9 From Conflict to Industry – Regulated Best Practice Guidelines: a Case Study of Estuarine Flood Plain Management of the Tweed River, Eastern Australia

I. White,[1] M. Melville,[2] B.C.T. Macdonald,[1] R. Quirk,[3] R. Hawken,[3] M. Tunks,[4] D. Buckley,[4] R. Beattie,[5] L. Heath[1] and J. Williams[6]

[1]*Centre for Resource and Environmental Studies, Australian National University, Canberra, Australia, e-mail: ian.white@anu.edu.au*
[2]*School of Biological, Earth and Environmental Sciences, University of New South Wales, Australia*
[3]*NSW Canegrowers, Condong Sugar Mill, New South Wales, Australia*
[4]*Tweed Shire Council, New South Wales, Australia*
[5]*NSW Sugar Milling Co-operative Limited, New South Wales, Australia*
[6]*NSW Department of Primary Industries, New South Wales, Australia*

Abstract

Different sectors of society claim rights to use valuable coastal ecosystem resources. Conflicts over their use are therefore inevitable. In eastern Australia, government-encouraged development and drainage of coastal flood plains, principally for agriculture, resulted in accelerated oxidation of acid sulphate soils and export of toxic acidic drainage to coastal streams. Major impacts on infrastructure, ecology, fisheries and aquaculture resulted. In 1987/1988, all gilled organisms were killed in 23 km of the Tweed River estuary by acid outflows from canelands. This generated major conflicts among fishers, environmentalists and sugarcane producers farming the flood plain. Here, we describe the evolution of a collaborative learning approach to coastal flood plain management involving cane farmers, local government and researchers, and the institutional response to this fish kill. Existing knowledge in Australia was inadequate and efforts centred on providing information and options for better management and regulation of sulphidic estuarine areas and on mitigating impacts on downstream ecosystems. Farmers, researchers and local government officers working collaboratively generated information on the properties and management of sulphidic flood plains under the highly variable rainfall conditions common in Australia. This provided options for management that were rapidly translated into practice and underpinned mandatory best management guidelines for the NSW sugar industry. Increases in productivity and decreases in acid water discharge have resulted. Essential features of the collaborative partnership are analysed and the institutional response, which led to the adoption of Australia's national strategy for the management of acid sulphate soils, is described.

 Environment and Livelihoods in Tropical Coastal Zones (eds C.T. Hoanh, T.P. Tuong, J.W. Gowing and B. Hardy)

Introduction

Global challenges of coastal zone management

Coastal ecosystems are both immensely valuable (Costanza *et al.*, 1997) and valued by their dependent communities. Despite this, they continue to degrade on a global scale because of natural and human-induced changes (Kremer and Crossland, 2002). Of human pressures, cropping, grazing and megacities in coastal catchments have the largest impacts (WRI, 2000), mainly because of enhanced discharges of nitrogen, carbon and sediment from changes in coastal land and water regimes (GESAMP, 2001). The principal drivers for exports into coastal areas are river and groundwater discharge, population density, agricultural activities and catchment area (Buddemeier *et al.*, 2002; Kremer and Crossland, 2002).

Sustainable resource use and maintenance of coastal system functions are enormous challenges. Some of the key challenges are (Kremer and Crossland, 2002):

- improving the availability and accessibility of resource and environmental information,
- fostering participatory approaches to coastal zone management,
- developing wise use options and agreements (context-specific best management practices),
- ensuring that planning and management cope with change, and
- developing policies that take into account risks and vulnerability.

The supply of reliable information, participatory approaches and the adoption of context-specific best management practices are of central importance to sustainable coastal zone management, as we shall attempt to demonstrate in this chapter.

Information on coastal ecosystems

Some believe that it is not possible to wait while knowledge gaps in coastal ecosystems are investigated. Instead, action learning or adaptive management has been proposed as the way forward (Jiggins, 2002). Adaptive management of complex situations assumes that mistakes due to incorrect information can be identified, through rigorous monitoring, and corrected (Dovers and Mobbs, 1999). This presupposes linear processes in which the consequences of wrong actions can be reversed readily. Estuaries appear to behave in a non-linear, hysteretic manner (Harris, 1999), that is, after relatively small changes they exhibit dramatic collapses that are not easily reversed.

Information on coastal ecosystem processes is patchy, even in intensively managed areas. The general paucity of data is evident in Australia. Relatively little research has been undertaken on the processes, consequences of environmental change or impacts of human activities in coastal eastern Australia, despite the concentration of population there (Thom, 2002). We argue here that the hysteretic nature of coastal acid sulphate soil systems means that reliable information is of fundamental importance to improved environmental outcomes. The effective transfer of information to bring about changes in land management presents challenges to conventional models of knowledge transfer (Esman and Uphoff 1984; Roling, 1988; Curtis, 1998).

Participatory approaches to coastal zone management

Participatory approaches to natural resource management are a key to successful coastal management (Thom and Harvey, 2000). Problems arising from the past management of coastal resources in eastern Australia have partly resulted from the plethora of conflicting visions and disparate goals among protection, rehabilitation, economic development and regional employment growth, as well as from the inheritance of past legislation and administrative goals (Thom, 2002) and the failure to involve communities. The establishment of a shared vision through involvement of all sectors (Chambers, 1983) is an essential step in reducing conflict in coastal areas. Substantial evidence shows that participation through local organizations can produce broad-based management changes (Chambers, 1983; Esman and Uphoff 1984; Roling, 1988; Curtis, 1998; Ashby, 2003). Here, we describe the evolution of such an approach.

Coastal stewardship, wise practice options and conflict resolution

Many different sectors of society claim right of access to and use of resources in coastal regions (UNESCO, 2002a). As a consequence, a number of government agencies and authorities have frequently conflicting responsibilities for the coastal zone. As a result, no specific agency or institution is responsible for their management, despite the ever-increasing demand for finite resources and space (Healthy Rivers Commission, 2000). Conflicts over their use are often inevitable. Some even claim that conflict is a key driver for change.

In any conflict resolution, the first steps are to describe the nature and cause of the conflict, to identify and to bring together all the stakeholders in order to try to reach a consensus or compromise agreement. To reach agreement, there needs to be a process or mechanism where conflicting parties are able to address and resolve conflicts. Independent, impartial, outside parties, such as universities, can assist in developing agreements (UNESCO, 2002a).

Coastal stewardship has been proposed as one way of reducing conflicts by promoting ownership. It involves voluntary compliance, strong commitment and willing participation in the sustainable use of coastal resources (UNESCO, 2002b). The challenges in coastal stewardship are to inform, educate, motivate and empower communities to become managers and custodians of their environment. We provide in this work examples of this model.

Wise coastal practices are actions, tools, principles or decisions that contribute significantly to the achievement of sustainable development (embracing environmental, social, cultural and economic considerations) of coastal areas. Several characteristics of wise practices are particularly relevant to conflict prevention and resolution. These include participatory processes, consensus building, effective and efficient communication processes, capacity building and the need to respect traditional frameworks (UNESCO, 2002a). Wise practice agreements bring together all stakeholders, including governments, in a framework of voluntary compliance (UNESCO, 2002b). There are increasing concerns, particularly among regulators, however, that, without strong underpinning regulations, voluntary compliance agreements contain no effective mechanisms to address persistent breaches. This is an important factor in the case study discussed here, in which we illustrate the development of mandatory, context-specific wise practice agreements.

