BLACKWATER AND FISH KILLS IN THE RICHMOND RIVER ESTUARY

DEFINING THE ISSUES – ASSESSING THE RISKS – PROVIDING MANAGEMENT OPTIONS

ANTHONY MOORE

SOUTHERN CROSS UNIVERSITY

TABLE OF CONTENTS

COVER PHOTOGRAPH: Blackwater from a canal entering the Richmond estuary, which is experiencing an acid and aluminium event (Rick Bowie, 1996).

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EXECUTIVE SUMMARY

Floods and fish mortality events are natural phenomena, however significant floodplain modification within the lower Richmond catchment has exacerbated the frequency and scale of these mortality events. Recent community concerns have been raised as to the frequency and scale of recent fish kills and their effects on fisheries and biodiversity. Blackwater is the largest cause of fish mortality events on the lower Richmond River followed by acid discharge from acid sulfate soil landscapes and changes to the estuary and floodplain. The impacts of these issues can be reduced, though some solutions are likely to have significant opportunity costs to the region. In particular the human induced changes to the floodplain and estuary such as the community's implementation of flood mitigation to reduce impacts of regular flooding, changed vegetation to non flooding tolerant species, dredging of drains and canal estates and degraded wetlands all of which impact on estuary and floodplain health.

Solutions to reduce blackwater formation involve changes in landscape management and farming practices. In some cases large-scale investment will be needed in some hot-spot areas to reverse long-term floodplain modification. Some changes are likely to be relatively easy to implement and are already happening, including changes in pasture management to more inundation tolerant species, and changes in harvest and trash management. Further floodplain management should continue and expand the already productive groundwater initiatives such as drainage modification, drain management and addition of groundwater retention structures. More difficult management options include returning areas back to natural wetland ecosystems. This technique should be very specifically targeted to hot-spot zones where other management practices are likely to have little chance of success. Funding could be sought from both State and Federal governments through various environmental and water initiatives. This practice is likely to be very expensive and cause the reduction of farming productivity, however the gains over long time periods are likely to be significant. It should be noted that for some areas, especially backswamp floodplains, remediation to a natural system will not totally eliminate fish mortality events as acid is naturally produced in these areas.

There remains little doubt that blackwater and acid export events are having a significant impact on fishery resources and biodiversity in the lower Richmond River. The loss in productivity remains unquantified, but is likely to significantly impact many important local industries such commercial and recreational fishing, commercial aquaculture, and tourism. Mortality events are also likely to affect other amenities such as, ecosystem function and changes to community structure. If fish kills are allowed to continue at the same rate, or at an increased rate due to climate change, we may see a long-term trend to more simplistic aquatic communities where sensitive species disappear and primary productivity diminishes.

1.0 INTRODUCTION

1.1 Richmond estuary and floodplain

The catchment of the Richmond River is approximately 6864 km^2 and comprises roughly 19 km2 of waterway area. The Richmond system is comprised of both the main Richmond River and a major tributary the Wilson's River (including Coopers Ck, Terania Ck, Goolmangar Ck and Leycester Ck), which converges at Coraki and drains the northern area of the catchment. The Richmond also encompasses many smaller sub-catchments including North Creek, Emigrant Creek (which includes Duck Ck and Maguires Ck), Tuckean Broadwater, Rocky Mouth Creek, Bungawalbin Ck (which includes Jackybulbin Ck and Sandy Ck), and upper Richmond River (including Walshs Ck, Tomki Ck, Shannon Brook and Spring Ck).

In geological terms the Richmond River floodplain and estuary is mature and represents the largest coastal floodplain on the NSW coast. (Hashinmoto *et al* 2006). In terms of catchment floodplain ratio the lower Richmond floodplain is large (1000 km^2) for the size of the catchment, as a result of high rainfall per area (average rainfall for the Richmond 1650 mm/6864 km^2 in contrast to 1072 mm/ 19800 km^2 for the Clarence with a floodplain of 500 km^2 (Walsh et al., 2004). This has major implications for health of estuarine systems like the Richmond in that the wash off from such a large floodplain following summer flooding into the relatively small receiving waters can deoxygenate extensive stretches of the estuary (ABER 2006). In comparison to an estuary like the Clarence where the reverse is the case and the ratio of waterway to floodplain sees an extensive catchment, larger river larger but a less mature and smaller floodplain.

1.1 Blackwater events and fish kills

Fish mortality events associated with flooding in NSW has been witnessed since the early 1900's, though they have only been recorded since the 1970's (Lugg, 2000). Many of the causes of these fish kills are natural processes, however human induced changes to the landscape have significantly exacerbated these processes (Sammut et al, 1996; Roach, 1997 in Corfield). Many of these processes on coastal riverine floodplains lead to the formation of blackwater, a dark coloured water often high in dissolved organic nutrients and depauperate levels of dissolved oxygen. This oxygen-poor blackwater is usually associated with flood events and is a process that often leads to fish mortality events (NSW Agriculture & Fisheries, 1989).

A very significant blackwater and fish mortality event occurred in the lower Richmond River in February 2001 (Figure 1), covering approximately 35 kilometres of river and estuary, from Coraki to the river mouth (Dawson, 2002). As a result of this very large blackwater event dissolved oxygen levels reached 0.03 mg/L, and remained depressed for several weeks. ANZECC (1992) guidelines recommend a minimum dissolved oxygen level of 6mg/L for sustainable fish health. Several weeks after the initial event, dissolved oxygen levels remained significantly depressed at 2.4 mg/L at the river mouth (Dawson, 2002).

Subsequent large rainfall events in June 2005 produced significant large-scale flooding of the Richmond floodplain, but failed to produce large volumes of blackwater and associated fish kill. The following report describes the mechanisms that lead to the formation of blackwater, types of blackwater, their roles in fish mortality events and what can be done to reduce their threat and impacts.

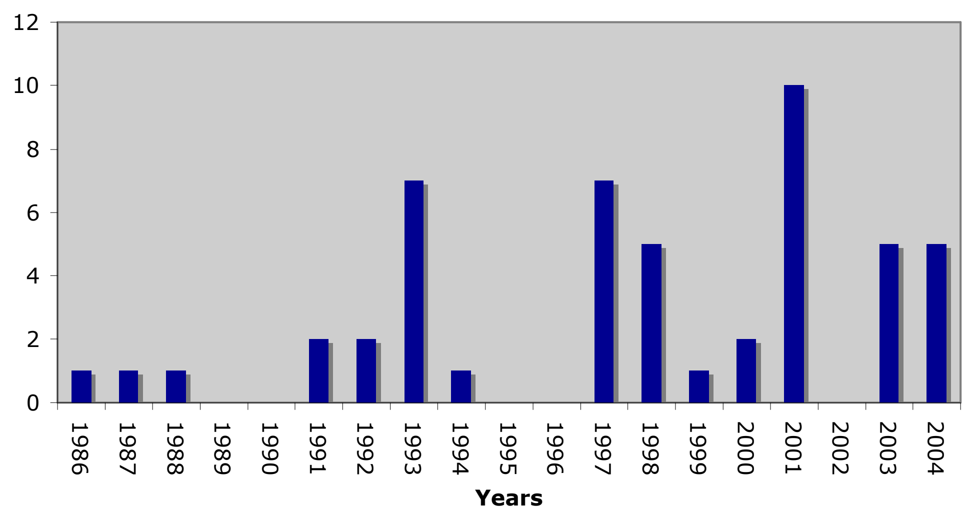

Figure 1: *Fish kill data for the Richmond River estuary from 1986 to 2004; Impact Factor was determined via a numerical weighting system based on the number of events per year and their magnitude (NSW DPI Fisheries Fish kill database).*

2.0 Types of blackwater

Blackwater can be categorised by the processes that lead to its formation. Blackwater events are mostly associated with poor water quality, mainly low dissolved oxygen (DO) and high organic carbon loads. However, not all blackwater events contain poor water quality and may form as a result of humic acids naturally leaching from decaying organic matter. Additionally, the same processes that lead to the formation of blackwater can stimulate the creation of other types of poor water quality. Though this water is typically not black, it poses significant environmental threats and will rely on similar remediation responses. Therefore, each type of blackwater is likely to have different ecological consequences and management options for remediation, which are discussed below.

