FACTORS AFFECTING THE ECOLOGY OF THE ANGLESEA RIVER

FINAL REPORT FOR THE CORANGAMITE CATCHMENT MANAGEMENT AUTHORITY

FINAL REPORT

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CORANGAMITE CMA

CAPIM

CENTRE FOR AQUATIC POLLUTION IDENTIFICATION AND MANAGEMENT

Factors Affecting the ecology of the Anglesea River

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1 Executive summary

The Victorian Centre for Aquatic Pollution Identification and Management (CAPIM) was engaged by the Corangamite Catchment Management Authority (CCMA) to assess the ecological resilience of the Anglesea River and estuary in relation to acid sulphate soil and acidic flush events.

The Anglesea River estuary is part of the Anglesea catchment, a small catchment in south-west Victoria lying within the Otway basin. The Anglesea River is characterised by swampy tidal flood plains which are split by a ridge at the Great Ocean Road. The Victorian coast line is considered microtidal with tides on average reaching one metre and neap tides reaching 0.3 m. At Anglesea, the main process that affects the estuary is wave action. This wave action contributes to the net along-shore transport of sand. This can result in a build-up of sand within the vicinity of the Anglesea River estuary mouth, which in times of low river flow creates a sand bar which closes the river mouth. During high flow events, river water builds up until it spills over the sand bar, scouring a channel to the sea.

There are a number of significant man-made modifications that have occurred within the Anglesea River estuary. After the 1983 fires Coogoorah Park was created as a bush reserve and recreational area. A fifty year old brown coal mining operation is currently providing power to the Alcoa smelter in Geelong and is located in the the lower portion of the Anglesea catchment, above the estuary.

Soils that contain iron sulphides are commonly referred to as acid sulphate soils (ASS). In coastal environments, Sulphidic sediments are formed in vegetated, tidal environments when sulphate from sea water is reduced to sulphides by microbial activity; the most common being pyrite. In Victoria, these iron sulfide layers commonly occur well below the soil surface within the soil saturation zone or below the watertable. These soils were likely formed in the last 10,000 years.

When left undisturbed and submerged by groundwater, pyrite is chemically inert. When soil dries out during drought, pyrite oxidizes in the presence of oxygen and hydrogen to form sulphuric acid. If the acid-buffering and neutralising capacity of the soils is exceeded, soils will become acidified. The rate at which pyrite is oxidised tends to be closely linked with pH, with oxidation increasing as pH decreases, and is usually only limited by the rate of supply of oxygen.

When small acid discharges enter an estuary such as the Anglesea River, the natural alkalinity or acid-neutralisation capacity of the estuary can usually buffer these changes in pH, however after flood events or prolonged rainfall, drainage from acidic areas can reduce alkalinity of estuaries and acidify tidal reaches. The influence of tidal exchange on acidification of estuaries and receiving waters is important, since the tidal exchange can marginally buffer acidic events. When the estuary mouth is open, it enables the acidified estuarine waters to mix with seawater which contains calcium carbonate that buffers the low pH, returning it to a more neutral level. However, this report has not assessed the ecological or potential acid generation impacts of artificially opening the estuary which are likely to be significant.

The oxidation of sulphidic materials can lead to heavy metals such as cadmium and lead and metalloids such as arsenic becoming more available in the environment. Waterways can change colour due to the release of iron or aluminium when the acidity of the water increases. Flocculation of metals results in crystal clear waters due to soil particles falling out of the water column. The increase in clarity will create an increase in the temperature and this can also increase the amount of light penetrating the water; this in turn will increase algal production within the water column and on the sediment. In addition, flocculation may also smother benthic habitat and deplete dissolved oxygen, resulting in changes to the water chemistry at the sediment / water interface.

An obvious effect of ASS on waterways is mortality in resident fauna (ie. fish and macroinvertebrates), whilst secondarily, or less obvious impacts can include die back and growth inhibition of seagrass communities, death of smaller microinvertebrates and impaired health and condition of riparian vegetation due to poor water quality. The overall impact is a change in food web dynamics and ecosystem health.

A common impact of lowered pH on fish, macroinvertebrates and seagrass are physiological changes. For instance, damage to the outer epithelial layers of skin, gills or cuticle, mucus membranes and other external respiration organs can often occur. Such damaging effects can lead to increased susceptibility to disease and infection from pathogens and subsequent weakened immunity, which may cause reduced fitness and ultimately increased risk of mortality. In addition, if algal blooms occur when biota is stressed from damaged respiratory tissues, they are at an even greater risk of mortality. Reproduction is also likely to be affected when conditions change, through either a reduction in the number of viable gametes that are produced and resultant lowered fertility, or through adverse effects on the vulnerable early life stages (such as reduced hatch rates, increased rates of deformity and lower larval survival). In addition to changes in pH, exposure to elevated heavy metal concentrations can also cause toxic effects in biota. For organisms that have exposed gills filaments such as fish and some invertebrates, they are likely to be the most sensitive to changes in pH and are most likely to be negatively affected.

When metals such as aluminium settle out and flocculate, seagrass meadows and biota such as non-mobile macroinvertebrates, and low-mobility snails can be smothered leading to mortality. This biota is essential in maintaining healthy, stabilised habitat; therefore its loss is likely to lead to such areas becoming barren and anoxic.

Changes to water quality in estuaries such as the Anglesea River can lead to a reduction in sensitive species, resulting in an unbalance to the system. A situation may arise whereby predators are removed, and thus prey can become overly abundant and change the dynamics of that system until predators return. It is likely that species that have adaptation to low pH conditions will have increased survival as these conditions arise. Avoidance of low pH conditions depends on the mobility and chemosensory abilities of the species. In open estuaries, black bream have been shown to go out to sea during periods of high rainfall and flood events and this indicates for instance, that in Anglesea, when acidic conditions arise after large rain events, this species may be able to avoid the primary acid slug by going out to sea (assuming the estuary mouth is open).

The acid events in the Anglesea River are the result of natural process. If the water within the Anglesea River is frequently exposed to low pH conditions, it is possible that fish or other biota within the system may, over generational time periods, build up some resilience to those conditions.

This review identified knowledge gaps in relation to our understanding of how the ecology of a system will be altered in response to changes in water quality associated with ASS. Although we have a general understanding of what species exist in local estuaries, little research has been carried out on the impacts that episodic changes to water quality have on these species. Before changes to management practices are considered, the risk to the overall biological impact on the system needs to be considered, as this was not assessed in this report. Further research is recommended to increase the knowledge base in relation to acid sulphate soil impacts and the recovery and resilience of the local ecology.

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4 Introduction

The Centre for Aquatic Pollution Identification and Management (CAPIM) was engaged by the Corangamite Catchment Management Authority (CMA) to assess the ecological resilience of the Anglesea River and estuary following presumed ASS-related acidification of the estuary after heavy rains in 2010. As the regional caretaker for river health, Corangamite CMA takes a leading role in estuary management, river health and community engagement on ecological issues as they arise. By reviewing all known information on coastal acid sulphate soils and their associated impacts on estuaries within Australia and overseas, this study will provide critical information for a detailed report which will be used to inform estuary managers and planners and provide technical content and support in the development of an updated Anglesea River estuary management plan.

4.1 Study objectives

The key objectives of this review are:

- Detailed discussion and explanation of the chemical interaction between acidic freshwater and seawater within estuaries, with particular reference to the Anglesea River
- Investigate and describe the impacts of acidification on estuarine ecology in general, including information on Coastal Acid Sulphate Soils (CASS) and the associated impact on estuarine ecology
- Detail the impact of acidic water on black bream, macroinvertebrates and seagrass
- Provide information on the history of acid water within the Anglesea River estuary
- Document ecological components of the Anglesea River that make it resilient to periods of highly acidic water, with reference to acid events of 2010
- Provide information on the recovery of ecological components within similar systems in the south-west region of Victoria
- Suggest potential methods to increase the rate of ecological recovery within the estuary, focusing on black bream, macroinvertebrates and seagrass.

4.2 Anglesea River estuary

The Anglesea River estuary is part of the Anglesea catchment, a small catchment 125km^2 in size and situated approximately 135 km^2 in south-west Victoria, lying within the Otway basin (Figure 1). The estuary itself is a small intermittently open estuary 15 Ha in size. The estuary includes Coogoorah Park, developed for recreational fishing and for community amenities (Figure 2). The Anglesea district comprises the towns of Anglesea, Aireys Inlet, Fairhaven, Moggs Creek and Eastern View. A large proportion of the Anglesea catchment is crown land, including Anglesea Heath (inclusive of the ALCOA lease), the Angahook-Lorne State park and various nature reserves. Most of the catchment's heath and woodland environments remain protected by the Alcoa mining lease. The Anglesea River is characterised by swampy tidal flood plains which are split by a ridge at the Great Ocean Road. A number of man-made modifications have occurred within the Anglesea River estuary. Coogoorah Park is a bush reserve and recreational area that was created following the 1983 fires, while mining operations north-west of Coogoorah Park have also modified the local landscape. Two dominant sub-catchments exist within the greater Anglesea catchment, Salt Creek and Marshy Creek, and both tributaries flow intermittently. While Anglesea generally experiences typical seasonal weather, with wet winters and hot dry summers, the Southern Oscillation can result in weather extremes and varied weather patterns. This may result in higher summer rainfalls and drier winters.

4.3 Coastal Acid-Sulphate Soils (CASS)

Acidification of coastal waterways is a well-recognized environmental, economic and social problem in Australia that requires urgent attention (National Working Party on Acid Sulfate Soils, 2000). Soils that contain iron sulphides are commonly referred to as acid sulphate soils (ASS). In coastal environments, Sulphidic sediments are formed in vegetated, tidal environments when sulphate from sea water is reduced to sulfides by microbial activity; the most common being pyrite (Sammut et al., 1996). In Victoria, these iron sulfide layers commonly occur well below the soil surface within the soil saturation zone or below the water-table (DPI, 2003) and were formed during the Holocene age (<10,000 BP). If left undisturbed and submerged by groundwater the pyrite is chemically inert (Melville et al., 1993).

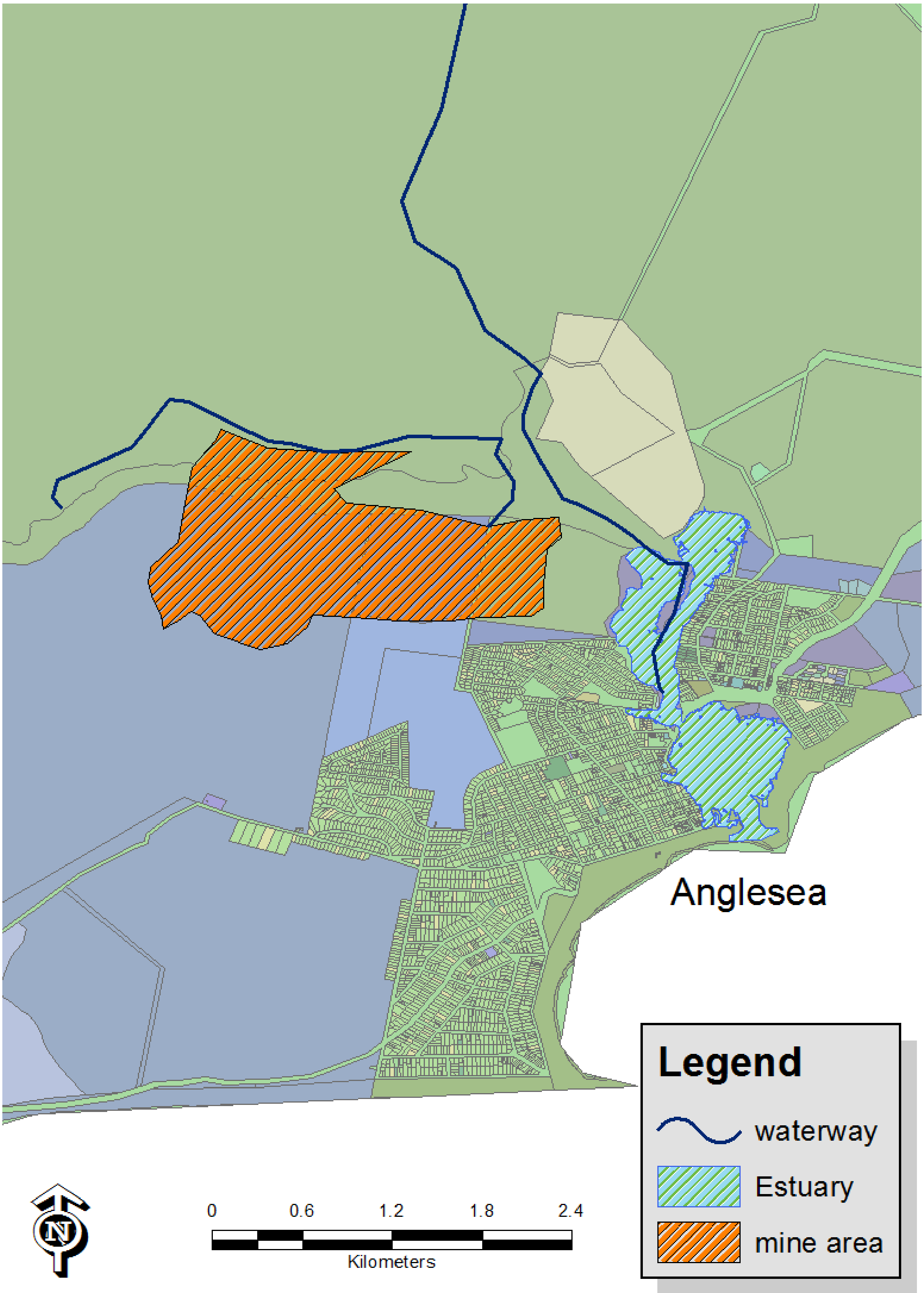
Anglesea
Legend
waterway
Estuary
mine area
0
0.6
1.2
1.8
2.4
Kilometers
N

Figure 1 Map of Anglesea showing the location of the Anglesea Estuary, Anglesea River and Alcoa coal mine.

If ground water falls below the elevation of the Sulfidic soil horizon, atmospheric oxygen is able to diffuse through overlying soil layers and the pyrite oxidizes to form sulphuric acid. If the acid-buffering and neutralising capacity of the soils is exceeded, soils will become acidified (Sammut et al., 1996). The catalysed oxidation of pyrite can be represented as (Willet et al., 1992)

$$\mathrm{FeS_2} + \frac{7}{2\mathrm{O_2}} + \mathrm{H_2O} \rightarrow \mathrm{Fe^{2+}} + 2\mathrm{SO_4^{2-}} + 2\mathrm{H^+} \quad (1)$$

The dissolved Fe^{2+}, $2SO_4^{2-}$ and H^+ produced in Equation 1 are readily transported in soil, water groundwater and drainage water (Sammut et al., 1996). When Fe^{2+} is exported, it can then be oxidised further to Fe^{3+} in surface waters producing iron oxyhydroxide. The hydroxide is commonly seen as a bright orange floc on surface waters. The oxidation rate of pyrite can be highly variable and is dependent on numerous factors, including the form of sulphur that exists, the concentration of oxygen, pH, flushing frequencies, presence of bacteria, and time of exposure to water and air (Dent, 1986). The rate at which pyrite is oxidised tends to be closely linked with pH, with oxidation increasing as pH is decreased, and is usually only limited by the rate of supply of O_2. The complete oxidisation of pyrite can be represented as

$$\mathrm{FeS_2} + \frac{15}{4\mathrm{O_2}} + 72\mathrm{H_2O} \rightarrow \mathrm{Fe(OH)_3} \downarrow + 2\mathrm{SO_4^{2-}} + 4\mathrm{H^+} \quad (2)$$

(1 Mol of pyrite generates 2 Mol of sulphuric acid)

Calcium carbonate and other exchangeable bases are important for the neutralisation of acid. When present, this reaction occurs instantaneously, thus when excess CaCO3 is present within potential acid sulphate soils, (PASS), acidification is prevented except in circumstances where the $CaCO_3$ is in a form that is not able to react within soil. Chemical weathering of soils and rock is an extremely important component of the biogeochemistry of ecosystems across the world (Johnson et al., 1994). Chemical weathering is the major acid neutralisation process, and consequently the relationship between acid inputs and the release of acid buffering cations, via the weathering process is critical in ecosystems where potential acid sulphate soils persist (Johnson et al., 1994). When acid reacts with mineral clays, silica and metal ions (such as iron, aluminium) are released (Nriagu, 1978). Reaction products such as aluminium and iron once released, can have detrimental effects on aquatic plants and gilled organisms (Jr Driscoll et al., 1980). When small acid discharges enter an estuary, the natural alkalinity or acid-neutralisation capacity of the estuary can usually buffer these changes in pH (Sammut et al., 1996), however after a flood event, drainage from acidic areas can reduce alkalinity of estuaries and acidify tidal reaches (Sammut et al., 1996).

