Acid Sulfate Soils

DAISY SUMMERFIELD

ABSTRACT

Acid Sulfate Soils are a major problem for the Australian environment and economy. It is a problem compounded by the fact that the owner of the source of pollution is not normally significantly affected by the problem; down stream agriculturists and aquaculturists are. An analysis of the literature shows that, whilst there is much activity to alleviate the problem, much scientific research remains to be done. In addition to geologic and geographic field work, research is still required into treatment techniques. This effort needs to be supported by good synchronised government law and structure.

KEY WORDS: Acid Sulfate Soils, ASS, literature, review, farming, environment, research.

I. INTRODUCTION

Acid Sulfate Soil (ASS) is a term used for soil and sediment that contains iron sulphides (the principal component being iron pyrite or iron di-sulphate) [DEC, 2004]. ASS that formed during the last ten thousand years (last major sea level rise) are of major concern throughout the world and particularly in Australia. The potential impact of ASS on the environment, economy and on animal and human health is currently a central focus of both the government and the scientific community. This literature review will attempt to explore the whole issue of ASS, its formation, impact, distribution and its current management strategy in Australia. This review will also try to identify knowledge gaps and current issues regarding ASS.

II. BACKGROUND

A. Acid Sulphate Soil

1) FORMATION

The formation of ASS is limited to low-lying areas of coastal flood plains or estuarine conditions. Other areas that are susceptible to ASS formation are as follows [DEC, 2004] :

- rivers;
- creeks;
- delta areas which have high saline or brackish water;
- back swamps;
- coastal flats; and
- seasonal or permanent fresh water (which were previously brackish).

Pyritic Soil and sediment are commonly found at any depth in the sediment and soil layer beneath the water table in coastal soil and sediment areas [DEC, 2004]. General coastal landscape formations occurred during the last sea level rise less than 10,000 years ago (Holocene) due to rapid sedimentation. Sulphuric acid is the direct product of oxidation processes during bacterial activities within highly organic sediments. Bacterial activities within the water logged sediments promotes a series of chemical reactions which lead to the conversion of sulphate (from tidal water) and iron (from sediment) into Pyrite (Fe_2SO_4), and exposure of Pyrite to oxygen (from the air) will lead to the oxidation reaction resulting sulphuric acid, which is referred to as acid sulphate soils. There are two categories of acid sulphate soils, one being referred to as potential acid sulphate soils and the other is referred to as actual acid sulphate soils. Water logged soil layers that contain pyrite can be clay, loam or sandy structures (dark grey in colour). The water between the soil pores prevents the oxidation process, with the oxidation reaction occurring when pyrite is exposed to oxygen. It is referred to as “potential acid soil” because it has the capability of developing into ASS as soon as it is exposed to air (and thus oxygen) [Sammut, 2000]. The other ASS category is the “actual acid sulphate” soil, and this refers to soil that has been oxidised, resulting in the formation of sulphuric acid, and is commonly known as ASS.

Pyrite oxidation products such as dissolved Fe^{2+}, $S0_4{}^{2-}$ and H^+ are highly mobile and are easily transported through soil water, ground water and through the drainage system. Fe^{2+} can readily oxidise in the water during mobilisation to form Fe^{3+} resulting formation of what is known as hydroxide flocs, and these flocs are known to coat benthic organisms [Sammut et al, 1996], in accordance with the following reaction:

$$FeS_2 + \frac{7}{2}O_2 + H_2O \rightleftharpoons Fe^{2+} + 2SO_4^{2-} + 2H^+$$

Once disturbed, oxidation process occurs and massive amounts of sulphuric acid are produced, causing problems to ground water quality and environmental damage, in particular affecting the ecosystem along estuarine areas, and an associated impact on the economy [Atkinson, 2000]. Development (such as residential estate, marinas, tourist developments) and different land use in the agriculture industries along Australian coastal regions involve drainage and large scale dewatering activities, which leads to the disturbance of ASS and the resulting oxidation process has lead to current ongoing problems with ASS in this region [DEC, 2004]. In the eastern coastal part of Australia, particularly in NSW, it is largely historically caused by government initiated flood mitigation schemes during the 1960s [Tulau, 2001].

Figure 1. Coastal acid sulphate soils in Australia. (original source, National Strategy for the Management of Coastal Acid Sulphate Soils, January 2000) [deh, 2004].