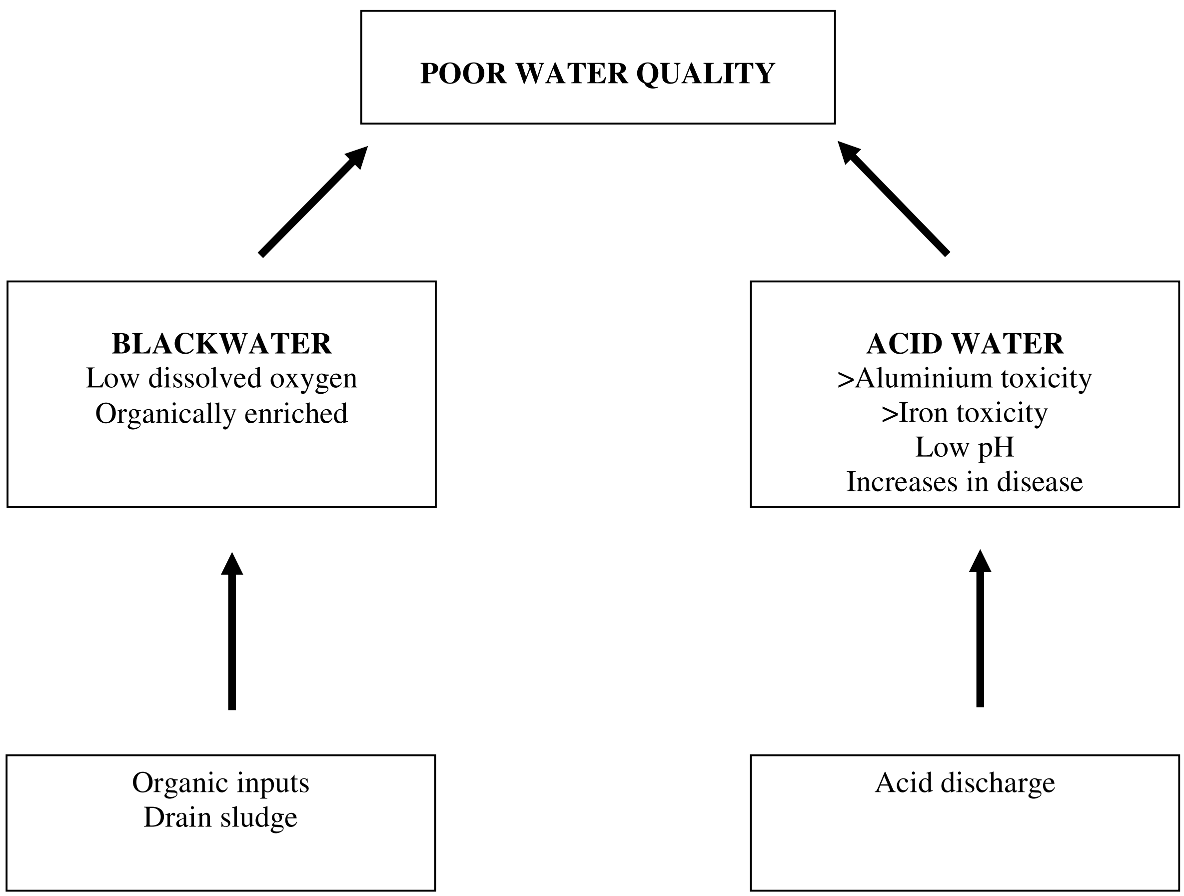

Figure 2: *Distinction between types of poor water quality of the Richmond floodplain.*

2.1 Organic carbon

The inundation of floodplains during peak flow events is likely to lead to the formation of blackwater via the death and decomposition of organic vegetation. These blackwater events have been shown to lead to stress, hypoxia and mortality in fish and crustaceans (Gehrke et al., 1993; Lugg, 2000; Dawson, 2002; Macbeth et al., 2002; Eyre and Kerr, in press; Kerr et al., in press). The expansion of farming over the last century saw a significant change in floodplain vegetative communities, especially from wetland dominated plant communities that could tolerate prolonged inundation, to agriculturally important crops and grazing pastures (Wilkinson, 2000). These crop and pasture species generally do not tolerate inundation by floodwaters and quickly die and decompose (Johnston, 2004). The process of plant decomposition is well known to deoxygenate surrounding waters due to microbial respiration and chemical oxidation (Witkamp, 1963).

Figure 3: *Blackwater entering a coastal river during flood event (Mitch Tulau).*

The rate of cessation in these vegetative communities will vary depending on the species' ability to tolerate inundation, the level of inundation, the length of the wetted period and the temperature. Small rainfall events may cause minor inundation, which will be beneficial to crop and pasture species and the soil profile. However, larger events, where the floodplain becomes inundated for several days, have been shown to lead to the cessation of crop and pasture species (Johnston et al., 2003a). Backswamp areas naturally retain water after rainfall and bank overtopping compared to other parts of the floodplain. Johnston (2004) found the depth, rate and length of inundation and temperature to be most important factors in the cessation of grasses and the loss of groundcover on the floodplain. Areas characterised by slow inundation, comparatively shallow flooding and shorter floodwater retention times, were able to maintain pre-flood levels of groundcover. Areas characterised by rapid inundation, deep flooding (up to 4 m) and longer retention times (several weeks) lost up to 70% groundcover. Wilkinson (2000) found pasture grasses, such as paspalum and couch (common to the Richmond floodplain), can start to decompose within 24 hours of inundation. Paspalum has been found to be more oxygen demanding than couch (Jonhston et al., 2005).

Wetland species are likely to be more tolerant to inundation, however prolonged wetted periods are likely to lead to significant mortality events even within these more tolerant communities (Wilkinson, 2000). Johnston (2004) found that even water tolerant species such as water couch (*Paspalum distichum*) and mud grass (*Pseudoraphis spinescens*) still suffer mortality events during prolonged inundation. Less tolerant species such as common couch (*Cynodon dactylon*) are affected more quickly and to a larger extent (NSW Agriculture and Fisheries, 1989; Wilkinson, 2000).

Additionally, and maybe more importantly from a management perspective, several farming practices leave non-harvest trash on the floodplain. Within the lower Richmond catchment this trash includes slashed pasture, dropped tea tree cuttings and cane harvest trash (Eyre and Kerr, in press). This trash is likely to start deoxygenating immediately upon inundation. Inundation of cow manure from grazing is likely to contribute further to them deoxygenation process.

The rate of oxygen consumption will depend on the prevailing temperature, the vegetation type and labile carbon content. Eyre and Kerr (in press), through laboratory and in situ experiments, found slashed pasture grass (*Paspalum distichum*) and (*Cynodon dactylon*) consumed the most oxygen (225±10 mg O_2 m^{-2} h^{-1}) followed by dropped tea tree cuttings (*Melaleuca quinuenervia*) (138±12 mg O_2 m^{-2} h^{-1}) and harvested cane trash (110±7.5 mg O_2 m^{-2} h^{-1}). Johnston et al., (2005) found litter from tea tree to be high in decay resistant compounds. Wetland species consumed less oxygen than pasture grasses and crop trash.

Over-drainage of floodplain draws water off the floodplain while it is oxidising or shortly thereafter. Waters draining off backswamps and leaving drains often become enriched with iron or organic matter and acidified. The result is often a significant deoxygenation and acidification of receiving waters (Johnston et al., 2003a), which contributes to fish mortality events. Leaving the water on the floodplain until the decomposition and oxidisation process is complete is likely to reduce the impacts on the receiving environment.

2.1.1 Eutrophication of channels

Increased nutrient augmentation in agriculture often leads to the mass loading and eutrophication of receiving waters, especially where flushing is poor. The eutrophication of floodplain drains is quite evident throughout the Richmond system (R. Bush pers. comm.; A. Moore pers. obs.). Freshwater aquatic habitats with high macrophyte density often suffer large diurnal fluctuations in dissolved oxygen (Moore, 2003). These fluctuations can limit the habitability of drains to other aquatic life and increases in macrophyte growth can further limit flow. Dissolved oxygen can be further reduced through the decomposition of organic matter and add to the organic load of the system, which in turn helps in the formation of drain sludges (MBOs) (Luethi, 2004).

Figures 4 & 5: *Eutrophication and choking of drains (Richard Bush, SCU).*

2.1.2 Management options

2.1.2.1 Do nothing

The community response to local fish kills demonstrated at the Flood and Fish Kill 2001– Five Years On meeting suggests that the community does not want the current trend of episodic fish kills to continue. Additionally, local economic and biodiversity impacts are sufficient to warrant change to floodplain management. However, given the long heritage of floodplain modification and the significant impact this has had to abiotic and biotic function, we can expect real changes to the number of fish mortality events to be long-term rather than in the immediate future. The opportunity costs to local communities are likely to be significant. The elimination of a large proportion of blackwater events would require significant physical modification to the floodplain and a significant reduction in existing uses, such as some forms of agriculture, infrastructure and housing. Many of these costs are likely to be too large for regional economies to accommodate and would require State and Federal Government assistance. However, the debate over what opportunity costs are reasonable and which are not has yet to take place. Additionally, even if the floodplain could be returned to a natural functioning wetland similar to pre-modification, fish mortality events are still likely to occur. Any perception in regard to management options needs to be achievable in terms of the scale of sub catchment contributions to poor water quality events. This is an important consideration and is discussed further throughout this report.