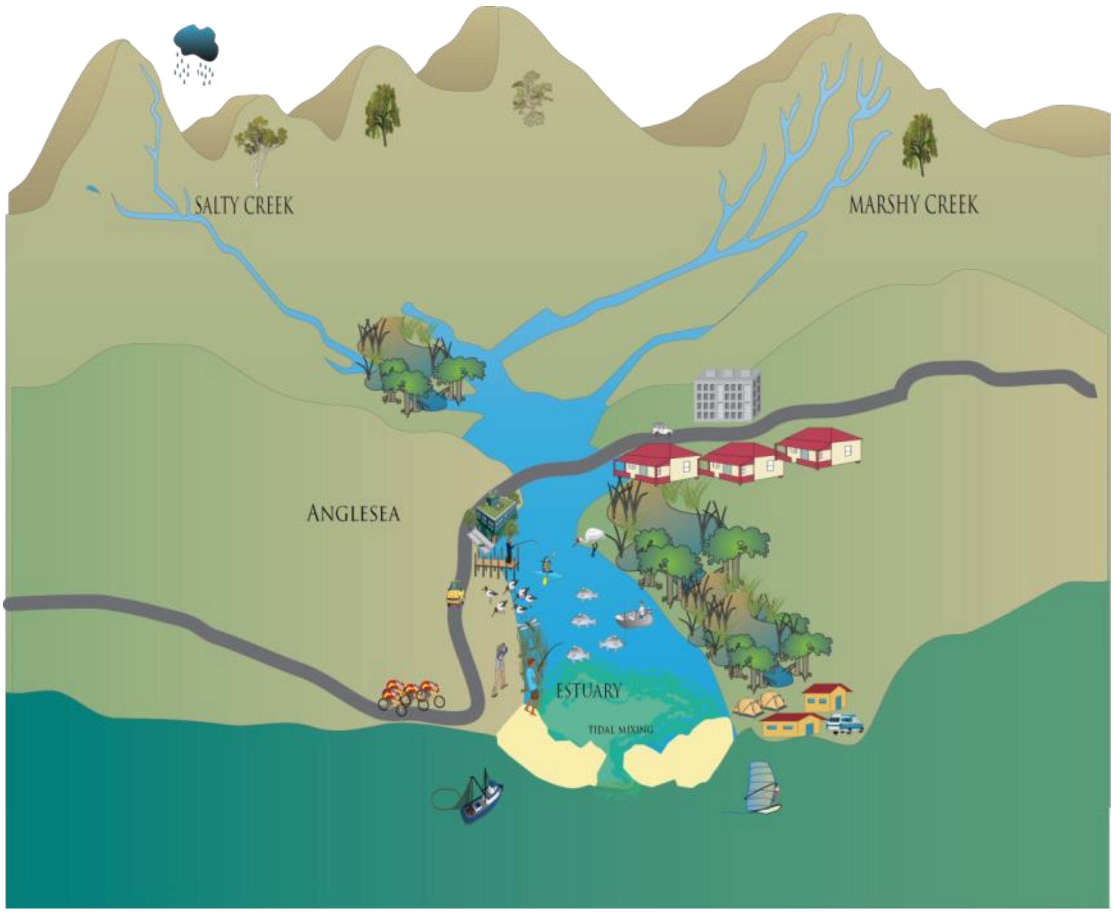

Figure 2 Diagram depicting the economic, ecological and social value of having a healthy estuary in Anglesea.

5 Estuary dynamics and acidity of tidal reaches

Estuaries are dynamic ecosystems in which conditions change constantly. The processes that are at play within estuaries (Table 1) are operating concurrently, and at any time can influence water circulation, sediment movement, water quality and levels (Barton and Sherwood, 2004).

Table 1 the time scale that various physical processes work on within estuarine ecosystems. Source: (Barton and Sherwood, 2004)

Process	Time-Scale
Ebb/flood tide cycle	~ 12 Hours
Spring/neap tide cycle	~ 14 days
Wind patterns	Hours to days
Changes in river discharge	Days to weeks

The Victorian coast line is considered micro-tidal, meaning that spring tides on average reach 1 m, while neap tides reach 0.3 m. At Anglesea, the main process that effects the estuary is wave action (Arrowsmith et al., 2010). This wave action contributes to the net alongshore transport of sand that results in a build-up of sand within the vicinity of the Anglesea River estuary mouth, which can in times of low river flow create a sand bar which closes the river mouth. During periods of high flow or prolonged rainfall , river water builds up until it spills over the sand bar, scouring a channel to the sea (Arrowsmith et al., 2010). River discharge into estuaries primarily reflect rainfall patterns, with high discharges in the winter and spring, and low discharges in the summer and autumn (Barton and Sherwood, 2004). These differences in seasonal flows can have a marked effect on the condition of the estuary. Salinity levels and water quality within an estuary can change markedly throughout the year. For example, saltwater is often flushed from an estuary during winter, then as discharges are reduced during spring seawater is allowed to re-enter the estuary. Over summer and autumn, as the mouth of the estuary closes, tidal exchange is reduced and the bottom salt wedge layer stagnates leading to possible anoxic conditions within the estuary (Barton and Sherwood, 2004).

The natural seasonal flows are complicated by the discharges from Alcoa's power plant operations. Waste water discharges from Alcoa's mining and power operations add approximately 4ML of water to the Anglesea River each day (Alcoa, 2010). This water interacts with natural discharges from the catchment, and given discharge waters remain pH neutral consistently throughout the year, may help neutralise acidic waters stemming from further within the catchment or from within the estuary. The maintenance and condition of estuary entrances is one of the most important factors controlling the broader environmental processes of the estuary. Being an intermittent estuary, the Anglesea estuary is continually changing. Water levels in the estuary can vary by as much as 1.6 m. While the main channel is always submerged within relatively steep-sided banks even at low levels, at high water levels, sections of the islands at Coogoorah Park are inundated (Arrowsmith et al., 2010).

In estuarine environments, the pH of waters is influenced by many factors including acidity, alkalinity and volume of marine and freshwater inputs that mix within the estuary (Pope, 2006). In addition, there are also many biological processes and interactions that can not only affect the quality of estuarine systems, but can dictate what communities exist within these systems (Heip and Herman, 1995). While pH is often more variable in freshwater environments compared to marine environments (ANZECC/ARMCANZ, 2000), pH is often ignored as a contributing factor to biotic changes in estuarine systems (Knezovitch, 1994). This is primarily because of the buffering capacity of marine waters. Sea water typically has a pH of around 8.2, whereas under normal circumstances, freshwater can vary between 6 and 8.

It is clear that when acid events have occurred in intermittent estuaries like Anglesea, flow has been a major contributor (Pope, 2006). This is especially true for catchments that are associated and susceptible to acid sulphate soils (Sammut et al., 1993; Sammut et al., 1996; Sammut et al., 1995), including Aireys inlet, Apollo Bay, Hordern vale, Johanna, Princetown and Peterborough in the south west of Victoria (DSE, 2009).The influence of tidal exchange on acidification of estuaries and receiving waters has received much attention, especially in areas where tidal gates are used to manage drainage schemes in low-lying agricultural floodplains (Johnston et al., 2005). The tidal buffering approach is based on the concept that incoming tides transport acid buffering agents through an estuary (Indraratna et al., 2002) . The major buffering constituents of seawater include bicarbonate $\mathrm{HCO_3^-}$ and carbonate $\mathrm{CO_3^{2-}}$. The state of the estuary and the hydrodynamics is critical in determining the concentration of the buffering agents. Equation 3 represents the buffering reaction of sulphuric acid (pKa= -3) in the formation of carbonic acid, (pKa = 3.8), which is a much weaker acid (Stumm and Morgan, 1996).

$$\mathrm{Ca^{2+} + HCO_3^- + H^+ + SO_4^{2-} \rightarrow + H_2CO_3 + Ca^{2+} + SO_4^{2-}} \qquad (3)$$

Seawater ASS oxidation weak carbonic acid

The key ingredient in the acid buffering process is the production of carbonic acid. Low ionisation capacity of carbonic acid differs to sulphuric acid which is highly ionised. Formation of carbonic acid allows for a larger affinity of carbonate and bicarbonate anions for hydrogen ions in solution. As shown in equation (4a)-(4c), the carbonic reaction mostly proceeds towards the left, while the sulphate reaction proceeds towards the right. The removal of $[\mathrm{H^+}]$ in solution by the formation of $\mathrm{H_2CO_3}$, leads to an increase in river water pH (Indraratna et al., 2002).

Strongly acidic and highly ionised:

$$\mathrm{H_2SO_4 \rightarrow 2H^+ + SO_4^{2-}} \qquad (4a)$$

Weak acid and less ionised:

$$H_2\,CO_3 \leftarrow \; HCO_3^- \; + H^+ \qquad (4b)$$

$$H_2\,CO_3 \leftarrow \; CO_3^- \; + 2H^+ \qquad (4c)$$

The quality of water in estuaries is often determined by the mixing of fresh and sea water with salinity the prime indicator of the mixing process. Due to the density of saltwater, saltwater and freshwater do not often combine without energy input from sources such as freshwater flows, tidal exchange or wind energy. When mixing does not occur, freshwater will form a separate layer on top of the saltwater leading to stratification (Figure 3) (Pope, 2006).

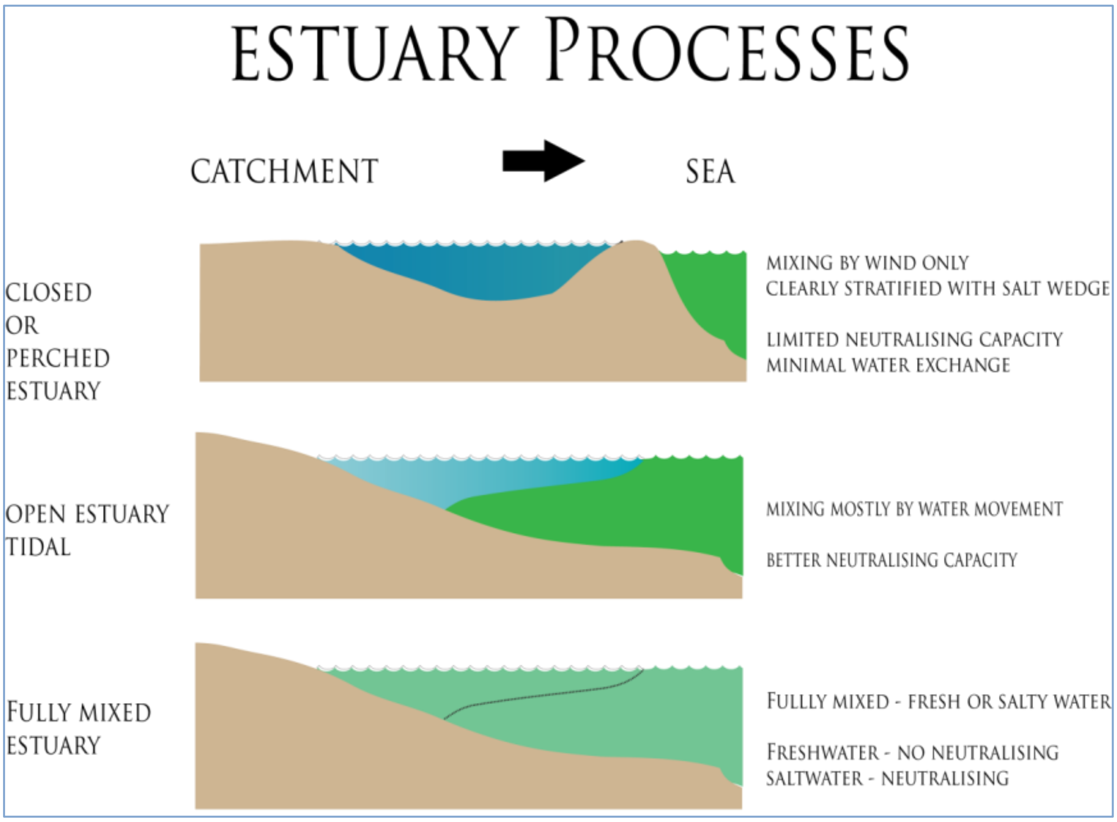

Figure 3 Conceptual diagram showing the different processes that exist within the Anglesea Estuary depending on whether the estuary is closed or open.

At Anglesea, salinity stratification is complex with numerous stratification patterns occurring, often depending on the amount of freshwater flow, the degree of tidal exchange (Pope, 2006) and is further complicated by the discharge from Alcoa. This is also true for pH, where (Pope, 2006) found that acid events within the Anglesea estuary were clearly flow related. Thus, the transportation of acid into the Anglesea estuary is also clearly linked to the local hydrological cycle. It is now clear that seasonal rainfall within the Anglesea catchment directly influences the rate of acid generation and transportation (Tutt, 2008). Any variation in weather patterns can affect acid generation and transportation. For example, extended periods of lower than average precipitation within a catchment can have the effect of lowering the watertable. This can lead to low ground water recharge and a potential build up of acid in the soil. Whereas, high groundwater recharge can increase oxidation of natural pyrite and facilitate transportation into local tributaries and finally into estuaries (Tutt, 2008). Hydrological modelling that was performed for the Anglesea catchment following an acid event in 2000, (Tutt, 2008) suggested that recharge volume may be the critical factor for an acid flush event to occur in the estuary. When considered in conjunction with the hypothesised process of acid drainage within the catchment, the models show that the extended dry period in between 1997-2000 and the higher than average rainfall in 2000 was the most probable cause of the acid event of 2000 that resulted in fish deaths (Tutt 2008).

6 Effects of acid sulphate soils in estuarine environments

Acid flush events can lead to direct and indirect changes to the water quality of estuarine systems. An associated problem with acidification of rivers, creeks and estuaries is the release of metals. The oxidation of sulfidic materials can lead to heavy metals such as cadmium and lead and metalloids such as arsenic becoming more available in the environment (Burton et al., 2006). When oxidised, metal sulphides that build up in the soils can be released, resulting in the release of heavy metals or metalloids into the pore water or into the water column.

In sedimentary pyrite, like that found in the marshes at Anglesea, several trace elements such as nickel (Ni), copper (Cu), zinc (Zn), lead (Pb) and arsenic (As) accumulate with iron (Fe). When pyrite oxidation occurs, this can lead to acidification and the release of the metals.

It has often been found that water in drains and creeks can change colour due to increased levels of iron or aluminium that are released when pH levels drop. For instance, blue-green or milky white water is often caused by aluminium flocculation, which normally occurs at pH levels of 4-5, while high levels of aluminium can also results in crystal clear waters due to soil particles falling out of the water column, which normally occurs when pH is at 5-6. Likewise, when flocculation of iron occurs (pH 4), waters can often have a red to brown tinge; while iron deposits on the bottom or banks of a creek or drain can be coated in reddish deposits, often called “iron staining”. These changes in colouration of the water and creek surfaces can also be good indicators of acidification of receiving waters. Although by the time these changes occur, there is a good chance the acidification has already caused major disturbance to the aquatic communities.

