

ACID SULFATE SOIL ASSESSMENT: COASTAL, INLAND AND MINESITE CONDITIONS

Rob Fitzpatrick¹, Richard Merry¹, John Williams², Ian White³, Greg Bowman⁴
and Graham Taylor¹

¹CSIRO Land & Water, PMB 2, Glen Osmond, South Australia 5064.

email: rob.fitzpatrick@csiro.au; richard.merry@csiro.au

²Wollonbar Agricultural Institute; ³Australian National University; ⁴CSIRO Land & Water, Canberra.

EXECUTIVE SUMMARY

In this audit, key information and results from the following three Australian acid sulfate soil (ASS) weathering environments should be brought together and assessed:

- coastal ASS (tidal mangrove swamps),
- inland ASS (non-tidal scalds driven by saline acid-sulfate discharge conditions),
- minesite ASS (waste rock stockpiles or tailing impoundments).

Nationally there is *an estimated* 50,000 km² of coastal ASS containing well over one billion tonnes of sulfidic compounds (pyrite). Left undisturbed coastal ASS are harmless, but disturbance by excavation or drainage exposes sulfidic compounds in the soil to air, resulting in the formation of sulfuric acid in huge quantities. When fully oxidised each tonne of pyrite produces 1.6 tonnes of sulfuric acid. Disturbance of ASS for flood mitigation, urban development and agricultural production has acidified large areas of coastal catchments nationally with significant environmental, social and economic impacts.

Coastal development, worth over 10 billion dollars is threatened by ASS impacts. Costs of treating and rehabilitating ASS associated with urban development and infrastructure projects total multi millions of dollars. As a consequence, many have stalled and some have been abandoned. Millions of dollars worth of infrastructure corroded by acid water has had to be replaced. Millions of dollars of oysters, prawns and fish have been destroyed, nursery areas have been decimated and vast areas of land has been degraded by poor ASS management. Acid drainage and poor water quality also pose considerable threats to coastal tourism and several communities reliant on good quality water.

The National Strategy recently developed by the National Working Party on Acid Sulfate Soils (1998) is an important first step in the national recognition, coordination and management of resources to ensure that **coastal** ASS are assessed and managed in a responsible manner. However, inland and minesite AAS conditions have not been adequately assessed nationally because of the poor state of knowledge of inland AAS potential areas and relation to rising watertables and salinity. Consequently, strategies are presented in this audit to show how the various common properties of ASS conditions for a variety of environments should be brought together and assessed with standard methods across Australia. Modern methodologies are proposed to produce a national map (1:2 million scale) as well as representative transect scale assessments of selected priority areas to predict areas at risk using classifications at different spatial scales (national, regional and catchment). This will establish a framework for national *communication* and *implementation* of technologies, which identifies economic, social, health and legal assessments and available options for amelioration and management.

OVERVIEW

Definition of Acid Sulfate Soils (ASS)

Acid sulfate materials are saline soils or sediments containing the build-up of iron sulfides in the upper soil layers under waterlogged or highly reducing conditions (ie. sulfidic conditions). However, when these ASS are exposed to air by drainage (as part of land management or development measures), they become strongly acidic (pH <3.5) and acid drainage water is produced. Development of ASS in the root zone of most plants causes loss of productivity on-site. Acid runoff causes adverse impacts to environment, coastal development, fishing, agricultural and mining industries. These soils are widespread around coastal Australia (especially when associated with mangrove swamps), occur to an unknown extent in inland areas and are often associated with certain mining activities (eg. waste rock stockpiles or tailing impoundments).

The source of acid sulfate problems is pyrite, FeS₂, which when oxidised generates sulfuric acid that brings the pH below 4, sometimes even below 3. Sulfuric acid may leak into drainage and floodwaters, corrode steel and concrete, and attack clay, liberating soluble aluminium, which is toxic to vegetation and aquatic life. Heavy metal contaminants, soluble at low pH, are transported off-site and impact on water and soils. The off-site environmental implication means that more attention should be paid to these soils following drainage or excavation through areas where conditions exist.

Acid sulfate soils are extensively developed around the Australian coastline, although they have only recently come to prominence in land use planning as a result of the detrimental environmental consequences that can arise from disturbing them. The recognition of acid sulfate sediments and soils in Australia, especially those that occur inland, and research into their behaviour has been limited.

Although a plethora of complex terminology and standards have evolved in the literature in relation to acid sulfate soils, in this report these have been simplified to the following two concepts:

- **Actual acid sulfate materials** (e.g. sulfuric horizon) are materials that once contained pyrites (coastal sediments, inland marshes or minesites) and may still contain some, but which have been exposed to the atmosphere by drainage or disturbance so that the pyrite has oxidised to form sulfuric acid, thereby decreasing the pH to less than 3.5. These materials are characterised by bright yellow or straw coloured mottles of the mineral jarosite and often contain dark reddish coloured streaks.
- **Potential acid sulfate materials** (e.g. sulfidic materials) are materials that contain iron pyrites that has not been oxidised. Consequently, the pH is usually near neutral (approximately 7.0).

The hazards presented by acid sulfate soils are magnified by their location and specific properties. For example, depth to the actual acid sulfate (e.g. sulfuric horizon) or potential acid sulfate (e.g. sulfidic materials) materials as well as the concentration of salts or minerals (e.g. sodium chloride, jarosite or pyrite) are critical.

Current National Issues about Acid Sulfate Soils

The Australia wide distribution of Acid Sulfate soils is unknown at any scale. There is no consistent standard for mapping their extent or severity. It is difficult to frame a national strategy for dealing with them without knowing where they are and their extent. Acid Sulfate soils are not all the same and nearly all characterisation has been in northern NSW and SE Queensland. For regulation and management, the range of soils likely to be encountered and the way they function must be known. For example, ASS under a 10m tidal range in tropical NW Australia will have vastly different properties from those in SE Australia with a 2m tidal range. Consequently, there is an urgent need for more pedological, chemical, mineralogical, physical and microbiological information about Acid Sulfate soils and degradation processes especially in southern Australia.