Recent developments in multi-agent-based simulations (MABS), coupled with role-playing games, provide powerful tools for studying interactions between societies and their environment (Bousquet *et al.*, 2002; Perez *et al.*, 2003). They have the potential to greatly reduce conflict over natural resource management and resource allocation; however, they were developed long after the work described here commenced.

In this chapter, we discuss issues involved in addressing some of these challenges. We describe a case study of a partnership developed to improve the sustainability of the acidified, coastal flood plain of the Tweed River in eastern Australia. The cooperative learning approach to coastal flood plain management described here evolved over the last 15 years. The partnership includes local government, cane farmers and their industry and academic institutions, and successfully addresses some of the important challenges outlined above. We first outline briefly issues concerned with coastal flood plain development in Australia.

Coastal Flood Plain Development in Eastern Australia

Coastal flood plains were the first regions in Australia developed for agriculture following European settlement. They have favourable temperatures and plentiful, young fertile soils, associated with large wetlands and low areas with high water tables (King, 1948).

While coastal flood plains were valuable drought refuges for cattle, waterlogging was a major constraint to increased cropping and improved pastures. Governments of all political persuasions encouraged land drainage. Landowner-initiated drainage in New South Wales (NSW), eastern Australia, dates back to the 1820s. The attendant increased investments in flood plain agriculture following drainage, however, required protection from frequent floods and storm surges, which involved the re-engineering of flood plain hydrology (Thom, 2002). As a result, the time scale for inundation of many backswamp areas was reduced from about 100 to around 5 days (White *et al.*, 1997).

Most coastal flood plains are now, on average, drier and export drainage waters at a much greater rate through more efficient drainage canals. Increased rates of drainage discharge, with accompanying sediment and chemical loads, often exceed the natural assimilative capacity of receiving waters. While naturally occurring, periodic droughts also dried out coastal flood plains (Lin and Melville, 1993) and natural drainage channels were much less efficient at delivering run-off to receiving waters than were constructed canals (Sammut *et al.*, 1996).

Institutional arrangements for flood plain drainage

Frequent floods in coastal NSW, particularly in the 1950s, led to joint Australian Commonwealth–NSW state government flood mitigation schemes. These schemes required participation from local governments and led to the construction of major levees, floodgates, retention basins and large primary canals on most of the river systems in NSW. These are now the responsibility of local governments.

The Drainage Act of 1904 established Drainage Unions, composed of local farmers who manage their secondary tributary drains feeding into main drains or directly into rivers. Drainage Unions had the authority to tax local landowners for maintenance and improvement of secondary drains and to carry out drainage work without prior state or local government approval. The major NSW water reforms of 2000 abolished many Drainage Unions, although some have been replaced by Drainage Boards, and their functions transferred to local governments.

Farm-level tertiary field drains, feeding into secondary drains, were constructed and maintained by individual landholders. Thousands of kilometres of drains have been constructed in coastal NSW. Many primary, secondary and tertiary drains are protected by one-way floodgates preventing tidal ingress of brackish water into low-lying backswamps. Floodgates impede fish passage to feeding and breeding areas (Sammut *et al.*, 1995). Figure 9.1 shows the high density of secondary and tertiary drains feeding into the Tweed River in eastern Australia.

Until the introduction in 1997 of the model provisions for Local Environment Plans (LEPs), there was little constraint on the construction of tertiary drains. Constructed drains and flood mitigation structures permitted widespread grazing, dairying, tea tree (*Leptospermum* sp.) and sugarcane industries to be established. Almost all of this government-encouraged development was carried out without recognition of the presence of acid sulphate soils or of the potential impacts of their drainage.

Acid sulphate soils in Australia

Many coastal flood plains throughout the world have Holocene-age soils (< 10,000 years old) containing iron sulphide minerals (Dent, 1986), mostly rich in the mineral pyrite, although in some regions, monosulphides are important (Bush *et al.*, 2004). Acid sulphate soils were recognized in Europe over 250 years ago (Pons, 1973). In Australia, their existence was appreciated relatively recently (Woodward, 1917; Teakle and Southern, 1937; Walker, 1972; Willett and Walker, 1982). Prior to the release of NSW acid sulphate soil risk maps (Naylor *et al.*, 1995), acid sulphate soils did not offi-

Fig. 9.1. Networks of secondary and tertiary drains on the upper flood plain of the Tweed River, northern NSW, eastern Australia. The river is at far left.

cially exist in Australia. As recently as 2002, some Australian states still denied their existence.

Walker (1972), in his comprehensive study, specifically warned of the dangers of continuing to drain sulphidic coastal flood plains. His advice was ignored. Preoccupation with the problems of inland agriculture in eastern Australia discouraged serious attention to issues in coastal areas. Detrimental impacts of acid sulphate soils in Australia include corrosion of engineering infrastructure (White *et al.*, 1996), massive fish kills and fish diseases (Brown *et al.*, 1983; Noller and Cusbert, 1985; Hart *et al.*, 1987; Easton, 1989; Callinan *et al.*, 1993; Sammut *et al.*, 1995), dramatic changes in stream ecology (Sammut *et al.*, 1995, 1996), blooms of harmful cyanobacteria (Dennison *et al.*, 1997) and emissions of sulphur dioxide (Macdonald *et al.*, 2004a). Acidic outflows can also threaten aquaculture (Simpson and Pedini, 1985).

Exported acidic materials have been found to be sequestered in the sediments of shallow receiving waters, from where they are available for subsequent remobilization (Macdonald *et al.*, 2004b). Thousands of tonnes of acidic products have been discharged from eastern Australian flood plains in single flood events (Sammut *et al.*, 1996; Wilson *et al.*, 1999).

Figure 9.2 shows an early attempt at identifying potential coastal areas of acid sulphate soils in Australia (White *et al.*, 1996). It is estimated that there are over 40,000 km^2 of acid sulphate soils, with some in every state of Australia. The current widespread recognition, policies and strategies on acid sulphate soils in Australia stemmed from a single incident.

Fish kills on the Tweed River

Heavy rains in early 1987 following a prolonged dry period strongly acidified the entire 23 km of the Tweed River estuary in north-eastern NSW, which drains to the sea at Tweed

