in} and GS_{out} are inflows and outflow of suspended sediment in groundwater (normally very small) and ΔSS is the change in suspended sediment stored in the water body and deposited on the wetland bed.

The above nutrient balances are based on the total measure of all forms of nitrogen and phosphorus moving into and out of and being stored in the wetland. A more detailed understanding of the processes controlling these balances can be gained by analysing transformations in the forms (i.e. dissolved, particulate, organic, inorganic) of these nutrients as they pass through the wetland. To do this requires more detailed water quality analyses, these are outlined below. Forms of nutrients measured by laboratory analysis are shown in blue text while those in red text are calculated by difference.

3.2.1. Nitrogen

- Total Nitrogen (TN) - This a measure of all forms of nitrogen present in a water sample. Nitrogen exists in water both as inorganic and organic forms. Organic nitrogen compounds are found in either dissolved or particulate forms while inorganic nitrogen is primarily in dissolved form.
- Total Dissolved Nitrogen (TDN) is determined by passing a sub-sample through a 0.4 µm cellulose filter (N.B. other analysis methods exist)
- Total Particulate Nitrogen (TPN) is determined by difference (i.e. TPN = TN – TDN)
- Dissolved Inorganic Nitrogen (DIN) is a combination of Nitrate (NO_3^-), Nitrite (NO_2^-) and Ammonium (NH_4^+). (i.e. DIN = NO_3^- + NO_2^- + NH_4^+)
- Dissolved Organic Nitrogen (DON) is determined by difference (i.e. DON = TDN – DIN)).
- Total Organic Nitrogen = TPN + DON
- Total Inorganic Nitrogen = DIN

The processing involved in changes to the form of nitrogen are illustrated by Figure 1.

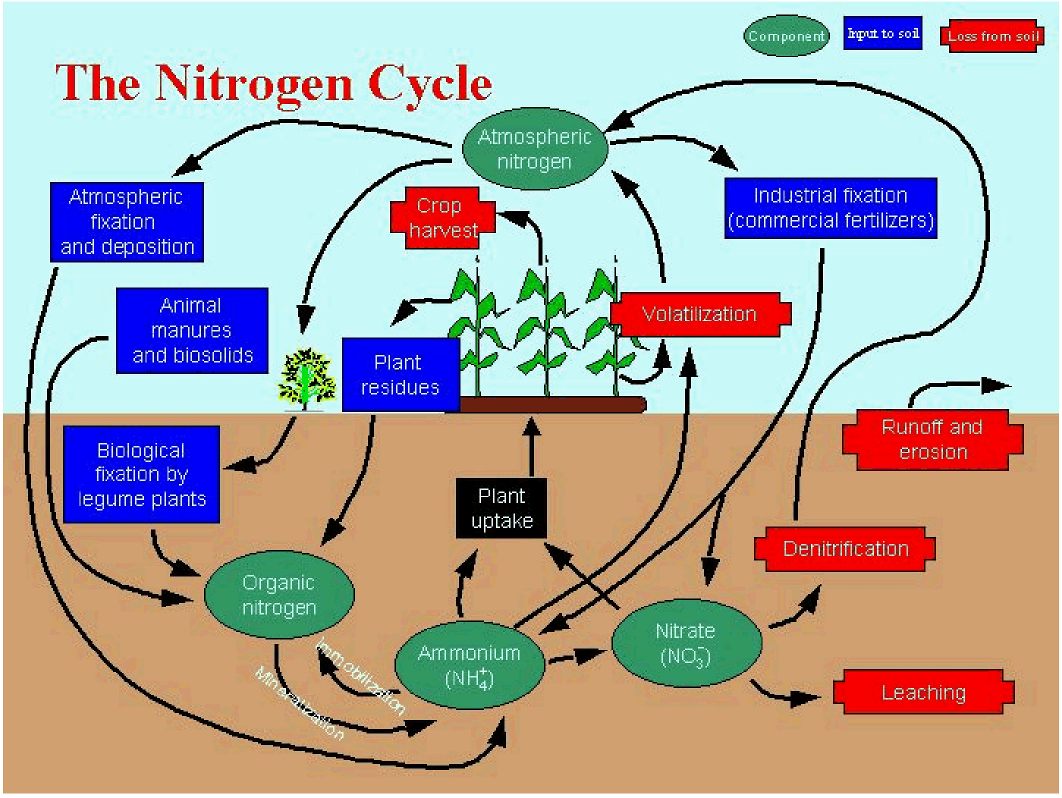

Figure 1. The nitrogen cycle.

Source: Mississippi State University Extension Service http://msucares.com/crops/soils/images/nitrogen.gif

The following processes are involved in the retention, cycling and release of nitrogen in wetlands (DeBusk 1999b):

- Transport – Dissolved forms of nitrogen are transferred via diffusion from surface water to soil solution and vice versa depending on concentration gradients. Other transport process may include faunal pumping, and possibly advection in permeable sediments
- Plant Uptake – Inorganic forms of nitrogen (NH_4^+ and NO_3^-) are taken up by plants from the soil or water
- Litter-fall – Dead plant tissues collects at the soil surface as detritus.
- Sedimentation – Particulate matter settles out onto the soil layer or plant surface. Particulate matter includes inorganic and/or organic sediment.
- Decomposition – Organic matter is broken down by micro-organisms which use the organic carbon as a source of energy. Organic compounds are ultimately broken down to ammonium (NH_4^+)
- Ammonia Volatilization – Under high pH conditions in wetland flood water ammonia (NH_3) concentration increases relative to NH_4^+) and is released to the atmosphere as ammonia gas.
- Nitrification – Microbial conversion of ammonia (NH_4^+) to nitrate (NO_3^-). This process occurs in aerobic conditions.
- Denitrification – Microbial conversion of nitrate (NO_3^-) to nitrogen gas (N_2) which is lost to the atmosphere. This process generally occurs in anaerobic conditions.
- Adsorption – Retention of nitrogen in the soil when ammonium ions (NH_4^+) become weakly bound to the soil particles by electrostatic attraction.
- Burial – Partially decomposed organic matter is buried and incorporated into the soil profile

3.2.2. Phosphorus

- Total Phosphorus (TP) is a measure of all forms of phosphorus present in a water sample. Phosphorus exists in water both as inorganic and organic forms. Organic phosphorus compounds are found in either dissolved or particulate forms while inorganic phosphorus is primarily in dissolved form (usually as orthophosphate).
- Total Dissolved Phosphorus (TDP only organic) is determined by passing a sub-sample through a 0.4 µm cellulose filter (N.B. other analysis methods exist)
- Total Particulate Phosphorus (TPP) is determined by difference (i.e. TPP = TP – TDP)
- Dissolved Inorganic Phosphorus (DIP) is determined from the measure of orthophosphates (FRP)
- Dissolved Organic Phosphorus (DOP) is determined by difference (i.e. DOP = TDP – FRP).
- Total Organic Phosphorus = TPP + DOP
- Total Inorganic Phosphorus = DIP (or FRP)

The processing involved in changes to the form of phosphorus are illustrated by Figure 2.