2.1.2.2 Return to wetland

Returning the floodplain to a re-naturalised wetland system governed by natural hydrological and ecological processes is likely to have the most positive effect on reducing blackwater and fish mortality events. However, the economic and social costs would be very large. It would require the loss of significant agricultural productivity from the floodplain. It is also likely to require the loss of some infrastructure such as roads, levees and houses. These losses are likely to have significant social consequences within the regional community and are therefore very unlikely to go ahead. For some blackwater hotspots like the Tuckean system, a Government buy-out of the main wetland area may be an appropriate management response.

2.1.2.3 Groundwater management and in-drain structures

The over-drainage of the floodplain has led to the exposure and oxidation of acid sulfate soils and the resultant production of acid in backswamp areas. The reduction of pH in the soil and surface waters often leads to scalding (vegetative mortality). Scalding events add another source of free carbon for export into receiving waters and expose further soil to the oxidative process. This process significantly reduces backswamp productivity.

Reducing drainage and maintaining a higher ground water is likely to limit ASS oxidation, acid production and acid export off the floodplain. The use of in-drain water retention structures such as penstocks, drop board culverts (Leese, 2000) and weirs can be used to adjust the height of ground water and reduce effluent groundwater gradients on the floodplain if strategically placed (Jonhston et al., 2003). These structures can also be used to limit saline water intrusion. Though the natural buffering capacity of saline water is beneficial further downstream, inundation of agricultural land is not desirable and is likely to lead to vegetative mortality events. However, these structures can form a barrier to fish passage during certain flow conditions, though given the likely benefits to water quality, limited fish access to backswamp areas might be a workable compromise.

Figure 6: *Fitting drop-board culvert to maintain low groundwater gradient (DPI).*

2.1.2.4 Wet pasture management

The reduction of groundwater gradients is also likely to increase surface water ponding in backswamps at certain times of the year. This change in hydrodynamics of the floodplain will require a change in vegetation management from dry land to wet pasture management. The change from dry land to wet pasture management is also likely to significantly increase the area and length of growing time of grazing production and limit mortality events caused by inundation. Wet pasture management is also likely to reduce oxidisation of acid sulfate soils and therefore acid production. Wet pasture management can be implemented by a change to native wet pasture grasses such as water couch (*P. distichum*) (Johnston et al., 2003b).

Changes in floodplain vegetation management are most likely to have the greatest likelihood of implementation and positive environmental outcomes with relatively low economic and social costs. Indeed these changes are likely to increase overall yields in backswamp areas where pasture losses through inundation and scalding are high.

Figures 7 & 8: *Freshwater wet pasture management in action (Chrisy Clay, DPI).*

2.1.2.5 Removal of cuttings from slashed pasture/ tea tree

Erye and Kerr (in press) have demonstrated the largest decomposer on the floodplain is slashed pasture used as windrows. They suggest the removal of these cuttings would reduce the organic load on the floodplain. This material is often used as silage for animal fodder, which would make use of the material, giving it an economic value and removing it from the floodplain. Where removal was not viable, the use of comb mowers to cut the grass into finer pieces instead of flail type slashers may accelerate decomposition between flood events. Erye and Kerr (in press) also suggest cane trash is in some cases collected during harvest for sale as mulch or to be burned at the sugar mill to produce power. Tea tree stems and leaf trash could be processed and sold as mulch for urban landscaping. Grazers such as sheep and goats could be used to consume trash where removal is impractical.

2.1.2.6 Alter levees and retain deoxygenated water on the floodplain

Anthropogenic structural changes to the floodplain, such as levee banks, have significantly changed the inundation pattern, hydrology and vegetative communities. The levees were constructed to keep floodwater off the floodplain. Therefore, the duration between flood events over the floodplain has increased and wetland plant communities are now often absent from these areas, having been replaced by dry land species. Eventually, large floods overtop the levee system inundating the floodplain and causing a mortality event in non-wetland vegetation. Re-engineering the levee system will allow more frequent wetting and the reestablishment of wetland plant communities. Additionally, deoxygenated water could be held on the floodplain for longer periods to let the oxygen consumption process be completed before being discharged. However, the cost in infrastructure, lost economic returns to the landholder and community are likely to be high. There are also likely to be human health issues associated with increased mosquito abundance and increased incidence of arbovirus.

2.1.2.7 Floodgate management (A dry weather option)

The strategic opening of floodgates for tidal flushing is likely to have many positive environmental outcomes. Praise must be given for the considerable advances being made by local NRM (Natural Resource Management) agencies, however a long-term commitment with high landholder support is required if this management strategy is to succeed. Continual strategic opening to allow tidal flushing has been shown to buffer acid build-up, reduce eutrophication and clogging of drains with macrophytes, help maintain groundwater levels especially when water retention structures are also used and increase dissolved oxygen levels, which is likely to reduce drain sludge accretion and provide fish access to the floodplain (Anderson, 2000; Johnston et al., 2005). However, given the differing land use practises and attitudes to floodgate management, finding a compromise in some of the larger and more complex systems will be a considerable NRM challenge for the future, but a very worthwhile one.

2.1.2.8 Management options summary

Table 1: *Management options for organic carbon, including economic and social costs and likelihood of implementation.*

MANAGEMENT ACTION	ECONOMIC COST	EASE OF IMPLEMENTATION/ LIKELIHOOD	SOCIAL COST/ TIMESCALE	ENVIRONMENTAL OUTCOME
Do nothing	Low	Straightforward/ High	Low/ Short	Poor
Return to wetland	Very High	Difficult/ Low	High/ Long-term	Excellent
Groundwater management	Low-medium	Intermediate/ Medium	Medium-High/ Medium-long-term	Good
Wet pasture management	Low-medium	Straightforward/ High	Low/ Short-medium-term	Good
Remove cuttings from slashed pasture/tea tree	Low	Straightforward/ High	Low/ Medium-term	Good
Alter levees & retain deoxygenated water on floodplain	Medium	Intermediate/ Low	High/ Medium-term	Good
Floodgate management	Low-Medium	Straightforward/ High	Low/ Short-ongoing	Good

2.2 Monosulfidic black ooze (Drain sludge)

MBO's are organic oozes enriched in iron monosulfides commonly found in coastal floodplain drain sediments. The natural process where MBO's are created is driven by the reduction of organic matter by sulfate-reducing bacteria in sediments producing hydrogen sulfide, which reacts with and precipitates soluble iron (Bush et al., 2004a). In natural undisturbed environments the creation of MBO's is thought to occur in low concentrations, eventually transforming into pyrite.

The formation of monosulfides in drains is most likely due to abundant vegetation reducing surface gas exchange, limiting wind driven mixing and providing large inputs of organic carbon (Luethi, 2004). The supply of carbon in many coastal drains from aquatic vegetation and terrestrial inputs is likely to exceed the aerobic decomposition potential of the system (Stevens, 2002). This excess organic material along with abundant iron from surrounding acid sulfate soils landscapes, creates reducing conditions conducive to the formation of monosulfides (Kerr et al., in press). These monosulfides are likely to continue to accumulate until transported from the system in peak flow events.

When monosulfides are brought into suspension by floodwater runoff they immediately begin to oxidize, consuming oxygen from the surrounding waters (Sullivan et al., 2002). As this is a chemical reaction, the process is very rapid and can deoxygenate large volumes of water in a very short time (Bush et al., 2004b). This process has been implicated as a significant contributor to the 2001 major fish mortality event in the Richmond River. Kerr et al., (in press) have calculated that if all the accumulated drain monosulfides during March 2003 (the highest concentration during their two year study) were animated into the water column and oxidized it would deoxygenate about 21.4 x 10^3 ML of saturated water at 25^oC, which they proposed is 4% of the initial one day peak flow of the February 2001 event.

This research suggests the effects of MBO runoff are likely to be locally significant to the Tuckean-Broadwater (where the highest concentrations of monosulfides are known to occur) (Fyfe, 2001), particularly in the preliminary stages of a flood event, though most likely of only secondary significance in the overall deoxygenation of the lower river and estuary (Kerr et al., in press). The combined impacts of these primary and secondary events, in addition to high water temperatures, excessive flooding throughout the catchment would have easily overwhelmed the assimilation capacity of the receiving system.

Figure 9: *Drain sludge from the Tuckean drain (Richard Bush, SCU).*

2.3 Acid sulfate production (Non-blackwater)

Coastal floodplains are often overlain on marine sediments (<10,000 years BP) high in the sulphides deposited under reducing conditions. Sulphides react with iron in these sediments to produce iron sulfides, such as pyrite (FeS^2). The process of deposition and formation continues in estuaries, coastal lakes and tidal bays throughout the world (Sammut et al, 1996). Coastal floodplains, back swamps, estuarine embayments and coastal wetlands with shallow water table are likely to contain sulfidic sediments. These soils are generally known as Acid Sulfate Soils (ASS) (Tulau, 1999).