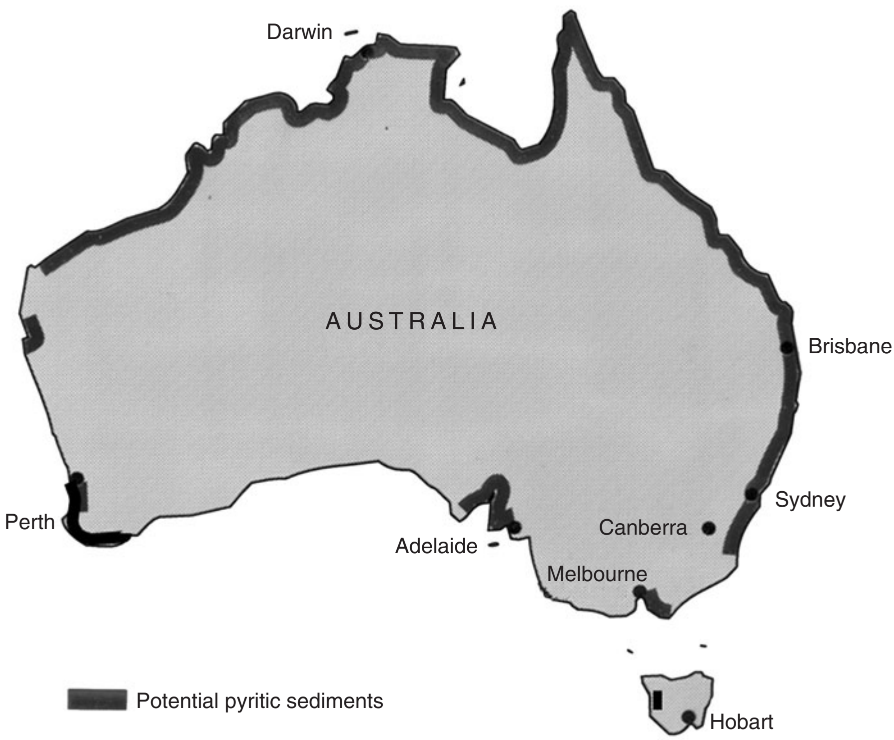

Fig. 9.2. An early attempt at identifying the potential location of acid sulphate soils in the Australian coastal zone from the distribution of mangroves (from White *et al.*, 1996).

Heads (see Fig. 9.3). The dissolved aluminium completely clarified the normally turbid estuary and all gilled organisms were killed (Easton, 1989). Possibly more than 1000 t of dissolved and colloidal aluminium was discharged in the event and the river remained almost sterile for a further 18 months.

The region surrounding the Tweed River is one of the fastest growing population centres in Australia because of its climate and highly prized natural amenities. It is a centre for tourism and recreational fishing. The fish kills on the Tweed attracted major media coverage and local attention because nearly 70% of the commercial fish species caught in Australia spend part of their lives in estuaries.

Over 80% of the 11,000 ha Tweed River flood plain is used for producing sugarcane. Many reasons were advanced for the fish kills and sugarcane farming was implicated in most of them. At first, pesticides were suspected. It was noticed that mosquito larvae had not been killed by the event. This precluded pesticides and led to the identification of acidic, aluminium-rich drainage from acid sulphate soils, which made up much of the canelands (Easton, 1989).

The 1987 fish kills on the Tweed generated serious conflicts between, on the one hand, commercial and recreational fishers, tourism operators, oyster farmers and environmentalists and, on the other, the sugarcane industry. Livelihoods on both sides were at risk. An initial public meeting of 500 locals ended in acrimony with threats to blow up or vandalize tidal floodgates on drains and inundate farmlands with brackish estuarine water, and counterthreats to shoot trespassers who interfered with drainage structures. One week later, the parties reconvened with cooler heads and elected representatives from each stakeholder group. This body became the Tweed River Advisory Committee (TRAC).

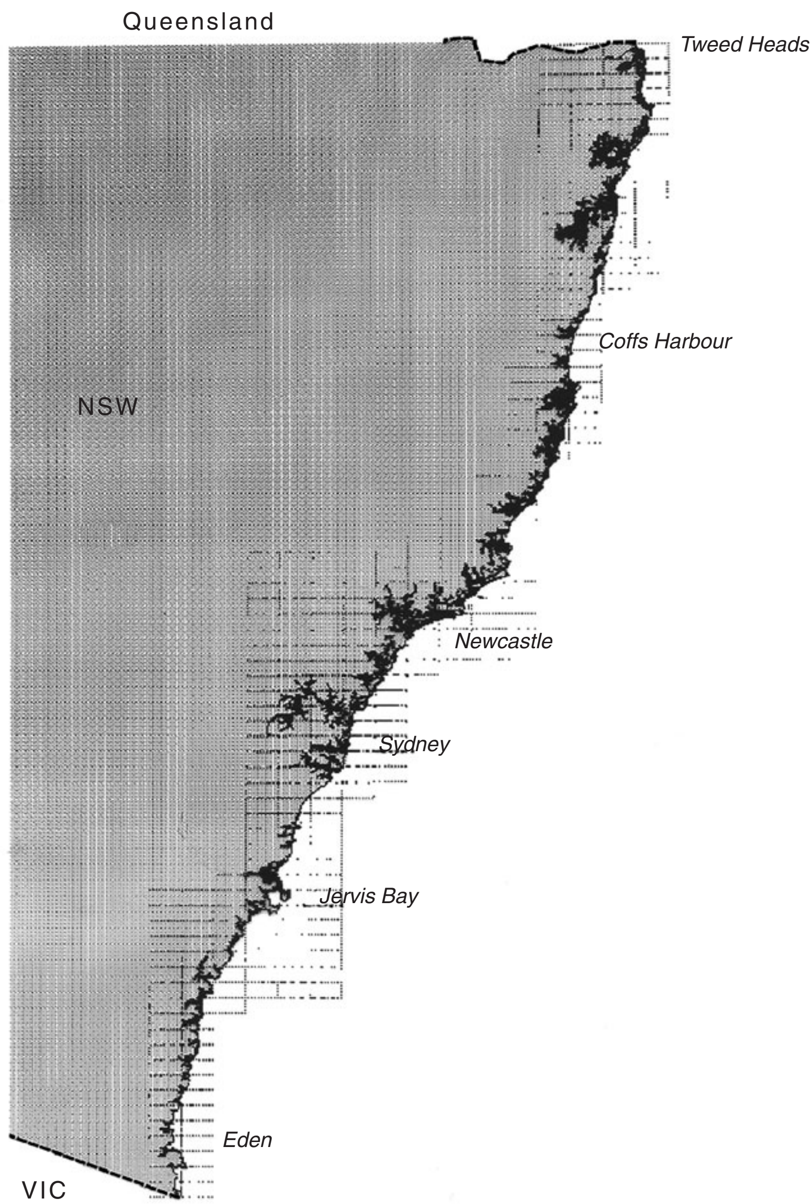

Fig. 9.3. Risk map of the distribution of acid sulphate soils in eastern Australia's state of New South Wales. The Tweed River discharges into the ocean at Tweed Heads (from Naylor *et al.*, 1995).

Evolution of a Cooperative Learning Partnership

In an attempt to find a formal way forward, the local government, Tweed Shire Council, convened a meeting of key representatives from TRAC in 1989. The meeting included farmers and fishers, oyster farmers, representatives from the sugar industry, local government and NSW state resource agencies, and researchers from university and federal research organizations. At the time, only three scientists in Australia had significant research experience in acid sulphate soils.

The aim of the Tweed meeting was to determine the cause of the fish kills and to explore possible solutions. Despite the animosity, the ultimate goals were to develop a shared vision for management and use of the flood plain and to initiate procedures to address the drainage water quality problems. The then six state government agencies with responsibilities for estuarine management had conflicting agendas and different opinions of the causes of the event. State agencies were wary of issues connected with coastal development which was, and continues to be, a major and controversial political question. Tweed Shire Council helped foster the development of a local acid sulphate soil committee, composed of the conflicting parties, local government and researchers, in 1990. It was finally agreed that information on the cause of the fish kills was incomplete and that research on the processes causing water quality problems should be carried out.