Importantly, inundation of marine salts into areas affected by acid events can initially result in an immediate increase in the release of acidity and trace metals due to the increasing ionic strength of the seawater which displaces trace metals and protons adsorbed on sediments. This causes the initial decrease in pH and in conjunction with the hydrolysis of desorbed acidic metals can contribute to further acidity and increased mobilisation of trace metals (Wong et al., 2010). Over time though, the seawater inundation eventually leads to reductive processes within the waters causing acidity to decrease and pH to increase (Johnston et al., 2009).

Another consequence of the sulphide rich soils often associated with ASS is the deoxygenation of the water column. When suphidic sediments are resuspended, they can rapidly oxidise, and in the process remove oxygen from the water (Sullivan et al., 2002). This can also lead to monosulphidic black ooze (MBO). Monosulphidic black ooze comprises organic materials enriched in iron monosulphides, and can often be found in creeks, rivers and wetlands high in nutrients. Nutrification increases the activity of algae and other microorganisms which creates the reductive environment needed to oxidise these sediments (Sullivan et al., 2002). Minor amounts of MBO (~ 1mg/L) can completely deoxygenate water within a few minutes, indicating that reactions can occur within very short time periods (Bush et al., 2004). In addition, under the right conditions, MBO can also produce acid. Again, acid production from MBO is primarily dictated by exposure to oxygen. In enclosed or intermittent estuaries like Anglesea and other estuaries in coastal Victoria, storm events or flushing of creeks and waterways can often disturb the sediment leading to the prerequisites for MBO to cause acidification or deoxygenation of the water column (Bush et al., 2004; Sullivan et al., 2002).

The consequences of acidification in estuarine environments can vary considerably depending on numerous factors including geomorphology, land use, anthropogenic disturbance, and temporal and spatial variation within estuaries.

7 Impact of acidification of estuaries

7.1 Acid Sulphate Soils

Acid sulphate soils are not restricted by geography or by political boundaries, but are found world-wide, being classed by many as the nastiest soils in the world (Dent and Pons, 1995). The sequence of sedimentation, accumulation of sulphides and burial of peat and other alluvium materials in addition to soil profile development produces a range of acid sulphate soils across the world that is either, unripe, raw or ripe. Soil ripening refers to the formation of soils from soft waterlogged materials, with the physical properties of the soil changing as the soil ripens. The degree of soil ripening critically influences drainage and mechanical strength of the soil, and is usually used in the classification of soils (Pons and Zonneveld, 1965). However, the genesis of ripe acid sulphate soils is often complex and for most of the time has not been determined for most AS soils investigated. The majority of ripe acid sulphate soils can be accounted for by changes in hydrology, such as changes to tidal input, flooding, estuary opening / closing and drops in regional water tables to below that of where pyrite has originally accumulated (Dent and Pons, 1995). In 1980, (Van Breemen, 1980) estimated that world-wide, there was approximately 14M Ha of Holocene coastal floodplains and tidal swamps where the topsoil was severely acidic or would become so if drained, which was in addition to the 28M Ha of land area where conditions for acid sulphate soils persist. Today, in Australia alone, it is estimated that there is approximately 95,000 km^2 or 9.5M Ha of coastal ASS, and a further 150,000 km^2 or 15M Ha of ASS in inland areas and it is estimated that ASS has the potential to affect approximately 8-9 times the area of dryland salinity in Australia, (Simpson et al., 2010). The environmental, social and economic costs of both inland and coastal ASS are significant. The economic impacts are broad and substantial. The cost alone to coastal development in prevention and treatment of ASS across Australia is estimated to be over $10B. The financial cost to fisheries, mostly in Northern NSW, is also estimated to be many 10’s of millions of dollars and the threat to coastal tourism in towns like Anglesea is considerable (National Working Party on Acid Sulfate Soils, 2000). Today, there is often conflict between farmers, fishers (both commercial and recreational), property developers, environmentalists, tourism dependent business and local residents on who should be carrying the burden of managing ASS, especially in coastal areas. Across Australia, different ecosystems and landscape management have seen different issues arise due to ASS.

7.2 Specific impact of ASS in estuaries

In Australia there are approximately 900 estuaries, each one with its own unique dynamics and landscape. The tremendous diversity of estuaries in Australia often results in grouping of estuaries based upon certain traits or character states. Australia is currently using a geomorphic classification system to group estuaries, which is generally based upon wave, tide and river characteristics (Boyd et al., 1992). In Victoria, a number of estuary classification schemes have been proposed (Mondon et al., 2003; OSRA, 2001), with the most recent proposed by (Barton, 2006), a modification of (Barton, 2003), which is a simple scheme based on the estuary's coastal energy and direction.

Acid sulphate soils are of major concern in numerous estuarine environments across the globe, and affects all ice free continents, with best estimates suggesting that 30% of all land and 50% of arable land may be affected by ASS (Uexküll and Mutert, 1995). Europe has had a long history of ASS, dating back to the 17th century where low lying tracts of land that is surrounded by embankments known as polders in the Netherlands were impacted by CASS. The major drainage projects that accompanied the reclamation of land in Holland also exposed vast quantities of ASS, which has proven problematic up until present day (Dent and Pons, 1995). In fact, Finland (3000 km^2) and Sweden (1400 km^2) have the largest ASS occurrences in Europe (Andriesse and van Mensvoort, 2002). This has primarily been a result of both isostatic land uplift and artificial farmland drainage. The intensification of this drainage has also led to significant increased mobility of metals and acidity throughout the local catchments (Osterholm and Åström, 2002). A point of interest here is considering a similar process involving drainage of estuarine wetlands, floodplain and land prone to inundation to gain expanded viable agricultural land in western Victoria via regular manipulation of estuary entrances (e.g. Gellibrand and Aire river valleys within Corangamite region).

In estuarine ecosystems, it is often difficult to determine exactly what stressor is actually impacting the ecology of the system. Differentiating between the different stressors is difficult because biota can sometimes respond in similar ways to the different stressors as they occur. An organism's tolerance to stressors is also important, not only when an impact occurs but when the stressor passes and the environment shifts to a state of recovery. Information pertaining to the influence acidic waters and acid sulphate run-off has on stream and estuarine biota is limited. In Australia, relatively few investigations have looked specifically at the response of the biota to acid-runoff or acid events. Results from these studies suggest that it is often the combination of changes to pH and soluble metals that causes changes to benthic communities. For instance, in a study which looked at the effect of acid-sulphate run-off on the macrobenthic community of the Richmond River in NSW, (Corfield, 2000) found that that the combined effect of chemical speciation of aluminium at certain pH ranges influenced the macrobenthos more so than pH or soluble aluminium concentrations individually.

The environmental effects of ASS can be subtle as well as obvious. One of the more obvious effects of ASS, especially in freshwater and estuarine environments is fish kills. The impact of ASS on fish populations will be discussed in detail in the next section, however, the socio-economic ramifications of fish deaths alone is immense. Coastal communities across Australia often depend on recreation (active and passive), fishing and other immeasurable factors such as amenity which can offer a means of financial support and community well-being. In addition to fish, other biological groups such as seagrass communities, other aquatic plants, invertebrates and riparian systems can wear the brunt of acid events when they occur. The Richmond River (northern NSW) floodplain is the largest coastal floodplain on the NSW coast. Since the early 1900's many fish mortality events have been recorded within coastal waterways in NSW, and while many of these kills have been attributed to natural events, anthropogenic landscape changes have significantly exacerbated these processes (Sammut et al., 1996). In 1994, a major flood event on the Richmond River produced a massive acid event in which over 1000 tonnes of sulphuric acid, 450 tonnes of aluminium and 300 tonnes of iron were released from a 4000 ha subcatchment. On this occasion, the tide moved the acid slug throughout the river and estuary for approximately seven weeks. With pH reaching as low as 2.6, the result was a dramatic change in the aquatic ecology and significant decreases in biodiversity (National Working Party on Acid Sulfate Soils, 2000). Throughout northern NSW, it was widely anticipated that following rain events, decreases in pH and oxidised ASS will occur. This prediction subsequently flagged the need to investigate the impact of acid water on the local fauna. Investigations in the 1990s clearly showed that acid events were likely to be having a significant impact on the fauna of coastal ecosystems (Sammut et al., 1994; Tunks, 1993).

The impact of acidification on the biota of lotic (flowing waterways) systems in particular stream invertebrates have been well studied for over 30 years across numerous countries including the U.K, Canada, the U.S.A. and Australia (Hall and Ide, 1987; Roach, 1997; Rosemond and Reice, 1992; Townsend et al., 1983). These studies have all showed that changes in invertebrate community structure occur as the pH of the waterways is reduced. Invertebrate densities were also often correlated with pH. In particular, density of Ephemeroptera (mayfly larvae) has been found to be highly correlated with pH (Rosemond and Reice, 1992), suggesting this species could be a good indicator or early warning taxa for pH. Acid-runoff is complex, with direct and indirect stressors often occurring simultaneously. While it currently unknown whether mayflies would be found within the estuarine environment at Anglesea, a previous study that examined the insect fauna of estuaries in Canada found that insects such as mayflies, stoneflies, caddisflies and chironomids are often abundant within these systems (Williams and Hamm, 2002). It is however likely that predominantly freshwater species such as mayflies and chironomids would occur within the upper freshwater regions of the Anglesea sub-catchment and thus it is suggested this method of early warning may be utilised in the upper catchment.

7.2.1 South-west Victorian estuaries

Investigations into the effect of local estuary water quality on aquatic biota in the south-west of Victoria are rare. While there are studies and programs that have investigated species composition within local estuaries and general water quality issues, such as the seagrass monitoring program, (Office of the Environmental monitor), and the estuary assessment in 2000 undertaken to classify Victoria's 60 estuaries (GeoScience Australia), very few studies exist that specifically investigated threats to the aquatic biota in estuarine systems. A study which looked at water quality effects on seagrass communities conducted at Corner Inlet, Gippsland, Victoria concluded that the major decline in seagrass communities was probably due to excess nutrient loads entering the estuary via effluent (Hindell *et al* 2009). In 2010, an investigation into the potential of stocking fish into estuaries was conducted. It concluded that of the 12 estuaries investigated on the basis of potential recruitment limitation, habitat availability, estuarine hydrology and fishery characteristics; only seven could be suitable for restocking of fish (Taylor, M. 2010). The report concluded that due to the lack of deeper water, the abundance of black bream and on-going water quality issues, that the Anglesea River did not provide good opportunities for releases of hatchery-reared estuary perch (*Macquaria colonorum*). However, the report did recommend Painkalac Creek as a suitable estuary for the trail release of estuary perch fingerlings due to the presence of suitable habitat and the brackish nature of the waterway.

While there have been investigations into anthropogenic threats to estuaries (Laidlaw *et al* 2005), linking these threats to ecological impacts is not common. Although the ecological impact of sudden water quality changes, such as when an acid event occurs can be apparent, (Pope, 2010), understanding subtle changes that occur within an estuary is more difficult. Investigations into basic biological and ecological requirements at a species level are required. Only when these requirements are understood, can you expect to know how the biota will respond to environmental fluxes. The remaining sections of this review will focus on understanding further the requirements, threats and responses of fish, macroinvertebrates and seagrass communities to fluxes in estuarine condition.

8 Ecological compartments: fish, macroinvertebrates and seagrass

8.1 Introduction

The Anglesea River is an important ecological component of the Anglesea catchment. It is home to a number of important fish species, seagrass communities and numerous macroinvertebrates that reside in both the freshwater and estuarine areas of the river proper (Figure 4).

8.2 Fish

Fish species within Anglesea River are quite diverse (Table 2, Pope 2006, DSE 2011). The species present utilise different habitat within Anglesea River and different life stages within the estuary and freshwater sections of the river dependant on the time of the year.

The Anglesea River is an important waterway for the recruitment, breeding and habitat availability for black bream (*Acanthopagrus butcheri*). The black bream is an economically important species to the local community as a recreational fish species and is considered as one of the most important recreational and commercial estuarine fisheries in southern Australia (Lenanton and Potter, 1987; Kailola *et al*.

, 1993, as cited by Sarre and Potter 2000). Estuary perch, trevally and luderick also reside in the Anglesea River although numbers of these fish are generally low.

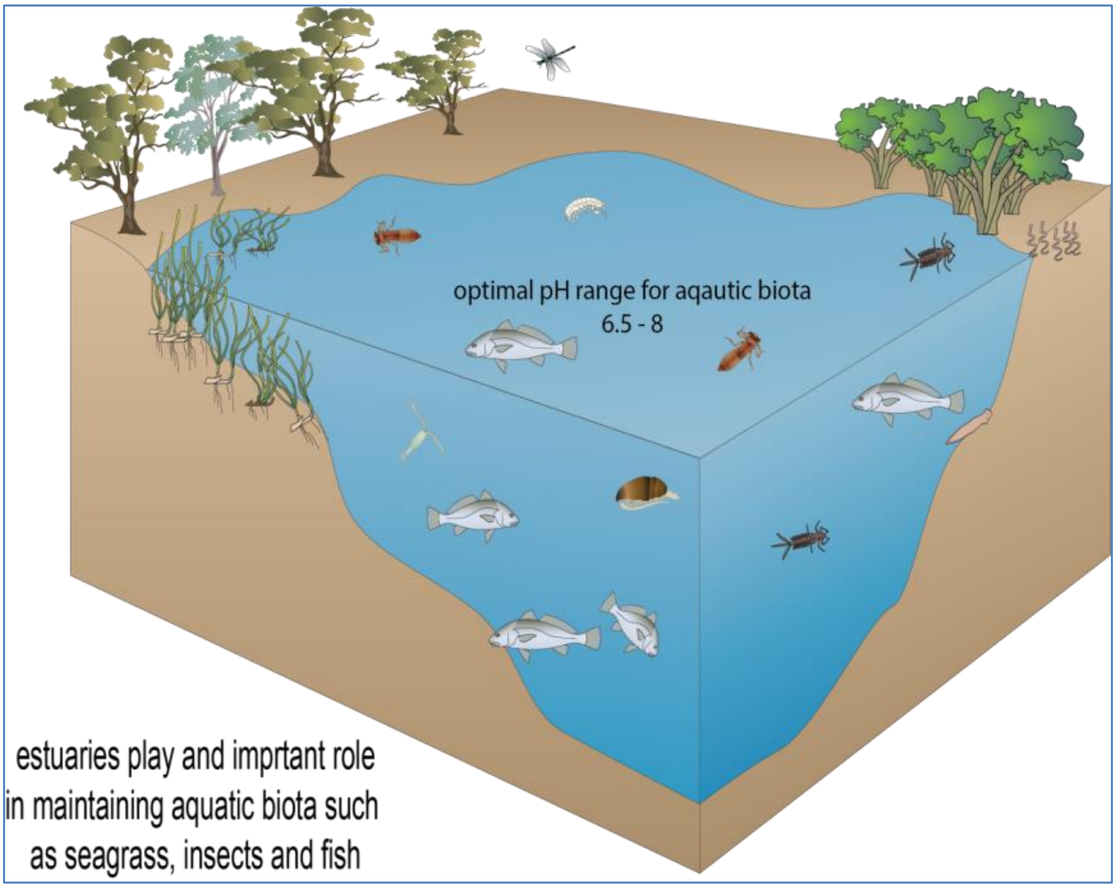

Figure 4 Conceptual diagram showing the interaction of the different biological groups within an estuary system.