2) DISTRIBUTION

The distribution areas of ASS in Australia are mainly in low-lying areas at the coastal regions. The dangers of draining ASS was scientifically identified in 1963, but the impacts of its existence has not been widely recognised until now. Its recognition is probably due to its large impact on the economy and the environment. ASS coverage distribution in coastal low-land areas of Australia has been identified through mapping exercises by respective state government organisations. Extensive ASS mapping programs have been conducted in South Australia, NSW and Queensland [DEC, 2004]. In NSW, a large scale ASS mapping exercise was conducted by the Department of Land and Water Conservation (DLWC), with 120 ASS soil risk maps produced covering the whole NSW coastal area (showing a total of 6,000 ha of ASS as at 1996) [Atkinson et al, 1996]. In addition to South Australia, Queensland and NSW, soil layers that contained sulphide are also commonly found in the coastal region of the Northern Territory, northern coastline of W.A., around Perth, Adelaide and Western Port Bay [Sammut, 2000], as shown in Figure 1 for ASS coverage in coastal Australian regions. Research by DEC (2004), has highlighted a wide distribution of ASS along the coastal region of Western Australia. The DEC (2004) research identified the following regions as ASS contaminated areas:

- South West of W.A. along estuarine, flood plain and wetland areas;
- Scott River Plain on the south coast extending to Albany;
- Katanning (where salinisation has occurred); and
- Coastal areas of the Northern part of W.A. (including Pilbara and Kimberley coast lines).

Atkinson et al (1998) claim that it took a decade since the discovery of ASS in NSW for the authority to issue a warning to the community regarding potential problems of ASS if land is subject to misuse, although the authors did not specify the type of land practices that are considered to be misusing the soil. It is therefore understandable that despite this warning, NSW coastal land practices have continued without taking into consideration future ASS impacts in the region. The authors also strongly emphasise that the environmental impacts of ASS was only beginning to be widely recognised (in contrast to its distribution) during 1993, when the first ASS Conference was conducted. Due to its existing role as being responsible for soil surveys in the NSW, it was then appropriately sensible for the DLWC to assume the responsibility of conducting ASS risk mapping along the region [Atkinson et al, 1996]. The authors also claim that the assumption was made (during the mapping) that, although there were evidence of the existence of Pleistocene pyritic sediments, it was assumed that it had either already been completely oxidised or it existed below sea level.

The results of the mapping activities have identified ASS risk areas which are classified or coded into high (0-1m soil depth), low (1-2m depth) and no risk (2-4m depth) categories. Atkinson (2000) claims that the maps will give a good indication of the depth of likely occurrence of ASS. One of the recommended strategies of the Draft National Strategy for the Management of the ASS is environmentally sensitive areas need to be identified and classified as hot spot (priority management) areas for rehabilitation. NSW flood plains that were considered hot spot areas due to ASS impacts on land and water have been mapped and were prioritised for remediation. According to Atkinson et al (2000), these priority management areas have been generally affected by previous flood mitigation schemes through drainage construction along wetlands and swamps. In NSW, the known coverage of these hot spot areas is approximately 54,500ha. The extent of the problems was also recognised in relation to the diversity (e.g. size, drainage system) of the individual hot spot areas [Atkinson, 2000].

B. Impact of ASS

1) ENVIRONMENTAL IMPACT

The impacts of ASS on the environment is quite devastating. It causes a massive reduction in conservation value, and reduces the value of tidal streams and estuaries that are subject to commercial and recreation use. Some of the major environmental impacts of ASS are fish kills, fish diseases, degradation of habitat and community instability amongst aquatic plants. Disturbance of water fowl habitats and frog populations has also been strongly linked to ASS. Massive fish kill events in NSW and Queensland have been strongly linked to the disturbance of some environmentally sensitive areas [NRME, 2003]. According to NRME

(2003), the variations of impact levels between sites are due to the following factors:

- nature of the disturbed environment;
- extent of the development;
- types of development (minor and major);
- nature of the adjacent waterways;
- concentration and mobility of acid, Al and Fe;
- local hydrology and ground water systems; and
- sensitivity of the receiving waters and their biota.