The following processes are involved in the retention, cycling and release of phosphorus in wetlands (DeBusk 1999c):

- Transport – Dissolved forms of phosphorus are transferred via diffusion from surface water to soil solution and vice versa depending on concentration gradients. Other transport process may include faunal pumping, and possibly advection in permeable sediments
- Plant Uptake – Inorganic forms of phosphorus (HPO_4^{2-} and $H_2PO_4^-$) are taken up by plants from the soil or water.
- Litter-fall – Dead plant tissues collects at the soil surface as detritus.

- Sedimentation – Particulate matter settles out onto the soil layer or plant surface. Particulate matter includes inorganic and/or organic sediment.
- Decomposition – Organic matter is broken down by micro-organisms which use the organic carbon as a source of energy. Organic compounds are ultimately broken down to orthophosphate.
- Sorption – This term applies to two processes, 1) adsorption of orthophosphate ions by clays and iron or aluminium oxides in the soil, and 2) precipitation of PO_4^{3-} with either iron and aluminium oxides or dissolved calcium to form solid compounds in the soil or water column.
- Burial – Partially decomposed organic matter is buried and incorporated into the soil profile.

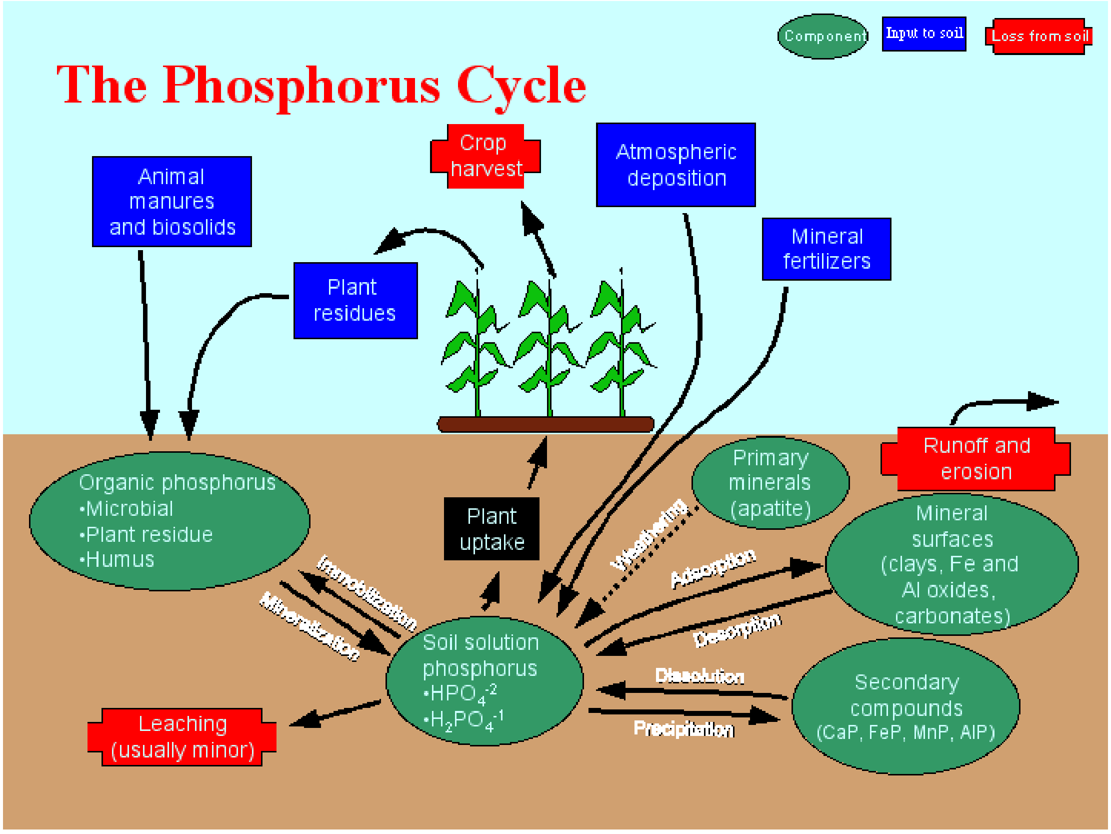

Figure 2. The phosphorus cycle.

Source: Mississippi State University Extension Service http://msucares.com/crops/soils/images/phosphorus.gif

4. An Overview of Wetland Filtering Processes: a temperate perspective

The aim of this section is to present the key processes that have been identified in wetland studies as being important to wetland filtering processes. Detailed reviews of the international literature on wetland filtering have been undertaken by Fisher and Acreman (2004) and Johnston (1991) so it is not the intention of this report to repeat these reviews. This section represents a synthesis of the findings from these reviews illustrated with examples from the literature. The section considers only the nutrient and sediment retention capability of wetlands, for information on the hydrological impacts of wetlands readers are referred to the comprehensive review of Bullock and Acreman (2003).

Fisher and Acreman (2004) undertook a review of research from 57 wetland from around the world with the aim of assessing whether or not natural wetlands reduce nutrient loading to water bodies. In this review 80% of studies exhibited nutrient retention, while nutrient addition was shown for 13% of studies and no net change in nutrients was shown for 7%. Of the reviewed studies that exhibited nutrient retention, slightly more reported reduced loadings of P than N which is surprising since wetlands are generally thought to be more efficient at reducing N loadings, primarily through denitrification which removes N from the system through gaseous loss. The review showed that riparian wetlands were more likely to reduce TN relative to swamps and marshes, however the latter exhibited a greater retention of ammonium. Riparian wetlands were more likely to exhibit reduced TP but they were also likely to increase loadings of soluble P. Although sediment and nutrient retention is most commonly observed it is important to note that some wetland locations may in fact act as sources at least at particular times of the year (e.g. Gehrels and Mulamoottil 1989; Ontkean et al. 2003; Raisin et al. 1999).

Evidence from this review also suggested that N reduction was greatest in wetter environments while P reduction was greatest in drier environments. The review notes that there was a paucity of studies on the effectiveness of nutrient retention for wetlands in tropical and subtropical locations. The studies available from these locations showed overall nutrient retention and no evidence that these wetlands are any less effective than those at higher latitudes. The authors comment that this would be expected given that the chemical transformation processes that are important to nutrient reduction are likely to occur at a greater rate at higher temperature and not be inhibited by an annual dormant season as in temperate climates. This impact of this comment is particularly important considering the area of wetlands in the tropical zone and the increasing threats to these wetlands from land use change. The hydrology of tropical locations is likely to be much more extreme than in other areas of the world and seasonal fluctuations in water inputs are likely to be much more pronounced as a result of distinct wet and dry seasons. The impact of such characteristics is currently uncertain and, hence, the capability of tropical wetlands to filter sediments and nutrients is largely unknown.

Also of importance to the design phase of studies aiming to quantify the filter function of wetland system is the observation of Fisher and Acreman (2004) that studies which sampled at regular weekly or monthly intervals, or avoided sampling during high flow recorded the highest reductions in N (>90%). Lower reduction in N (<50%) or variable reduction in N was reported from studies where samples were taken daily or which sampled more regularly during high flows, or which sampled from many locations within the wetland. Clearly the choice of a suitable sampling strategy is crucial to an unbiased set of results.