Under reducing (submerged anoxic) conditions, iron pyrite is stable. When pyrite is exposed to oxygen through the draining of soils and wetlands (no longer in a waterlogged anaerobic state) it oxidises. The process of oxidisation produces sulphuric acid and other iron forms. When the rate of acid production exceeds the buffering capacity of the surrounding environment (i.e. neutralising capacity of clays and carbonates), the pH is likely to drop significantly (Tulau, 1999). As a by-product, other mineral species are likely to be leaching from the soil such as aluminium. Additionally, the process is likely to significantly affect the soil profile, with aluminium flocculation clay particles that are not easily rewetted causing soil shrinkage (White et al., 1997). When this acid mobilises after rainfall it can cause significant reductions in pH in receiving waters (Hallinan, 1998) and aluminium (Ferguson and Eyre, 1999) prevents the uptake of oxygen across the gills of fish and crustaceans. Additionally, secondary oxydisation of Fe^{2+} consumes oxygen, White et al., (1997), which depletes dissolved oxygen from surrounding waters as detailed by Lin *et al* (2004) in Rocky Mouth Creek in the mid Richmond River estuary.

Small acid discharges from the floodplain into the estuary are likely to be naturally buffered by alkalinity inherent in seawater. However, during large discharges associated with flooding, the estuary has significantly less buffering capacity (Sammut et al., 1996). The result is usually a decrease in pH as tributaries of the river acidify. The acidification of coastal rivers has strong links with dermal infection and lesions on fish and fish mortality events (Callinan et al., 1996; Roach, 1997).

Maintaining groundcover and inundation on ASS are critical to reducing the acidification of the soil and surrounding environment and preventing acid scalds (Rosicky et al., 2003). The removal of vegetative cover increases surface evaporation of soil moisture allowing toxic solutes to build up in the soil surface precipitating ASS scalds (Rosicky et al., 2004). Rosicky et al., (2004) found the main contributors to the removal of vegetative cover on north coast floodplains include fire, flood, flood-scouring, deliberate topsoil removal, surface pyrite oxidisation, saltwater inundation of freshwater paddocks, saltwater exclusion from saltmarsh or mangroves, changes to vegetative regimes, excessive vehicle traffic and overgrazing. These authors suggest floodplain and especially backswamp management needs to ensure soil exposure is kept to a minimum.

The effects of acidification on receiving environments has been documented as the development of stress, behavioural effects (Kroon, 2005), ulcerative diseases (Epizootic Ulcerative Syndrome), breakdown of metabolic processes (Malley and Chang, 1985 in Corfield, 1999), modification of estuarine processes (Kelly et al., 1984) mortality events (Callinan et al., 1993; Callinan et al., 1996; Roach, 1997, Corfield, 1999) and changes in community structure (Neal, 1993; Ferguson and Eyre, 1995) and productivity (Alongi, 1998 in Corfield, 1999). On the floodplain itself acid scalds have been shown to dramatically reduce both total number and species diversity of soil invertebrates (Baker, 1998). Acidification of estuaries is also likely to alter the movement, migration, spawning, nursery colonisation, habitat use, feeding of fish (Kroon, 2005) and significantly decrease available forage sources. Macrobenthic communities, which provide the major forage source for many commercially and recreationally important fish species, have been shown to be significantly effected by acid water discharges (Corfield, 1999). Sedentary and sessile organisms are likely to be significantly affected by acid water plumes as many cannot move, or move too slowly to escape.

Figures 10 & 11: *Epizootic Ulcerative Syndrome infecting two commercially and recreationally important estuarine species, dusky flathead (Platycephalus fuscus) (Dick Callinan, NSW DPI) and yellow fin bream (Acanthopagrus australis) (Mike Cappo, AIMS).*

A by-product of the acidification of soils is the leachate of other minerals including several species of aluminium (Brown et al., 1983; White et al., 1997), which are toxic to fish and other biota (Teien et al., 2006). Under acidified conditions insoluble acid volatile sulphides are replaced by soluble aluminium mono-sulphides (Ferguson and Eyre, 1995). The response of biota is not always related to total amount of aluminium present, but rather to the species of aluminium, which in turn is a result of pH. Aluminium is known to deposit on the gills preventing the transfer of oxygen across epithelial membranes, leading to hypoxia and mortality (Teien et al., 2006). Therefore, in some blackwater events, dissolved oxygen can be at saturation levels, but biota is unable to access it. Corfield (1999) found polychaete abundance was significantly influenced by the chemical speciation of aluminium with varying pH, rather than to either pH or soluble aluminium concentration.

Figure 12: *Blackwater discharge from a drain into the acidified and aluminium rich Richmond River at Swan Bay (Rick Bowie, 1996).*

2.3.1 Management options

The process of formation and remediation for both MBO's and acid production are interrelated, this report will treat them as such.

2.3.1.1 Do nothing

The community response to local fish kills demonstrated at the Flood and Fish Kill 2001 – Five Years On meeting suggests that the community does not want the current trend of episodic fish kills to continue. Additionally, local economic and biodiversity impacts are sufficient to warrant change to floodplain management.

2.3.1.2 Return to wetland

Returning the floodplain to a re-naturalised wetland system governed by natural hydrological processes is likely to have the most positive effect on reducing blackwater and fish mortality events. However, the economic and social costs would be very large. It would require the loss of significant agricultural productivity from the floodplain. It is also likely to require the loss of some infrastructure such as roads, levees and houses. These losses are likely to have significant social consequences within the regional community and are therefore very unlikely to go ahead. For some blackwater hotspots like the Tuckean system, a Government buy-out of the main wetland area may be an appropriate management response.

2.3.1.3 Groundwater management and in-drain structures

The over-drainage of the floodplain has led to the exposure and oxidation of acid sulfate soils and the resultant production of acid in backswamp areas. The reduction in pH within soil and surface waters often leads to scalding (vegetative mortality)

(Baker, 1998). Scalding events add another source of free carbon for export into receiving waters and expose further soil to the oxidative process. This process significantly reduces backswamp productivity.

Over drainage of the floodplain has changed the hydraulic gradient of many systems (Henderson, 1997). However, reducing drainage and maintaining a higher ground water is likely to limit ASS oxidation, acid production and acid export off the floodplain. The use of in-drain water retention structures such as penstocks, dropboard culverts and weirs can be used to adjust the height of ground water and reduce effluent groundwater gradients on the floodplain if strategically placed (Jonhston et al., 2003). Such structures have been shown to reduce the export of acid off the floodplain (Stone, 2005). These structures can also be used to limit saline water intrusion. Though the natural buffering capacity of saline water is beneficial further downstream, inundation of agricultural land is not desirable and is likely to lead to vegetative mortality events. However, these structures can form a barrier to fish passage (Cawley, 1995; Moore, in prep) during certain flow conditions, though given the likely benefits to water quality, limited access to backswamp areas might be a workable compromise.

2.3.1.4 Wet pasture management

The reduction of groundwater gradients is also likely to increase surface water ponding in backswamps at certain times of the year. This change in hydrodynamics of the floodplain will require a change in vegetation management from dry land to wet pasture management. The change from dry land to wet pasture management is also likely to significantly increase the area and length of growing time of grazing production and limit mortality events caused by inundation. Wet pasture management is also likely to reduce oxidisation of acid sulfate soils and therefore acid production. Wet pasture management can be implemented by a change to native wet pasture grasses such as water couch (*P. distichum*) (Johnston et al., 2003b).

Figure 13: *Freshwater wet pasture management of back swamps and the positive effects for production and ecosystem function (G. Wilkinson , Clarence Valley Council).*

Changes in floodplain vegetation management are most likely to have the greatest likelihood of implementation and positive environmental outcomes with relatively low economic and social costs. Indeed these changes are likely to increase overall yields in backswamp areas where pasture losses through inundation and scalding are high.

Figure 14: *Iron staining on the floodplain (Rebecca Lines-Kelly, DPI).*

2.3.1.5 Laser levelling, drain filling and reshaping

The development of laser levelling techniques where crop paddocks can be manipulated to self-drain has enabled the infilling on many drains used by the sugarcane and T-tree industries. The acid sulfate horizon has been shown to be quite shallow in several areas of the Richmond floodplain (Naylor, 1992; Barkwill, 1994).

The shallowing and reshaping of drains so as to raise the drain bed above the acid sulfate horizon has also had a major affect on reducing ASS exposure, oxidation and acid export, particularly in backswamp areas (Johnston et al., 2003b). Infilling and shallowing can also be used to partially restore former wetland floodplain hydrology in backswamp grazing pastures (Johnston et al., 2003b). Both these techniques can be incorporated into an integrated sustainable floodplain drainage management system that not only has considerable environmental outcomes, but is also likely to increase productivity.