2) IMPACT ON HABITAT & PLANT PRODUCTIVITY

Degradation of waterway habitats is one of the major impacts of oxidised ASS. As previously mentioned, acidic water exposes the entire aquatic community and its habitat to harm. Destruction of food resources, promoting displacement of the entire biota to other areas, as well as the precipitation of iron and changing the chemical and physical properties of the water are all serious impacts of acidic water in the waterway habitats [NRME, 2003].

Reduction of pH is one of the direct impacts of ASS affecting plant growth development in low pH areas. Low pH promotes scalding, and vegetation coverage along these affected areas are either absent, very depleted or inhabited by acid tolerant plants. Scald affected areas will become prone to soil degradation such as soil erosion, and are commonly found in coastal swamps and farmland.

3) MARINE FAUNA AND FLORA

Oxidised ASS has a great affect on marine fauna and flora. Its impact is commonly seen through massive death amongst fish and other organisms. Oysters, crustaceans, annelida and shell fish are the most vulnerable amongst these communities due to their immobility during acid runoff. Acidic water will also affect aquatic plants and benthic organisms that are unable to tolerate acidic water. Runoff during heavy rainfall helps transport acid and other mobile elements such as aluminium (Al) and Manganese (Mn). Sudden input of acid into the water ways during runoff exposes aquatic plant and animal communities to rapid pH changes and high (toxic) level of Al and Mn, in addition to the consequential dissolved oxygen drop [NRME, 2003].

4) FISH DISEASE

Red spot (EUS) is a disease that attacks the fish community when exposed to acidic water and other toxic heavy metals such as aluminium and manganese. Several studies by different organisations such as NRME have found that a massive outbreaks of red spot disease can have a severe effect on the fish community within the acid contaminated areas (affecting up to 80% of a fish catch) [NRME, 2003].

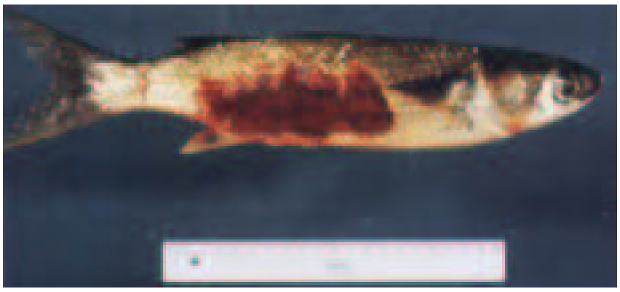

Figure 2. Red spot (EUS) disease that affects fish and other aquatic life through damage to their gills and skin resulting in massive economic losses to the commercial fishing industry [Sammut, 2002].

5) IMPACTS ON HUMAN HEALTH

Sulphuric acid mobilises heavy metals such aluminium, iron and manganese as it moves through the soil structure. High levels in the soil will lead to the death of plants that can not tolerate high acidity [Sammut, 2000]. Scientific studies imply that heavy metals can have an affect on human and animal health. Utilisation and consumption of water and other resources that contain heavy metals, such as Al and Mn, which are mobilised by sulphuric acid, is a main concern in these ASS contaminated areas. Studies on human health and heavy metal exposure by Hu (2002) indicates that exposure to high levels of Al and Mn can trigger brain dis-function in people that have kidney disease (undergoing dialysis) and it is also closely linked from population studies to people that have Alzheimer's disease (as a result of high levels of Al in soil and water). Parkinson's disease was also closely linked to high levels of manganese [Hu et al, 2002].

6) ECONOMIC IMPACTS ON ENGINEERING

Coastal development and drainage construction in acid soil areas has resulted a significant damage of the environment, costing approximately $10 billion [NiS, 1999]. In coastal regions of NSW, current land practices, flood mitigation, road construction, aquaculture, sand mining and ongoing coastal development are some of the activities that have caused significant problems associated with the disturbance of ASS [Sammut, 2000]. Acid soil impacts, to a large extent, on economic activities, including devastation of the aquaculture industry (e.g. oyster farms and commercial fisheries), high maintenance required for engineering infrastructures (as shown in Figure 3), tourist amenities and recreational fisheries. Construction of bore wells in coastal areas, such as those in Queensland, involves pumping of ground water, which leads to lowering of the water table, promoting oxidation of ASS, resulting in acidificationacidification of the aquifer or precipitation of iron flocs. This activity will lead to the degradation of aquifers and water wells, resulting in high maintenance costs (from clogging of water pump filters) as shown in Figure 4.