The factors that have been identified by Fisher and Acreman (2004) as contributing most to the capability of a wetland to filter nutrients are as follows:

4.1. Oxygen content of wetland sediments

Fisher and Acreman (2004) found that the most commonly reported factor as being important for the retention of nutrients was oxygen content of the within wetland sediments. Of particular interest from this review was the finding that efficient N and P removal requires different wetland types. The influence of the oxic status of the sediments is not clear. In wetlands receiving high nitrate loadings anoxic sediments are likely to be advantageous because high rates of denitrification will be fed by nitrate from the water column. Anoxic sediments will however inhibit nitrification and thus wetlands receiving high nitrogen loadings in an organic form will benefit mostly from oxic sediments

It is interesting to note that changes from reducing to oxidising conditions in the wetland substrate can result in temporal fluctuations in nutrient retention. Working in the Masurian Lakeland in Poland, Rzepecki (2002) observed increased soluble P transport but highest denitrification when waterlogged conditions prevailed. The importance of oxygen in wetland soils has also been investigated by Flynn *et al.* (1999) who looked at the nitrogen dynamics of soils at different locations on a floodplain under flood conditions and showed increased capacity for denitrification in poorer drained soils. The duration of water logging and spatial extent can then be considered very important to denitrification (Baker and Maltby 1995).

4.2. Hydraulic loading, retention times and hydraulic efficiency

Hydraulic loading and residence times are important for determining sedimentation rates, the likelihood of nutrients being flushed from the wetland, the contact time between nutrient inputs and sediments and vegetation and denitrification and phosphorus retention processes.

Holland *et al.* (2004) looked at the effects of wetland depth and flow rates on the distribution of residence times across a stormwater wetland. They found that changing water levels had more influence than flow rates on residence time distributions and that increasing water depth elicited a decrease in hydraulic efficiency. The hydraulic efficiency refers to the ability of a wetland to distribute its flow uniformly throughout its volume, thus, maximising contact time of nutrients in the system and optimizing the ability to breakdown these nutrients. Blahnik and Day (2000) demonstrated the potential to process higher nutrient loadings in a wetland by maximising wetted surface area.

The importance of wetland morphology and vegetation to hydraulic efficiency of constructed wetlands has been highlighted by Wong *et al*. (1999). Using field measurements and modelling techniques Wong *et al.* (1999) have been able to demonstrate the importance of vegetation in reducing flow velocities and distributing flows to enhance hydraulic efficiency.

4.3. Vegetation processes

According to the review of Fisher and Acreman (2004) the importance of vegetation to wetland filtering is multi-faceted. It is generally thought that direct nutrient reduction by plant uptake is relatively unimportant compared to sediment and chemical transformation processes. Johnston *et al.* (1984) argue that uptake by plants is not as long-term as via other methods because plants return nutrients as litter which is easily leached and eroded. The organic matter shed by vegetation can, however, be important in determining the sediment composition and its ability to transform nutrients. Although vegetation is not a large net annual store for nutrients it can act to regulate nutrient flows through uptake and transformation during growing seasons and release during non-active growing seasons (Nichols 1983).

Above ground vegetation is also important in slowing flow velocities and controlling flow paths (Wong et al. 1999). Vegetation encourages sediment deposition, provides a carbon source for denitrification and controls sediment oxygen and water content through respiration. Aquatic plants also have a large biomass below ground in the roots. The roots create an extensive matrix which binds the soil and creates a large surface area for uptake of nutrients and delivery of oxygen into the soil for utilisation by aerobic micro-organisms (Shutes 2001). Transport of O2 into the sediment via roots also allows nitrification to take place within the sediment, thus stimulating denitrification (Reddy et al. 1989).

4.4. Nutrient loading

A wetland system will be most effective as a filter when nutrient delivery to the wetland is equivalent to nutrient processes capability. Too little nutrient and the full capability is not realised too much and the filtering ability is exceeded. A review of research in artificial wetlands by Nichols (1983) showed that the percentage of wetland nutrient retention is inversely related to nutrient loading. This review showed that excessive loads of nutrient can overload the removal mechanisms of the wetland so that nutrient retention capability of the wetland is greatly reduced in subsequent years. This review is supported by a wetland modelling study by Dørge (1994) which showed that nutrient removal and retention is strongly tied to loading.

Carbon content of the wetland

Readily available carbon is an important regulator of denitrification activity because it provides a respiratory substrate for soil organisms (Baker and Maltby 1995). Several studies have alluded to the of carbon rich sediments in riparian zone denitrification (Cooper 1990; Haycock and Burt 1993). Cooper (1990) investigated denitrification rates in mineral and organic soils on the same floodplain and found greater rates of nitrate removal in the organic soils. These organic soils were found in distinct locations towards the back of the floodplain often associated with characteristic wetland feature such as oxbow lakes and relict channels.

Hogan *et al.* (2004) investigated phosphorus retention in restored and natural wetlands on Kent Island, USA. They note that the organic carbon in restored wetlands was much less than the natural wetlands and as a result soil chemistry was very different. The restored wetlands had lower carbon content and hence lower concentration of organically bound Al. Concentrations of Al and Fe were higher due to previous cultivation on the restoration site allowing for greater P sorption potential. The authors note that as the restored wetland moves to a hydric state the potential to retain P will be reduced. Such information is important for gauging the potential success of created and restored wetlands for sediment and nutrient filtering and illustrates the need for such wetlands to mature before they reach their true potential.

4.5. Scale and location

A number of authors have noted the importance of scale and landscape setting to the effectiveness of wetland systems (Maltby 1999; Mitsch and Gosselink 2000; Mitsch and Wang 2000). The importance of scale and landscape setting is particularly important when taking a catchment view to the effectiveness of these systems at filtering sediments and nutrient. A wetland on a floodplain may be very effective at retaining and removing the nutrients and sediment it receives, however, the total load of sediment and nutrient delivered from the entire catchment may make this filtering effect insignificant. To be effective filters, wetlands need to be spatially distributed, and linked to the hydrological processes occurring in the catchment (Mitsch and Gosselink 2000). Mitsch and Gosselink (2000) suggest that 3-7% of the catchment should be wetlands to provide adequate flood control and water quality benefits for the catchment in temperate zones. Similar estimates for tropical locations are not available.

Mitsch and Wang (2000) undertook a modelling study to determine the potential for wetland restoration to improve water quality of the Great Lakes, USA. Their modelling showed that restoration of 31.2 km^2 of wetland would retain 53% of the phosphorus from upstream while restoration of 17.3 km^2 would retain 12% of the phosphorus from upstream. The modelling exercise highlighted the importance of spatial location of restored wetlands, particularly in respect to connectivity to main channels and location relative to main delivery pathways. Using a GIS system Jansson *et al.* (1998) estimated that remaining area of wetlands in the drainage basin of the Baltic Sea was capable of retaining only 57,000-145,000 t N/y (5 -13% of total nitrogen inputs). They estimate that restoration of all drained wetlands in the drainage basin could potentially lead to 196,000-261,000 t N/y (18 - 24%), thus, greatly reducing the potential for eutrophication of the Baltic Sea.

5. Conceptual understanding of tropical wetland filtering

Based on the factors identified as being beneficial to wetland filtering in temperate studies, it is possible to start considering the characteristics of tropical wetlands which may enhance or degrade filtering ability. The relative importance of these factors, which will be discussed below, will combine to determine the actual filtering capability of a tropical wetland.