2.3.1.6 Floodgate management

The strategic opening of floodgates for tidal flushing is likely to have many positive environmental outcomes (Johnston, 2004). Praise must be given for the considerable advances being made by local NRM agencies, however a long-term commitment with high landholder support is required if this management strategy is to succeed. Continual strategic opening to allow tidal flushing has been shown to buffer acid build-up, reduce eutrophication and clogging of drains with macrophytes, and increase dissolved oxygen levels (Anderson, 2000; Johnston et al., 2003b; Johnston et al., 2005), which is likely to reduce drain sludge accretion and provide fish access to the floodplain. However, given the differing land use practises and attitudes to floodgate management, finding a compromise in some of the larger and more complex system will be a considerable NRM challenge for the future.

Figure 15 & 16: *Drain clogged with macrophytes; Floodgate structure open to allow flushing and fish passage (DPI).*

Figure 17 & 18: *Floodgate obstructing fish passage (Scott Johnston, DPI); Automatic tidal floodgates where floating mechanism closes gate.*

Figure 19: *Floodgate management in action - Reardon' s Canal Swan Bay (M. Wood, RRCC)*

2.3.1.7 Management options summary

Table 2: Management options for acid formation/ discharge and drain sludge accumulation, including economic and social costs and likelihood of implementation.

MANAGEMENT ACTION	ECONOMIC COST	EASE OF IMPLEMENTATION/ LIKELIHOOD	SOCIAL COST/ TIMESCALE	ENVIRONMENTAL OUTCOME
Do nothing	Low	Straightforward/ High	Low/ Short-term	Poor
Return to wetland	High	Difficult/ Low	High/ Long-term	Excellent
Groundwater management	Low-medium	Intermediate/ Medium	Medium-High/ Medium-long-term	Good
Wet pasture management	Low-medium	Straightforward/ High	Low/ Short-medium-term	Good
Laser level cane farms & fill drains	Medium	Low-medium/ High	Low/ Short-medium-term	Good
Modify and shallow drains	Low-Medium	Medium/ Medium-high	Low/ Short-long-term	Good
Manage floodgates for tidal flushing	Low	Straightforward/ High	Low/ Short-long-term	Good

2.4 Humic acid

Blackwater can be generated through natural organic leachates such as tannins and humic acids via the decomposition of organic material (Gehrke et al., 1993). The formation of these tannin stained acidic waters is a natural process in wetlands and is not a known deoxygenation process, and is unlikely to cause fish mortality. Indeed these waters form a significant habitat type in and around coastal heaths and are the most common habitat types in dune wetlands (Pressey and Harris, 1988; Arthington, 1996). These dunal wetlands form critical habitat for several species such as the endangered Oxleyan pygmy perch (*Nannoperca oxleyana*) (Arthington, 1996; Knight, 2000) and one of the smallest and rarest crayfish in the world *(Tenuibranchiurus* spp.*)* (J. Coughran pers. comm.). As the formation of tannin acidic waters pose little threat to aquatic ecosystems during flood events, no management options are considered for this process.

2.4.1 Management options summary

Table 3: Management options for humic acid formulation, including economic and social costs and likelihood of implementation.

MANAGEMENT ACTION	ECONOMIC COST	EASE OF IMPLEMENTATION/ LIKELIHOOD	SOCIAL COST/ TIMESCALE	ENVIRONMENTAL OUTCOME
Do nothing	Low	Straightforward/ High	Low	Excellent

2.5 Seasonal effects

One of the major factors contributing to the generation of blackwater from vegetative decomposition is ambient temperature (Eyre and Kerr, in press). The impact of summer floods is by far the greatest risk of generating large volumes of blackwater and subsequently impacting on the receiving environment. High summer temperatures accelerate the microbial decomposition of organic material when inundated (Johnston, 2004).

Winter floods do produce blackwater events, but are localised in tributaries and generally a MBO driven event. Blackwater produced from carbon decomposition is also on a far reduced scale due to decreased organic microbial decomposition, though a change in season may have little effect on acid water export. This reduced decomposition can depress blackwater events, though it can still produce a sag in dissolved oxygen concentrations < 4 mg/L in the receiving environment (Eyre and Kerr, in press). This sag is likely to stress biota or cause very localised fill kills, but is unlikely to produce large-scale mortality events like those witnessed in summer blackwater events. The June flood of 2005 is a good example of this with no fish mortality but a fall in DO to marginal levels.

The 2001 summer floods in February and March (see graph below) and blackwater event was the most significant fish mortality event recorded in Australia (Walsh et al., 2004) and can be considered the worst case scenario for such impacts on the river. Factors that contributed to such a prolonged and devastating river trauma include ambient temperature, residence time of floodwater on the floodplain, coinciding king tides, wave run-up and setup, low barometric pressure causing higher sea levels and the high intensity rainfall followed by clear hot conditions (35^0 C plus). Water temperatures on the 6th February were found to be 22-30°C (M. Wood, pers. comm.). The primary deoxygenators were from carbon (vegetation decomposition) and drain sludges (MBOs). The 2005 winter flood event in contrast did not produce a mortality event, despite being a similar sized flood. The river experienced a sag in DO (4 mg/L) which is not lethal. The controlling factor is likely to be colder conditions reducing the rate of organic decomposition. However, tributaries like the Tuckean and Rocky Mouth Creek were deoxygenanted by the circulation of sulfide rich drain sludges.

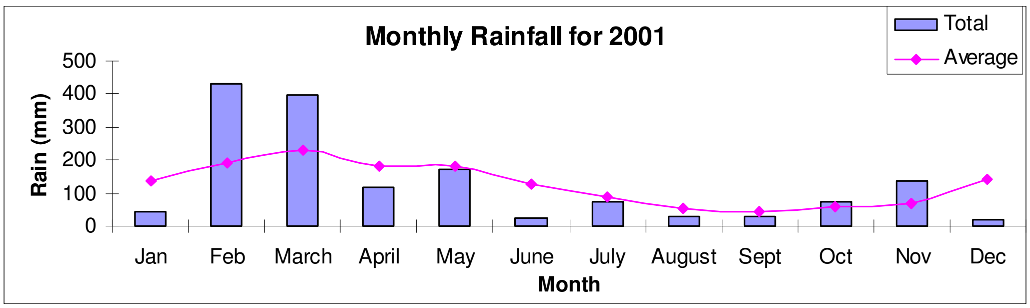

Figure 20. Monthly rainfall figures for Meerschaum Vale, Tuckean Swamp 2001

3.0 RISK ASSESSMENT MODEL

To provide a synopsis of the risk blackwater events pose to local ecosystems, primarily focusing on commercially and recreationally important fisheries and biodiversity, REEHMS (Richmond Estuary Ecosystem Health Monitoring Strategy) have developed a risk assessment model (**see Attachment - A**). The model assesses risk from a sub-catchment perspective, where potential and realised threats are prioritised based on existing knowledge of each sub-catchment and the risk each threat poses to the receiving environment. The model or matrix is based on management zones identified by the REEHMS group in 2000 (**see Attachment - B**). Known research on blackwater and acid sources was used as a basis for scale of impact.

3.1 Rating of sub-catchment contribution/ impact to estuary

3.1.1 Rationale for risk assessment

Initial discussions by the scientific committee identified the difficulty of prioritising catchments in order of impact. This is primarily due to the variability of rainfall and flooding across the floodplain. For example: How much rain fell? Where? And for how long? For example, a Bungawalbyn or Tuckean flood as opposed to other sub-catchment floods. To understand the dynamics better it was recommended that impact modeling that included water quality, vegetation and land-use would provide greater accuracy for predicting scales of impact. The matrix in Attachment A shows sub-catchments like the Tuckean and Bungawalbyn to be capable of impacting extensive sections of the estuary. In the case of the Tuckean research by Southern Cross University shows monosulfidic black ooze concentrations sufficient to deoxygenate the lower estuary and the Bungawalbyn catchment's carbon loading also capable of impacting the mid and lower estuary. Impact modeling noted Slavich 2001 on the most likely major source of the blackwater in the 2001 fish kill was the Bungawalbyn which took over the flow of the Richmond River. Other major sources were Rocky Mouth Creek and as noted above the Tuckean.

3.2 Impacts on Fisheries

The impact of the 2001 flood and subsequent fish mortality event demonstrated that a large-scale anoxic event with a prolonged duration can have catastrophic effects on the receiving system. The event resulted in the cessation of an entire section of riverine ecosystem and the loss of millions of fish and crustaceans (see table 4). The mortality event was ecosystem wide and included yellowfin bream (*Acanthopagrus australis*), dusky flathead (*Platycephalus fuscus*), Australian bass (*Macquaria novemaculeata*), sea mullet (*Mugil cephalus*), sand whiting (*Sillago ciliata*), longfinned eel (*Anguilla reinhardtii*), luderick (*Girella tricuspidata*), southern herring (*Herklotsicht castelnaui*), sole (*Achlyopa nigra*), forktail catfish (*Arius graeffei*), eel tail catfish (*Tandanus* sp.), bullrout (*Notesthes robusta*), school prawns (*Metapenaeus macleayi*), mud crabs (*Scylla serrata*), worm (*Australonereis ehleersii*) (Macbeth et al., 2002; Walsh et al., 2004), bull sharks (*Carcharhinus leucas*), and various unidentified gobies (A. Moore pers. obs).