Figure 3. Corroded concrete due to sulphuric acid [nrm, 2002].

Figure 4. Clogged water pump due to the formation of iron precipitate resulting high maintenance costs [nrm, 2002].

C. ASS Management

1) Government Approach

Atkinson (2000) claims that in NSW, these problems are causing increasing concern amongst the community, resulting in a State Government response of formulating an integrated strategy which aims to address the ASS issue. According to Atkinson (2000), this government strategy will have the following components:

- coordination;
- identification;
- prevention;
- remediation;
- education; and
- research.

The establishment of Acid Sulfate Soils Management Advisory Committee (ASSMAC) is one of the major components of the government response. This committee is composed of industry representatives, local government, universities, state agency representatives, the environmental movement and the land owners. The development of the strategic plan was a result of ASSMAC, and the main aim of the strategic plan was to identify ASS affected regions in NSW. Community awareness of the ASS drainage problems and education campaigns of stakeholders regarding ASS management were also one of the main aims of the strategic plan. The plan will also address prevention of acid outflow into the water ways through neutralisation treatment for new developments. Previously disturbed ASS will be rehabilitated as part of the strategic plan. The author also claimed that ASS disturbance preventive measures were also undertaken by the strategic plan through adoption of codes of best drainage practice by self regulation of the concerned industry. Development controls for ASS will be addressed through the use of local environment plans. Development Control Plans and Farm Drainage Plans are also part of the strategic plan.

2) ASS Management Practices

Major problems with ASS in Australia has led to the development of a National Strategy for the Management of Coastal ASS (NSMCASS). State level guidelines have also been developed over the past several years since the identification of the severity of the ASS problem across Australian coastal areas. It was recognised by the working party of NSMCASS in 1999, that for better management the strategy is to formulate and implement of uniform approach regarding ASS soils [NWPASS,1999]. According to NWPASS (1999) this uniform approach includes:

- uniform definitions;
- standards;
- analytical methods; and
- assessment protocols.

Identification of the extent of distribution of ASS within landowners and resource managers was strongly emphasised by the NSMCASS document. Some of the important points for the management strategy of ASS is to avoid the disturbance of ASS affected coastal areas. It was also recognised that prevention of disturbance of the ASS is the best economic approach, as rehabilitation involves a high cost. However, if development is unavoidable, proper management approach and techniques (provided through education programmes) must be implemented. Increased acid water discharge into streams must be strongly avoided during the development [NWPASS,1999]. The NSMCASS document emphasises that, in order to achieve successful rehabilitation of the affected areas (such as previously excavated or drainage areas), the above components of the NSMCASS need to address concerns of stakeholders, including individual landowners, Federal Government, Community catchment groups, state and territory governments, local governments and statutory authorities, and industry organisations [NWPASS,1999].

3) Policy and Legislation

Recognition of the severity of the ASS problems across the country has lead to the development of state and federal guidelines on how to tackle the existing and future problems of ASS. A national working party which is composed of the Standing Committee on Agriculture and Resource Management and the Agriculture and Resource Management Council of Australia and New Zealand, has been set up to address the formulation of the National Strategy for the Management of Coastal ASS. State level guidelines, such as Planning Guidelines for ASS in Western Australia, Queensland and NSW ensures that existing problems of ASS will be addressed and future development will be conducted in accordance to those guidelines. State level ASS Technical Manuals have also been developed.

D. Social Issues Related Due to ASS

1) Stakeholder Conflict

The agriculture industry in the coastal region around Australia has been a very productive one. Previous governments have been very supportive with their development through flood mitigation schemes, which has resulted in massive re-engineering of the coastal flood plains and its hydrology. Current ASS problems in this area have generated major conflicts between stakeholders such as farmers, aquaculturalists and fishers, which in turn put pressure on both local and state governments [NWPASS, 1999]. The authors of the NWPASS further claim that, due to better understanding of the source of acid water discharge which has impacted the fishing and oyster industries, there have been further demands for action from land owners and from the government to resolve these problems which have economically damaged their income stream. Neutralisation through the application of lime in drain banks is a very costly exercise and the agriculture industry claims that the government should assist with rectifying this current problem. The agriculture industry seems to have a good reason for hesitating on the neutralisation of these drains, as this process will only address the environmental part of the problem.