Adequacy of understanding

Further research is often proposed as a way to postpone difficult choices and decisions in natural resource management. In 1990, when research on the Tweed began, there was a considerable body of knowledge external to Australia about acid sulphate soils and some of the general principles of their management were well established (Dent, 1986). However, significant knowledge gaps existed, particularly in the Australian context with its extremely variable climate and hydrology. One of the principal issues was the comparative contribution of natural and farming-related processes to acid discharge. Adaptive management was not considered since the effects of a single day's drainage excavations of acid sulphate soils can have impacts that last for decades (White *et al.*, 1997).

A number of factors made the Tweed River flood plain particularly attractive to researchers. There is essentially a single land use on the sulphidic flood plain – sugarcane production – and the sugarcane industry is a well-structured cooperative, and therefore results of research are readily transferable. A single local government, Tweed Shire Council, managed the catchment, and the council was determined to find solutions. Finally, the connection between land use and estuarine water quality seemed straightforward.

Knowledge gaps

In 1989, most previous work on acid sulphate soils had focused on improving their agronomic performance (Dent, 1986), mainly due to experience in the Netherlands and in areas where off-site environmental impacts were discounted. Little attention had been paid to the downstream and off-site impacts of developing acid sulphate soils for agriculture, although Walker (1972) was an exception to this. Existing knowledge had focused on acid generation from the continuing oxidation of pyrite. To stop oxidation, air must be prevented from entering the sulphidic horizon, usually by reflooding the soil or by raising the groundwater level above the sulphidic horizon. Reflooding was expected to reverse the acidification processes by reducing oxidized sulphate back to sulphides through the microbially catalysed oxidation reaction involving organic matter (Dent, 1986):

$$\begin{aligned} &4FeOOH(s) + 4SO_4^{2-} + 9CH_2O + 8H^+ \\ &\rightarrow 4FeS(s) + 9CO_2 + 15H_2O \end{aligned} \qquad (9.1)$$

Reflooding of sulphidic flood plains is still the most common management strategy recommended for acid sulphate soils but is anathema to coastal landowners. Previous work also suggested that lengthy, detailed and expensive soil surveys were required to determine the distribution of acid sulphate soils in coastal catchments.

Armed with this set of beliefs, research began on the Tweed in early February 1990. Monitoring by the Tweed Shire Council had identified the McLeods Creek (a re-engineered secondary drainage canal) catchment as one of the acid-exporting 'hot spots' on the Tweed River. It was clear from even preliminary measurements that the flood plain did not conform to conventional wisdom. Soil profiles showed that the surface soil had a pH above 4, making this technically not an acid sulphate soil despite obvious indicators of sulphide oxidation in the subsoil (Fig. 9.4).

One feature of the farmed flood plain was the complex, dense and seemingly over-constructed farm-level drainage system excavated without engineering drainage design (see Fig. 9.1). It was clear that an understanding of the hydrology, mostly ignored in previous studies, and its relation to the soil stratigraphy, groundwater and drain water quality were essential to understanding the processes.

Distribution of acid sulphate soils

Determination of the spatial extent of acid sulphate soils in the Tweed River flood plain was fundamentally important to improved management. A conventional soil survey would have taken too long and would have been too expensive. A geomorphic approach to mapping based on the conditions necessary for sulphide accumulation in estuarine sediments was developed. Over the last 6500 years, sea levels have remained fairly constant, the eastern Australian land surface has been tectonically relatively stable over that time and fluvial sediment accumulation there has not been large (Lin and Melville, 1993).

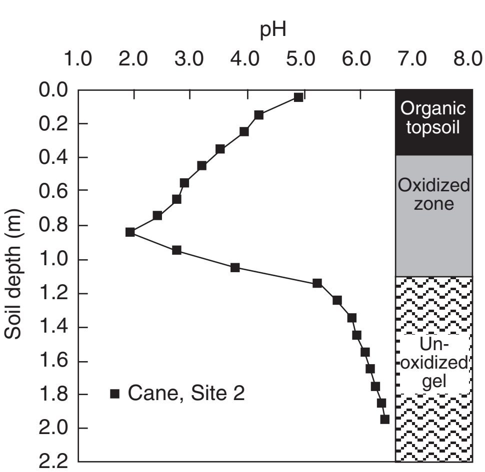

Fig. 9.4. Profile of soil pH in an acid sulphate soil in a caneland on the Tweed River flood plain taken from a cane farm on Fig. 9.1.

Based on this, the top of the sulphidic horizon in Australian Holocene coastal sediments should be close to where it was last formed, at about mean high-tide level (about 1 m Australian Height Datum, in eastern Australia). Because this horizon has been buried by a variable thickness of alluvium, it was predicted that Holocene coastal sulphidic sediments in eastern Australia would be found at sites with surface elevations of less than about 5 m AHD (Melville *et al.*, 1990, 1993; White and Melville, 1993). This prediction provided the basis for producing acid sulphate soil risk maps for the entire state of NSW (see Fig. 9.3, Naylor *et al.*, 1995). These maps have been both remarkably accurate and useful planning tools and form the basis for Local Environment Plans, Development Control Plans and Development Assessments that control developments in acid sulphate soil areas in NSW.

Cane farmers' response

Initial discussions between researchers and cane farmers in the McLeods Creek catchment and sugar mill officers during the preliminary site visit were less than encouraging. The cane industry rejected the suggestion that acidification of streams was attributable to their soils, some suggesting instead that it was road gravel that caused the problem. Rejection is a readily identified first stage in many areas of natural resource management (see Fig. 9.5). Frequently, many do not progress beyond this stage.

The industry wanted to lower water tables further by up to 1 m to improve cane production since waterlogging was perceived to be a main impediment to cane production. Cane farmers were divided on whether researchers should be invited into the catchment. The strong opposition was understandable since the prevailing wisdom was that, to control acid discharges, low-lying areas should be reflooded with brackish estuarine water, thereby eliminating cane production and farmers' livelihoods and property values. In addition, farmers felt they were being blamed unfairly for acidic

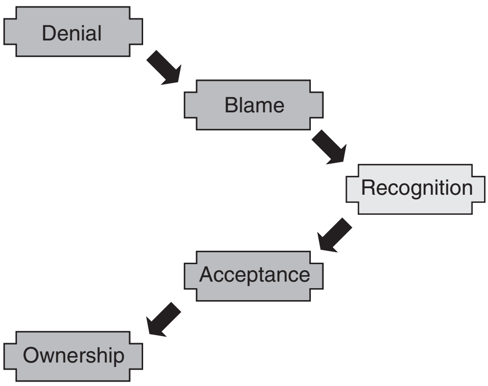

Fig. 9.5. The five stages of response to issues in natural resource management.

drain discharges from areas approved for agriculture and drained with continued encouragement from governments.

Despite their misgivings, farmers in McLeods Creek gave permission for researchers to work on their lands. The support of Tweed Shire Council for continued research and monitoring was a crucial element in persuading farmers to tolerate research directed at understanding the processes involved in the generation and export of acidity, its environmental impacts and the identification of amelioration options

Cooperative learning

In the early days of the research on the Tweed, there was some mutual mistrust between researchers and farmers. The culture and reward systems for both groups differed fundamentally. It took nearly 3 years for mutual understanding and trust to develop. This gradual evolution was assisted by the continued interest and support of local government staff and state-level initiatives in acid sulphate soils.