Coastal Acid Sulfate Soil Conditions

The following discussion is based largely on information prepared by the National Working Party on Acid Sulfate Soils (1998). Coastal ASS have formed and been oxidised throughout geologic time as part of the global sulfur cycle. Those soils of most concern in coastal Australia are sulfidic sediments, which were deposited during the last 10,000 years (the Holocene period). Sea level rise, following the end of the last Ice Age, drowned coastal embayments and sediment blocked off coastal lagoons. During and following the sea level rise, which ended about 6,500 years ago, sea water or brackish water, containing dissolved sulfate, covered organic debris from swamp vegetation, such as mangroves, tea trees and salt marsh. Combined with iron from the sediments, under generally air-free conditions iron sulfides were produced.

Five conditions are necessary for the formation of iron sulfides. These are:

- a supply of dissolved sulfate, with concentration greater than 10 mg/L,
- a supply of readily decomposed organic matter,
- an adequate source of iron,
- generally oxygen-free conditions, and
- tidal flushing to remove soluble reaction products.

Such conditions occur in wave-protected mangrove and salt marshes, outer barrier tidal lakes, and back swamps; areas that can accumulate large amounts of organic debris and contain oxygen-free sediments. In Australia, coastal ASS occur in soils ranging from thick deposits (>10 m) of unconsolidated estuarine mud to thin bands in the coarse sands of outer barrier systems and in gravels in coastal river beds. Many are covered by a variable thickness of more recent river alluvium or aeolian sands.

Sulfides are still being produced in mangrove swamps, salt marshes, coastal lakes and in sea and estuarine bottom sediments. Because fresh river water is low in dissolved sulfate, significant ASS deposits are not usually found in freshwater alluvium or in estuarine river systems with outflows much larger than the tidal exchange.

The unique properties of coastal ASS arise from their sulfide content. Sulfide concentrations (as iron pyrite Fe S_2) range from about 0.01 per cent to as high as 15 per cent. Not all acid produced by oxidation of sulfides is released into streams because the acid soil water can react chemically partly or even completely with the sediments in which it was produced. The reaction between acid and soil constituents, mainly clay minerals, liberates dissolved aluminium, iron, manganese, heavy metals such as arsenic and copper into soil and drainage waters. These ions remain dissolved, provided the solution remains acid (pH generally less than 4.5), and can be extremely toxic to plants and gilled organisms.

The reaction of acid with the soil also brings about permanent change to the soil itself in a process called soil ripening. Many of the unconsolidated, back swamp, sulfidic sediments are soils containing up to 80 per cent water and they have a very small capacity to transmit water. Ripening produces soils with lower water contents and higher hydraulic conductivities. Ripening also can cause the soils to shrink by up to 50 per cent of their volume. Shrinkage is further enhanced if peat top soils are oxidised and/or back swamps are drained. The net result is that soil surface elevations in drained back swamp areas are lower than in the undrained state.

The rate of oxidation of ASS is critical to their management, since it determines the persistence and magnitude of acidic outflows. In areas with vigorous crops or native vegetation, where the unoxidised sediments have low hydraulic conductivity, evapotranspiration can withdraw water faster than it is supplied by inflow from drains or creeks. This evapotranspiration lowers water tables below the position of the unoxidised sulfides and exposes them to air. Even in present-day, undrained mangrove communities, oxidation of the newly formed sulfides to sulfuric acid occurs at every low tide, although the acid is neutralised by the subsequent high tide.

Fish kills are not necessarily indicators of the onset of acidification nor do they reliably determine the duration and extent of acidification. Plant toxicity appears to be related to the change in balance of metal ions caused by the presence of aluminium ions and the actual ionic species of aluminium present, rather than the absolute amount of aluminium present. There are wide variations in the tolerance of plant species, and of varieties within species, to toxicities produced by ASS. The effects of ASS on plant production can be confused when there are sediments of peat or alluvium overlying the ASS. Under these conditions plant roots may be restricted to the surface layer and plant production may be less affected. Soils with different buffering capacity will also produce a marked difference in plant response to acid soil-water. In addition, the impact of climate on the hydrologic regime directly influences the way ASS affect plant growth. In climates with pronounced dry periods the impacts are more severe than in those with temperate climates.

Inland Acid Sulfate Soil Conditions

Mobilisation and accumulation of S and Fe causes the formation of Inland Saline Acid Sulfate Soils (ASS) in scalded discharge areas and is now a recognised phenomenon (Fitzpatrick *et al.* 1992; 1993; 1996). Such areas are increasing in extent in Australia. Dam excavations into pyrite containing rocks or sediments may expose ASS materials resulting in acidification of dams. These conditions have now been reported sporadically from the WA wheatbelt, Eyre Peninsula, eastern Mt Lofty Ranges, Kangaroo Is, upper SE of SA, SW Victoria, the Griffith area under irrigation, the Yass valley and SE Qld. However, the groundwater geochemistry, national spatial significance and risk are not well understood.

In some specific, non-coastal Australian landscapes, the mobilisation and accumulation of sulfur, iron, clay and heavy metals in soils with rising saline groundwater tables is causing formation of ASS in catchment discharge areas. Under oxidised conditions, sulfuric acid forms and soil pH can seasonally drop below 3.5. There is a high capacity to decompose soil weatherable minerals, which contribute to increased salinity, cause severe soil structural decline, waterlogging and erosion, as well as poor quality catchment water. Where these processes have surface expression they develop into unsightly scalds devoid of vegetation. In some instances, iron oxide precipitation and clay clogging is believed to contribute to further waterlogging and local spread of the toxic condition. Expression of the problem requires the correct groundwater geochemistry (ie. source of S, with hydrological involvement) and soil oxidation/reduction (redox) conditions. These mechanisms require further research. However, the following processes and causes are involved in the formation of inland ASS conditions:

- Accumulation of sulfates, sulfides, iron oxides and salinity under conditions of seasonal and/or permanent waterlogging (from rising groundwater & perched water tables).
- Acidification (under oxidised conditions sulfuric acid forms and soil pH can seasonally drop below 4.2).
- Development of bared soil surfaces in discharge areas (ie. die-back of vegetation).
- Soil structure decline during cycles of wetting and drying:

On wetting:

Sulfidic conditions destroy micro-aggregates by dissolving Fe-oxides.

Saline conditions flocculate clay particles.

Low soil strength develops.

Overland flow occurs due to saturation excess.

On drying:

Concentration & recrystallization of salt and iron minerals occur on soil surfaces by evaporation.