However, impacts on many other sessile, benthic and small biota would likely have gone unnoticed due to generally being inconspicuous. Therefore the impact of these episodic catastrophic mortality events is not only likely to affect commercially and recreationally important groups. There may be other, longer-term effects on those important groups, that aren't immediately evident after the initial event, but may stem from complications associated with the loss of these smaller biota.

Table 4: *Reported species and mortality abundance data for the 2001 Richmond event.*

Reproduced from Walsh et al., (2004)

Species	**Estimated numbers of each species killed in 2001 blackwater event**							
	<2000	<5000	<10000	<30000	<150000	<300000	<500000	<1000000+
Prawn (*Metapenaeus macleayi*)*								√
Worm (*Australonereis ehlersi*) ^							√	
Bream (*Acanthopagrus australis*)* #						√		
Flathead (*Platycephalus fuscus*)* #					√			
Herring (*Herklotsicht castelnaui*) ^				√				
Bass (*Macquaria novemaculeata*) #			√					
Eels (*Anguilla reinhardtii*)*			√					
Mudcrab (*Scylla serrata*)* #			√					
Mullett (*Mugil cephalus*)* # ^			√					
Whiting (*Sillago ciliata*)* #			√					
Sole (*Achlyopa nigra*) #		√						
Luderick (*Girella tricuspidata*)* #		√						
Catfish (*Tandanus* sp.) #		√						
Bullrout (*Centropogon marmoratus*)	√							
Catfish (*Arius graeffei*)	√							

**denotes commercially important species & # denotes recreationally important species & ^ denotes bait and forage species in the Richmond system*

***Table 5:** Species common to the Richmond and likely to be affected by fish mortality events.*

Common name	Scientific name	Common name	Scientific name
Flat tail mullet	*Liza argentea*	Eastern King prawn	*Penaeus plabejus*
Fan tail mullet	*Valamugil georgii*	Giant Tiger prawn	*Penaeus monodon*
Sand mullet	*Myxus elongatus*	Tiger prawn	*Penaeus esculentus*
Tarwine	*Rhabdosargus sarba*	Rock prawn	*Macrobrachium sp.*
Tailor	*Pomatomus saltatrix*	Glass prawn	*Acetes sp.*
Sand flathead	*Platycephalus arenarius*	Greasyback prawn	*Metapenaeus bennettae*
Happy moment	*Siganus nebulosus*	Pebble crab	*Ixa inermis*
Black sole	*Aesopia microcephalus*	Soldier crab	*Mictyris longicarpus*
Peppered sole	*Aseraggodes* sp.	Coral crab	*Charybdis cruciata*
Lemmon-tongue sole	*Paraplagusia unicolor*	Blue swimmer crab	*Portunus pelagicus*
Large-tooth flounder	*Pseudorhombus arsius*	Snapping shrimp	*Alpheus* sp.
Common toadfish	*Tetractenos hamiltoni*	Carid prawn	*Caridea* sp.
Smooth toadfish	*Tetractenos glaber*	Hardy head	*Atherinomorus ogilbyi*
Stripey	*Microcanthus strigatus*	Australian anchovy	*Engraulis australis*
Trumpeter	*Pelates quadrilineatus*	Pacific blue-eye	*Pseudomugil signifer*
Spotted scat	*Scatophagus argus*	Silver trevally	*Pseudocaranx dentex*
Silver batfish	*Monodactylus argenteus*	Giant trevally	*Caranx ignobilis*
Moses perch	*Lutjanus russelli*	Big-eye trevally	*Caranx sexfasciatus*
Ambassid	*Ambassis marianus*	Bridled goby	*Arenigobius bifrenatus*
Mulloway	*Argyrosomus japonicus*	Longfin pike	*Dinolestes lewini*
Fortescue	*Centropogon australis*	Sandy sprat	*Hyperlophus vittatus*
Freshwater herring	*Potamalosa richmondia*	Common stingray	*Dasyatis* sp.
Stink fish	*Foetorepus calauropomus*	Whiptail ray	*Dasyatis* sp.
Snub-nosed garfish	*Arrhamphus sclerolepis*	Eagle ray	*Myliobatis australis*
River garfish	*Hyporhamphus regularis*	Crescent perch	*Terapon jarbua*
Sea garfish	*Hyporhamphus australis*	Stargazer	*Ichthyscopus lebeck*
Yellowtail scad	*Trachurus novaezelandiae*	Anglerfish	*Antennariidae* sp.
Dart	*Trachinotus coppingeri*	Smooth Flutemouth	*Fistularia commersonii*
Javelin fish	*Pomadasys kaakan*	Pipefish	*Syngnathid* sp.
Queenfish	*Scomberoides lysan*	Handfish	*Bachionichthys* sp.
Oxeye herring	*Megalops cyprinoides*	Various blenny	*Blenniidae* sp.
Mud flathead	*Suggrundus jugosus*	Flathead gudgeon	*Philypnodon grandiceps*
Bottle squid	*Loliolus* sp.	Estuarine catfish	*Cnidoglanis macrocephalus*
Silver biddy	*Gerres subfasciatus*	Australian mado	*Atypichthys stringatus*
Triple tail	*Lobotes surinamensis*	Sandy goby	*Favonigobius tamarensis*
Shortfinned eel	*Anguilla australis*	Spotted sand dragonet	*Repomucenus calcaratus*
Hairtail	*Chelidonichthys kumu*	Dwarf gudgeon	*Philypnodon* sp.
Freshwater mullet	*Myxus petardi*	Striped catfish	*Plotosus lineatus*
Narrowlined puffer	*Arothron manillensis*	Weeping toadfish	*Torquigener pleurogramma*
Flagtail flathead	*Platycephalus endrachtensis*	Longtom	*Tylosurus gavialoides*
Mangrove jack	*Lutjanus argentimaculatus*	Snapper	*Pagrus auratus*

**data from Macbeth et al., 2002 and A. Moore unpublished data*

The absence of mortality data for many of the species known to inhabit the Richmond estuary (Table 5) is likely to be as a result from the combination of the visual census technique used, the delay between the mortality event and census and the inconspicuousness of certain groups. It is common for only a fraction of the fish killed to be directly counted as many are carried offshore or consumed by carnivores, many are small and inconspicuous, not all dead biota floats, and only certain groups are easily seen when floating (Labay and Buzan, 1999). Identification after a few days also becomes difficult, highlighting the need for a rapid response. Therefore, counts made by visual census are often gross underestimates of the total mortality event.

The fish kill resulted in the closure of Richmond River to commercial and recreational fishing for 3 months. There remains little data on how well the ecosystem has recovered after the 2001 mortality event, especially for species that are not commercially or recreationally harvested. Whilst anecdotally the recovery of various species is noticed through some recreational and commercial catches there is also comment of little recovery. The full impact of these catastrophic entire ecosystem events on fisheries and biodiversity is still poorly understood, though likely to be significant and long lasting. A post fish survey suggested that some species of estuarine fish and crustaceans were recovering (Macbeth et al., 2002), though the impact on population dynamics, recruitment, and ecosystem function were not tested. These questions remain unanswered.

The Richmond River estuarine ecology has evolved to cope with a highly changeable environment, however, anthropogenic cause a widening of environmental extremes (ABER 2006). To assess the impact of blackwater on the fish communities is very difficult due to the confounding effects of both large-scale episodic events and smaller scale chronic pollution. Large-scale events, as evidenced by the 2001 flood, have catastrophic effects for the receiving environment causing a whole aquatic ecosystem cessation event. However, the system also has to contend with ongoing chronic water quality issues like eutrophication via nutrient enrichment, increased sediment loads and natural and human mediated pollutants.

The ability of any particular environment to cope with stochastic perturbations will be a function of its pre-existing health, the specific environmental fluctuation, synergistic interactions with other events/ pollutants and the adaptive potential of the receiving ecosystem (Connell et al., 1999). Each contributing event/ pollutant is likely to compound the effects on the receiving environment. If repeated events occur too frequently they may overwhelm the ability of the system to recover in its entirety, resulting in either lower overall fishery productivity and/ or a more simplistic aquatic ecosystem, with an absence on key species (Fleeger et al., 2003). This in turn could alter the species composition and ecosystem function if missing groups included keystone species. The loss of keystone species (species imperative to the function of an ecosystem) has been known to lead to trophic cascade effects and a further simplifying of ecosystem function (Fischer et al., 2006). In their review of the topic, Fleeger et al., (2003) found 60% of manipulative studies of contaminant/ ecological response demonstrated significant trophic cascades. Identifying keystone species and there roles is often difficult (Petchey, 2004; Libralato et al., 2006) and has not been studied in north coast estuaries. This is a very real concern for the Richmond system given the inherent chronic issues and the frequency and magnitude of episodic blackwater events.