The seagrass community present at Anglesea provides ideal habitat for black bream to feed, grow and reproduce within. A common seagrass to this area is *Zostra* spp, which has been seen as critical to black bream, especially in nursery areas and areas that can provide protection to young fish (Pope, 2006). *Zostra spp*. has also been found to be important in the maintenance of shellfish and other organisms important to bream (Butcher 1945a). The Victorian Department of Primary Industry (DPI) states that successful spawning, larval survival, settlement and growth of juvenile black bream is primarily dependant on the quantity and quality of suitable habitat and environmental conditions available in each estuary (DPI 2006). In 2008, DPI listed the biggest threats to black bream were the reduction of freshwater inflows (Jenkins et al., 2010), excessive nutrient inputs and associated algal blooms, excessive sediment inputs from catchment erosion and physical disturbance from activities such as recreational boating foreshore development/modification (DPI 2008). Monitoring programs have been recommended to ensure that black bream habitat remains intact and free from these threats (DPI 2008).

Table 2 Species of fish observed within the Anglesea River after Pope (2006) and DSE (2011)..

Common Name	***Species Name***	**Migration Pattern**	**Breeding Months**
Black Bream	*Acanthopagrus butheri*	Breed and live in estuaries	October – January
Yellow-eyed Mullet	*Aldrichetta forsteri*	Breed in the ocean juveniles and adults utilise estuaries	December – February
*Sea Mullet	*Mugil cephalus*	Breed in the ocean juveniles and adults utilise estuaries	June - August
Smooth Toadfish	*Tetractenos glaber*	Breed and live in estuaries	
Short finned Eel	*Anguilla australis*	Breed in the ocean and live in freshwater	January - May
Common Galaxias	*Galaxias maculatus*	Breed in estuaries and live in freshwater	August – November August - September
Cobbler	*Gymnapistes marmoratus*	Lives in estuary	November – February
Flathead Gudgeon	*Philypnodon grandiceps*	Lives in f/w and estuary	June - October
Eastern Blue Spot Goby	*Pseudogobius sp.*	Lives in estuary	
Green-back Flounder	*Rhombosidea tapirina*	Lives in estuary	
Luderick	*Girella tricuspidata*	Coastal, larval and juveniles in	June - August

Common Name	***Species Name***	**Migration Pattern**	**Breeding Months**
		the estuary	
Marbled Fish	*Aplodactylus arctidens*	Lives in coastal reefs and seagrass beds	
Southern Longfin Goby	*Favonigobius lateralis*	Lives in estuary	
Spotted Galaxid	*Galaxias truttaceus*	Adults in f/w and larvae in ocean	March - August
Tamar River Goby	*Afurcagobius tamarensis*	Lives in f/w and estuary	September – November
Tasmanian Blenny	*Parablennius tasmanianus*	Lives in estuary	
Tupong	*Psuedaphritis urvilli*	Males live in estuaries, females live in f/w	March – August
Western Australian Salmon	*Arripis truttaceus*	Lives off the coast and in estuaries	March – April

*Only stated in Pope (2006)

As discussed in detail in the preceding chapters, acid flushes have been known to occur within the Anglesea catchment due to the high sulphur rich soils at the top of the catchment. While the highly alkaline water being discharged daily from the Alcoa mine is likely to buffer against the high acidic flows, it has now been generally accepted that when acidic inflow from the catchment exceeds the volume discharged from the mine it is more likely that acid events may occur if conditions further up in the catchment are conducive to waters low in pH.

Given it is accepted that natural sources of acidic water occur within the catchment (Maher, 2011) (Figure 5), it can be assumed that many previous acid flushes have occurred over time each resulting in changes to the water quality in the Anglesea River estuary. Little is known of the impact of events prior to 2000; though Alcoa have records of pH level dating back to the 1960s showing highly variable pH, routinely well below 7. Data has been collected to document recent events including two acid flushes in September/October 2000, three in 2001 and the 2010 acid flush which caused widespread fish death summarised within the EPA commissioned report by Adam Pope of Deakin University in 2010. Dr. Pope also documented the 2000 and 2001 episodes of acidity and surmised the acid events may have been in response to hydrodynamic changes within the catchment (Pope 2006; 2010).
The review will further investigate what effects acid events are likely to have on black bream populations and what is known about the ability of black bream at an individual, population and species level to adapt to an acid event. It will also briefly discuss any approaches or management actions that could limit or decrease the impact that acid fluxes may have on the ecology of black bream.

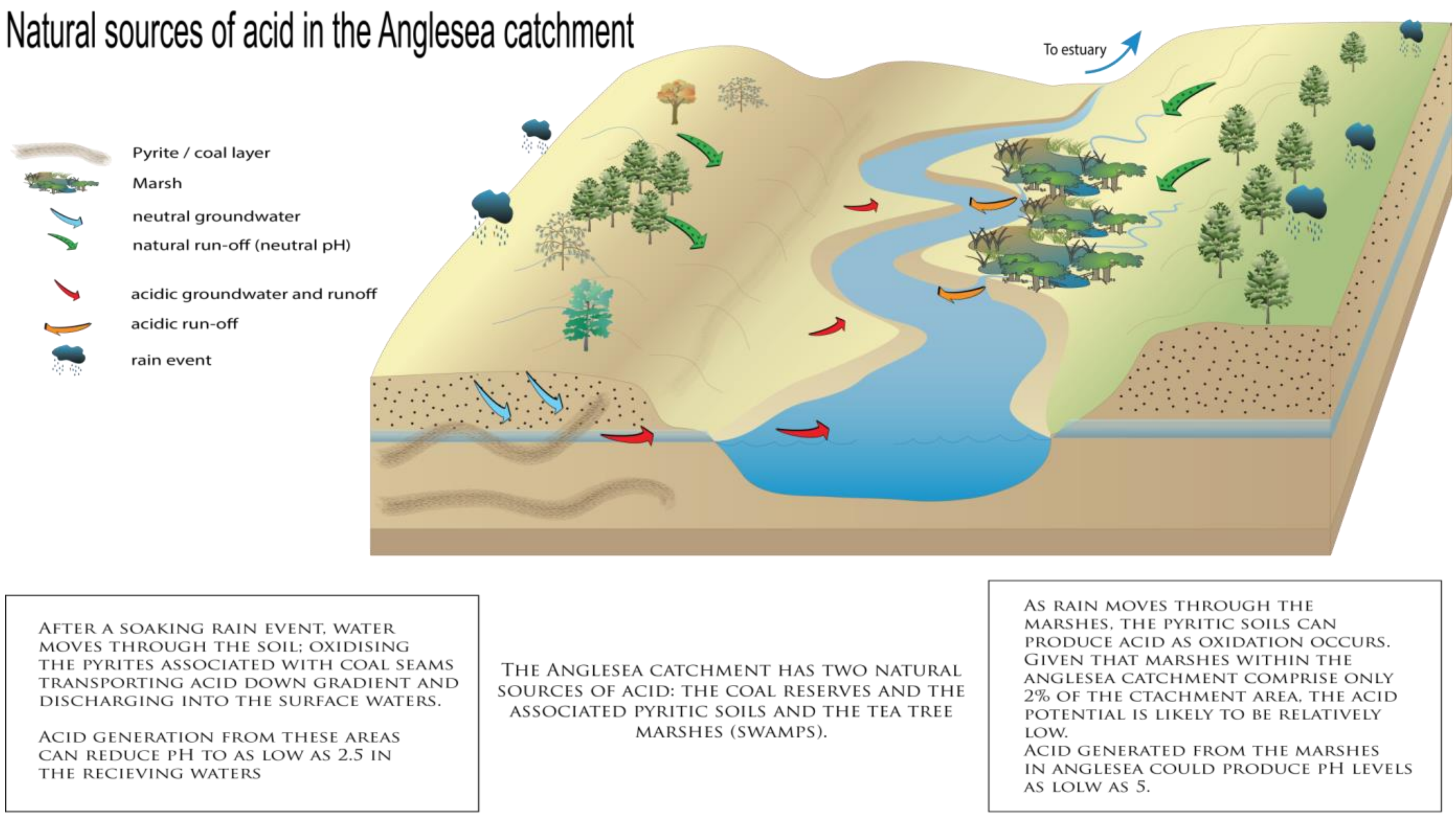

Figure 5 Conceptual model of the natural source of acid in the Anglesea catchment.

8.2.1 **Acid flush impacts on the Anglesea estuary**

8.2.1.1 Fish

Fish species that are observed within estuaries may belong to the following types of life history groups; estuarine resident, estuarine dependent, estuarine opportunist, and marine straggler species (Potter and Hyndes, 1999) (Figure 2). The type of fish present within an estuary at a time will be dependent on the dynamics at play within the estuary, for instance whether or not the mouth of the waterway is open or closed, water levels, salinity dynamics and dissolved oxygen levels . Resident species are those fish that occur within the estuary throughout their entire life-cycle, such as black bream, which breed in the brackish sections of an estuary, then all life stages remaining in the estuary unless circumstance leads to, for example the flushing of fish into marine waters, after flooding events.

Opportunist species often pass through estuaries, to get to preferred habitat. While they may feed in estuaries for periods at a time, they are generally passing through to get to the upstream freshwater or oceanic habitats. An example of a vagrant species would be the Short Finned Eel (*Anguilla australis*). This species inhabit freshwater environments until they are ready to breed which occurs in the ocean. Juvenile eels then make their way from the ocean back up to freshwater habitats where they stay until they are ready to breed. Dependant species are those species that have at least one stage living within in at least one ecology type. An example of this type of species is the Common Galaxias (*Galaxias maculates*). The adults live in freshwater environments until an environmental cue such as a flood or a king or spring tide initiates a breeding migration downstream into the estuary where they breed in the fringing vegetation of the estuary. Larval Common Galaxias grow to juvenile stage within the ocean environment and migrate upstream to the original adult habitat.

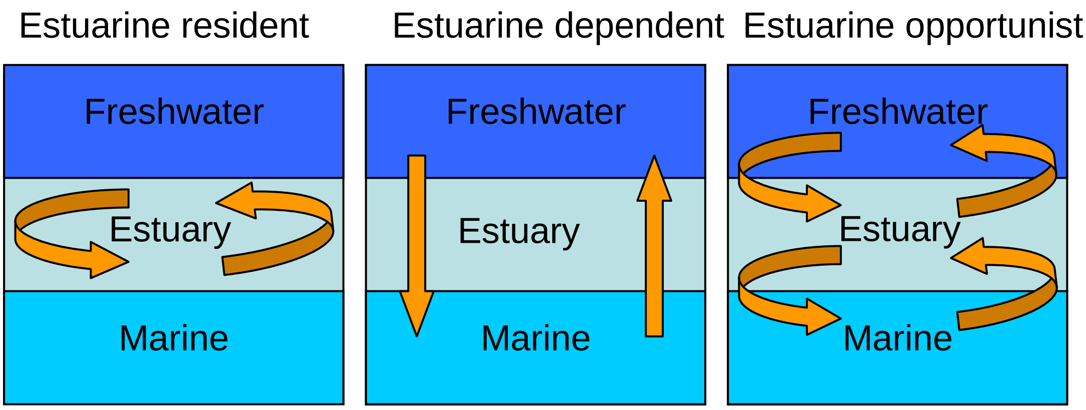

Figure 6. schematic diagram of the three types of fish that may occur within an estuary, after (Potter and Hyndes, 1999).

Black Bream is an estuarine resident species with all life cycle stages occurring within the estuary. Black Bream is an important recreational fish species throughout south Western Australia, southern Australia (including Tasmania) and eastern Australia. There have been studies that show that there is a clear genetic difference between fish found in south Western Australia estuaries indicating little to no migration between estuaries (Chaplin *et al*. 1998; Potter and Hyndes, 1999). This suggests that if a population within an estuary becomes extinct there will be little to no recruitment. However, Hindell *et al*. (2008) demonstrated through a tagging study on adult black bream, that adults will move between rivers that flow into the Gippsland Lakes, suggesting that gene flow is possible between estuaries. A recent study (DSE 2011) conducted on the Anglesea River showed that in October 2011, only 2 black bream were found within the estuary. However black bream seemed to recover quite quickly, with 39 individuals founds in April 2011 and 223 individuals in November 2011. The report showed that water quality differences between October 2010 and April and November 2011 were marked, with pH of <4 recorded in October 2010 compared to April and November 2011 where pH was consistently found above 7 especially in the lower reaches of the estuary. This suggests that pH may have been driving the reduction in black bream numbers in spring 2010.

A study conducted in 1998 (Morison *et al*. 1998) on the age determination of black bream within Gippsland Lakes, found that recruitment since 1981 was episodic and recruitment was low throughout the previous three years. This trend was observed in a 2010 study (Jenkins *et al*. 2010). Jenkins *et al*. (2010) surmised that black bream populations may be further impacted by climate change if the effects of climate change including less rainfall, higher evaporation and higher salinities and lower stratification were to be realised. The effects of climate change may be further exacerbated by human activities that occur within a catchment by causing a reduction in the freshwater flows or cause an increase in the marine incursion. Similarly, Nicholson *et al*. (2008) examining the black bream eggs and larvae within two intermittently open estuaries of the Glenelg and the Hopkins, found that there were implications for climate change on the black bream population with low flows creating high salinity and low dissolved oxygen and the subsequent change in water quality may potentially have an effect on the spawning success of black bream (Nicholson *et al*. 2008). In addition, Nicholson *et* al. (2008) found that high salinity in terms of water column density was a major determinant on the distribution of black bream eggs and yolk-sac larvae.

There are strong linkages between the presence of black bream, macroinvertebrates and seagrass with each group having some reliance on the other group for survival, whether as a source of protection, food source or habitat for breeding. If there are pulses of highly acidic water into the estuary, it is likely that there will be subsequent changes to the dynamics within the estuary. What and how these changes impact upon the myriad of animals that inhabit these areas will depend on the spatial and temporal extent of the acid flush.

8.2.2 **Direct impacts to acid events**

There is a direct and immediate impact on the health of fish species that are affected by acid run off; with acid becoming lethal to fish species between a pH 3 to 4 (Ikuta and Kitamura, 1995). Acidified waters can also directly affect the morphology of the fish, commonly in the form of lesions (removal of the outer epithelial layer) (Table 3), (Sammut et al., 1995). This can also lead to secondary infections due to bacteria, fungi and parasites. Low pH conditions from acidic runoff can also impact fish respiration by affecting the acid-base regulatory function of gill chloride cells (Ikuta and Kitamura, 1995).

Table 3 Summary of physiological changes within fish in relation to pH

Acidic	⟷	Neutral
Low survival to death	Increased respiration (operculum opening)	Increase in parasite cover
	Air surface gulping	Loss of body mucous
	Larger lesions	Erratic movement
	Increase in parasitic cover	Small lesions
	Impaired reproduction organs	Migration out of acidified zone
	Growth ceases	Damaged gill cells
	Increase necrosis of gill cells	Growth rates are reduced
	Increase in erratic movement	Poor immunisation

Low pH may lead to disturbance in water and ion regulation, as well as oxygen transport mechanisms within fish (Wendelaar Bonga and Dederen 1986). The water and ion regulation changes are formed from the substantial increase in ph-mediated permeability causing osmotic water uptake. Urine rates increase causing a decrease in Na^+ and Cl^- ions. The increase in permeability causes H+ ions to penetrate the blood which effectively causes the blood to become acidified. The acidification can also impact oxygen transport. As pH decreases, calcium carbonate concentration increases, directly affecting also CO_2 concentration in the blood. One of the side effects of too much CO_2 in the blood is a reduction in oxygen binding to haemoglobin, thus affecting oxygen transport around the body. (Wendelaar Bonga and Dederen 1986). It has also been shown that chronic exposure of low pH waters can affect the growth and reproduction of flathead minnows with (Mount, 1973). The results clearly showed that a pH of 5.2 or lower severely affected spawning and the number of eggs produced. It has been shown that growth may be slowed by the loss of Na^+ and Cl^- ions and the subsequent increase in activity of the gills to increase the active uptake of the Na^+ and Cl^- ions, thus diverting resources away from processes needed to sustain normal growth (Wendelaar Bonga and Dederen 1986). In addition, some species of fish have shown to lose calcium from their bones in low pH conditions which can also impact growth (Wendelaar Bong and Dederen 1986).