Hard impermeable soil layers form (soil pore clogging by clay, iron and silica cementation/ compaction).

Overland flow increases due to reduced infiltration.

- Saturated zones increase up the slope because of:
 - restricted throughflow,
 - increased groundwater pressures, and

development of impermeable soil layers.

- Accelerated erosion.
- Poor quality of catchment water.

The economic impacts of inland ASS conditions have not been systematically evaluated. This is partly the result of poor knowledge of their spatial distribution and environmental effects. Economic impacts are very likely to occur through:

- withdrawal of grazing and cropping land (remediation by fencing and stock exclusion);
- fencing and revegetation costs;
- loss of water quality in dams for stock or human use and its effect on infrastructures (roads, pipes and pumps) and off site;
- loss of plant yield including trees on sites where ASS exist in the subsoil and resist root penetration.

Minesite Acid Sulfate Soil Conditions

Both metalliferous and coal deposits are commonly associated with pyrite-rich host rocks. Other rocks particularly black shales and their metamorphic equivalents may also be pyrite-rich. Exposure of these rocks during mining to the atmosphere and moisture may lead to sulfide oxidation and the formation of ASS and acidic mine drainage (AMD) conditions. Experience to date has shown that this occurs particularly from mine wastes (waste rock dumps, tailings, adits and shafts). This leads to low pH (often <2), increased solubility of heavy metals, increased salinity and off-site contamination. Existing techniques to ameliorate these high intensity point sources of AMD are seldom effective in the long term. Severe AMD is associated with several mines in Australia (eg. Environment Australia 1997; Harries 1997 and Taylor, 1996). Mineral processing, particularly the smelting of sulfide-rich ores results in SO₄-rich emanations leading to acid rain and wide-spread formation of ASS conditions. Scrubbing of such smelter gases, although becoming more common, still results in widespread acidification of soils from smelters. The impact of AMD in Australia has not been fully quantified and the remediation costs is largely unknown.

Similarities between Coastal, Inland & Minesite Acid Sulfate Soil Conditions

Coastal (mangrove swamp), inland (non-tidal) and minesite ASS weathering environments were recently compared by Fitzpatrick and Self (1996). These workers compared the properties between these three ASS under undisturbed and disturbed (i.e. drained or eroded) conditions. The three ASS environments represent the range of acid sulfate weathering situations from relatively stable (coastal ASS) to non-stable (inland ASS) to rapid weathering (minesite ASS). The range in properties recorded in Table 1 highlight the commonalities as well as the differences in these environments. The most striking differences are reflected in the soil type and iron mineralogy.

Undisturbed coastal ASS's have strongly developed sulfidic materials with high n-values (Table 1). Iron oxyhydroxide minerals seldom crystallise as thick precipitates in or on these soils and so the soil colour is black with some grey mottles. Consequently, the dominant process is the strong build up of sulfidic material because of negative Eh and high S, Fe and organic matter content in the tidal flushing environment. In contrast, conditions in minesite ASS are generally not ideal for secondary pyrite to form because of a combination of low organic matter content and positive values of Eh. Weathering environments associated with minesite ASS are more oxidising compared with undisturbed coastal ASS. Consequently, sulfide formation only occurs in very local pockets in minesite ASS. The relatively more oxidising conditions in minesite ASS are more favourable to the formation on or near the soil surface of minerals such as ferrihydrite, lepidocrocite, goethite, jarosite and schwertmannite. The formation of this unique mixture of iron minerals is indicative of rapidly changing local environments and variations in

the rate of Fe and S mineralisation processes. Undisturbed inland ASS has properties intermediate between those of the undisturbed coastal and minesite ASS (Table 1). The processes occurring in inland ASS are seasonal with moderate development of sulfidic materials during wet periods and strong development of iron oxyhydroxides during drier times. Iron oxyhydroxide precipitates occur at the surface of undisturbed inland ASS throughout the year (Table 1).

As with undisturbed soils, the characteristics of disturbed (i.e. drained or dried) acid sulfate soils are dependent on environment and are diagnostic of the ASS forming environment. The highly developed sulfidic materials in coastal ASS can cause strong acidity when the soils are drained (Table 1). Consequently, in disturbed coastal ASS the oxidation of sulfides to sulfates and development of acid conditions favour the formation of jarosite and goethite giving rise to bright-yellow streaking along root channels and pores. These minerals, together with ferrihydrite, are also seen as precipitates on surfaces of coastal ASS. The lesser development of sulfides in inland ASS and minesite ASS means that there is less sulfidic material and therefore less acidification on drying.

Social Costs/Benefits

A number of Australian researchers are actively engaged in investigating the environmental and economic impacts of coastal ASS disturbance. Reviews of recent work have been published by National Working Party on Acid Sulfate Soils (1998), White *et al.* (1995) and Sammut *et al.* (1996). Most of the information that follows below is drawn from these sources and is gratefully acknowledged. Coastal flood plains have the longest record of productive agricultural use of any region in Australia. Successive Australian governments at all levels have continued to encourage development, particularly through drainage and flood mitigation initiatives. However, significant problems have been created in coastal ASS areas. This has resulted in major conflicts between farmers, fishers and aquaculturalists and in complaints to local government. In some areas residents have complained to authorities of foul smelling, iron stained waters in canals for several weeks following heavy rain. This is an unrecognised consequence of up-stream ASS disturbance resulting in deoxygenated acidified water, which accumulates in the canals.

As understanding of coastal ASS has improved, local fishing and oyster industries have identified sources of acid water discharge, which have adversely affected their livelihoods. These industries are seeking action from government and land owners to correct these spill-over effects which cause them serious economic hardship. Left unresolved, these effects will act as an ongoing source of conflict between industries and in the broader local community.

Agricultural industries have indicated they are not prepared to shoulder the responsibility for acid drainage water alone, noting that the government initiated drainage and flood mitigation schemes often were the cause of over drainage of the flood plain. Furthermore, many land owners cannot afford the massive capital investment which will be required in most areas to improve water quality. Landowners also raise an equity issue, questioning why they should invest in works, eg. liming drain banks, which do not improve agricultural productivity. They also seek assurance that changes to land use practices, which they may introduce will result in improved quality of drainage water. It is also likely that, as more is understood, restrictions on land use and planning controls will be introduced which will limit land owners' options to diversify.