Given that tropical floodplain wetlands exhibit many of the characteristics widely though to be responsible for enhanced nutrient retention and removal they show the potential to be good filters for the catchment. The factors which that are likely to contribute to nutrient retention and removal by a tropical floodplain wetlands are:

- Permanent water with constantly water logged sediment – many tropical floodplain wetland are perennial thus promoting denitrification
- Surface and groundwater inputs – many floodplain wetlands are fed by both groundwater and surface water inputs increase both delivery and removal pathways
- Abundant aquatic and fringing vegetation for most of the year – tropical wetlands are usually abundant with aquatic vegetation which enhances plant uptake and filtering
- Constant warm conditions – the warm tropical conditions promote biogeochemical transformations, and prevent ‘dormant’ periods
- Very wet conditions – high rainfall inputs which lead to wet conditions which favour N removal
- Hydraulic retention times – during the dry season water remains in the wetland for a long time providing opportunity to process nutrients following wet season inputs
- High nutrient loading – nutrient inputs are likely to be seasonally high with large inputs and/or flushing during the wet season

Although tropical wetlands exhibit many of the characteristics that enhance wetland filtering there are also factors which may any to impede their ability to retain and remove nutrients. These factors could potentially include:

- Excessive sediment and nutrient loading – this is particularly relevant to agricultural situations where events following fertiliser application and tillage are likely to produce ‘first flushes’ which have high concentration which could overload the removal and storage mechanisms of the wetland
- Excessive hydraulics loading – Particularly large events associated with monsoonal depressions and cyclones will completely swamp the wetland leading to short retention times, scouring of wetland sediments and nutrients, flushing of aquatic vegetation and greatly reduced hydraulic efficiency

Based on hydrologic understanding of tropical systems and the factors likely to contribute to wetland nutrient retention it is possible to construct a conceptual model of wetland functioning in the Wet Tropics of north Queensland which can then in turn be used to design a sampling strategy which aims to measure the filter function. Such a conceptual model for surface water flows is shown in Figure 3, similar behaviour is expected of groundwater flows. The model is based on a tropical floodplain wetland which has continuous input and output of water.

The top graph in Figure 3 shows a synthetic time series of flow into a wetland system. On this figure the red line indicates the flow level at which out-of-bank flooding occurs (i.e. floodplain is inundated). During these floods the large volumes of water flowing across the floodplain and wetland are likely to flush any freely available sediment and nutrients and carry then downstream, it is for this reason that these floods could be considered ‘resetting’ events for the wetland. When water retreats to within the wetland again then the new supply (or load) of sediment and nutrient is delivered to the system and filtering commences again. Based on the wet and dry season cycles encountered in tropical locations there are then likely to be two distinct periods of increased hydraulic, sediment, and nutrient loading; one at the end of the wet season after the last resetting of the season and one during the build-up to the next wet season. These two periods are indicated on the top graph of Figure 3 and a conceptual representation of how this may relate to cumulative load is shown by the middle graph.

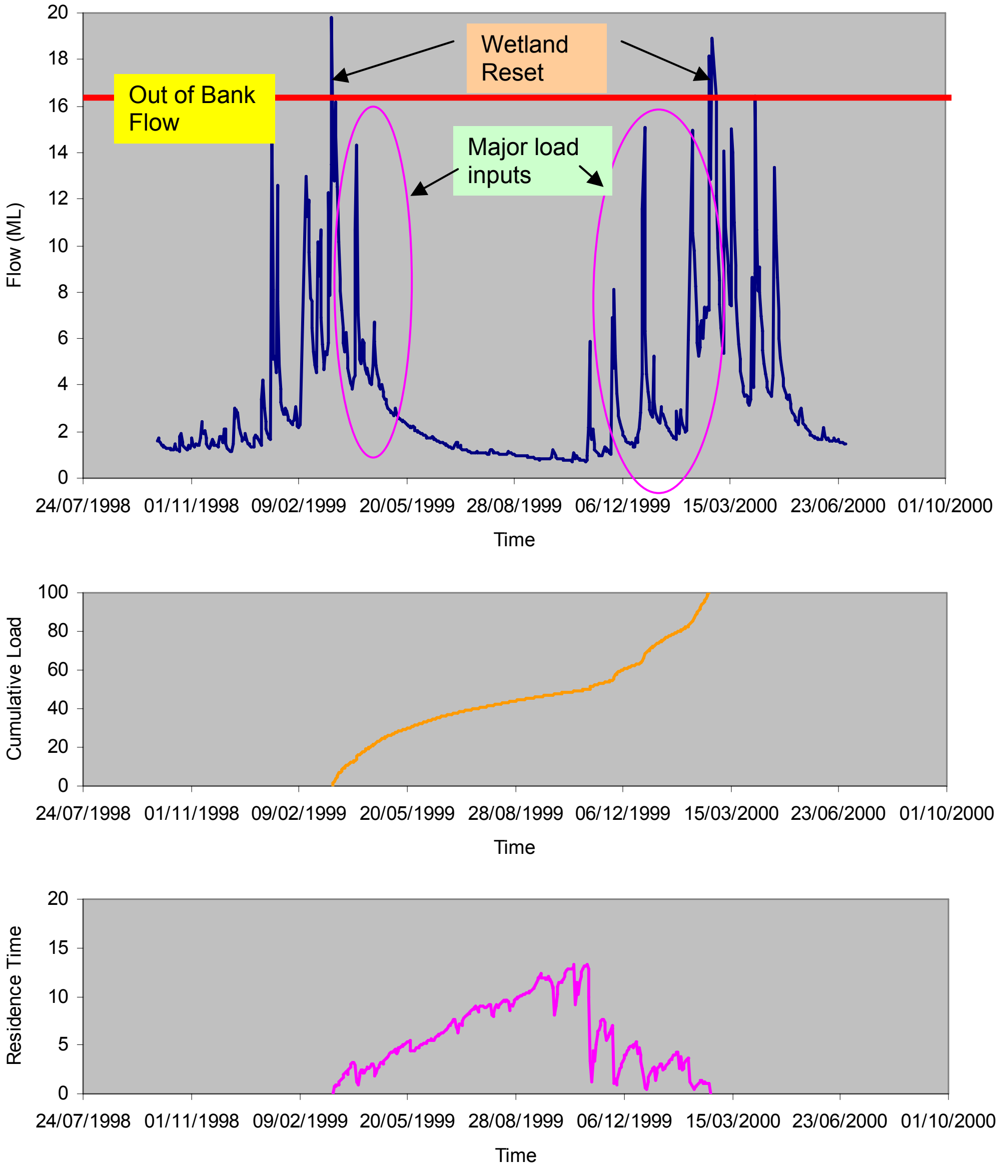

Figure 3. Conceptual depiction of typical wet/dry season flows into a wetland (top), cumulative input load (middle), and residence time of water in wetland. Units are meaningless and figures are to support the conceptual model.

Experience from other water quality studies in the tropics (McJannet et al. 2005) shows that, despite low concentrations of sediment and nutrients, loads at the tail end of the wet season are likely to be high because of large flow volumes. The loads delivered at the end of the wet season are particularly important because there is the potential for filtering to occur throughout the dry season. While the contribution of sediment and nutrient loads from the start of the wet season have been observed to be less significant than those later in the season (McJannet et al. 2005), concentrations can be very high due to ‘first flush’ effects. Loads of sediment and nutrient delivered in the early wet season could potentially greatly impact on wetland processes or be flushed through the system by subsequent flood events before retention and transformation can take place.