Researchers initially had a narrow focus on soil (Melville *et al.*, 1993), hydrological (White *et al.*, 1993) and environmental issues (Callinan *et al.*, 1993). Work had also expanded into the more biophysically and socially complex and larger Richmond River flood plain south of the Tweed, where there were also major acid discharges (see Fig. 9.6, Sammut *et al.*, 1996). Researchers came round to a growing appreciation that acid sulphate soil management was but one of a broad range of issues that had to be faced and dealt with by farmers, fishers and local governments. They recognized that farmers, fishers and regulators have to deal with and integrate a bewildering range of soil, climate, crop, nutrient, disease, pest, social, regulatory, financial, political and institutional issues in their daily tasks. It became increasingly apparent to researchers that they needed to understand these broader issues in order to transfer their research findings effectively.

Frequent informal discussions were held in the field, where both research results and information on the current issues faced by farmers, fishers and local government were exchanged. These were interspersed with more formal meetings with the NSW Sugar Industry and Tweed Shire Council representatives and various committees such as the Tweed River Management Plan Advisory Committee. It became increasingly clear to researchers that their task was to provide a range of practical management options for farmers, fishers and regulators, not single prescriptive solutions.

The training of graduate students and postdoctoral fellows in field acid sulphate soil and related research was a key component in the partnership. This has been an invaluable opportunity for cooperative learning. Graduate students and postdoctoral fellows are highly motivated and can focus on key issues exclusively. They are also less threatening than senior researchers. The opportunity for them to do research in partnership with experienced farmers is an unparalleled, two-way learning opportunity. Additionally, there remains a real dearth of trained people with field experience in coastal soils, hydrology and environmental impacts in Australia.

Farmers began to appreciate that researchers were not there to apportion blame. Indeed, researchers' message that acid sulphate soils were part of the global sulphur cycle, a naturally occurring phenomenon that has existed for hundreds of millions of years, brought about a shift in attitude. Farmers started to talk about *their*

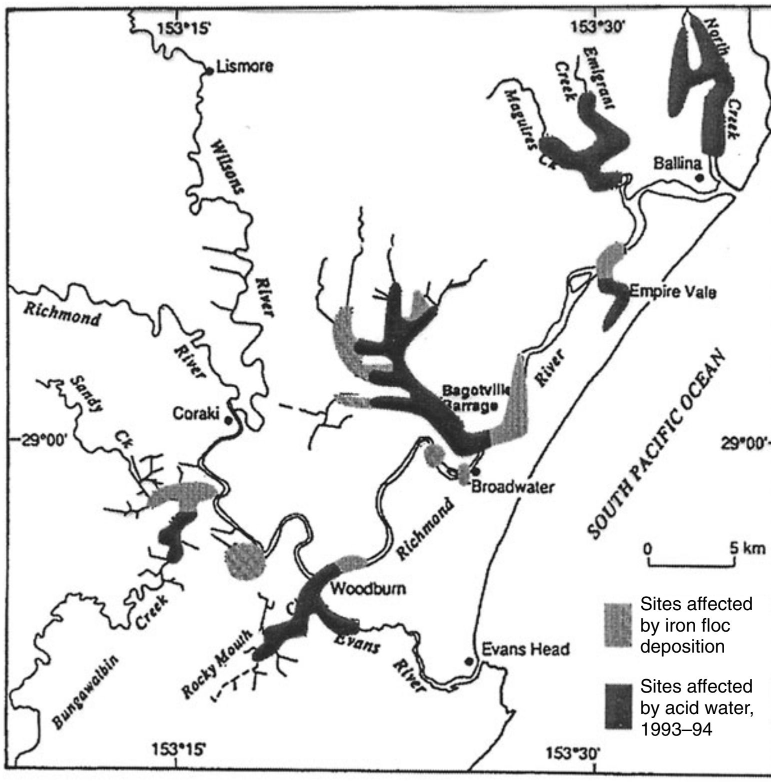

Fig. 9.6. Extent of acid-impacted areas in the Richmond River estuary, 1993–1994, from drainage of acid sulphate soils (from Sammut *et al.*, 1996).

acid sulphate soils and to carry pH meters. Once that happened, farmers became initiators of the research.

Research Findings

Some of the research findings in the Tweed were counter to the prevailing wisdom and resulted in significant land management changes. During dry periods, it was found that sugarcane survives on shallow groundwater (White *et al.*, 1993). The industry's quest to further lower water tables by increasing drain depths would result in decreased crop production. In addition, the shrink–swell nature of the gel sublayer dictates that lowering the water table also lowers the elevation of the soil surface (White *et al.*, 2001).

Because of the exceedingly small hydraulic conductivity of the oxidized clay gels making up the potential acid sulphate horizon (White, 2002; White *et al.*, 2003), crop evapotranspiration was the main determinant of water table level, not drain water level. Drains were essentially disconnected from the water table in the interior of cane blocks so that the prime function of drains was to remove surface water following floods and heavy rains, not to control water table elevation (White *et al.*, 1997). By using laser levelling to improve the shedding of surface water, waterlogging could be reduced and drain depth and density decreased (White *et al.*, 1997).

The research also shed light on a major source of acidity exported from acid sulphate soils. Vast quantities of existing acid products, equivalent to about 50 t/ha of sulphuric acid, from previous oxidation of acid sulphate soils and subsequent reactions with the soil, were found stored within the subsoil above the sulphidic layer (Smith, 2000; Donner and Melville, 2002). Sugarcane evolved in such environments and appears acid-tolerant, although responses to lime additions have been noted. The highest levels of stored acidity in the flood plain follow former natural drainage lines (Smith, 2000). This is consistent with the observation that most exported acidity is sourced from a few metres around drains (White *et al.*, 1997) and is readily released during the recession phase of floods, independent of any further oxidation of sulphides (Wilson *et al.*, 1999). Some of the exported, metal-rich acidic species were found to be stored as iron monosulphide in the drain-bottom sediments (Sammut *et al.*, 1996), others were sequestered in shallow sediments in receiving water bodies (Macdonald *et al.*, 2004b). The average annual flux of acidic products from drained flood plains (as sulphuric acid) was estimated to be from 0.3 to 0.5 t/ha/year (Sammut *et al.*, 1996; Wilson *et al.*, 1999) although some oxidation products are exported in the atmosphere as sulphur dioxide (SO_2) (Macdonald *et al.*, 2004a).

The store of acidic products in the soil has accumulated from more than just the influence of constructed drainage. Some are the result of prolonged dry periods (Lin and Melville, 1993) linked to the Pacific Decadal Oscillation, and some appear to be due to a small isostatic uplift of the east coast of Australia (Kinsela and Melville, 2004).

These findings changed the focus of management from the prevention of sulphide oxidation to the retention of as much of the stored acidity as possible within the soil-drain system by manipulating the volumes of surface run-off and flood recession flow. In addition, decreasing drainage density profoundly decreases acid export.

The collaborative research led to the development by farmers of new goals for drainage management. These were to leave as much of the stored soil acidity in the flood plain as possible and to prevent the development of any additional acidity.

Changed Land Management

Because research was being carried out in a cooperative learning process long before research was published, the farmers in the catchment were able to adapt land management strategies where appropriate. Researchers were amazed by the rapid implementation by farmers of even preliminary research findings, particularly since implementation often meant the expenditure of significant farmer funds. Farmers later explained that they weighed information very carefully before acting.