Under these circumstances landowners can be expected to seek support and incentives from government. Similarly, the fishing and water-based industries will demand tangible action to stop further acid water discharge into streams and waterways. Government response must be sensitive to these different expectations and an effective communication strategy will be essential. It is clear that all levels of government must work with industries and the local

community to support projects and initiatives, which will address these social conflicts, as well as economic and environmental issues.

The health status of farming communities living in Asia on ASS and drinking acidified water is notably poor. Aluminium rich waters may have significant impacts on human and animal health. These impacts could include stunted growth, poor health and mental impairment. Because highly acid, aluminium rich waters can be exceptionally clear due to sediment flocculation, there is a danger that they may be considered fit for consumption. However, in most Australian estuaries, waters tend to be brackish and are not often used for drinking or stock watering. Indeed stock often refuse to drink acidic waters. Some cases of industrial dermatitis, caused by the handling or skin contact with acid soil materials, have been reported. Epidermal absorption of heavy metals is also a possibility.

In addition to these direct health impacts, there are related acid drainage impacts on human and animal health which have been assessed at present. These include the interaction of acidic drainage with populations of disease carrying organisms. For example, it is known that certain species of swamp mosquito actively seek out acid drainage for breeding.

Economic impacts

ASS underlie significant areas of coastal Australia where the majority of Australians reside. Substantial developments, including urbanisation, industrialisation, infrastructure and utility supply, agriculture, aquaculture, sand and gravel extraction as well as dredging, in these areas have disturbed ASS.

ASS impacts now economically threaten these industries, **whose total value is conservatively estimated at \$10 billion**, in three important ways:

Avoidance costs: Economic losses can be incurred in the transfer of developments to non-ASS areas. These costs accrue in the form of decreased land values, increased transport costs as well as loss of income from foregone expansion of industries such as sugar cane and tea tree oil production.

Treatment and rehabilitation costs: ASS's corrode steel, aluminium and concrete. Metals such as iron and aluminium are quickly corroded in acidic solutions. Aluminium boats are chemically attacked by acid waters. Many ASS are gel-like with low load bearing capacity. As a consequence, foundations or earthworks built on these materials may settle or subside unevenly. Many surface structures may require either extensive piles or the laying of an extensive load spreading membrane, thereby increasing construction costs. Such constructions must be carried out in conjunction with extensive drainage. Coastal urban development, such as housing, resorts, marinas and canal estates, together with the provision of their services and infrastructure, are quite likely to disturb ASS. In 1996, developments worth over two billion dollars were proposed on ASS in Queensland. On the Gold Coast in southern Queensland, 90 per cent of development applications were required to consider ASS in their environmental management plans. Treatment technologies to avoid or prevent the formation of acid drainage associated with these developments in Queensland are estimated to cost in excess of **\$100 million annually**.

The adoption of treatment and preventive practices is also driven by fear of litigation as legal action over corrosion and subsidence of major projects built on ASS in the United States of America is currently before their courts.

Loss of product: Fishing and oyster industries have reported substantial financial losses after fish kill events, both through loss of saleable product and loss of consumer confidence in the quality of their product. In 1995 over one million dollars of sea mullet was discarded by New South Wales commercial fishers because of red spot disease. Oyster growers in many northern New South Wales estuaries have reported a reduction in productive lease areas over many years

as a result of acid drainage waters. Losses in production of Sydney rock oysters from ASS impacts were estimated at seven million dollars over the last six years.

The soil water in ASS or drainage from exposed ASS materials can limit plant production in several ways.

In many locations, ASS has degraded farmland by reducing pasture quality. Very few pasture plants can withstand the toxic effects of high acidity and high concentrations of toxic metals, sugar cane and tea tree being notable exceptions. Numerous coastal and inland swamp areas, as well as in acidic drain spoils and scalds have remained un-vegetated for many years.

Another engineering consequence of ASS can be the blocking or impairment of drain systems due to the precipitation of red ochre, iron hydroxide and oxide flocs, when fresh or neutral pH water meets acid iron-rich water. Ground water pumping in aquifers, where significant pyritic oxidation has occurred, can lead to the movement of acidic drain water and the landward incursion of seawater into the aquifer. When the well-buffered seawater encounters acidic iron-rich waters it is possible that precipitation of ferric hydroxide/oxides can occur in the aquifer. If this takes place, seawater intrusions may be 'frozen' in place with little likelihood of being displaced seaward. As well as aquifer clogging, iron-rich waters can cause blocking or clogging of water wells, drains and pumps when exposed to air, due to iron hydroxide/oxide floc precipitation or due to the trapping of long strands of bacterial mats and filamentous bacteria.

The current principal land uses in coastal ASS areas include (from National Working Party on Acid Sulfate Soils (1998):

Agriculture:

- sugar cane,
- dairying,
- tea tree,
- grazing,
- cropping.

Urban development:

- housing,
- resorts,
- marinas/canal estates.

Infrastructure:

- roads,
- railways,
- bridges,
- port facilities,
- flood gates,
- dredging.

Aquaculture:

- prawns,
- oysters.

Mining:

- mineral extraction (eg. gold, uranium, coal, pyrite),
- sand extraction,
- gravel extraction,
- dredging.

Undeveloped areas:

- mangrove swamps,
- salt marshes,
- national, state and local parks and reserves,
- coastal wetlands,
- coastal lakes.

All these land uses generate significant regional employment. However, developments on ASS, particularly large scale drainage and flood mitigation schemes, can lead to widespread acidification of land and streams and subsequent economic losses onsite or in adjacent areas.

Technical coordination

Long term impacts of coastal, inland and minesoil ASS is still not fully understood and the technology for dealing with current problems are still in the early stages of development. Though many countries have had problems associated with the treatment and management of ASS, each instance tends to be unique and the treatment peculiar to the *situation*. As a consequence the transfer of international research to Australian circumstances may not be practical.

The complex nature of this problem requires effective coordination of limited government resources and policies at commonwealth, state and local levels. Under NSW legislation, developments likely to significantly disturb ASS require environmentally sound management plans. Effective regulation by state and local government and compliance by industry are essential. The National Strategy recently developed by the National Working Party on Acid Sulfate Soils (1998) is an important step in the national recognition, coordination and management of resources to ensure ASS are assessed and managed in a responsible manner.