A study undertaken in North America using both laboratory and *in situ* field studies on striped bass (*Morone saxatilis*), blueback herring (*Alosa*) and American shad (*Alosa sapidissima*) showed that the larvae of these anadromous species (ie. migrate from seawater to freshwater to reproduce) are adversely affected at pH ranges between 6.0 to 6.5 (Hall et al., 1985; Klauda and Palmer, 1986, 1987a, 1987b; Klauda et al., 1987, 1988; Klauda and Bender, 1987; Buckler et al., 1987), which is quite high, indicating that these species could be quite sensitive to changes in pH. Klauda (1989; as cited by Hall Jr et al. 1993) reported that early life stages of anadromous species such as blueback herring, alewife (*Alosa pseudoharengus*), white perch (*Morone Americana*) and yellow perch (*Perca flavescens)* may be adversely affected in Maryland coastal plain streams (non-tidal freshwater areas) because spawning occurs in these habitats concurrently with potentially toxic pH and aluminium. The level of impact on four different species due to low pH is provided in Table 4.

Table 4 Results on the impact of acid and inorganic monomeric aluminium on three different life stages (feeding, pre-feeding and larvae) Critical acidic conditions (CAC) by species defined as 50% direct mortality of the most sensitive life stage (Klauda, 1989). (from Hall Jr et al.1993).

Species	*Life Stage*	**Critical Acidic Conditions**
Yellow Perch	Feeding larvae	pH between 4.5 and 5.5 concurrently with inorganic monomeric aluminium of 50-150/.tg/l with at least 2 mg/1 of dissolved Ca
Blueback Herring / Alewife*	Pre-feeding larvae	pH between 5.5 and 6.2 concurrently with total monomeric aluminium of 15-137/lg/1 for 8-96 h with dissolved Ca of at least 2 mg/L
White Perch**	Larvae	pH 6.5 and 6.7 concurrently with total monomeric aluminium of 25 /tg/1 for 7 days with at least 2 mg/1of dissolved Ca

*Blueback herring data used for alewife.

**Striped bass data used for white perch.

Studies have shown that spawning may cease in pH higher than those at which major fish-kills have occurred (Beamish 1976; Vuorinen *et al*. 1992; Sayer *et al*. 1993), primarily due to failure of the adult fish to release viable eggs and/or sperm or an inability for adult fish to produce viable eggs (Sayer *et al*. 1993). Even if gamete release is successful, fertilisation still may not occur.

There is likely to be long-term impact on fish that reside within a low pH environment. For example, Hildén and Hirvi (1987) found that the survival of larval redfin perch *Perca fluviatus* from acid was dependant on the duration. Furthermore, populations of redfin perch sourced from waters with low pH survived for longer periods at lower pH levels in the laboratory than individuals sourced from a waterway with neutral pH, indicating that the ability to adapt to changes in pH could be heritable Hildén and Hirvi (1987). While this data specifically relates to redfin perch, we speculate that black bream may adapt to low pH conditions,

8.2.3 **Heavy metals impacts**

The process of oxidation of pyrite will release trace metals which can cause the activation Mobilisation of metals such as nickel, cobalt, copper, zinc, lead and arsenic (van Beemen, 1993). Aluminium oxidation has been regarded as a major factor in the loss of fisheries in soft acid waters (low pH and low in calcium carbonate cations) (Sayer *et al*. 1993). It is likely that the release and oxidisation of aluminium into the Anglesea estuary (*see next section*) could have an impact on species present in the system. However, this does not preclude entirely the impact of other heavy metals that may be released into the estuary at the same time.

A literature review conducted by Fältmarsch et al. (2008) found that the metals cobalt, nickel, zinc, cadmium and manganese do not normally exist in acid sulphate soils but are partly integrated into sulphides (Åström, 1988). Metals commonly found in the Anglesea Estuary include aluminium, copper, zinc, nickel and mercury which is associated with coal seams (see Appendix 1). Through the weathering process, sulphides naturally oxidise, releasing metals (Palko and Yli-Halla, 1988, 1990; as cited by Fältmarsch 2008). The metal concentration within waterways associated with acid sulphate soils can be increased by the weathering of other minerals such as aluminosilicate which can contribute to increasing metal concentrations (Sohlenius and Öborn 2004). It has been shown that heavy metal concentration may be between 10 and 50 times higher than typical background conditions due to the weathering process (Fältmarsch *et al*. 2008). The solubility of a metal is particularly important when trying to determine the likely impact of that metal in the environment. Metal solubility is important in the speciation of metals. For instance, chromium is less likely to become mobile because it is less soluble than other metals, however at low pH levels between 2.5 and 3.5 a relatively large amount of chromium can be mobilised (Åstrom, 2001), primarily due to the change in pH (Fältmarsch *et al*. 2008). Speciation of metals is complex and beyond the scope of this review, however as the chemical form of a metal is changed due to changes in other factors such as pH and dissolved organic carbon, the availability of those metals will change. As pH and dissolved organic carbon decreases, the mobility and availability of a given metal will increase (Reddy et al., 1995).

It has been estimated that the combination of low pH and high metal concentrations in waterways could be one of the biggest factors affecting fish diversity and community structure in CASS environments (Fältmarsch *et al*. 2008) (Figure 7). The release of metals into waterways often causes the formation of floc. The process by which a metal or chemical goes from an in solution state to a solid state is known as flocculation. This has been known to settle and smother substrate in benthic systems (Cook *et al*., 2000). The timing of flocculation is important because of the impact it can potentially have on the breeding grounds and the fecundity and survivorship of species on the benthos.

8.2.3.1Aluminium

The impact on fish species from acidification may initially be from the high concentration of hydrogen ions; a consequence of acidification is the mobilisation of aluminium into solution (Jr Driscoll, 1980). Subsequently fish kills have been associated with acidic water and high concentrations of dissolved aluminium (Brown et al., 1983; Hart et al., 1987; Fraser et al., 1992). Furthermore, while pH levels of 3-4 are likely to be lethal to most fish (Wendelaar Bonga and Dedren 1986), it has been found that elevated concentrations of inorganic aluminium (i.e. does not contain any carbon atoms) are most likely the primary cause for fish mortality in acidified waters (Jr Driscoll et al., 1980). A study which exposed fish to pH 3.1 and 5.1, with and without aluminium, showed that while gill and fish lesions were induced within 1 hour of exposure to pH 3, the addition of aluminium increased the clinical signs of stress and morbidity (Sammut (2002). Furthermore, it was found that aluminium had greater effects at pH 3.1 compared to 5.1. Interestingly, the addition of aluminium to water with a pH of 5.1 decreased the time that stress was induced; suggesting that at higher pH levels, exposure to aluminium was still likely to impact fish populations. Elevated aluminium has also been implicated in much reduced ability to regulate ions, resulting in decreased respiratory efficiency in brook trout (*Salvelinus fontinalis)* (Tietge *et al*. 1988).

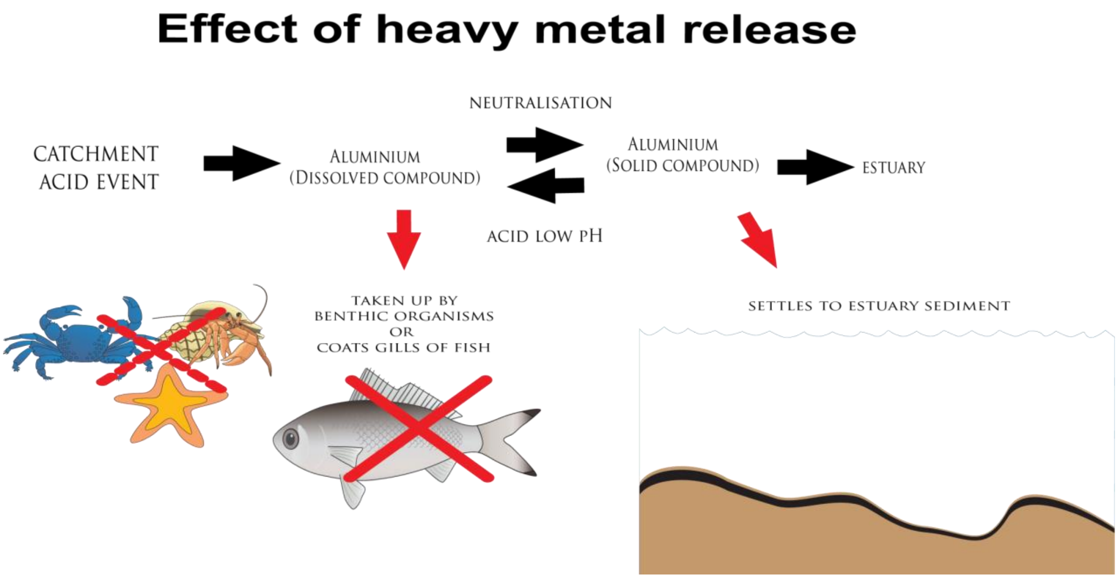

Figure 7 Conceptual model of the effect an acid event may have on estuarine biota and how the metal interacts with the estuarine system

The survivorship of fish during periods of high acidity is affected by a number of interacting factors. For instance, it was found that the survival of larval perch during acidic periods is dependent on the complex combination of the degree and duration of acidity, salinity gradients, aluminium speciation and overall water chemistry (Hilden and Hirvi 1987). Importantly, this study also showed that there are usually pockets within most estuaries that allow for survival of the larvae when acid events occur, which is primarily due to the salinity gradient and the hydrodynamics of the estuary. Results from this study also indicated that the presence of metals in the water column increased the critical pH level, suggesting that it may only take a subtle change in pH for there to be ecological impacts if metals are also available. Interestingly, the majority of the black bream collected in the March 2011 DSE Anglesea fish surveys were less than 100mm, indicating that larvae may have survived the acid pulse that occurred in October 2010, also suggesting that there could be protective pockets in the estuary where bream survived.

In a another example, survival in Australian bass exposed to pH ≥4.0 was found to be similar to that of fish in untreated freshwater after 96 hours, however, the survival at pH 4.0 was reduced to 65% when 500 µg/l of aluminium was added (Hyne and Wilson 1997), indicating that soluble aluminium has an additive impact on the health of fish after an acid flush. It has been suggested that the primary cause of mortality in fish from aluminium is anoxia resulting from gill hyperplasia (Driscoll *et al*. 1980), with aluminium concentrations within the gills of dead fish after an acid flush having between 17 and 30 times higher aluminium concentrations than a live fish captured after the fish kill (Brown *et al*. 1983). To date, the authors have not been able to locate any studies relating to the effects of aluminium on black bream. In the northern hemishphere, a study that investigated the effect that age and heredity had on tolerance to low pH on salmonids found that tolerance to pH changes decreased with age suggesting that older fish may not be able to adapt as strongly to abrupt changes in pH (Jensen and Snekvik 1972; Dunson and Martin 1973; Grande *et al*. 1978), while in contrast, another study (Leivestad and Muniz 1976) found newly hatched fry were more sensitive than adult trout to lowered pH. Furthermore, Brown *et al*. (1983) found that juvenile salmon tail catfish *Hexanematichrhys feptaspis* had the greatest sensitivity to the low pH and elevated aluminium conditions of all the species and age groups that were studied as part of a fish kill.

8.2.4 Indirect impacts

There is clear evidence linking low dissolved oxygen to the enrichment of estuaries and coastal waters with increased levels of nutrients and organic matter (Lee and Olsen 1985). Studies have also linked low dissolved oxygen levels with disease; for instance, Callinan *et al.* (1989) showed that red spot disease in fish populations increases in water subjected to low dissolved oxygen. Low dissolved oxygen can be brought on by a myriad of factors and conditions, however, in waters subjected to low pH conditions there is a tendency for iron to flocculate and remove oxygen from the water (Cook *et al*. 2000). When this occurs, anoxic conditions persist, affecting most of the aquatic biota in these areas (Callinan *et al*. 1995). For instance, anoxic conditions have been found to have metabolic implications for fish, usually reducing aerobic capacity, thus making these fish less able to adapt to other changes within the environment such as algal blooms or making then more susceptible to attack from pathogens (Webb *et al*. 2005). There are recent publications that describe the effects of low dissolved oxygen on black bream early life stages that you could include here.

For black bream to breed they require an increase in freshwater flow in the upper reaches of a river system. In the Victorian estuaries of the Glenelg and Hopkins Rivers, black bream have been shown to move upstream in response to an encroaching salt wedge and spawn in salinities of 20–25 g L^{-1} (Newton 1996). Poor quality water from systems may create barriers to movement, which may potentially affect migration and recruitment of fish and mobile invertebrate species (Kroon *et al*. 2004). For instance, acid sulphate discharge has been implicated in the population collapse of the Australian bass (*Macquaria novaemaculeata*) within the Hastings and Manning Rivers (New South Wales) due to recruitment failure (Harris, 1989; as cited by Kroon *et al*. 2004).

Locally, acid flushes that occur in the Anglesea River may activate avoidance mechanisms in black bream, which could, depending on the timing of the event, affect black bream recruitment. Another threat to the biota in rivers often affected by acid events is hydrogen sulphide. Hydrogen sulphide can lead to subtle behavioural changes to fish and other biota with studies showing that high sulphide concentrations and low dissolved oxygen levels can cause fish to gasp at the water surface and can lead to a loss of ionic equilibrium (Bagarainao 1992). Physiological responses to sulphides include; stimulation and depression of both ventilation and circulation systems in fish (Torrans and Clemens 1982; Bagarinao and Vetter 1989), reduced survival, reduced swimming endurance, tissue irritation and necrosis, lower food consumption and conversion, inhibited spawning behaviour, inhibit the growth of salt marsh species (Ingold and Havill 1984), reduced egg production, lower survival of eggs, smaller egg size and a higher incidence of deformities for newly-hatched larvae (Adelman and Smith 1970; Oseid and Smith 972; Smith and Oseid 1974; Smith *et al*. 1976b,c; Reynolds and Haines 1980). Given, however that sulphides generally oxidise quite rapidly, it is likely that these effects will be transient in nature and may only affect fish and other mobile organisms for short periods of time.

The release of hydrogen sulphide occurs at night since photosynthetic bacteria efficiently oxidize sulphide during the day (Bagarainao 1992). Coastal wetlands, particularly mudflats and salt marshes are major sources of H_2S, dimethyl sulphide and other forms of biogenic sulphur, and can contribute to acid precipitation (Aneja and Cooper 1989; Cooper et al., 1989; Saltzman and Cooper 1989). Bagarainao (1992) found that there is a sudden occurrence of high sulphide concentrations within the water column when there are severe storms or underwater volcanic eruptions which can cause mass mortalities in the local fauna of fjords, eutrophic seas and even the deep sea (Gunter 1935; Brongersma-Sanders 1957; Theede *et al*. 1969; Macdonald and Mudie 1974). Sulfide can influence the survival, distribution, recruitment and growth of freshwater fishes, salt marsh plants, mangroves and various invertebrates (Smith and Oseid 1974; Groenendaal 1979; Ingold and Havill 1984; Nickerson and Thibodeau 1985; Vismann 1990). In Salt creek, a tributary of the Anglesea River, low Cl: SO_4 ratios were found indicating acid generation due to oxidation of sulphide minerals is occurring in the Anglesea catchment and driving acid events when conditions are right. (van Breemen 1992 as cited by Pope 2006).