An early application of the research was that farmers abandoned plans for increased drainage. Instead, they focused on control and rapid removal of surface water. Progressive laser levelling of cane fields was undertaken. This removed waterlogged areas and enabled the elimination of some field drains. In some cases, drain density decreased by a factor of two and drain depth also decreased. The decrease in drain density made more land available for cane planting and eliminated the need for new drains. Lime was added to drainage lines and to cane fields at a rate that exceeded the mean annual acid export rate.

The rapid removal of surface water resulted in better-quality water during the rising limb of the hydrograph that could be discharged safely into streams. Farmers were then able to store as much of the acidic discharge as possible during the recession phase within drains. A range of options to treat acidic drainwater before discharge was also tested by farmers. Techniques included lime dosing of drain discharge, discharge of drainwater through closed-tank lime-bed reactors and discharge into constructed wetlands to precipitate iron monosulphides. As well, farmers modified tidal floodgates to permit their opening in dry periods. This allowed both tidal exchange with drainwater and increased fish passage.

Farmers recognized that the availability of organic matter was a key to driving the oxidation reaction backward (equation 9.1). They tested green cane harvesting with the retention of surface cane trash to increase organic matter availability. This has been coupled with the use of ‘raised beds’ for cane production, which, with trash retention, has greatly increased soil fauna.

Changes in land management came at a

considerable cost to landowners and were only possible because of the relatively high per-hectare returns of sugar production. Advisers in the industry had initially opposed the general use of lime, claiming it had no agronomic value. Farmer-initiated trials, however, have found about a 10% increase in yield with lime use in some soils. As well, removal of drains has increased the area for cane planting. The net result of these changes has been up to a 30% increase in production. The episodic nature of acid discharges makes it difficult to estimate precisely changes in acidic exports. Recent results suggest that these strategies have decreased the flux during alternate-year floods by 90%.

Development of guidelines for best practice

Most of the above changes in land management in the Tweed flood plain had the support of the Tweed Shire Council. There was limited interest in other cane-growing catchments in northern NSW and it was recognized that some form of regulation was necessary to prevent further acidification of coastal flood plains. The statutory instrument chosen was Local Environment Plans (Williams, 2002) administered by local governments.

It was recognized that the introduction of LEPs would result in development controls on even the most trivial of farming activities. The solution proposed by the NSW Cane Industry was self-regulation and the industry commenced developing the NSW Sugar Industry Best Practice Guidelines for Acid Sulphate Soils. Planning NSW, the state consent authority, authorized the NSW Sugar Milling Cooperative in conjunction with local governments to be the consent authorities and provided for strict audits and reviews of performance by local government and relevant state authorities. The research work on the Tweed and Richmond provided the basis for the guidelines, which were developed by Tweed Shire Council, the NSW Sugar Industry, cane farmers, NSW Agriculture and researchers. An acid sulphate soil survey by the industry of all farms underpinned the guidelines and helped raise awareness of acid sulphate soils among cane farmers outside the Tweed.

The intended purpose of Best Practice Guidelines is to provide guidelines based on the best available information for cane farmers with acid sulphate soils in order that they:

- minimize the export of acidity from their farms,
- minimize any downstream environmental impacts caused by acid export,
- maximize production from their land, and
- adhere to the intent of Local Environment Plans on acid sulphate soils.

Unlike wise practice agreements (UNESCO, 2002a,b), the NSW Sugar Industry Best Practice Guidelines for Acid Sulphate Soils are not voluntary. The Sugar Milling Cooperative is a cane farmers'-owned cooperative that can refuse to process cane from farmers who ignore the guidelines. In essence, the guidelines are mandatory.

Institutional and Policy Developments

Parallel to the developments on the Tweed, progress was occurring simultaneously at the state level. Concern over fish kills on the Tweed and in other coastal rivers spread rapidly throughout NSW and into neighbouring Queensland. The commercial fishing industry seized on environmental problems generated by acid sulphate soil drainage, especially fish kills, as an indicator of general malaise in coastal and estuarine management in eastern Australia. As late as 2002, the Healthy Rivers Commission (2000, 2002) concluded that, because so many government agencies had responsibilities for coastal lake and estuary management, ultimately no one had an abiding responsibility. The fishing industry made effective use of the media, which both raised public awareness of the problems of acid sulphate soils and spread the conflict to other regions.

In 1993, the NSW Department of Agriculture, the lead agency in the state, sponsored the first Australian National Conference on acid sulphate soils in

Coolangatta on the NSW/Queensland border. This conference served as a venue to present what was known of the properties and distribution of acid sulphate soils in Australia and to learn of overseas experience. It did nothing, however, to abate the conflicts over the use and management of acid sulphate soils. Many in the farming industry, local government and indeed in other states were in the denial phase (see Fig. 9.5). Queensland, the neighbouring state to the north of NSW, continued officially to deny the existence of acid sulphate soils until 1995.

Acid Sulphate Soil Management Advisory Committee

Faced with escalating conflicts between two industries within his portfolio, the then NSW Minister for Agriculture and Fisheries, Mr Ian Causely, in 1994 formed the whole-of-government Acid Sulphate Soil Management Advisory Committee (ASSMAC) to provide him with advice on the use and management of acid sulphate soils. ASSMAC initially consisted of representatives of the then five government agencies with significant responsibilities in coastal and estuarine matters, together with representatives from the NSW Farmers' Association, the seafood industry and the research community. Membership later broadened to include all the significant coastal industries, including the oyster, sugarcane, dairying, tea tree and urban development industries. The predominant focus of ASSMAC, however, remained on agricultural solutions and strategies, since the predominant developments on acid sulphate soil were agricultural. At farmers' insistence, ASSMAC was chaired by NSW Agriculture, which also provided technical support. ASSMAC was supported by a technical committee to provide it with specialist advice on acid sulphate soils.

Tensions between the farming and fishing industry representatives were apparent, with one in denial mode and the other insisting on the immediate reflooding of coastal lowlands. Additional differences between state management and regulatory agencies surfaced. Some advocated the introduction of Environmental Impact Statements for farming activities. Others suggested a specific acid sulphate soil State Environment Protection Plan (SEPP), a NSW instrument loathed by landowners, and some suggested use of the prosecuting powers of the Clean Waters Act for discharge of acidic drainage. More moderate opinions recognized that the Government was ultimately responsible for the developments on acid sulphate soils within the state.

Faced with these tensions, ASSMAC developed a strategic approach to its task and identified the prevention of further disturbance of acid sulphate soils and the remediation of problem areas as its main functions. ASSMAC's approach was based on raising awareness of acid sulphate soils, on promoting education and training on their properties and use, on sponsoring appropriate research and on exploring the adequacy of existing policy and legislation. One essential task in this strategic approach was the military-like production and promotion of acid sulphate risk maps for the entire state coastal zone in 1995 (see Fig. 9.3, Naylor *et al.*, 1995). These showed that the state had 4000 km^2 of high-risk acid sulphate soils.

Other early tasks included the publication of acid sulphate soil management guidelines in 1995 (Blunden and Naylor, 1995) and the formation of acid sulphate soil local action groups, ASSLAGs, modelled on the committee set up by the Tweed Shire Council in 1990. ASSLAGs had varying successes depending on the support and enthusiasm of local governments and the involvement of researchers and facilitators on the committees. Additional educational and publicity materials and a national newsletter (ASSAY) were also produced, and the second national conference on acid sulphate soils was sponsored by ASSMAC and held in 1996.