Drainage and reclamation of back swamps for agriculture in the coastal region of NSW, particularly in the Kempsey region, is currently one of the main focus areas for the ASS problem. Tulau (2001), claims that in spite of the danger of ASS draining being known since the 1960s, massive drainage construction has been conducted during this period by the drainage union and landowners, fully supported and funded by the local and state governments. The author further claimed that in spite of numerous previous scientific works, it was not until detrimental environmental events such as massive fish kills that community and government attention was triggered. Increasing pressure on the governments from community and some industries (e.g. oyster farmers) have lead to the establishment of committees and the development of strategies, guidelines and regulations (E.g. Floodgate Regulations, ASS Guidelines) for addressing the ASS problems.

III. Discussion

A. Acid Sulphate Soil Formation

ASS is actively forming in low lying coastal regions of Australia, including estuaries, mangrove forests and salt marshes, although as previously mentioned, the most concern are for those formed during the last sea level rise (< 10,000 years ago) [Sammut, 2000], [Sammut et al, 1996]. Researchers in ASS have a general mutual agreement regarding ASS formation. They generally agree that as long as they remain undisturbed they will not cause any harm and the areas are termed as Potential Acid Sulphate Soils ([Atkinson, 2000], [Tulau, 1999]).

B. Identification and Distribution of ASS

The authors of the National Strategy for the Management of Coastal ASS claim that in order to improve local management of ASS, it is essentially important to understand the distribution coverage of ASS in their catchment areas. This can be done through the use of risk based maps which have be an successfully used in Queensland and New South Wales. Organisations like the Sugar Cane Industry have successfully produced field based maps as a supplement to the risk based maps. The field based maps have been produced through sampling and testing at each property [NWPASS, 1999]. Woodhead (1999) claims that there are differences in farmers' level of knowledge of ASS "best practice". Although the majority have acknowledge the existence of ASS on their property, they don't believe they have the capability to deal with this problem and there are some minority groups that don't believe that their property has ASS. There are also claims amongst farmers regarding the accuracy of the ASS Risk Maps, as the scale is apparently too large and is not available through the local councils [Woodhead, 1999]. Numerous assumptions that were made during the production of the ASS Risk Maps according to Atkinson et al (1996). They claim that Pleistocene pyritic sedimentary deposits is largely unexplored and its occurrence in the NSW regions is assumed to be very unlikely. This assertion needs to be validated.

C. Land Use and Remediation

1) Lime

Different remediation strategies have been conducted in some affected areas. One of these strategies is the application of lime, and as it has been recognised that it is a very costly solution and it does not deliver any increase in productivity to the farmers, it is not a very popular choice [Tulau, 2001], [Woodhead, 1999]. Tulau (2001) further claims that, apart from the cost of lime, there are some disadvantages due to its insolubility. It is quite apparent from Tulau (2001) that further research, including into techniques, needs to be developed for better results for remediation using liming methods.

2) Neutralisation with Estuarine Water

Other remediation strategies such as neutralisation with sea water in drains through floodgate opening, neutralisation by re-flooding land with sea water and containment of acid in the soil profile are approaches that are currently being trialed [Tulau, 2001]. Like liming, these other remediation approaches also have some significant issues that need to be addressed. For neutralisation with carbonate from sea water through opening of the flood gates (which has been strongly promoted in the dry land agriculture region such as sugar cane cultivation), the effectiveness of this method is highly dependent on the carbonate content of the water that is adjacent to the ASS affected area [Tulau, 2001]. High carbonate content sea water content is mainly found in the lower reaches of the estuary and the majority of the highly affected areas (hot spot) are not located in the lower estuary. Loss of nutrients such as calcium, which is an essential component of some marine organisms (E.g. crustacean), is one of many concerns resulting from neutralisation of acid water. The author further claims that the effect of each individual drain might only be relatively small, but the effect of all drains for the whole estuary system can have a devastating affect on these marine organisms. Further research on the impact of the acid neutralisation in the estuary ecosystem has been strongly emphasised by Tulau (2001). Farmers are unlikely to use re-flooding of land with the sea water as a method of neutralisation due to obvious reasons such as subjecting their land to salinity (back swamp). Lastly, the containment of acid in the soil profile can only be applied to selective environments and ground water levels need to be closely monitored and controlled.