After heavy rainfall, some systems can be prone to the release of vast amounts of soluble iron (Fe^{2+}). The influence of turbulent waters can rapidly oxidise the Fe^{2+} to Fe^{3+} (Powell and Martens, 2005). The change in iron types deoxygenates the water in an ecosystem producing what is known as black ooze. Black ooze occurred in a 20 km stretch of the Richmond River, New South Wales in 2001, causing ecological impairment through the system (Bush *et al*. 2004a, b; Powell and Martens 2005).

8.2.5 **Behavioural consequences**

Animals can respond to threats in various ways, including physiological responses or through changes in their behaviour. Unless adapted to threats, most animals would find it difficult to protect themselves solely through physiological responses. Often they need to adjust their behaviour in response to a threat or numerous threats. Animals can do this in numerous ways, including through the use of chemoreceptive membranes. These membranes in aquatic animals are directly exposed to the environment and are primarily used to assess the quality of the immediate environment and as a communication tool. Studies suggest that chemoreceptor's can be employed as a mechanism to avoid pollution, with differences amongst species in avoidance efficacy; snapper shows strong avoidance compared to school prawn which exhibits weak responses to polluted environments (Kroon 2005). Given the amount of novel chemicals entering waterways is constantly changing, there is concern that these chemicals entering the environment could be interfering with receptor function, breaking down vital communication between these animals and their environment (Sutterlin, 1974). Other laboratory studies conducted on behavioural responses to acid water have found that avoidance was stronger for dissolved aluminium than low pH alone (Kroon 2005). It is believed that the differences between species that can be related to differences in natural distribution, life history stage and chemosensory detection for acid. Kroon (2005) found that because juveniles of snapper occur within estuaries and bays and are less likely to naturally encounter acidic conditions; these fish are going to be more sensitive to the changes in pH. Whereas school prawns occur in brackish to freshwater and Kroon (2005) suggesting that this species may have adapted to fluctuations in pH.

Avoidance behaviour observed in the field for fish and prawns will be affected by a number of other motivational or environmental factors, including reproduction, competition, feeding, predation, as well as water quality, water velocity and habitat availability (Kroon 2005). It was deemed by Kroon (2005) that other factors may override potential avoidance of acid sulphate discharge. Kroon (2005) suggests that presence of suitable habitat may alleviate strong avoidance behaviour to low acid levels. Is it suggested that further research be conducted within the Anglesea River to assess whether fish avoidance behaviour could be affecting fish numbers within the estuary, especially when acid events occur. Open and closed estuaries
The management of estuaries, in particular how tidal inundation is managed, is seen as critical in the management of fish populations in areas prone to acid sulphate soils. The use of floodgates to control run-off from catchments directly influences how much water enters an estuary from local tributaries while also manipulating the natural tidal exchange process within estuaries. Recent studies suggest that any increase in the frequency of floodgate closures (i.e. not allowing seawater to enter the estuary) in conjunction with any decrease in water quality during high rainfall periods can impact on the recruitment of fish species (Kroon et al 2004). Furthermore, it has also been suggested that keeping floodgates open during periods of low rainfall will positively influence the recruitment of those species that breed during these periods.

8.2.6 **Summary**

Waters impacted by low pH and high acidity can effect fish in numerous ways, including physiological and behavioural. Variation in pH levels can affect fish reproduction, respiration rates and increase fish lesions. In particular, this damage to the epithelial layer can leave fish vulnerable to attack by pathogens and other diseases. By increasing metal availability, especially aluminium, acid discharges can also impact upon fish by increasing their risk to metal poisoning with metals likely to accumulate over time. Oxidation of metals can also increase the risks of anoxia within a waterway, often having a tremendous impact on the biota within these systems. Timing, extent and duration of acid events are critical when determining the full extent of an impact. If the acid sulphate soil discharge occurs during breeding, or when the fish are in the early life stages, there is likely to be reproductive effects such as, abnormal sperm and eggs, deformities in larvae and in severe instances, complete lack of production of any viable gametes. Flocculation of metals such as iron and aluminium, a common by-product of low pH environments can smother surfaces such as fish gills, leaves and sediments. While flocs exist, fish and other benthic biota can be affected with animal fitness and fecundity often reduced under these conditions.

Ecologically, a severe change in the dynamics of an estuarine ecosystem is likely to occur when there is a large loss of seagrass. The change may be caused from a direct change in the amount of food and habitat available for macroinvertebrates, juvenile fishes and ultimately larger fish species, especially black bream in the case of Anglesea River. This is demonstrated by the Victorian Department of Primary Industries (DPI) stating that the successful survival and growth of juvenile black bream was qualified by the amount and distribution of seagrass habitat (and the availability of other types of suitable settlement habitat), food availability and the ability to avoid predators such as cormorants (DPI 2008).

8.3 Macroinvertebrates

Macroinvertebrates play an important part of all ecosystems; macroinvertebrate feeding group roles within an ecosystem are varied, specialised and ultimately essential to the functioning of that ecosystem. For black bream adults and juveniles - macroinvertebrates are a food source. In relation to seagrass, macroinvertebrate groups feed on sections of seagrass, decaying and dead seagrass, and organic material, and may utilise seagrass as a habitat. Macroinvertebrates are generally found in a high abundance and diversity within seagrass meadows due to the complexity of habitat and food availability. Macroinvertebrates within a seagrass meadow digest coarse organic matter into smaller particles, either via the digestion tract or through the chewing process. This digestion process enables bacteria and fungi to feed on the smaller fine particle matter. The bacteria and fungi inturn digest the fine particles releasing nutrients into the sediment. The nutrients are then taken up by seagrass and the cycle continues.

Poore (1982) conducted a study comparing density and diversity of macroinvertebrates within different habitats within the Gippsland Lakes and found that there was a total of ninety species that occurred within the Gippsland Lakes. These species lived in numerous habitats including sandy and muddy substrates as well as in seagrass communities, with the greatest diversity and density occurring in the seagrass. There have been few studies on the community structure, diversity and composition of aquatic macroinvertebrates in western Victorian estuaries (Moverley and Hirst, 1999). While there currently is little information on the species composition of invertebrates in western Victorian Estuaries, several studies have assessed this group as potential indicators of estuarine condition (Barton, 2003; Moverley and Hirst, 1999). The relatively low species richness and spatial patchiness of invertebrates in estuarine systems compared to freshwater systems indicates that estuarine invertebrates may not be able to easily assess changes in estuarine systems, compared to other groups such as fish and submerged vegetation (Barton, 2003; Mondon et al., 2003; Moverley and Hirst, 1999).

8.3.1 **Ecological impacts**

In response to acidic discharge, there is a likelihood that the macroinvertebrate fauna will change over time, as species sensitive to low pH drop out of the system. This then allows more tolerant species to become more abundant (Rosemond *et al*. 1992) while other more sensitive species can become locally extinct (Sommer and

Horwitz 2001). In general, acid discharges have been known to decrease primary production, functional diversity and biomass (McCullough and Horwitz 2010). Changes in pH can not only influence species composition in aquatic environments but also how these species behave. For instance, feeding, burying and foraging behaviour have all been known to be affected by changes in acidity (Dangles and Guérold 2001; Allard and Moreau 1989). The impact of pH on macroinvertebrate diversity and density has been well studied. These studies suggest that a reduction in pH usually results in a reduction in stream diversity and overall density of the biomass Herricks and Carins (1974; as cited by Zischke *et al*., 1981; Zishke *et al*. (1983). Other studies suggest that insect emergence can be retarded due to lowered pH (Hall *et al*. 1980; Bell 1970, as cited by Zischke *et al*. 1983). Although emergence rates are probably not a true estimate of environmental degradation due to the overwhelming influence of tolerant species that colonise areas as sensitive species exit (Zishke *et al*. (1983). The use of indicator species is now an accepted practice world-wide, with the majority of indicators being those that are sensitive to particular aspects of their environment. A study conducted in the early 1980s looked at the sensitivity of particular groups of macroinvertebrates in regards to acidity. The results suggested that species such as mayflies, corixids and chironomids show little response to increasing acidity, while other species such as isopods, leeches, amphipods, physid snails and damselflies had a much greater response as pH decreased (Zishke *et al*. 1983). Similarly, caddisflies, damselflies and some Lepidopteran species have been shown to have reduced emergence in tests investigating increased acidity Zishke *et al*. 1983). Considering the importance of these groups in the maintenance of aquatic food webs, it is likely these systems are being stressed by acid events.

Furthermore, changes in behaviour can have deferred effects. For instance, it was found that the gastropod *Gyraulus sp* become unresponsive and stopped feeding in highly acidic conditions (Havens 1992); while a survey in Nova Scotia lakes found that under conditions where pH fell below 6, gastropods would become locally extinct for these periods (Schell and Kerekes 1989).

While community structure can be affected by numerous parameters including flow, food availability and water quality, Rosemond *et al*. (1992) found that pH and metal mobility affected macroinvertebrate communities in a similar way, although community structure was more correlated with pH, while population density correlated more strongly with metal mobility. This study also looked at the response of high acidity on individual groups and found that the mayflies and caddisflies did not respond well to low pH conditions, with decreases found in both density and diversity for both groups. In this same study, it was found that low pH also caused a general decrease in grazers, allowing algae to become dominant under low pH conditions. Periodic changes in water quality stemming from high rainfall events and associated acidity in acid prone environments has generally been found to lead to an impoverished fauna, although no studies have been able to directly disassociate other factors such as salinity and sediment quality as the main contributor to the lack of animals (Fältmarsch *et al*. 2008). A translocation study within a Finnish river (Vuori 1996) of the filter feeding trichopteran larvae, Hydropsychidae into a field location impacted from acid sulphate soil, found that the most sensitive species were unable to survive acute field exposure to low acidity and high metal concentrations. This study (Vuori 1996) found that the survival of species was dependant on where the species was collected from. If the species was collected and translocated into the study site from a polluted site then the species survived better and did not show any morphological abnormalities.

8.3.2 Physiological direct impacts

The filter-feeding Sydney rock oyster *Saccostrea glomerata* has been shown to decrease in population size due to estuarine acidification via acid sulphatesulphate soils. The cause could be due to an increase in abnormalities of *S. glomerata* embryos (Wilson and Hyne 1997), impacts on growth and mortality (Dove and Sammut 2007a) and filtration rate (Dove and Sammut 2007b). Mortality in *S.*

glomerata may be more likely in small oysters from the acid sulphate soil run off entering small oysters through a perforated left valve caused by the acid affecting the soft tissue of the oyster (Dove and Sammut 2007a). Dove and Sammut (2007a) states that this is because small oysters are more likely to be impacted due to their smaller, thin fragile shells.

Vuori (1996) found that there was a higher incidence of morphological abnormalities in ion-regulation and respiration organs in the caddisfly and that these abnormalities appeared to impede the larval development and growth. Whilst, Havens (1992) found that toxicity of aluminium and acid to taxa were those that had external gill structures which were more likely to be damaged; alternatively, groups that were more tolerant to changes in pH were found to lack external respiration organs, for example, chironomids and mites.

Acidic impacts have been shown to have significant mortality on the eggs of mayfly nymphs and that this was shown to have occurred before the hatch was complete, whilst the hatching rate of another mayfly species was significantly retarded (Rowe *et al*. 1988). Finally, Rosemond *et al*. (1992) concluded from the study on acidic impacts on macroinvertebrates and fish stated that the direct impact on invertebrates from low pH is more important than indirect effects, such as changes in food source availability (*see below*).

8.3.3 Indirect impacts

A secondary impact on the aquatic community from an acid flush within a waterway is that it will increase the clarity. The clarity is caused by suspended solids clumping and sinking to the substrate. This increase in clarity will create an increase in the temperature and also increase in the amount of light reaching the substrate; this will then increase on the algal production in the water column and on the sediment. Changes in pH have been shown to cause changes in algal food sources (Mulholland et al, 1986). In addition, the clumping of the suspended solids may also smother benthic habitat and depleting oxygen and changing the water chemistry at the sediment / water interface.

As with certain fish species, acid impactson the Sydney rock oyster, included damage to the gill and mantle soft tissues of oysters and were highly impacted by iron and aluminium from acid sulphate soil affected waters (Dove and Sammut2007b). Similarly, Dove and Sammut (2007b) found that there high concentrations of iron at acidified field sites were contributing to the high mortality rates and slow growth. However, a laboratory study by Dove and Sammut (2007b) conducted on the impact of iron in solution on Sydney rock oysters found that there was no direct impact due to iron toxicity, but the authors postulated that iron would impair gill function by congesting the ciliary junctions causing feeding processes and gas exchange to be impacted. Dove and Sammut (2007b) declared that iron ingested by oysters in an acid sulphatesulphate flush will have effects on the long-term health of oysters because floc will impact on gill membranes. The release of aluminium due to acid sulphate soil has been shown to cause impaired respiration and osmoregulation by the aluminium hydroxide smothering respiration membranes in mayflies (Herrmann and Andersson 1986). As previously stated it was those taxa that have exposed gill filaments and other fine tissue organs that are likely to be more sensitive to changes in pH and heavy metal toxicity.

Summary Macroinvertebrates are an important group within all ecosystems and most studies on acid sulphate impacts on macroinvertebrates indicated that there will be a definite change in abundance initially and subsequently in diversity. As pH decreases species that are sensitive to acid decline and those species that are more tolerate increase due to the increase in food source and habitat availability. A reason for the change in diversity indicates that aluminium floc and hydrogen ions impact on the respiration and osmoregulation membranes of the more sensitive species. Oysters were found to be impacted from the gill being impaired by settling of iron floc into the gill causing high mortality and slow growth. The physiological impacts are likely to be similar to fish species such as damage of external gill membranes in low pH conditions.. The changes to taxa impacted by acid may increase the likelihood that the invertebrate will be more likely to be predated on, less likely to produce healthy young and if the taxa occurs as an aquatic larva there is evidence to suggest that the taxa is unlikely to emerge.

8.4 Seagrass

Introduction Seagrass is a marine flowering angiosperm. This vegetation type is located throughout the world and is found in specific regions of the Victorian coastline that suit this ecotype. The Anglesea River estuary usually contains two different species of seagrass, *Zostera spp* and *Ruppia spp*. A PhD thesis completed by Pope (2006) found that the cover of seagrass within the Anglesea River displayed seasonal peaks of cover, with high abundance in warmer seasons.

Seagrass is important for fish for habitat use, as a breeding locality, as a food source,, as a larval settling location and nursery area, and for juvenile growth . In relation to black bream populations and seagrass, as early as 1945 a direct link has been made with the reduction in the abundance of black bream within the Gippsland Lakes (Butcher 1945). In terms of fish and in particular black bream food sources, seagrass is an important habitat for invertebrates, especially those invertebrates that utilise seagrass as a food source, habitat and for breeding. Finally, seagrass is integral for the sediment stabilisation within an estuary.

The extent of seagrass habitats worldwide has been reduced through human induced habitat changes (Short and Wyllie-Echeverria 1996; Orth et al. 2010; Waycott et al. 2009). Human impacts on seagrass can generally be divided into two categories direct and indirect. Direct impacts are those due to physical alteration of the benthic habitat through channel dredging, inlet modification, boat scarring and dock building and indirect impacts can include those caused by nutrient enrichment and eutrophication (Burkholder et al. 2007) and acidification.

A study on *Zostera mulleri* in Western Port, Victoria found that there was an increase in leaf biomass after short term nutrient enrichment (Morris *et al*. 2007). However, if there is long term enrichment the species *Zostera marina* can cause die off due to enrichment via sediment prompted growth (Touchette and Burkholder 2000). A significant threat to seagrass ecosystems is contamination from heavy metals (Schlacher-Hoenlinger and Schlacher 1998). Seagrass also has a strong ability to sequester heavy metals within the leaves and rhizomes (Amado-Filho, 2008, Pulich, 1980; Amado Filho *et al*., 2004). In these circumstances, due to the uptake of heavy metals there may be a bioaccumulation of heavy metals ending in fish..