ASSESSING ACID SULFATE CONDITIONS

Outcomes

One of the products from this audit will be a compilation of the major factors influencing acid sulfate soil conditions arising from three main sources around Australia. An example of the range of tools and methods to be used is given in figure 1 and of the type of compiled information is given in the following list:

Representative Transects, possibly composed of the following range of priority examples:

- Tropical Coastal ASS Transect, Cairns Qld. (e.g. East Trinity).
- Sub-tropical Coastal ASS Transects Qld/NSW (e.g. Pimpama & Tweed, Richmond),
- Temperate Coastal ASS Transect SA (MFP site/St Kilda),
- Inland ASS Transect in the Adelaide Hills, SA (Herrmanns catchment),
- Inland ASS Transect on the Dundas Tableland, Victoria (Red Barren catchment),
- Minesite ASS Transect in the Adelaide Hills, SA.(Brukunga abandoned pyrite mine),
- Minesite ASS Transect in the Bowen Basin, Qld (Colliery example).

Area (ha)/ length of transect (km).

Dominant soil and geology type.

Environmental hazard assessment, composed of the following:

- acidity hazard rating (eg derived from: Soil Taxonomy and/or Dent & Bowman and/or more complex QASSIT methodology),
- pollution hazard rating (e.g. Al, Fe, Mn production and export),
- contamination hazard rating (e.g. heavy metals, As, etc liberation and export),
- infrastructure impact rating such as likely physical (eg subsidence) or chemical (eg corrosion) effects on infrastructures,
- environmental sensitivity rating (depends on biophysical setting, such as proximity to Great Barrier Reef or local freshwater swamps, threat to biodiversity, threatened species, susceptible vegetation).

Major cause of ASS conditions

Annual Climate

- Rainfall, evaporation and evaporation deficit.

Watertable Depth (inland ASS) (m)

- Temporal trend (?)

Tide (coastal ASS)(m)

Drainage Status (%)

- Surface or subsurface

Drainage Volume/Quality

- Surface Store

- Subsurface Store

returned to groundwater or river/stream?

Dominant Land Uses: - Sugar (ha)

- Pasture (ha)

Salt/ Acidity Balance - Balance (1st year)

- Temporal trend

Off-site impacts

Economic hazard assessments (\$'s), possibly composed of the following:

- Industry Impact Rating (\$ value of local industries at risk: tourism, development, sugar),
- Environmental Compliance Costs (\$ cost to meet ASS guidelines/regulations),
- Environmental Remediation Costs (\$ cost to correct past degradation),
- Industry Goodwill Costs (\$ loss in goodwill due to perceived and actual additional cost to industry).

Social hazard assessments (\$'s), possibly composed of the following:

- Community Impact Rating. Integrate social costs and benefits such as unemployment (or extra employment in remediation work etc), loss of utility (eg. loss of wilderness value, natural attributes, perceived lifestyle changes) caused by environ/eco impacts of ASS).

Health hazard assessment (\$'s), possibly composed of the following:

- Direct Health Effect (eg possible cost/rating of AI, As etc in environment - unlikely to be major except where impacting on rural drinking water, but evidence of severe impacts overseas could be applicable here (eg Macquarie Harbour impact study addressed some of this as a result of acid mine drainage from Mt Lyell Mine - see L. Koehnken OSSS Report #126),
- Indirect Health Effects (eg. poorer community health due to unemployment, poverty etc caused by economic impact of ASS).

Social and legal impacts (to be developed)

Essential outputs

To achieve a comprehensive assessment and evaluation of Australian ASS conditions, as outlined in Figure 1, the following **three essential outputs** are envisaged:

(1) “National” and “Representative Transect” scale assessments

- Use available spatial (GIS based) approaches to assess the “national scale” (via 1:2 million base scale map) and “representative scale” (via selected priority transects at regional or catchment scales) occurrences of coastal, inland and minesite ASS.
- Use available maps, models and tools (GIS models and remote sensing).
- Use standardised tests and procedures to assess ASS (field and laboratory methods).

(2) Economic, social and legal assessments.

- Document impacts (environmental, economic and social) of ASS on industry and the community. Costs involved in: lost production (agriculture, fisheries, infrastructures, mining); community infrastructure capital works to ameliorate and combat ASS; in land being lost through ASS conditions; human health risks; water quality (purification ect.).

(3) Available options for amelioration and management

- Suggest *available* ways of practically managing ASS at risk. Impact of land use change on development of ASS conditions.
- Policy *available* options for management.