Residence times are identified as a key factor in retention and removal of sediment and nutrients and in tropical systems this is likely to show strong seasonal variations. A conceptual model of seasonal residence times is shown in the bottom graph of Figure 3. In the transition time between wet and dry seasons residence times will increase and reach a maximum before the build up to the next wet season which will increase flows through the system.

Given the potential for tropical wetland systems to be flushed during extreme out-of-bank events and the large season variations in flow and load delivery, such systems are likely to exhibit temporal variation in retention and removal of sediment and nutrient. In fact, they are likely to be sources of sediment and nutrient for certain periods and filters at others. Understanding of these fluctuations and the net filtering effects is central to the development of a good sampling strategy. Such a sampling design should reveal the conditions which result in optimal nutrient removal and be very useful in the design of artificial wetlands to maximise nutrient filtering.

Using the state of knowledge on the function of wetland systems from the literature it is possible to speculate as to the likely seasonal variations in wetland filtering. A conceptual model of wetland function is presented in Figure 4. This figure shows monthly net filtration and illustrates potential fluctuations in filtering which are expected given seasonal variation in load delivery and flows. A measurement system and a sampling strategy designed to capture such information is described in the next section.

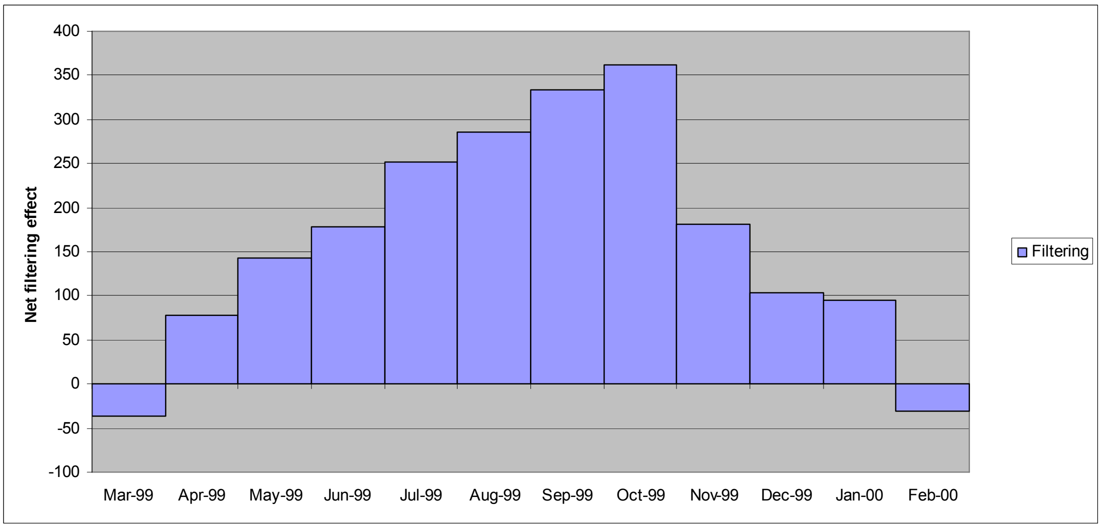

Figure 4. Conceptual depiction of the net filtering effect of a wetland during a year. Units are meaningless and purely illustrative.

6. Measurement and Sampling Strategy

Based on the basic measurement requirements and conceptual understanding of the processes occurring in tropical wetlands systems, this section describes the developing a field measurement program for determining the filter function of a wetland in the tropics of north Queensland. It outlines the water balance instrumentation design and describes the development of a preliminary water quality sampling strategy for a previously ungauged location.

6.1. Field Site Selection

In order to select a suitable natural wetland system for filter function monitoring a number of key attributes were required:

- Access in all but the largest floods for sample collection
- Distinct surface inflow and outflow to minimise measurement requirements
- Co-operative landholders (including Council and Traditional Owners)
- Existing research and surveys as background information
- Year round flow
- Large contributing area
- Minimal artificial drainage inputs (i.e. cane drains)
- Reasonable size
- Minimal degradation

After extensive field reconnaissance a field site that met these criteria was located. It is known as the Kyambul Wetlands (or Gaynbul to traditional owners) and is on the Tully-Murray Floodplain (

Figure 5). An aerial view of the configuration of the Kyambul wetland system is shown in Figure 6 and a ground level view of the wetland is shown in Figure 7.

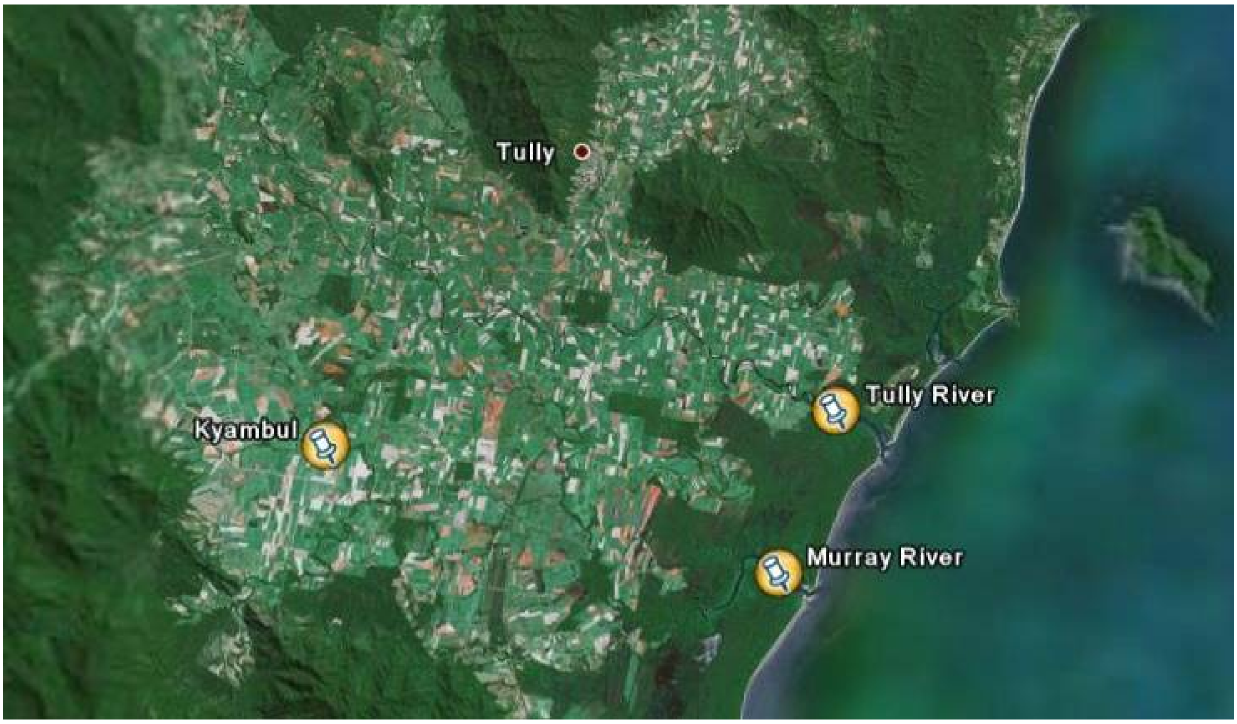

Figure 5. Location of Kyambul Wetland on the Tully-Murray Floodplain. (source - Google Earth)

Figure 6. Aerial view of Kyambul Wetland. Flow direction is from left to right (source – Cardwell Shire Council)

Figure 7. Kyambul Lagoon looking upstream.