3.2.1 Chronic effects on reproduction, migration and movement

Small-scale or chronic blackwater events that occur within distinct parts of the catchment are likely to have very immediate and localised effects. Many commercially and recreationally important fish species are highly mobile and actively avoid poor water quality (Kroon, 2005). However, the timing and location of these events may be very important for breeding, recruitment, movement, migration, colonisation and foraging of estuarine fish species.

Chronic discharges or localised blackwater events have the potential to interrupt the migration and reproductive process of estuarine or catadromous species. For example, Australian bass migrate downstream from freshwater to the estuary from May to August to spawn. The species, as a relatively recent marine derivative, relies on the correct salinity (12-17ppt; 11-18^{o}C) for sperm motility and egg buoyancy (Harris and Rowland, 1996). A localised blackwater event in this area may significantly impact on the mortality of spawners, gametes or juveniles or in sublethal cases may stifle the reproductive process. Chronic discharges are thought to alter migration to and from breeding habitats in the Richmond system. The confluence of Bungawalbyn Creek and the Richmond River episodically suffers acidification (Davison, 2001), which appears to create an impenetrable barrier to fish movement (A. Moore, pers. obs.). Due to the hydrology at the confluence of these systems, this often large slug of water becomes trapped and is tidally pumped back and forth for several weeks. This acidic plume is thought to limit the recruitment of both adult and juvenile bass back into the system after migration, which in some years has a very drastic effect of the fishery (A. Moore pers. obs.). Additionally, poor water quality is thought to drive bass further downstream in some years where they come into contact with commercial fishing nets. Bass are not a commercial species, and can be problematic for commercial fishers, whilst impacting spawning fish and recruitment.

Chronic discharges of poor water quality may impact on the movement of juvenile fish and crustaceans into nursery habitats or push them out once they are established. For example (Kroon, 2005) has shown the movement of juvenile commercially and recreationally important fish and prawn species can be affected by chronic acid water discharge. These changes in behaviour may alter recruitment patterns of nursery environments, leading to impacts on recruitment levels and overall fisheries production. Additionally, these chronic discharges may well prevent re-colonisation of denuded areas that have been created by large mortality events. Again this may influence productivity at certain locations and overall estuarine productivity for the system.

3.2.2 Effects on prawns

Several commercially and recreationally import prawn species including school (*Metapenaeus macleayi*), eastern king (*Penaeus plebejus*), tiger prawn (*P. esculentus*), giant tiger prawn (*P. monodon*) and greasyback prawn (*M. bennettae*) are likely to be affected by chronic discharges and blackwater events. Laboratory based research has demonstrated avoidance of acidic water for the school prawn (Kroon, 2005), however, these experiments were conducted in a fluviarium with no substrate. The response of prawns to the toxicant (acidic water) may have been different if the prawns could bury into the substrate as they do naturally. Additionally, prawns are generally known to bury in the sediment throughout the day, feed during the night and move during certain moon phases. This behaviour raises questions about movement ability and response times to blackwater events. Mortality may be far higher in prawns (compared to fish that rapidly move) if they are unwilling to move until the correct moon phase. This may be the reason why so many prawns were killed during the 2001 event (Table 4).

3.2.3 Episodic and chronic effects on feeding behaviour

The reduction of benthic invertebrates as a result of the 2001 and subsequent mortality events is likely to have real consequences further up the food chain. A lack of forage species may well prevent the re-colonisation of habitats until prey abundance recovers. This relationship is likely to be a threshold effect where prey species do not have to fully recover, but increase in density to a point where it is worth a predator's time to feed in the area. The model of blackwater event, mortality and recovery is likely to fit a source sink population model, where re-colonisation occurs from unaffected sink populations. An alternative hypothesis would be an evolutionary response, where individuals that survived the selective event (blackwater event) recolonised denuded areas. Re-colonisation of benthic invertebrates may take longer in some locations, for instance areas close to chronic inputs, blackwater hotspots or areas a large distance from the source population. For example, polychaete (*Notomastus torquatus and Nephtys ausrtaliensis*) abundance in the Tuckean broadwater was significantly influenced by bio-available species of aluminium as a result of decreased pH (Corfield, 1999). In some cases chronic inputs or areas that are frequently affected may never fully recover, with productivity remaining depressed. Decreased crustacean productivity due to acid inputs has been found in the aquaculture industry and is believed to be as a result of disruption of calcium uptake during moulting, leading to reduced growth and increased mortality (Alongi, 1998 and Malley and Chang, 1985 in Corfield, 1999).

3.2.4 Rationale for risk assessment

The rationale behind the risk assessment model for fisheries was based on the premise that: 1) whole of catchment blackwater events are likely to be catastrophic to the system; 2) certain areas are far more vulnerable to disruption of migration, spawning, feeding, etc.; 3) certain areas have higher abundances of commercially and recreationally important species present; and 4) there are distinct hotspots for blackwater and chronic inputs.

3.3 Impacts on biodiversity

Prolonged blackwater events like 2001, are whole of system events, which have impacts on the entire ecosystem. The impacts of these large-scale events is well known to cause mortality events, however they are also likely to cause disruption to ecosystem function far beyond the period directly around the flood event. Unfortunately, there are no studies of large-scale ecosystem function and a very poor understanding of the role of many species. We really only have small-scale studies, usually single species interactions between the biotic and abiotic environment. There remain no long-term studies to determine point source, chronic or episodic impacts on aquatic biodiversity over meaningful time scales. There is also little information on recruitment and recovery for the vast number of unexploited estuarine species. This lack of data makes benchmarking for before and after impact comparisons impossible. Only a long-term monitoring program will provide robust evidence of impact and processes.

3.3.1 Invertebrate and benthic communities

Only two invertebrates (school prawn *Metapenaeus macleayi* and the polychaete *Austalonereis ehlersi*) were documented in the 2001 fish kill data (Walsh et al., 2004). Surveys of the lower Richmond estuaries highlighted at least 5 commercially and recreationally important prawn species and 20-30 macro and micro-benthic species (see Corfield, 1999 for an in depth species coverage). Despite the paucity of mortality data for other invertebrate groups, it is very unlikely these species were unaffected, but rather is more likely indicative of the cryptic nature of these organisms. It is true that macro and micro-benthic communities fluctuate with natural flood events due to the input of freshwater, however the contribution of blackwater events is likely to be substantial and should not be ignored (J. Corfield pers. comm). The contribution of groups like mysid shrimps have been shown to play a very significant role in the early diet of estuarine species like mulloway (M. Taylor pers. comm.) and a lack of these species at particular times may retard recruitment of certain species.

3.3.2 Rationale for risk assessment

The rationale behind the risk assessment model for biodiversity was based on the premise that: 1) biodiversity increases downstream; 2) impacts are not only based on obvious mortality but include cryptic mortality, sublethal effects, and disruptions to ecosystem function; and 3) there are distinct hotspots for blackwater and chronic inputs.

3.4 Environmental monitoring

Despite the obvious consequences of blackwater events (lots of moribund or dead fish in certain areas) there remains a paucity of data on chronic issues and other factors including changes in ecology, behaviour, reproduction, recruitment, feeding, productivity and ecosystem function. Additionally, our understanding of recolonisation, specifically what species recover in what timeframes and how long it takes for ecological communities to stabilise. Some long-term studies of flood impact have demonstrated that species recolonisation may not plateau for up to five years post event and full stability was still not been reached after nine years (Saenger et al., 1988).

It is often very difficult to measure and tease apart complex relationships like ecosystem function or in-situ behavioural changes and how they relate to biology and ecology. A more practical approach is local abundance measures of key species. Taken in specific locations, including around hotspots, these data can be compared over long time periods and pre/ post event. However, because general species abundance varies due to many other biotic and abiotic factors, community abundance measures are often poor indicators of change or impact. To ultimately define impact, key indicator species should be used. The indicator species would need to be susceptible to the same impacts as the community in question, though may be more or less sensitive, and occur in reasonable densities throughout the study sites. Ideally, the indicator species should be fairly stable over long periods with the variable (pollutant) in question the major influence. A scoping study would be required to determine a suitable indicator species.

3.5 Climate change

Global climate change is expected to increase the number of flooding events, though the period between flooding is expected to be drier for longer. The consequences of these climatic variations on local flooding and formation of blackwater events is likely to be considerable. The formation of acid water is likely to increase through the dry periods as the soil moisture content is drawn down. Drain sludges (MBOs) are also likely to accumulate to larger levels as a by-product of the acidification process and reduction in flows and flushing events. Decreased flows often lead to lower DO concentrations, especially if drains have become eutrophied, which may increase anoxic conditions, needed for sludge formation. Increased frequency of heavy rainfall and floodplain inundation is likely to continue or exacerbate issues relating to vegetation cessation, and decomposition. Therefore, the frequency of blackwater events is likely to increase if the current trend of floodplain use continues.