Figure 1

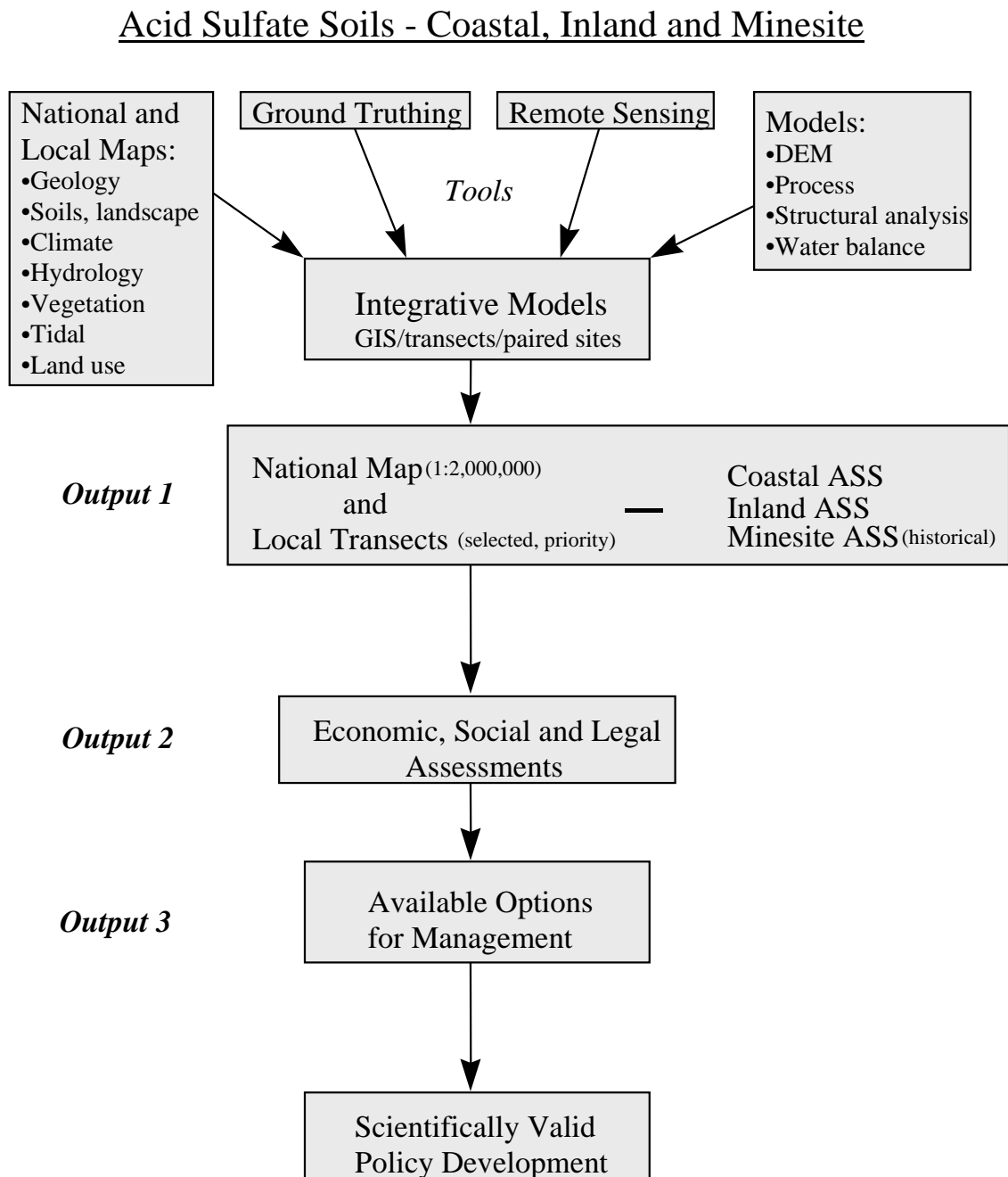


Figure 1: Flow diagram outlining the tools that will be used to achieve the three outputs and the key products that will be produced in the ASS National Land and Water Resources Audit.

Options

1. National scale prediction

Objective:

Produce a national map of Australia (1:2 million base scale; output **1**) showing the spatial distribution of coastal, inland and minesite ASS (actual and potential) together with a report giving outputs **(2)** and **(3)**.

Methodology:

This national scale evaluation will use existing tools and data (Fig. 1) to achieve output **(1)** with limited ground truthing. Outputs **(2)** and **(3)** will also be produced but with general (reduced) information.

The methodology will involve assembling and linking geological, soil, mineralogical, hydrological, tidal, climate, biological and remotely sensed data through GIS. This methodology will be used to produce a map (1:2 million base scale) delineating areas at risk using a standard classification. These predictions will then be verified and refined by limited field work in key regions across Australia. The work should be done following a national workshop of all key workers (CSIRO, AGSO, Universities, State Departments, Private consultants etc.) to decide on exactly how to gather and link the following vital pieces of information using integrative models (see Figure 1):

- (i) geology with known sulfide sediments (coastal and inland) and sulfidic ore bodies or sources of high sulfur with Fe,
- (ii) other regolith information relating to deep weathering, salt loads and particular types of soils and topography,
- (iii) ground water depths, pressures and quality, tidal flows,
- (iv) climate and
- (v) land use.

2. Representative scale prediction from selected priority transects

Objective:

Produce a series of selected transects to: (i) assess accuracy of national scale mapping; (ii) collect data along transects, (iii) assess potential of remote sensing methods for mapping ASS. The transects will be published together with a series of accompanying reports that will give outputs **(2)** and **(3)** for representative scales. The national map of Australia (1:2 million base scale) showing both the overall spatial distribution of coastal, inland and minesite ASS as well as the localities of the representative transects will also be published.

Methodology:

Priority transects (including paired sites) will be selected using available regional and/or catchment maps (e.g. scales ranging from 1:20 000 to 1:100 000), existing tools and data to achieve output **(2)** with ground truthing and some limited monitoring (Fig. 1). Outputs **(2)** and **(3)** will also be produced.

Detailed published map information for the NSW (i.e. DLWC has mapped ASS risk at 1:25 000 scale as part of the RACAC resource inventory program) and Queensland coastal areas will be used to complete this product. Little detailed work has commenced in the other States. Some detailed information exists for inland ASS areas such as in the Mt. Lofty Ranges and Dundas Tablelands but not on Kangaroo Island and in other parts of Australia. Similarly, detailed information is available for some minesite ASS areas such as in the Bowen Basin.

This work should be highly collaborative and involve key groups from CSIRO, AGSO, Universities, State Authorities etc. New, but readily available, innovative research data will be evaluated (e.g. sulfur isotopes, quantitative mineralogy, hydrological fluxes, site-specific drainage) along selected priority transects. GIS modelling techniques (e.g. using digital elevation models and derived wetness indices) and remote sensing (e.g. polarimetric, synthetic aperture radar) information will be applied to the existing soil and hydrological data to develop predictive models for waterlogging. These techniques may assist in extending the identification of processes from the selected priority transects to broader scales. Consequently, selected computer-based tools (eg. WAVES, TOPOG, SWIM, LEACHM, coastal ones) will be used as appropriate, to understand and quantify water and solute transport under current and the proposed improved management. Existing data (e.g. groundwater levels and sources and loads of solutes and iron moving through surface and sub-surface soil layers) from previously instrumented coastal, inland and minesite catchments will be used in the models wherever possible. No additional data will be collected specifically for these models.

This information will fill some of the gaps in our understanding of the degradation processes and available management options at representative scale. The outcomes of this product will be the publication and dissemination of the national map (1) and accompanying reports on each representative transect with information on outcomes (2) and (3).