6.2. Water balance measurements

In order to measure all components of the wetland water balance (Equation 1) a combination of surface and subsurface measurements is required. Each of these measurements is detailed below.

6.2.1. Rainfall

Rain inputs to the wetland will be measured with a standard (200 mm diameter) tipping bucket rain gauge. Rain gauges will be installed at inlet and outlet stations at a height of 3 m to keep above flood waters. Rainfall events, ten minute totals and daily totals will be recorded using a CR10X data logger (Campbell Scientific Australia, Townsville). Rainfall depth will be multiplied by wetland surface area to calculate the volume of rainfall entering the wetland. Surface area will be determined from survey and bathymetry data as described below.

6.2.2. Evaporation

Evaporation from the wetland surface will be calculated using the Penman-Monteith method which is based on measurements of net radiation, wind speed, temperature, humidity, atmospheric pressure and wetland heat storage (Monteith 1965). These measurements will be made above the wetland water body using a floating weather station. Wetland heat storage will be estimated using a string of five water temperature sensors suspended beneath the weather station using the method of Spence *et al.* (2003). 10 minute and daily averages and/or totals of all sensor measurements will be stored in a CR10X data logger (Campbell Scientific Australia, Townsville). Remote and automated data collection will be enabled through CDMA telemetry. As with rainfall, evaporation will be multiplied by wetland surface area to calculate the volume of water lost through direct evaporation from the water body.

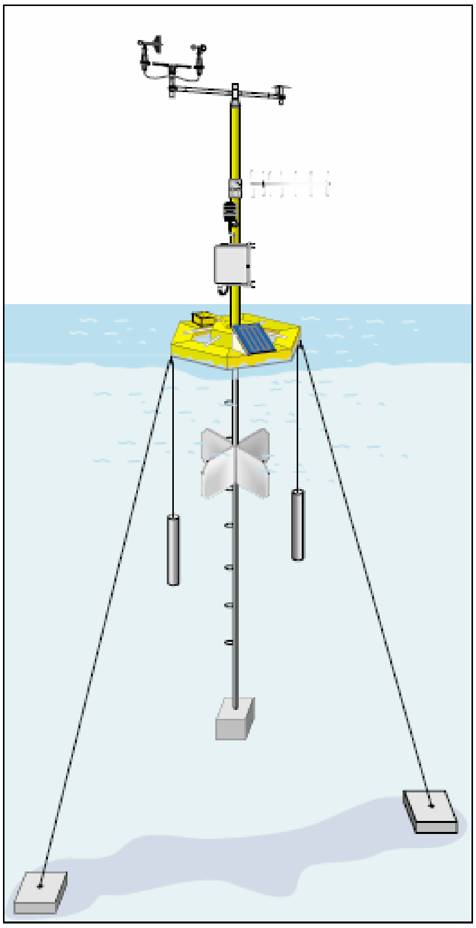

Figure 8. Floating weather station design (source – CSA)

6.2.3. Surface inflows and outflows

Inflow and outflow of surface water will be monitored using acoustic Doppler velocity sensors (Figure 9) (Argonaut, SonTek, California). These sensors are well suited to determining velocity and depth of flow in natural stream channels. By determining the variation in channel cross sectional area with depth via a cross section surveys at wetland inlet and outlet the Argonaut is capable of continuously recording flow.

Figure 9. Acoustic Doppler velocity sensor for monitoring flow. (Source – SonTek)

Data logging and control equipment, rain gauges, solar panels, batteries and automatic sampling equipment will be stored on a platform as shown by Figure 10. A platform such as this will be installed at wetland inlet and outlet positions. The platform is 3m high to ensure than electronics and valuable equipment is kept above the flood water.

Figure 10. Typical stand for mounting sampling equipment, data loggers, solar panels and rain gauge and telemetry equipment above flood levels

6.2.4. Groundwater inflows and outflows

Groundwater inputs and outputs to wetland systems are ignored in many studies, however, they are believed to be a significant pathway on the Tully-Murray floodplain based on unpublished field measurements in nearby locations. Groundwater flow direction (inflow or outflow) will be estimated by measuring the slope of the groundwater surface across transects running perpendicular to the wetland. The slope of this groundwater surface will determine the hydraulic head which can in turn be combined with measurements of soil hydraulic properties to determine groundwater flow. Because of the low gradients of the floodplain, groundwater surfaces are likely to be very gently sloped, therefore, particularly accurate groundwater depth measurements are required. The instrument selected for this task is the Orpheus Mini (OTT Hydrometry, Germany) which on a 5 m scale is accurate to within 0.5 mm (Figure 11). These sensors will be mounted in professionally drilled bores with slotted casing. A total of four wells will be initially drilled, further wells may be required if groundwater transport is more complicated than first thought. The conductivity of the groundwater system surrounding the wetland will be determined using pump tests and the calculation methodology of Youngs (1991).

Figure 11. Groundwater level sensors use to measure hydraulic head and hence groundwater flow (Source - OTT Hydrometry)

6.2.5. Wetland volume and surface area

Information regarding the volume and surface area of the wetland is crucial for determining the storage, evaporation and rainfall components of the water balance. The volume of the wetland will be determined through the use of ground-based surveying and a boat mounted sounder to determine bathymetry. These two surveys will be joined together to develop a digital elevation model of the site which can then be used to develop relationships between wetland depth and volume and wetland depth and surface area. An example of a bathymetric survey of a wetland is shown in Figure 12. Over a longer time period it may also be possible to use repeated surveys to determine whether sediment fluxes are causing infilling of the wetland.

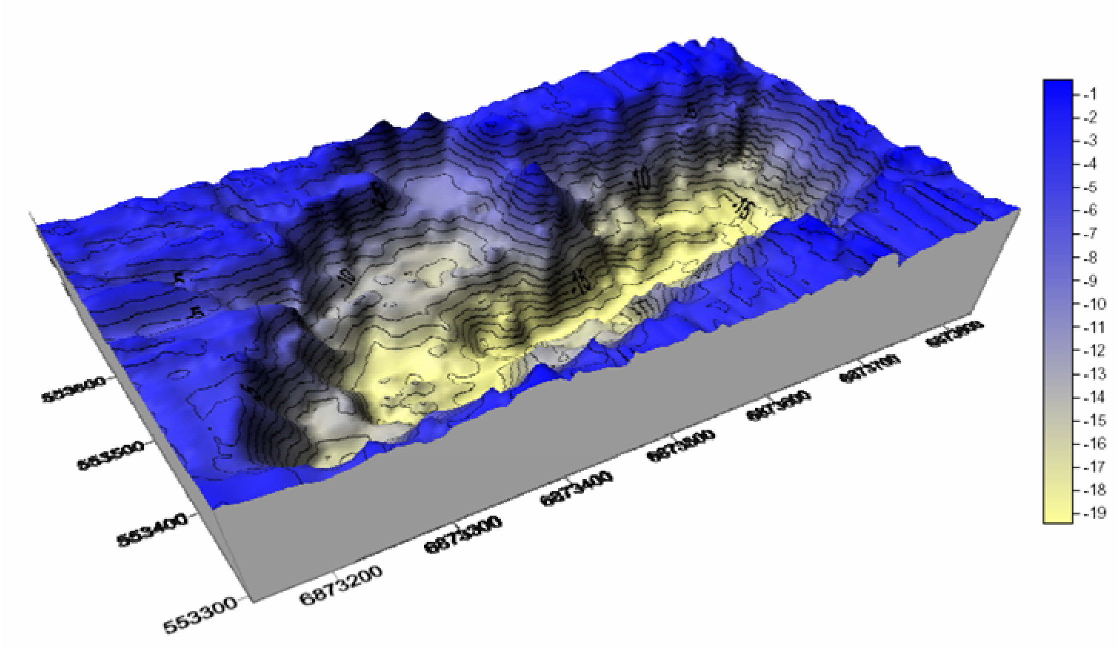

Figure 12. Bathymetry of a wetland system that can be used to determine variations in surface area and volume with depth fluctuations.