There are no known studies examining the effect of acid on seagrass meadows in Victoria and Australia, however, there are a few articles regarding the impacts from acid sulphate soil releases from international studies.

8.4.1 Direct impacts

Acid is likely to have an impact on aquatic macrophytes by general plant cell degradation through acidic processes. An acid flush causing low pH is likely to inhibit growth. But pH at a critical level and duration, the impact may potentially cause death of individuals or cessation of leaves of individuals. Luven and Wolfs (1988) found that rate of decomposition of the macrophyte *Juncus bulbosus* leaves was reduced within an acidic environment. Extrapolating this information, with the rate of decomposition reduced, and then the amount of reduction in decay rate will reduce the amount of nutrients that return into the sediment after the breakdown of organic material. The study found that as well as pH, alkalinity and aluminium concentration were likely to have the greatest impact on the decay rate of the organic matter of *Juncus bulbosus*.

Acidification has been shown to have an inhibition on plant growth including a limitation of nutrient uptake by sulfide (Van Der Welle *et al*., 2007) and iron (Watanabe *et al*., 2006), there may also be osmoregulatory failure caused by hydrogen ions themselves (Lopes *et al*., 1999) and direct toxicity from soluble metal and metalloids (Markich *et al*., 2001). A study conducted in the Tinto River, Spain, on the exotic species *Spartina densiflora* found that germination was not affected by acid and heavy metal pollution but the subterranean and aerial growth was impacted and that the seedlings that germinated in poor quality sediment were found to have a high percentage of mortality (Curado *et al*. 2010). Curado *et al*. (2010) found that there was an inhibition of root growth due to acidic conditions and was found to affect the *S. densiflora* seedlings the inhibition of root growth impacted the macrophyte by limiting the water and nutrient uptake capacity and / or their anchoring capacity to resist river runoff, currents and waves. Results of a PhD study conducted by Meriläinen (1989; as cited by Fältmarsch et al. 2008) found that in the estuary of Kyrönjoki that the distribution of some sensitive aquatic vegetation species was considered to indicate growth inhibition due to acidity. It was concluded from Meriläinen (1989) that a high nutrient status in an inner estuary might alleviate the detrimental effects of monomeric inorganic Aluminium on aquatic vegetation. The direct effect of low pH and high concentration of aluminium may cause smothering of the benthic communities (Cook et al. 2011) and this may include seagrass. If there is an area that becomes bare from changes in water quality this leaves an area where an introduced or more tolerant species may be able to take over or dominate (Curado *et al.* 2010; Lavoie *et al*. 2010).

A study conducted as part of a PhD by Pope (2006) found the decline in seagrass present within the Anglesea River estuary was closely related to floods and that there was a reduction in the habitat after the tidal states were altered. Pope (2006) found that periods of drought and extended mouth closure were related to establishment and expansion of beds. The Anglesea River has highly variable hydrology which can impact more strongly on the productivity of seagrass meadows than large marine influenced bays (Pope 2006).

In Anglesea River in early 2000 (April), the extent of *Zostera* decreased and the extent of *Ruppia* had increased, resulting in large areas of pure *Ruppia* beds, particularly in the shallower parts of the estuary (Pope 2006). This change was deemed as most likely associated with a reduction in the salinity of the estuary (Pope 2006). In December 2000, Pope (2006) reported that there had been a large reduction in the area of seagrass beds, present as mixed beds. These changes were stated by Pope (2006) as being due to the estuary becoming tidal which was either permanently or intermittently exposing seagrasses.

A study on the *Zostera* beds in Westernport Bay stated that smothering by mobile sediments was regarded as an important impact on this species (Edgar *et al*. 1994). In relation to acid impacts which indicate it likely that *Zostera* will be photosynthetically inhibited as pH decreases below 7.8 (Millhouse and Strother 1986) and as salinity increases or decreases away from the concentration of seawater (Kerr and Strother 1985), this is important when considering the opening / closing nature of the Anglesea River estuary. When the freshwater inflow is reduced and the estuary is open? then the salinity will increase and when the freshwater inflow is increased and the mouth is closed the salinity will decrease. Pope (2006) found that the changes in the distribution of *Zostera* within the Anglesea River was related to the increase in freshwater and was caused by a reduction in photosynthesis (as shown in Kerr and Strother 1985).

Pope (2006) suggested that the changes in *Zostera* cover may potentially be due to interactions of the expanding *Ruppia spp*. beds. Pope (2006) found that in 2001 there were substantial decreases in the mean cover of *Zostera sp* and the reduction could be related to the major flood in April 2001. This flood subsequently increased the depositional rates and erosion regions. At the end of this flood event in 2001 catchment rainfall filled the estuary with acidic water and this resulted in a deep opening and the depositional zones being lowered by around one metre thus exposing large portions of beds and causing desiccation and mortality (Pope 2006). The largest impact to seagrass within the Anglesea River indicate hydrological state and stratification patterns as the largest contributor to changes in seagrass extent which can create changes in both the area and quality of habitat.

8.4.2 Summary

There is little to no studies on acidic and heavy metal impacts on seagrass communities through the world, nationally or in Victoria. However, due to the fine structure of the leaves, it is likely that the leaves will degrade and from this there is likely to be large areas of die off. Recovery of the seagrass will occur once the conditions return to optimal for seagrass growth. The sequestering of heavy metals into the leaves of seagrass is likely to impact on the estuarine ecosystem.

8.5 Terrestrial vegetation

There are vast areas of dying terrestrial vegetation on the approach to Coogoorah park these show severe signs of acid stress. Iron reducing bacteria is also clear to see as inundated water from the area recedes.

Moonah (*Melaleuca lanceolata*) are an important estuarine plant community which is present through large sections of the lower eastern flank of the Anglesea River estuary. Moonah only provide habitat for fish and invertebrate species during times of high water and floodplain inundation. They do provide structure to attract sediment.

There is a likelihood that regeneration of Moonah may be hampered when acidic conditions are present, in a study conducted by Amaral *et al*. (2011) found that the likely impacts from acid sulphate soil discharges may hamper the growth of mangrove seedlings.

9 Ecosystem Recovery after acid flush

The recovery of the Anglesea River ecosystem is dependent on freshwater and or tidal flow that enters into the system. The recovery rate will be dependent on the flow rate and quantity. The volume from tidal flow will be dependent on the time of year, how regularly the mouth of the Anglesea River is open, and the volume of freshwater flow coming down the river. The flushing will physically remove acidic water present within the estuary and at the same time increase the pH level. The recovery of the system is likely to be faster from tidal inflows because these have a greater capacity to neutralise the acid present within the estuary due to the buffering capacity of the seawater.

In relation to behavioural responses by fish to acid flush recovery this will be dependent on the mouth of the Anglesea River being open when an acid event occurs. Black bream have shown a propensity to move out into the ocean during flood events and return once water quality improves, or potentially even migrate into a nearby estuary . Successful black bream reproduction within the estuary will only occur if there is quality breeding and residential habitat available. In addition, an important factor for fish habitat is seagrass, and there is likely to be damage to the existing seagrass from an acid flush. Seagrass health is likely to be further hampered if tidal flows are either non-existent (too much freshwater/ mouth closed) or extreme (seagrass being exposed and impacted by desiccation).

In relation to invertebrate recovery rates, the relatively mobile prawn has shown a weak propensity to move away from poor water quality localities (Kroon *et al*. 2004). This indicates that if an acid event occurs, prawns may have the propensity to avoid or move away. The successfulness of the recovery may be dependent on the volume of acidic water and the availability of suitable habitat with good water quality sulphate.In a freshwater invertebrates, an example is provided via the mayfly, Fiance (1978) found that older cohorts of the insect mayfly taxa when present in low pH conditions were found to move from a low dissolved oxygen region to a higher oxygenated area, demonstrating avoidance.

Mobility or lack of mobility appears to be a defining method of recovery from acid sulphate flushes, in a study by Amaral *et al*. (2011) examining estuarine acidification found that oysters are impacted the greatest due to their immobility, followed by gastropods and the least impacted were crabs. In addition, the crabs used in that study were seen to have long-term acclimation and genetic selection toward resistance. Finally, crabs are likely to respond physiologically better than molluscs to acid by increasing the calcification in their carapace, molluscs have been shown to decrease calcification and shell dissolution will occur (Amaral *et al*. 2011). Furthermore, if the crabs are burrowing they can avoid acid affected waters in tidal systems, by plugging their burrows and re-emerging when the tide recedes (Amaral *et al*. 2011).

If there is habitat rehabilitation post acid flush this may enhance the survival and likelihood that individuals may recover and reproduce. This is observed with Russell *et al*. (2011) who found that for their study area of Firewood Creek that the hydrological and other management changes made after the commencement of the rehabilitation works, resulted in a sufficient net improvement in the health of the system. The rehabilitation was deemed as a probable measure for rapid recolonisation. Furthermore, this study (Russell *et al*. 2011) suggested that by improving the habitat quality, it prevented fish deaths downstream of a seawall.

Studies have found that fish native to acidic waters are less sensitive to more severe acid or acid / aluminium challenges (Rahel 1983; Mcwilliams 1980; Brown 1981) and may have a genetic selection or adaption to acid and / or aluminium concentrations

(Rahel 1983) Mount et al. 1990) Brown 1981 Gjedrem 1976, as cited by Brown 1981; Robinson et al. 1976. Brown (1981) concluded that it was difficult to determine if the difference in survival was due to genetic, adaptive or a combination of both. . (Orr et al. 1986; Callinan et al. 1993)

While there is some evidence to suggest that that black bream survived the pulse of acidic water in 2010 (DSE, 2011), the extent to which black bream may have adapted to low pH conditions remain unknown. Given that only two black bream were found in fish surveys following the acid events in 2010, suggest that this species was probably severely affected by the acid event in 2010, and whilst recovery was evident in April 2011, the reasons for this recovery are still unknown (DSE, 2011).

Whilst it is possible some black bream individuals may have survived in protected pockets, it is possible that the black bream population may have been enhanced by individuals immigrating into the estuary. This is a knowledge gap regarding black bream regeneration and ultimately population recovery. It is strongly suggested that a more thorough study be conducted on the population genetic structure of black bream in the Anglesea Estuary. This would allow a better understanding of how black bream populations are maintained, and help determine the level of immigration and emigration that might be occurring within the estuary for this species.

There are no ecological components of the Anglesea River that would assist in the resilience of high acid events. Since the data that exists indicates that acidity within the Anglesea River is naturally occurring, it is likely that local biota that are sedentary in behaviour will over time adapt to local conditions. Thus, if water within the Anglesea River is frequently exposed to low pH conditions, fish or other biota within the system may, over generational time periods, build up resilience to those conditions. Northern Hemisphere studies have shown that salmonoids can adapt to acidic waters with studies showing that this tolerance can be inherited. There is no literature on the resilience of black bream from acid events; but there is a potential that black bream may move away from poor water quality. The lack of knowledge we currently have on the drivers of black bream recovery suggest that further research is required within the Anglesea Estuary to determine how black bream move, and more importantly how this species may be adapting to on-going acid events. Potential food web implications from acid flush events

Acid flush can affect taxa differently depending on how sensitive or tolerant the taxa are to acid. In a simple design using black bream, black bream's main food source of macroinvertebrates and seagrass, we aim to show examples of scenarios of how a population of each of these groups may recover after an acid event dependent on which group is sensitive (Figures 2 – 5).

Scenario 1

Seagrass is the least resilient to acidic events and thus has the greatest decline in abundance of the groups during time (Figure 8). The impact on the loss of seagrass causes the decline in the macroinvertebrate community due to the limited food and habitat available. After the decline of the macroinvertebrate abundance, black bream will subsequently decline due to the lack of food source available only after the macroinvertebrate community reaches a critical abundance.

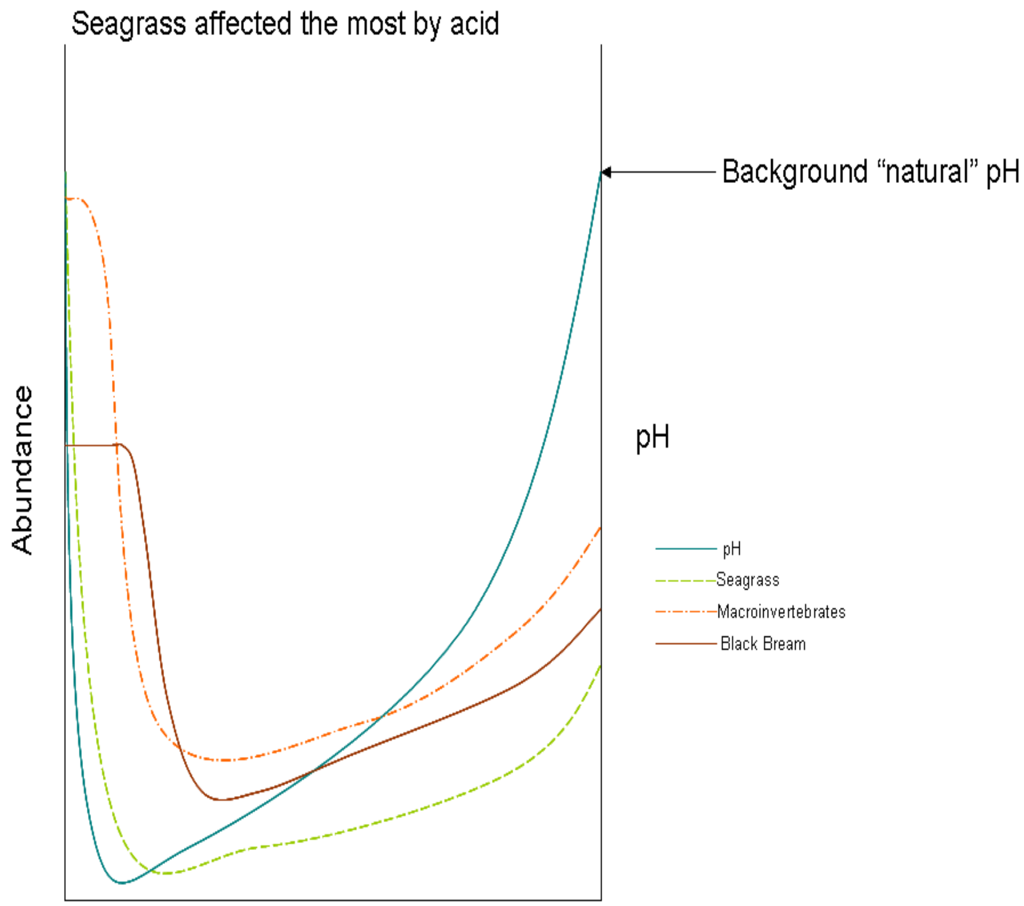

Figure 8 Theoretical population dynamics if seagrass is the least resilient and has the greatest loss in abundance (Scenario 1).

Scenario 2

Macroinvertebrates are least resilient of the groups to acidic events and thus have the greatest rate of decline in abundance during time (Figure 9). The decline in macroinvertebrate abundance is likely to have little impact on seagrass unless they are gastropods and grazers who feed upon the sea grass and other organic matter. Black bream may decline initially due to the chemistry of the acid flush. Once macroinvertebrates decline to a critical point, black bream abundance is then affected, due to a loss of prey. After the decline in the black bream population, the macroinvertebrate community recovers due to the decrease in predation pressure from the black bream. The increase in black bream abundance occurs after the macroinvertebrate community begins increasing in population and the water quality improves. The increase in black bream increases the predatory pressure, and this causes the macroinvertebrate abundance to decline again.