COSTING OF OPTIONS

Option 1 *National scale prediction*

(1) Produce a 1:2 million scale map of Australia showing the spatial distribution of coastal, inland and minesite ASS. Collate soil, geological and hydrological data, including information on laboratory data on methodologies. An accompanying report will briefly include the following general output information:

- (2) Economic, social and legal assessments.
- (3) Available options for amelioration and management

Timeframe - July 1998 - January 2000

Project development meeting	\$5K
Acquiring, processing and interpreting ASS data	\$50K
Collation, GIS mapping and map production	\$40K
Part time salaries	\$180K
Supervision (6 months)	\$30K
Total	\$305K

Option 2 *Representative priority transect prediction*

(1) Produce a series of selected *priority* transects across key regions or catchments (e.g. 1:20 000 to 1:100 000) as well a national map of Australia (1:2 million base scale) showing the spatial distribution of coastal, inland and minesite ASS. A series of accompanying reports will be produced for the following two outputs for representative priority transects at local scales:

- (2) Economic, social and legal assessments.
- (2) Available options for amelioration and management.

Timeframe - July 1998 - January 2001.

- Field verification,
- Production of several reports,
- Obtaining local opinion and verification on available management options,
- Obtaining and interpreting detailed data via resource economist.

- Obtaining and interpreting detailed data from commercial soil testing labs, if available.

Project development meeting	\$10K
Acquiring, processing and interpreting ASS data	\$100K
Collation, GIS mapping and map production	\$150K
Part time salaries	\$300K
Supervision (12 months)	\$80K
Total	\$650K

Preferred Option

Option 2, which will also include all the products from options 1 and 2.

Acknowledgements

We would like to thank the following referees for their constructive comments:

- Dr Roger Swift (coastal, inland and minesite ASS)
- Dr Ian Willett (coastal ASS).
- Mr Bernie Powell (coastal ASS in Qld.).
- Dr Bill Gardner (inland ASS in Victoria).
- Mr Bruce Munday (inland ASS in South Australia).
- Dr John Harries (Minesite ASS).

SELECTED KEY REFERENCES

Coastal Acid Sulfate Soil Conditions

- Ahern, C., Powell, B. and Ahern, M. (QASSIT), (1997). Sampling and Analysis. Procedure for Lowland Acid Sulfate Soils (ASS) in Queensland (Draft). Queensland Acid Sulfate Soils Investigation Team, Brisbane. p1-27.
- Bloomfield, C. and Coulter, J.K., (1973). 'Genesis and Management of Acid Sulfate Soils'. **Advances in Agronomy**. p265-326.
- Bowman, G.M., (1993). 'Case Studies of ASS Management'. In Bush, R. (ed.), **Proceedings of the First National Conference on Acid Sulfate Soils**, Coolangatta. p95-115.
- Bowman, G.M. (1996). An overview of acid sulfate soil treatment. "Proceedings 2nd National Conference of Acid Sulfate Soils" Robert J Smith and Associates and ASSMAC, Australia, 200-206.
- Dent, D. and Bowman, G. (1996). Quick, quantitative assessment of the acid sulphate hazard. CSIRO Division of Soils, Divisional Report 128.
- Dent, D.L. and Pons, L.J., (1995). 'A World Perspective on Acid Sulfate Soils'. **Geoderma**, 67:263-276.
- Lin, C., Melville, M.D. and Hafer, S., (1995). 'Acid Sulfate Soil-Landscape Relationships in an Undrained, Tide-dominated Estuarine Floodplain, Eastern Australia'. **Catena**, 24:177-194.
- Melville, M.D., White, I. and Lin, C., (1993). 'The Origins of Acid Sulfate Soils'. In Bush, R. (ed.), **Proceedings of the First National Conference on Acid Sulfate Soils**, Coolangatta. p19-25.
- Mulvey, P., (1993). Pollution, 'Prevention and Management of Sulfidic Clays and Sands'. In Bush, R. (ed.), **Proceedings of the First National Conference on Acid Sulfate Soils**, Coolangatta. p116-129.
- National Working Party on Coastal Acid Sulfate Soils. (1998). Draft National Strategy for the Management of Acid Sulfate Soils (Compiled by John Williams, Chairman NWP-ASS) ISBN 0 7310 9842 0. (DRAFT REPORT: in review). See following www site:
<http://www.dpie.gov.au/dpie/armcanz/pubsinfo/ass/ass.html>
- Sammut, J., Callinan, R.B and Fraser, G.C. (1996). An overview of the ecological impacts of acid sulfate soils in Australia. "**Proceedings 2nd National Conference of Acid Sulfate Soils**" Robert J Smith and Associates and ASSMAC, Australia, 140-145.
- Sammut, J., Melville, M.D., Callinan, R.B. and Fraser, G.C., (1995). 'Estuarine Acidification: Impacts on Aquatic Biota of Draining Acid Sulfate Soils'. **Australian Geographical Studies**, 33(1):89-100.
- Sammut, J., White, I. and Melville, M.D., (1996). 'Acidification of an Estuarine Tributary in Eastern Australia Due to Drainage of Acid Sulfate Soils'. *Mar. Freshwater Res.*, 47:669-684.
- Smith, R.J. and Smith, H.J. (1996). "Proceedings of the 2nd National Conference of Acid Sulfate Soils" held at Coff's Harbour 5-6 September 1996. Published by Robert J Smith and Associates and ASSMAC.

- Stone, Y.N., (1993). 'A State Perspective on Planning for Acid Sulfate Soils'. In Bush, R. (ed.), **Proceedings of the First National Conference on Acid Sulfate Soils**, Coolangatta. p84-93.
- White, I., and Melville, (1993). Treatment and containment of acid sulfate soils. **Technical Report No. 53**. CSIRO Centre of Environmental Mechanics: Canberra. p103.
- White, I., Melville, M.D., Wilson, B.P., Price, C.B. and Willett, I.R., (1993). 'Understanding Acid Sulfate Soils in Canelands'. In Bush, R. (ed.) **Proceeding of the First National Conference on Acid Sulfate Soils**. Coolangatta. p130.
- White, I., Melville, M.D., Sammut, J., Wilson, B.P., and Bowman, G. M. (1996). Downstream impacts from Acid Sulfate Soils. *In Hunter et al*, (ed.) *Downstream Effects of Land Use*. 165-172. **Department of Natural Resources**. Queensland, Australia p165-172.