3) Self Motivated Self Assistance

Although Atkinson (2000) has claimed that there are increasing pressures amongst the community regarding ASS, he was unable to clarify what method he had used to measure the extent of community concern, assuming a large amount in order to trigger the government response of the establishment of ASSMAC and on the resulting development of the ASS Strategic Plan. The author claimed that this plan will address the prevention of acid outflow into the water ways through neutralisation treatment for new developments. Previously disturbed ASS will be rehabilitated as part of the strategic plan.

The author also claimed that the preventive measures on ASS disturbance were also undertaken by the strategic plan through adoption of codes of best drainage practice by self regulation of concerned industry. Assurance of proper best practice through self regulation within the industry seems very unreliable and the author's research did not cover the type of mechanism or how ASSMAC will monitor that this part of the regulation will be properly implemented and practised by industry members. A comprehensive technical manual has also been produced by ASSMAC but the author did not state how accessible this manual is to the industry members, land owners etc. An industry survey by Woodhead (1999) shows some dissatisfaction with the availability of the resources to farmers and land owners. These farmers want a one stop shop for obtaining information on how to deal with the ASS issue. Woodhead (1999) claimed that the only industry that is currently doing the "right" management of ASS is the cane industry, although her biased treatment towards the cane industry is very apparent in her literature on "ASS : Farming Community ideas about the way forward". She strongly implies that technical and financial industry assistance is significantly important in order to have success in managing ASS. This author also claims disadvantages for other farmers such as beef farmers. Rehabilitation through neutralisation of the drain banks with lime does not give these farmers any increase in productivity, as it is mainly for down stream environmental purposes. These farmers and land owners want financial assistance from the government.

4) Ponding and Drain Infilling

As a result of research suggesting that remediation strategies which do not involve major re-development, including removal, of the drainage systems, it has been proposed to fill in drains, modify land use and re-introduce native grass species, and stabilise the water table through use of fresh water ponds and weirs [Talau and Henderson, 2001]. This strategy ensures that the ASS layer is kept below the water table, with the ponds or weirs being tapped up by nearby rivers if necessary. However, and as stated by the authors, this approach itself needs further research to validate its success.

5) Costs

The impacts of ASS is costing Australia billions of dollars [NiS, 1999]. Previous and current land practices, such as installation of deep drainage system in low-lying coastal agriculture areas and major coastal development, have accelerated the problems. As previously mentioned, ASS is classified into two categories, one being Potential Acid Sulphate Soils (PASS). This type of ASS is quite harmless as long as it is not disturbed. However, the other type, which is the Actual Acid Sulphate Soils (AASS), is the currently active category and is considered to be the main problem along the coastal areas where land practices, such as reclamation (commonly in flood plain areas), have been carried out in order to maximise agriculture land for uses such as pasture.

D. Social Issues Related to ASS

1) Rehabilitation Costs & Incentives

The farmers will not gain any financial benefits nor increase their productivity for the lime application remediation process [NWPASS, 1999], [Tulau, 2001]. The authors have failed to clarify if further acid water discharge will halt upon the application of the lime on the drain banks and within the drain during dry period or whether this is just a temporary measure and recurrence is expected. Given this state of affairs, farmers are even less likely to undertake liming.

2) Regulation Issues

There are a number of laws which may cover ASS treatment that are inconsistent. The laws do not necessarily help environmental remediation work and sometimes impede it [Tulau, 2001]. The author also claims that there are cases where legal action to enforce environmental remediation have not been effective because the farmer can not afford it. In addition there are a number of organisations and communities responsible for management of the ASS problem, which cannot help speedy rectification. Local, state and federal governments need to review the current management structure and reorganise and redraft law to better address management of the problem.

3) Health Issues

Previous research has clearly emphasised the impacts of ASS and its oxidised by-products such as heavy metals (Aluminium) on human health [Sammut, 2000], [Hu et al, 2002]. Smith's research claims that drought and coastal development such as subdivision of upland properties have lead to massive reclamation of back swamps for grazing [Smith, no date]. This reclamation activity involved drainage construction and, as previously mentioned, has lead to oxidation of ASS. Smith (no date), claims that cattle drink highly contaminated acid water on these converted swamp grazing areas, which could have a devastating affect on the cattle's health. Smith added that there is increasing concern about the impact on the cattle that consume iron-coated pasture. This implies further research is needed for the affects of Al coated pasture on cattle.