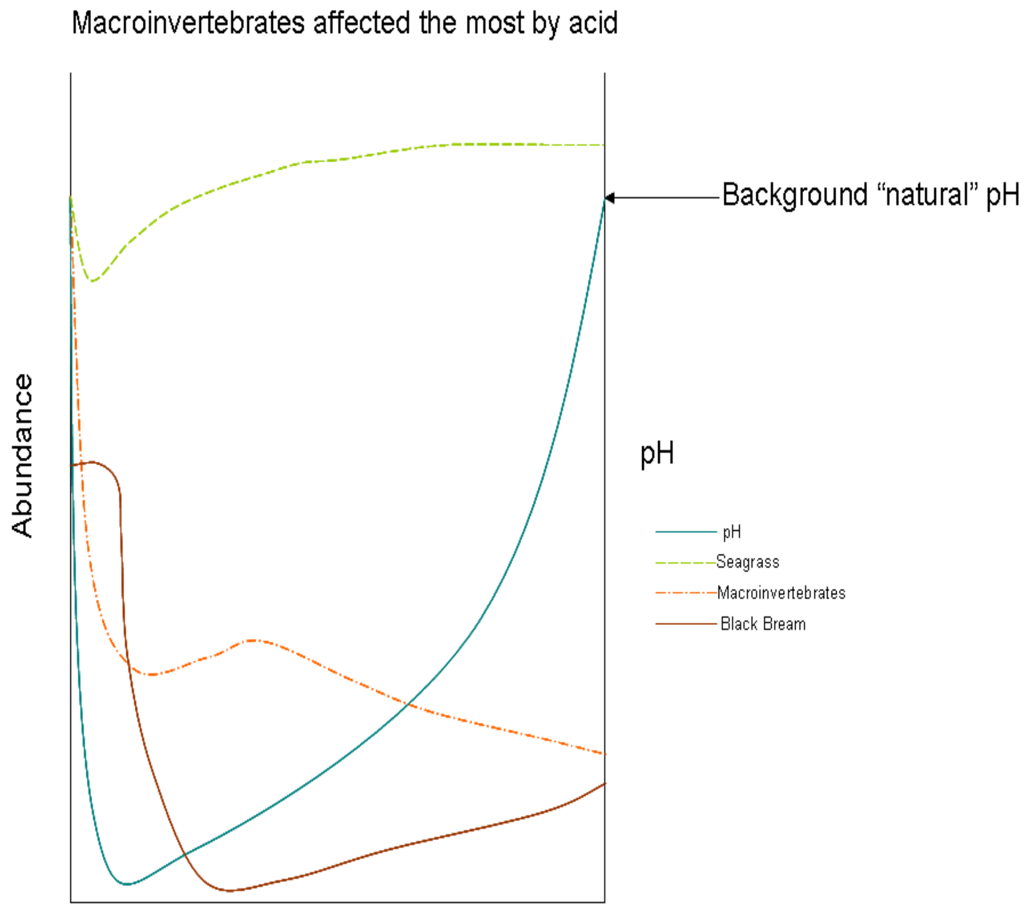

Figure 9. Theoretical population dynamics if macroinvertebrates are the least resilient and have the greatest loss in abundance (Scenario 2).

Scenario 3

Black bream are the least resilient of the groups to acidic events and have the greatest rate of abundance decline (Figure 4)). Initially, there is likely to be minimal impact on the macroinvertebrate and seagrass abundances. As the predatory pressure onto macroinvertebrates is reduced, grazing pressure increases and such the abundance of seagrass then decreases. As the water quality improves the black bream population increases in abundance, subsequently, the macroinvertebrate grazing pressure is reduced via predation. The reduced grazing pressure improves the growth of the sea grass.

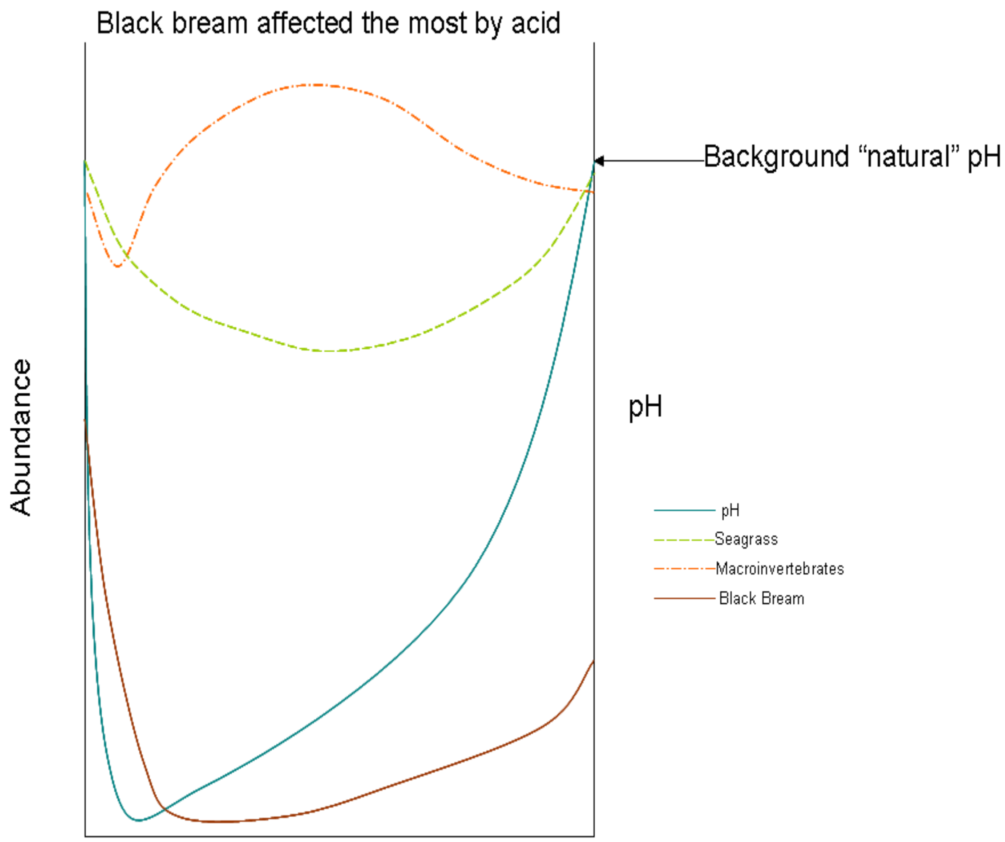

Figure 10 Theoretical population dynamics if black bream are the least resilient and have the greatest loss in abundance (Scenario 3)

<u>Scenario 4</u>

When all three groups are equally impacted and similarly resilient (Figure 5) the end result then depends on the resilience and recovery of each group. In this example, sea grass is affected the least and recovers the earliest and the poorest in recovery and resilience is black bream. This model shows that black bream abundance fluctuates and such the macroinvertebrate and sea grass abundance fluctuates as the predatory and grazing pressure change through time.

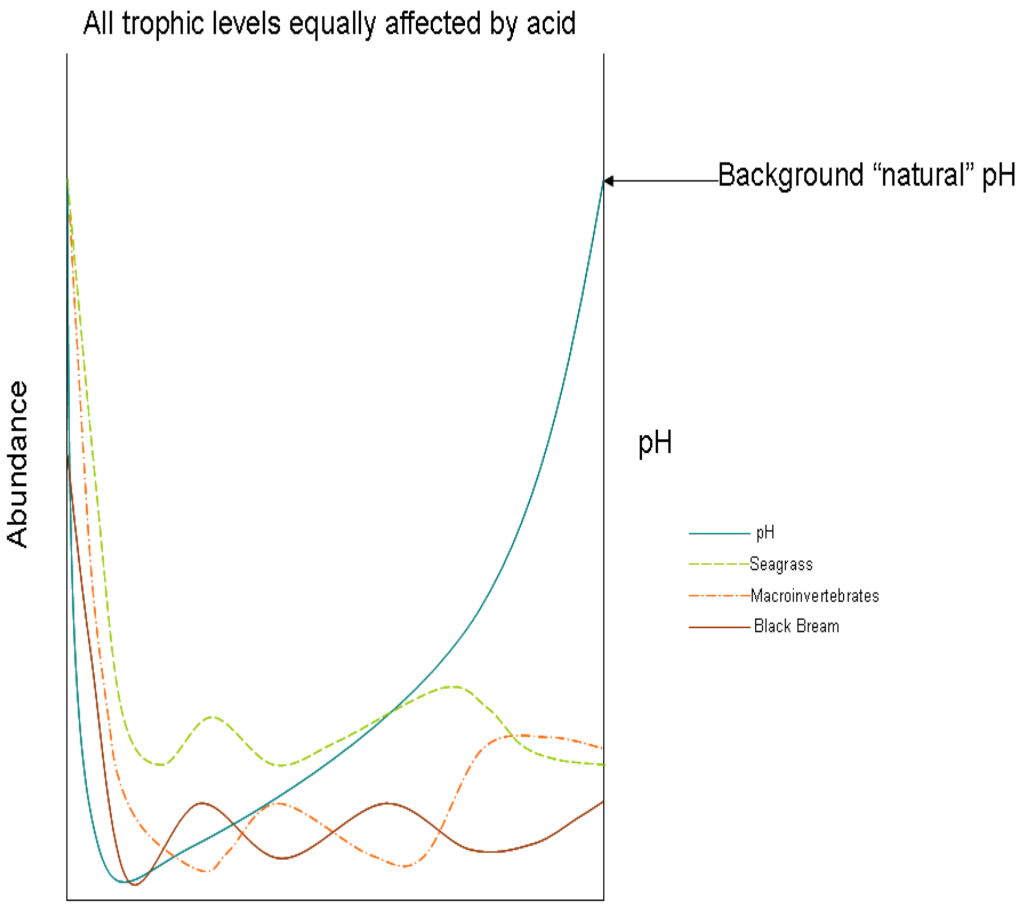

Figure 11 Population dynamics if all simple trophic levels are similarly impacted (Scenario 4)

Based upon all the scenarios, it is clear that the seagrass is the most important ecological component within the Anglesea Estuary. Under all modelled scenarios, when seagrass communities crash all other components (macroinvertebrates and fish) will crash and recovery will be hampered. The results emphasise that seagrass communities should have priority management over the other components (macroinvertebrates and fish). A suggested management measure is to increase the tidal inundation into the Anglesea River estuary and deepening the Anglesea River channel. A ramification of the deepening is likely to lead to seagrass desiccation (caused by exposing the seagrass meadows in low tide). As the preceding models suggest after seagrass communities disappear or growth is hampered then the overall recovery of the ecosystem may be slowed. The deployment of artificial seagrass could be a management option open for consideration if deepening of the estuary proceeds. Whilst artificial seagrass would not supply oxygen to the estuary or directly act as a food source, it would provide habitat for fish and invertebrates and over time would be colonised by bacteria and microalgae that would provide food for grazing invertebrates.

10 Recommendations

Further studies are required within Anglesea River and other local estuaries:

- Population assessment on seagrass cover, fish abundance and invertebrate communities; collect baseline ecological and biological information (ie. foraging behaviours, species interactions, reproductive cycle assessments).
- Investigate ecological community responses when sudden episodic changes to water quality occur. How would that be done?
- Determining the role of each ecological compartment in the process of rehabilitation after sudden episodic changes to water quality occur.
- Black bream movement response to high flows within Anglesea River (tagging studies, genetic studies)
- Growth rates in 'newly' arrived black bream recruits to Anglesea River.
- Black bream life stages (gametes, larvae, juvenile and adult) sensitivity and tolerance to pH and heavy metals Lab or field?
- Understanding the heritability of pH resilience for black bream
- Use wetlands or retarding basins to intercept acidic water flowing down from the catchments
- Deployment of artificial seagrass units?
- Restocking of Anglesea River with bream from nearby estuaries?
- Assessment of other fish fauna that are less likely to avoid the acid conditions, and therefore are probably acid-tolerant, resilient populations. (ie gobies or gudgeons).

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13 Appendix 1

In December 2010, CAPIM conducted heavy metal testing on sediments within the Anglesea Estuary for the Surf Coast Shire. Below is a summary of the findings and an indication as to whether or not a particular heavy metal has the potential to impact upon the ecology of the estuary.

Sediments are often considered as being sinks for contamination. They accumulate contaminants over time, and are an excellent indicator of historical land use. Sediments are also habitat for numerous species, where they often feed, live and reproduce, and are an excellent vehicle for the movement of contaminants. The ANZECC/ARMCANZ (2000) Australian Water quality guidelines have trigger values for many chemicals for the protection of aquatic ecosystems. If the trigger value is exceeded then some level of impairment will occur to the aquatic ecosystems. Guidelines exist for freshwaters and marine waters and usually the marine guidelines would be applied to estuaries as they usually have similar salinities to marine waters. Given that the Anglesea estuary currently has salinities less than marine waters, the freshwater trigger values were compared to the concentrations of various elements measured in the water samples. The concentrations of the substances measured in sediments and surface waters are presented in the attached Excel spreadsheet. The in situ water quality results are presented in Table 1 below.

Those substances that exceeded the guidelines were:

1. Aluminium. The concentrations in surface waters in Anglesea estuary ranged from 0.93 (at the uppermost site 4) to 0.19 mg/L at the most downstream site. These concentrations exceed the 90% trigger value (TV) of 0.08 mg/L. However, it is unlikely that aluminium would be causing toxicity as the water samples were not filtered and much of the aluminium is likely to be in a non bioavailable form (e.g. attach to or part of silt and other suspended particles).
2. Copper. Surface water concentrations throughout the estuary slightly exceeded the 90%TV.
3. Zinc. Surface water concentrations in the estuary ranged from 0.099 to 0.145 mg/L, much higher than the 90% TV for zinc in fresh (0.015 mg/L) and marine (0.023 mg/L). Zinc concentrations in sediments were above the ISQG-high of 410 mg/kg in the lower estuary between about the Great Ocean Road to the mouth of the estuary. However, zinc concentrations in the upper estuary sites were well below the ISQG-high. This suggests that zinc is a major pollution issue in the estuary and that the source of this pollution is from urban areas, including road runoff.
4. Nickel pollution followed a similar pattern to zinc pollution. Nickel concentrations in water ranged from 0.07 to 0.08 mg/L, which exceeded the 90%TV of 0.013 mg/L for freshwaters. The sediments in the lower section of the estuary had nickel concentrations that exceeded the ISQG-high, whereas the concentrations were relatively low in the upper estuary. It is possible that an industrial or urban point source, whether present or historical, has contributed to this pollution.

Other interesting results were:

1 High concentrations of manganese in surface waters indicate that the waters have been anaerobic. In addition to the acidic waters reported, low concentrations of oxygen would also lead to fish kills and kill other aquatic animals.

2. Boron concentrations were high in sediments from the lower estuary (sites 1 to 3) and in surface waters throughout the estuary. It is difficult to determine the source and environmental impact of boron. The source of boron may be from natural sources, as it is common in sedimentary rocks derived from marine waters. A major anthropogenic source of boron into the environment is from detergents. The boron concentrations in surface waters in the estuary increased up the estuary, with the lowest concentration of 4.9 mg/L occurring at Site 1 to 6.89 mg/L at Site 4. The 90%TV for boron in freshwaters is 0.68 mg/L.

3. No guidelines exist for boron in marine waters where boron naturally occurs at concentrations of 4.5 to 5.1 mg/L (see ANZECC/ARMCANZ guidelines, section 8.3.7.1 for more information). However, as the salinities in the estuary were reasonably fresh, with conductivities ranging from 4,000 to 6,000 ms/cm, compared to around 30,000 in sea water, boron could be a major toxicant present in the estuary and the source of contamination should be identified to determine how this pollution can be reduced.

4. Arsenic, which is apparently often common in local rocks and soils, was not present in high concentrations in waters or sediments.

5. Mercury, which can be a contaminant in coal, was only present in low concentrations in estuary sediment and below guideline values in surface waters. Therefore, mercury does not pose a threat to the aquatic ecosystem in the estuary.

In summary, there are many interesting pollution issues existing in the estuary and some contaminants such as mercury and arsenic have been identified as being less important.

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