Inland Acid Sulfate Soil Conditions

- Fitzpatrick R.W., R. Naidu and P.G. Self (1992). Iron deposits and microorganisms occurring in saline sulfidic soils with altered soil water regime in the Mt. Lofty Ranges, South Australia. In "Biomineralization Processes of Iron and Manganese -Modern and Ancient Environments". (eds. H.C.W. Skinner and R.W. Fitzpatrick). **Catena Supplement No. 21**, p 263-286.
- Fitzpatrick, R.W., Fritsch, E. and Self, P.G., (1993). 'Australia's Unique Saline Acid Sulfate Soils Associated with Dryland Salinity'. In Bush, R. (ed.), **Proceedings of the First National Conference on Acid Sulfate Soils**, Coolangatta. p41-56.
- Fitzpatrick R.W., E. Fritsch and P.G. Self (1996). Interpretation of soil features produced by ancient and modern processes in degraded landscapes: V Development of saline sulfidic features in non-tidal seepage areas. **Geoderma 69**, 1-29.
- Fitzpatrick R.W., J.W. Cox, J. and J. Bourne (1997). Managing waterlogged and saline catchments in the Mt. Lofty Ranges, South Australia: A soil-landscape and vegetation key with on-farm management options. Catchment Management Series. **CSIRO Publishing, Melbourne**, Australia, 36 pp. ISBN 1 876162 30 9.
- Gardner W. and Hindhaugh C. 1994. Does discharge clogging add to salinity effects? **Aust. J. Soil and Water Conserv.** 7(4) p 34-36.

Minesite Acid Sulfate Soil Conditions

- Environment Australia (1997). Managing sulphidic mine wastes and acid drainage. Best practice environmental management in mining. Office of the Supervising Scientist, Environment Australia, PO Box E 305, Kingston. ACT 2604. Australia. ISBN 0642 19449 1.
- Fitzpatrick R.W. and P.G. Self (1996). Iron oxyhydroxides, sulfides and oxyhydroxysulfates as indicators of acid sulphate surface weathering environment. *In*: K. Auerswald, H. Stanjek and J.M. Bigham (eds.). *Soils and Environment: Soil Processes from Mineral to Landscape Scale*. **Advances in GeoEcology 30**: 227-240.
- Harries J. (1997). Acid mine drainage in Australia: its extent and failure liability. Supervising Scientist, Report 125. Supervising Scientist, Canberra.
- Jones, D. Chapman, B.M. (1995). Wetland to Treat AMD – Facts and Fallacies. In Proc. Second Australian Acid Mine drainage workshop, Carters Towers Queensland. 28-31. March, 1995. Eds. N.J. Grundon & L.C. Bell pp 127-145. Australian Centre for Minesite Rehabilitation Research, Brisbane, Australia.
- Miller S. Jeffrey, J. (1995). Advances in the prediction of acid generating mine waste materials. In Proc. Second Australian Acid Mine drainage workshop, Carters Towers Queensland. 28-31. March, 1995. Eds. N.J. Grundon & L.C. Bell pp 33-43. Australian Centre for Minesite Rehabilitation Research, Brisbane, Australia.
- Taylor, C.F. (1996). Exploration, mining and mineral processing. In R. Naidu et al. (eds.) *Contaminants in the soil environment in the Australian-Pacific Region*. Kluwer. pp213-266.

Table 1. Comparison of morphological features, physico-chemical and mineralogical properties for undisturbed and disturbed acid sulfate soils (ASS) in coastal (tidal), inland (non-tidal) and minesite environments (modified from Fitzpatrick and Self, 1996)

Environment Type of material	Coastal ASS (Tidal environments)				Inland ASS (Non-tidal seepage environments)			Minesite ASS (mining environments)		
	Soil ¹ (sulfidic material)	Surface precipitates	Soil ² (sulfuric horizon)	Surface precipitates	Soil	Soil	Surface precipitates	Soil	Soil	Surface precipitates
Condition ³⁻⁵	³ UW	³ UW	³ DD	DD	UW	⁴ UD, DD	UW, UD, DD	UW	UD, DD	UW, UD, DD
Morphological features	Black; few grey mottles	-	Bright yellow streaks	Bright yellow and red-brown precipitates	Black; many grey mottles	Dark reddish-brown stains	Red-brown gelatinous precipitate	Brown-black; many grey mottles	Dark reddish-brown stains	Red-brown gelatinous precipitate
n-value	>1	-	0.7 - 1.0	-	1 - 2	<1	-	1.0 - 1.4	<1.0	-
pH 1:5 soil:H ₂ O	7.5 - 8.5	-	<3	2.5 - 5.0	6.5 - 8.5	3.8 - 5.5	6.5 - 7.0	6 - 7	3 - 5	4.0 - 6.5
Organic carbon %	5 - 20	-	5 - 20	2 - 15	2 - 10	2 - 10	-	<2	<2	-
Sulphur %	1 - 8	-	1 - 8	-	0.2 - 1.0	0.1 - 1.0	-	<0.5	<0.5	-
EC 1:5 soil:H ₂ O (dS/m)	3 - 16	-	3 - 16	10 - 20	1 - 10	5 - 15	-	<1	<1	-
Eh (mV)	-200 to 0	-	-	-	-100 to 50	-	-	0 to 100	-	-
Minerals (in order of abundance)	Pyrite framboids	Rare: Bacterial sulphur	Jarosite Goethite	Jarosite Ferrihydrite Goethite	Pyrite framboids Ferrihydrite	Ferrihydrite Goethite Schwertmannite	Ferrihydrite Lepidocrocite Goethite	Poorly cryst. Fe-sulfides Ferrihydrite	Jarosite Ferrihydrite	Ferrihydrite Schwertmannite Goethite Lepidocrocite
Dominant Processes	Sulfidization	None	Sulfuricization	Sulfuricization Ferritization	Sulfidization	Sulfuricization Ferritization	Sulfuricization Ferritization	Sulfidization	Sulfuricization Ferritization	Sulfuricization Ferritization
Development of processes	Strong	None	Strong	Strong	Medium	Medium	Strong	Weak	Weak	Strong

¹Sulfidic material = potential acid sulfate soil condition; ²Sulfuric horizon = actual acid sulfate soil condition.

³UW = Undisturbed wet condition, ⁴UD = Undisturbed dry condition and ⁵DD = Disturbed (e.g. drained or eroded) dry condition.