4.0 RECOMMENDATIONS

Slavich (2001) identified seven recommendations which in part are mirrored in the recommendations of this report, listed below. In terms of adoption and implementation there is already a concerted effort by local government, agencies, industry and NGO. To realise a ramping up of effort it will be important to recognise different time frames depending on availability of resources, answers to important research to give direction for on-ground works and community acceptance of responsibility for the past, recognition of current works and support future management and recognition of what is practical and realistic for the sustainable management of the Richmond River estuary and floodplain.

1. Continue and expand current groundwater management on the floodplain to lower groundwater gradient and keep ASS inundated – using dropboards, penstocks, weirs, etc. (Groundwater management is a key strategy in ASS management but there is very little information on groundwater movement and behaviour)

2. Continue, expand and monitor current floodgate management program on the floodplain (tidal flushing in dry weather has tangible outcomes but is quickly overwhelmed during runoff events. Tidal flushing can be more effective if complimented with groundwater management options).

3. Continue to encourage and develop wet pasture management across the floodplain, with particular emphasis on back swamps (this can produce long-term management outcomes although not practical in cropping areas. Saltwater inundation in areas of actual acid sulphate soils is not recommended even in areas previously exposed to saline incursion. (New research shows extensive ground surface scalding results)

4. Continue to encourage and develop integrated sustainable floodplain drainage management system with the use of laser levelling, drain infilling and shallowing (Laser levelling is industry specific e.g. cane farming. Drain modification or infilling has real and effective outcomes)

5. NRM agencies should increase and augment funding either internally or through a number of environmental granting agencies

6. Encourage and develop cut pasture and crop management to reduce excessive organic inputs from the floodplain (Remove cuttings and slashed grass from pastures. Baling of cut pasture is an option. Wide scale adoption is questionable without economic return).

7. Implement a scoping study to determine an appropriate aquatic indicator species. (Little or no information exists and anecdotal data is not robust or scientifically reliable).

8. Instigate a more comprehensive biological monitoring program to assess the chronic and episodic impacts on biodiversity and fisheries

9. Investigate strategic purchase through federally funded buy-out schemes for hotspots like the Tuckean and important remnant wetland systems.

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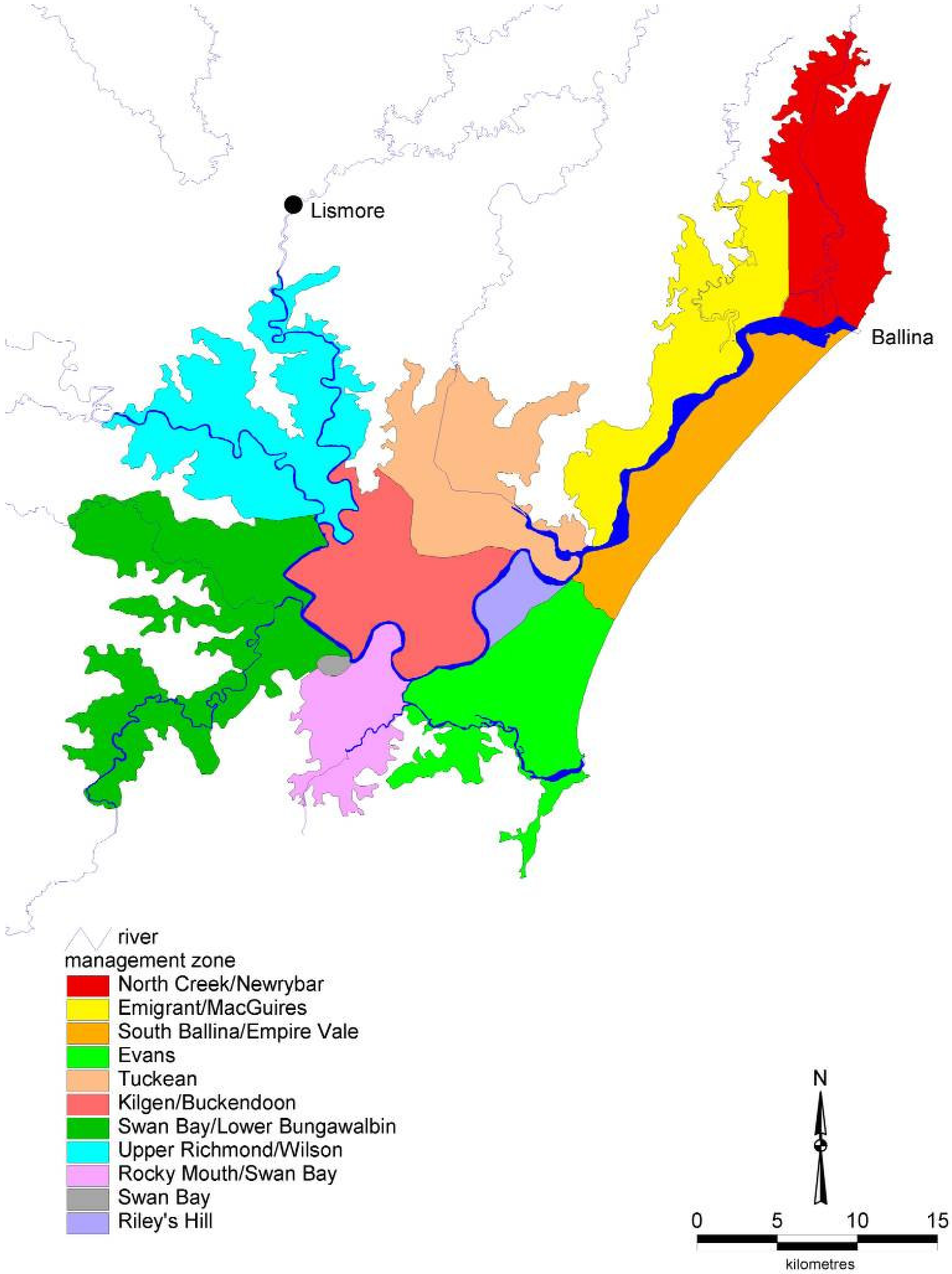
ATTACHMENTS

1. *Risk assessment matrix*
2. *management zone map*

Sub-catchments	*Water quality problems*			*Impact on fisheries/biodiversity*				*Actions to date*				
	Acid water	*Blackwater from drain sludge*	*Blackwater from rotting veg*	*Impact upon fisheries*	*Impact upon Biodiversity*	*Localised impacts around floodgates*	*Impact upon entire estuary*	*Education effort by agencies & council*	*Site specific management strategies identified*			*Management strategies implemented*
									Acid water	*Blackwater from drain sludge*	*Blackwater from rotting veg*	
Tuckean	*h*	*h*	*h*	*h*	*h*	*h*	*h*	*h*	*yes*	*yes*	*no*	*partially*
Rocky Mouth Creek	*h*	*m*	*h*	*h*	*h*	*h*	*m*	*h*		*yes*	*partially*	*partially*
Sandy Creek / Bungawalbyn	*m*	*m*	*h*	*h*	*h*	*h*	*h*	*h*	*yes*	*yes*	*partially*	
Kilgin / Buckendoon / Dungarubba	*h*	*l*	*m*	*h*	*h*	*h*	*m*	*m*	*partially*	*yes*	*partially*	*partially*
Swan Bay	*h*	*h*	*l*	*m*	*h*	*m*	*l*	*m*	*partially*	*partially*	*no*	*partially*
North Creek/Newrybar	*m*	*m*	*m*	*m*	*m*	*m*	*l*	*l*	*no*	*partially*	*no*	*partially*
Emigrant / McGuire's Creek	*m*	*l*	*m*	*l*	*m*	*m*	*l*	*l*	*no*	*no*	*no*	*nil*
Lower Wilson/Richmond	*l*	*l*	*h*	*l*	*l*	*l*	*m*	*l*	*no*	*no*	*no*	*nil*
Sth Ballina / Empire Vale	*l*	*l*	*m*	*m*	*m*	*m*	*l*	*m*	*partially*	*no*	*no*	*partially*
Back Channel	*l*	*l*	*l*	*l*	*l*	*l*	*l*	*l*	*no*	*partially*	*no*	*partially*
Evans	*l*	*l*	*l*	*l*	*l*	*l*	*l*	*l*	*no*	*no*	*no*	*partially*
Riley's Hill	*l*	*l*	*l*	*l*	*l*	*l*	*l*	*l*	*no*	*no*	*no*	*nil*


Lismore
Ballina
river
management zone
North Creek/Newrybar
Emigrant/MacGuires
South Ballina/Empire Vale
Evans
Tuckean
Kilgen/Buckendoon
Swan Bay/Lower Bungawalbin
Upper Richmond/Wilson
Rocky Mouth/Swan Bay
Swan Bay
Riley's Hill
N
0
5
10
15
kilometres