6.3. Water quality sampling

6.3.1. Electronic measurements

At wetland inlet and outlet locations electronic measurements of temperature, turbidity and conductivity will be made. The warm tropical conditions experienced at this field site are conducive to the formation of bio-films that can degrade measurement quality. In response to this these sensors will require regular (i.e. monthly) servicing and re-calibration. The turbidity sensor in particular is vulnerable to measurement degradation because it uses an optical sensor, therefore, a sensor which has an automatic wiper incorporated has been selected for the task. Electronic water quality measurements will be recorded on the data logger every 10 minutes.

Figure 13. Analite 195 turbidity sensor with integral wiper (Source - McVan)

Electronic measurements, particularly turbidity, have been shown in other studies to be a good surrogate for some water quality parameters and as such can save large amounts of sample analysis funds. Electronic and laboratory analysed datasets will be compared to look for such relationships which can then lead to semi-continuous approximations of material fluxes.

6.3.2. Manual Sample Collection

Groundwater water quality research in the Tully area suggests that groundwater shows much less variability in nutrient concentrations that surface waters (Pers. Comm. Armour, QNRMW – Mareeba). Based on this information, the water quality of the groundwater system will be determined by collecting manual samples from each transect at monthly intervals. Initial periods of more intensive sample collection will be used to test this assumption before the less intensive manual sampling is initiated.

Wetland storage samples will also be collected at a monthly interval using manual sampling. The initial and final storage of the wetland for each month is crucial to determining the amount of sediment and nutrient actually retained and removed by the wetland. Because the wetland is a large water body a large spatial distribution of samples will be collected but rather than analyse each sample, all samples will be bulked and a sub-sample will be drawn off for sediment and nutrient analysis. This process makes the assumption that by combining a large number of spatially distributed samples the wetland average can be obtained from a sub-sample. Wetland storage samples will be collected from a boat using sample bottles fixed to a collection pole. Manually collected samples will be filtered in the field and transported in refrigeration to the laboratory for analysis.

6.3.3. Automatic Sample collection

Automatic collection of water samples is required at the inlets and outlets to the wetland where sediment and nutrient concentrations are most variable. The advantage of the automatic collection system is that samples can be collected at any time of the day or night in response to a defined sampling strategy (see below). Automatic sample collection at Kyambul wetland will undertaken using the ISCO Avalanche (ISCO, USA). The ISCO Avalanche (Figure 14) has a carrousel of 14 bottles each holding 950 ml which are housed in a refrigerated compartment. The system has low power consumption and is designed to run on a 12 volt source. When sample collection is triggered the system purges the collection line then diverts collected water into one of the sample bottles. This system also has composite sampling capability (i.e. multiple sub-samples to each bottle) which can improve temporal representation of water quality parameters. Collected samples are identified with a unique identifier and are kept below 4ºC. Using a telemetry system, project staff are notified of the number of samples and time since collection.

Figure 14. ISCO Avalanche refrigerated auto-sampler and bottle carrousel (Source - Avensys)

6.4. Automatic Sampling Strategy

To be able to quantify the filtering ability of Kyambul Wetland it will be necessary to determine all fluxes of sediment and nutrient as accurately as possible. As reported by Owen (1995), combined uncertainties in both concentration of water quality parameters and flow can lead to enormous uncertainties in components of the final budget. The use of the acoustic Doppler velocity meters at Kyambul Lagoon will help to minimise errors in inputs and losses from the wetland in surface flow but collection of representative water quality data will require a well designed sampling strategy.

A number of sampling strategies exist for collecting water quality samples and all have there pro's and con's (see Richards (1999) and Letcher *et al.* (1999)). Sampling strategies are usually time or flow based. Time based sampling is good in that they can be applied without any prior knowledge of the system however they are considered to be not well suited to load estimation during events because they ignore changes in flow that occur during the integration period. For this reason load estimates from time based sampling during events are usually underestimates.

Flow based sampling strategies are considered to produce the most precise and accurate load estimates (Richards 1999) but are difficult to implement because of the need for flow history and specialised equipment. Once the requirements of flow based sampling are met the developed strategy is relatively easy to implement and calculation of loads is relatively straight forward using trapezoidal integration. Loads can be calculated as data becomes available unlike other model based load estimation techniques that require a full season or more of data before load estimation can take place. One disadvantage of flow based sampling is that measures of uncertainty are not straight forward although there are some modelling based techniques that can be used to achieve this.

The specialised equipment required for flow based sampling has already been selected for the Kyambul Wetland therefore the only limitation is flow history as this wetland is ungauged. The process used to develop an synthetic wetland flow dataset and a preliminary flow based sampling strategy is outlined in the next section.

6.4.1. Synthetic dataset production

To design a flow based sampling strategy it is first necessary to estimate flows into and out of the wetland. The Kyambul Wetland is ungauged therefore a synthetic data set based on gauged stream data from the area was developed. The first step in this process was to develop a cross sectional profile of the either the outlet or the inlet to the lagoon making the assumption that the flows in each will be roughly similar. We used a rough estimate of the outlet cross section (Figure 15) for which we then calculated a rating curve using a program called WinXSPro which has been developed by the USDA (http://www.stream.fs.fed.us/publications/winxspro.html). Using this rating curve we determined what the minimum and maximum flow through the channel. Maximum flows are equal to the flow before out of bank flows occurred. A time series of gauging from the nearby Murray River (NRM Station 114001) was then analysed to determine minimum and maximum flows with maximum flows being constrained to those in-channel. We then linearly scaled the flows from the Murray River to produce a synthetic data set for Kyambul wetland. Data from the NRM station was at irregular time intervals, therefore we used interpolation to produce an hourly dataset.