IV. Conclusion

Much work still needs to be done to ameliorate the acid sulphate soil problems. The risk maps require ground truthing. Governments and organisations need to recognise to provide better support and the funding levels and distribution requires re-examination. From a science perspective, research is required to verify the usefulness of the proposed and operational remediation strategies, including the usefulness of liming methods employed or proposed, the feasibility of drain infilling and ponding, and the effects of aluminium coated pasture on cattle. Finally, further geological survey work is required to analyse environmental problems.

References

[Atkinson, 2000] Acid Sulfate Soils Assessment and Management in New South Wales. NSW Department of Land and Water Conservation.

[Atkinson et al, 1996] Atkinson, G., Naylor, S.D., Flewin, T.C., Chapman, G.A., Murphy, C.L., Tulau, M.J., Milford, H.B. and Morand, D.T. 1996. DLWC Acid Sulphate Soil Risk Mapping. Department of Land and Water Conservation. PO Box 177 Kempsey, 2440.

[Atkinson, 2000] Acid Sulfate Soils Assessment and Management in New South Wales. NSW Department of Land and Water Conservation.

[DEC, 2004] Denmark Environmental Centre (DEC). 2004. Acid Sulfate Soils. http://members.westnet.com.au/environ/other.htm#soil.

[deh, 2004] deh. 2004. What are Coastal Acid Sulfate Soils? http://www.deh.gov.au/coasts/cass/ (Picture source of ASS Australia coverage).

[NiS, 1999] News in Science. 1999. $10 billion problem with acid soils.http://www.abc.net.au/science/news/stories/s22646.htm

[Sammut, 2000] An Introduction to Acid Sulfate Soils. National Heritage Trust.

[NRME, 2003] Environmental impacts associated with ASS. Natural Resources, Mines and Energy. http://www.nrm.qld.gov.au/land/ass/impacts/environmental.htm

[Hu et al, 2002] Hu, H. and McCally, M. 2002. Other Metals of Concern. Human Health and Heavy Metals Exposure.

[NWPASS,1999] NWPASS.1999.Principal Aims and Objectives in the Management of Coastal Acid Sulfate Soils. http://www.affa.gov.au/docs/operating_environment/armcanz/pubsinfo/ass/6.html

[NWPASS, 1999] NWPASS, 1999. National Strategy for the Management of Coastal Acid Sulfate Soils 1999 : Resources to Achieve Desired Outcome.

[NWPASS, 1999] NWPASS, 1999. National Strategy for the Management of Coastal Acid Sulfate Soils 1999 : Environmental, Social and Economic Impacts.

[nrm, 2002] Natural Resources, Mines and Energy (nrm). 2002. Economic and engineering impacts associated with ASS. http://www.nrm.qld.gov.au/land/ass/impacts/eco_eng.html

[Sammut et al, 1996] Sammut, J. White, I. and Melville, D. Acidification of an Estuarine Tributary in Eastern Australia due to Drainage of Acid Sulfate Soils. School of Geography, the Uni. of NSW, Sydney, NSW 2052, Australia. CSIRO Centre for Env. Mechanics. and CRES, The National University, Canberra, ACT 0200, Australia.

[Sammut, 2002] Sammut, J. 2002. http://www.agric.nsw.gov.au/reader/soil-acidss/acid-intro.htm

[Smith, no date] Smith, B. No date. Coastal Backswamp : Restoring Their values.Wetland Management Consultant. Wetland Care Australia. Ballina, NSW, 2478.

[Tulau, 1999] Tulau, M. 1999. Management of Acid Sulfate Soils in New South Wales - Policy, Organisation, and Regulation.

[Tulau, 2001] Tulau, M.J. 2001. Agricultural Drainage in ASS Backswamps in NSW, Australia. NSW DLWC, PO Box 149, West Kempsey, NSW,2440.

[Talau and Henderson, 2001] Tulau, M., and Henderson, S., 2001. Remediation of Drained Acid Sulfate Soil Backswamps in New South Wales, Australia - Technical and Policy Responses.

[Woodhead, 1999] Woodhead, A. 1999. Acid Sulfate Soils: farming community attitudes about the way forward. NSW Agriculture. ASS Management Advisory Committee.