The review of legislation revealed that there were already adequate laws in NSW to prevent increasing acidic discharge. However, it was reasoned that, without a specific instrument, continued disturbance was possible. Since local government approves most flood plain developments, it was concluded that state government–mandated LEPs, that forced local governments to develop an LEP covering the disturbance of acid sulphate soils and approved by the relevant state agency, were the preferred statutory instrument. A model LEP, based on the published acid sulphate soil risk maps for each estuary, was developed in consultation with coastal councils, government agencies and stakeholders (Williams, 2002).

ASSMAC received a boost to its meagre resources through the Acid Soil Action Programme in 1997, which provided AUS$ 2.1 million funding over 3 years. This funded the Acid Sulphate Soils Programme (ASSPRO) initiative to support research and trials of remediation strategies for problematic acid sulphate areas in the state. The Tweed region benefited significantly from the ASSPRO initiative. ASSPRO also commissioned a survey identifying acid sulphate soil 'hot spots' in estuaries, those areas likely to be contributing disproportionately to acid fluxes. This formed the basis of a 1999 Hot Spot Programme designed to remediate problem areas. Only a small fraction of the state government's promised AUS$ 13.4 million was allocated to the production of remediation plans. Major structural rearrangements in natural resource management in NSW, at the encouragement of the federal government, through the establishment of Catchment Management Authorities and the Natural Resources Commission, led to the abolition of the Acid Soil Action Programme, the demise of ASSMAC in 2004 and reallocation of Hot Spot funds. The impetus for change and acid sulphate soil management have been set back by this shift in the government natural resource management service delivery model. Most other Australian state jurisdictions that are making progress are managing acid sulphate soils as a specific issue and seeking support from regional service delivery organizations.

National strategy for managing coastal acid sulphate soils

As part of its strategic approach, ASSMAC encouraged the establishment of a similar body in Queensland, QASSMAC, which by 1995 recognized that it also had acid sulphate soils. Major urban developments have continued to occur in coastal southern Queensland over the past decade, and the focus of QASSMAC, unlike the agricultural thrust of ASSMAC, has been largely on urban development on acid sulphate soils.

ASSMAC also worked towards the development of an Australia-wide strategy on acid sulphate soils. Eventually, the Commonwealth's Standing Committee on Agricultural and Resource Management formed a national working party in 1998 to develop a national strategy for managing coastal acid sulphate soils. Both ASSMAC and QASSMAC were represented on this working party. The national strategy was accepted and released by the Agricultural and Resource Management Council of Australia and New Zealand, the Australian and New Zealand Environment and Conservation Council, and the Ministerial Council for Fisheries, Forestry and Aquaculture in 2000.

The aims of this national strategy are as follows:

1. Improve the management and use of coastal acid sulphate soils in Australia to protect and improve water quality in coastal flood plains and embayments.
2. Assist governments, industry and the community in identifying and playing their roles in managing coastal acid sulphate soils.

To achieve these overriding aims, the strategy has the following four principal objectives:

1. Identify and define coastal acid sulphate soils in Australia.
2. Avoid disturbance of coastal acid sulphate soils.
3. Mitigate impacts when acid sulphate soil disturbance is unavoidable.
4. Rehabilitate disturbed acid sulphate soil and acid drainage.

To date, the national strategy has enabled the rapid transfer of techniques and information and has catalysed policy development and the mapping of acid sulphate soils in other states and territories in Australia.

Concluding Comments

Acidic discharge from acid sulphate soils has had significant environmental impacts throughout the world. We have examined here a particular case study where fish kills in eastern Australia due to acid sulphate drainage eventually culminated in publication of the world's first national strategy on acid sulphate soil management. These fish kills led to the evolution of a participatory approach to agricultural land management in a coastal flood plain that involved farmers, local government and researchers as equal partners. As mutual trust grew, the process evolved into a cooperative learning opportunity. This participatory process generated new information on acid sulphate soils, which was almost immediately translated into a range of management options that both significantly improved cane production and decreased acid discharge, and formed the basis for the establishment of enforceable and mandatory best management guidelines for the NSW sugarcane industry.

Some of the outcomes here are dependent on the particular institutions and governance arrangements for natural resources in Australia. However, we believe that some lessons are applicable elsewhere. We have attempted to show that local government played a vital role in identifying the issues, in initiating the participation process and in providing support for the developing collaboration. Farmers belonged to an industry that was a well-structured and profitable cooperative that fosters innovation. This ensured the rapid translation of collaborative research results into practice. Researchers and students had a broad range of skills in soil science, hydrology, geomorphology, geochemistry, agriculture and environmental management. There were sources of funding to support the work and sufficient time for the partnership to develop. Regulation and policy frameworks existed that were directed at positive environmental outcomes. Lastly, the 1987 fish kills were a highly visible and widely publicized environmental impact that galvanized attention at all levels. Many of the fundamental principles of participatory resource management (Ashby, 2003) are evident in this case study, such as the importance of including stakeholders in joint enquiry, co-development of new resource management regimes and the need to combine local and scientific knowledge and expertise.

Other lessons emerging from the statewide response are that a whole-of-government and industry approach, embodied in ASSMAC, was more effective in addressing problems caused by acid sulphate soils than approaches by individual agencies. There, a strategic approach based on consensus and cooperation, rather than heavy-handed application of existing regulations, brought about quantifiable behavioural change. Focusing a whole-of-government effort on a single issue, such as acid sulphate soils, at a strategic state level and fostering action at the local level appears to have been a far more effective approach than natural resource management reforms based on broadscale integrated catchment management. Finally, the parallel development of a national strategy on acid sulphate soils has been very effective in coordinating a national focus on the problem. It has enabled the rapid and effective transfer of knowledge to states and territories in Australia where the problems of acid sulphate soils are only just being recognized.

Much has been written about integrated natural resource management and participatory processes. In the case study examined here, farmers and local government provided both the integration and the participation. Farmers integrate a broad range of soil, climate, crop, disease, economic, social, regulatory and institutional issues in running their farms. Local, democratically elected governments, responsive to their electorates, are aware of the social, environmental and economic aspects of improved coastal management. The researchers' understanding of these issues greatly expanded in the process. Mutual understanding of the different cultures under which the partners operated took at least three years to develop. Once that occurred, the dynamics of the process changed and farmers started to initiate and drive the research. An important aspect of this case study was that farmers had sufficient resources to initiate changes in land management.

Acknowledgements

This work has been supported by the Australian Research Council, ASSPRO, NSW Canegrowers, NSW Sugar Milling Cooperative, the Natural Heritage Trust, the Tweed River Management and Planning Committee, the Tweed Shire Council and Environment Australia's Coastal Acid Sulphate Soil Programme.

References

Ashby, J. (2003) Introduction: uniting science and participation in the process of innovation – research for development. In: Pound, B., Snapp, S., McDougall, C. and Braun, A. (eds) *Managing Natural Resources for Sustainable Livelihoods: Uniting Science and Participation*. Earthscan Publications, London.

Blunden, B. and Naylor, S.D. (1995) *Assessing and Managing Acid Sulphate Soils: Guidelines for Land Management in NSW Coastal Areas*. NSW EPA, Chatswood, NSW, Australia.

Bousquet, F., Barreteau, O., d'Aquino, P., Etienne, M., Boissau, S., Aubert, S., Le Page, C., Babin, D. and Castella, J.-C. (2002) Multi-agent systems and role games: collective learning processes for ecosystem management. In: Janssen, M.A. (ed.) *Complexity and Ecosystem Management: The Theory and Practice of Multi-Agent Systems*. Edward Elgar Publishers, Cheltenham, UK, pp. 248–285.