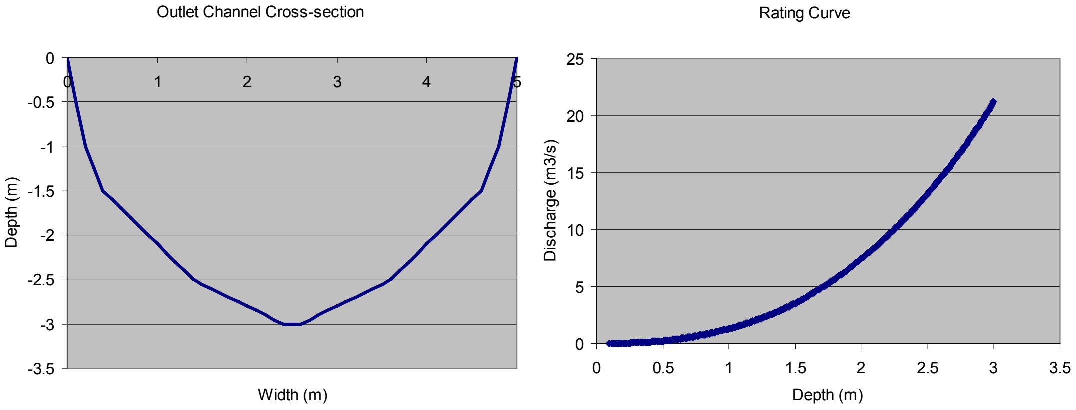

Figure 15. Outlet channel synthetic cross-section (left) and outlet channel rating curve produced by WinXSPro.

6.4.2. Sampling strategy design

The design of the inlet and outlet sampling strategy is largely controlled by the budget available for samples. In this study enough money was available for 200 surface water samples (or 100 samples per station). A flow based sampling strategy which triggers sample collection after a set volume of water has passed the station will produce many samples in the wet and dry seasons. Experience from water quality sampling in other streams in north Queensland (McJannet et al. 2005) shows that dry season flows are not particularly variable and that weekly samples should be adequate to capture any trends. Based on this we have decided to adopt a two phased sampling strategy that reduces sampling in the dry season and increases it in the wet season when variability is highest.

During the dry season, which is defined as the months June through October, a temporal sampling strategy is proposed which requires manual activation of the automatic sampler once per week. This design makes that assumption that dry season variation in water quality parameters are minor compared to those in the wet season when most of the load is delivered. Preliminary daily sampling will be conducted to test this assumption. This design reduces sample collection, freight, processing and analysis costs free up resources for the wet season.

The weekly sampling during the dry season utilises about 20 of the 100 samples available for each station. The remaining 80 samples are assigned based on average flow for the wet season month derived from the synthetic dataset i.e. total flow for these months was divided by the number of samples available. For the Kyambul Lagoon dataset this results in the collection of a sample each time 5 ML of water passes an automatic station. During the wet season flows concentrations of water quality parameters are likely to be highly variable with time therefore we have also chosen to make our samples composites. This means that instead of 1 sample collected every 5ML we are in fact collecting four sub-samples (i.e. one every 1.25ML). The advantage of this is that composite samples capture more of the changes that occur during the collection time for each bottle and as such a more representative result is gained (Richards 1999).

The performance of our sampling strategy across four wet seasons is shown in Figure 16. In this figure wet season and dry season sampling is denoted by different colours. This figure illustrates that our 2 phased sampling strategy which combines time based sampling during the dry season and flow based sampling in the wet season appears to be well matched with flow, and presumably water quality, fluctuations.

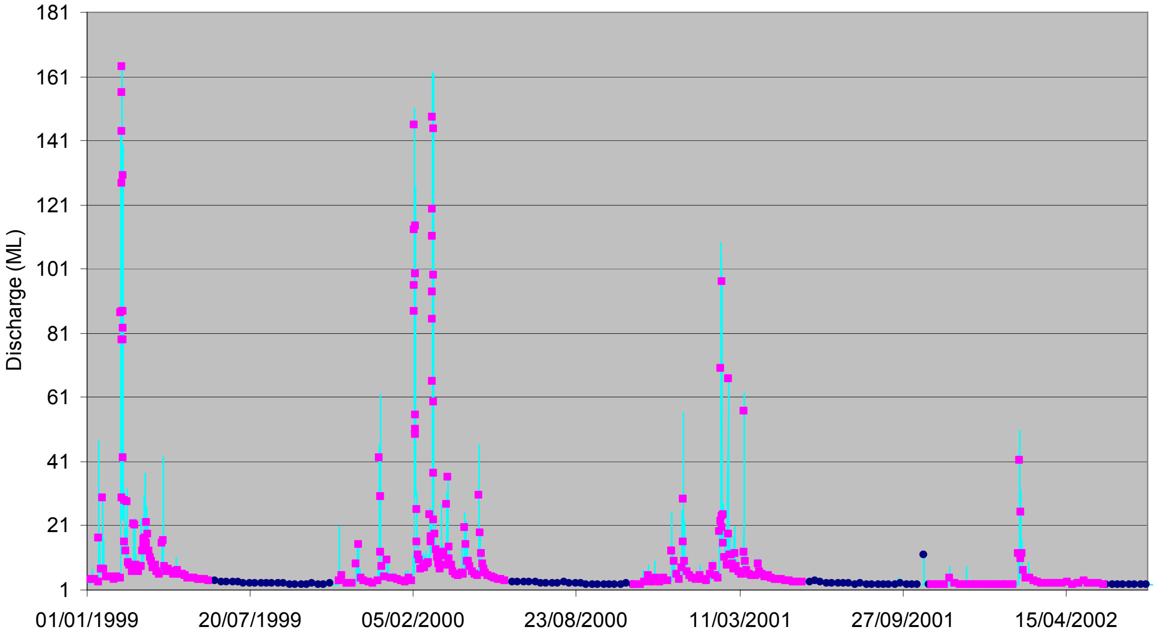

Figure 16. Performance of the wet season (pink) and dry season (blue) sampling strategies on the synthetic dataset.

The performance of the two phase flow paced sampling strategy was also tested on a longer time series (33 years) of flow data and was shown to perform very well. The case for weekly dry season sampling is strengthened by the fact that only a few events occurred during defined dry months. Our ability to remotely control the sampler and modify the sampling strategy enables would enable us to respond to any major dry season events, thus improving confidence in the employment of this less intensive period of the sampling strategy.

The sampling strategy presented here is considered a preliminary strategy and the plan is to implement it and monitor it's performance. As data becomes available the strategy will be refined and improved allowing us to produce reliable load flux estimates.

7. Conclusions

The creation, protection and restoration of wetland systems has been proposed as a means to filter agricultural runoff before it enters the GBR lagoon. Research in temperate locations supports the notion that wetlands are efficient filters, however, similar research in tropical locations is lacking. Some of the characteristics of tropical locations suggest that wetlands in these areas should be efficient filters (i.e. warm temperatures, permanent water), while others characteristics (i.e. seasonality and extreme nature of rainfall) suggest that the filtering ability of these wetlands could potentially be overwhelmed. As such the usefulness of investing in large scale wetland restoration is currently uncertain and some basic underpinning science is required to better inform decision in this area.

Based on the understanding of functions considered important in wetland filtering a conceptual model of the processes likely to be occurring in tropical systems was presented. This model was used to develop a field measurement program and a water quality sampling strategy. Field measurements and sampling were targeted at developing a better understanding the biogeochemical process occurring within a natural tropical wetland while also allowing determination of water, sediment and nutrient balances.

The development of a sampling strategy involved the production of a synthetic dataset for the wetland which resulted in the production of a two phase sampling approach combining both temporal and flow based methods. This preliminary sampling strategy will be implemented and refined over time to enable the filter function of the Kyambul Wetland system in north Queensland to be quantified. Findings from this project will help in the future design and construction of wetland systems in the tropics which will in turn result in better investment of funds available for protection of the GBR lagoon.

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