Brown, T.E., Morley, A.W., Sanderson, N.T. and Tait, R.D. (1983) Report on a large fish kill resulting from natural acid water conditions in Australia. *Journal of Fish Biology* 22, 333–350.

Buddemeier, R.W., Smith, S.V., Swaney, D.P. and Crossland, C.J. (eds) (2002) *The Role of the Coastal Ocean in the Disturbed and Undisturbed Nutrient and Carbon Cycles*. LOICZ Reports and Studies No. 24, LOICZ, Texel, The Netherlands, 83 pp.

Bush, R.T., McGrath, R. and Sullivan, L.A. (2004) Occurrence of marcasite in an organic-rich Holocene estuarine mud. *Australian Journal of Soil Research* 42, 617–621.

Callinan, R.B., Fraser, G.C. and Melville, M.D. (1993) Seasonally recurrent fish mortalities and ulcerative disease outbreaks associated with acid sulfate soils in Australian estuaries. In: Dent, D.L. and van Mensvoort, M.E.F. (eds) *Selected Papers from the Ho Chi Minh City Symposium on Acid Sulphate Soils*, March 1992. IILRI Pub. No. 53, International Institute for Land Reclamation and Improvement, Wageningen, Netherlands, pp. 403–410.

Chambers, R. (1983) *Rural Development: Putting the First Last*. Pearson Education, Harlow, UK.

Costanza, R., D'Arge, R., de Groot, R., Faber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruello, J., Raskin, R.G., Sutton, P. and Van Den Belt, M. (1997) The value of the world's ecosystem services and natural capital. *Nature* 387, 253–260.

Curtis, A. (1998) The agency/community partnership in Landcare: lessons from state-sponsored citizen resource management. *Environmental Management* 22, 656–674.

Dennison, W.C., O'Neil, J.M., Duffy, E., Oliver, P. and Shaw, G. (1997) Blooms of the cyanobacterium *Lyngbia majuscula* in coastal waters of Queensland. In: Charpy, L. and Larkum, A.W.D. (eds) *Proceedings of the International Symposium on Marine Cyanobacteria*, November 1997. Institut Oceanographique, Paris.

Dent, D.L. (1986). *Acid Sulphate Soils: A Baseline for Research and Development*. IILRI Publication No. 39, International Institute for Land Reclamation and Improvement, Wageningen, Netherlands.

Donner, E.N.S. and Melville, M.D. (2002) The effects of flood plain land use on the chemistry and hydrology of coastal acid sulfate soils. In: *5th International Acid Sulfate Soils Conference*, Tweed Heads, Australia, 26–30 August 2002. ASSMAC, Wollongbar, NSW, Australia, pp. 1–2.

Dovers, S.R. and Mobbs, C. (1999) An alluring prospect? Ecology and the requirements of adaptive management. In: Bossemann, K. and Richardson, B. (eds) *Environmental Justice and Market Place Mechanisms*. Kluwer International, London.

Easton, C. (1989) The trouble with the Tweed. *Fishing World*, March 1989, pp. 58–59.

Esman, M.J. and Uphoff, N.T. (1984) *Local Organisations: Intermediaries in Rural Development*. Cornell University Press, New York.

GESAMP (2001) *A Sea of Troubles*. GESAMP (IMO/FAO/UNESCO-IOC/WMO/IAEA/UN/UNEP Joint

Group of Experts on the Scientific Aspects of Marine Environmental Protection) Report Study GESAMP No. 70, p. 35 and No. 71, p. 162.

Harris, G.P. (1999) Comparison of the biogeochemistry of lakes and estuaries: ecosystem processes, functional groups, hysteresis effects and interaction between macro- and microbiology. *Marine and Freshwater Research* 50, 791–811.

Hart, B.T., Ottoway, E.M. and Noller, B.N. (1987) Magela Creek System, Northern Australia. I. 1982–83 wet season water quality. *Australian Journal of Marine and Freshwater Research* 38, 261–288.

Healthy Rivers Commission (2000) *Securing Healthy Coastal Rivers: a Strategic Perspective*. Healthy Rivers Commission of New South Wales, Sydney, Australia.

Healthy Rivers Commission (2002) *Independent Inquiry into Coastal Lakes*. Final Report, April 2002. Healthy Rivers Commission of New South Wales, Sydney, Australia, p. 74.

Jiggins, J. (2002) Interagency learning process. In: *OECD Workshop on an Interdisciplinary Dialogue: Agricultural Production and Integrated Ecosystem Management of Soil and Water*, Balina, Australia, 10–16 November 2002. OECD, NSW Agriculture, University of Western Sydney, Australia, pp. 86–94.

King, C.J. (1948) The first fifty years of agriculture in New South Wales. *Review of Marketing and Agricultural Economics, Sydney* 16, 362–386.

Kinsela, A.S. and Melville, M.D. (2004) Mechanisms of acid sulfate soil oxidation and leaching under sugarcane cropping. *Australian Journal of Soil Research* 42, 569–578.

Kremer, H.H. and Crossland, C.J. (2002) Coastal change and the 'Anthropocene'. Past and future directions of IGBP-LOICZ project. In: *Low-lying Coastal Areas – Hydrology and Integrated Coastal Zone Management*. International Symposium, Bremerhaven, Germany, 9–12 September 2002. Deutches IHP/OHP-Nationalkomittee, Koblenz, Germany, pp. 3–19.

Lin, C. and Melville, M.D. (1993) Control of soil acidification by fluvial sedimentation in an estuarine flood plain, eastern Australia. *Sedimentary Geology* 85, 1–13.

Macdonald, B.C.T., Denmead, O.T., White, I. and Melville, M.D. (2004a) Natural sulfur dioxide emissions from sulfuric soils. *Atmospheric Environment* 38, 1473–1480.

Macdonald, B.C.T., Smith, J., Keene, A.F., Tunks, M., Kinsela, A. and White, I. (2004b) Impact of run-off from sulfuric soils on sediment chemistry in an estuarine lake. *Science of the Total Environment* 329, 115–130.

Melville, M.D., White, I. and Willett, I.R. (1990) Problems of acid sulphate soils and water degradation in Holocene pyritic systems. In: *Proceedings of the Workshop on Applied Quarternary Studies,* Australian National University, 2–3 July 1990, Canberra, Australia, pp. 89–95.

Melville, M.D., White, I. and Lin, C. 1993. The origins of acid sulphate soils. In: *Proceedings of the National Conference on Acid Sulphate Soils.* Coolangatta, 24–25 June 1993, NSW Agriculture, Wollongbar, Australia, pp. 19–25.

Naylor, S.D., Chapman, G.A., Atkinson, G., Murphy, C.L., Tulau, M.J., Flewin, T.C., Milford, H.B. and Morand, D.T. (1995) *Guidelines for the Use of Acid Sulphate Soils Risk Maps*. NSW Soil Conservation Service, Department of Land and Water Conservation, Sydney, Australia.

Noller, B.N. and Cusbert, P.J. (1985) Mobilization of aluminium from a tropical flood plain and its role in natural fish kills: a conceptual model. In: Lekkas, T.D. (ed.) *Proceedings of the 5th Conference on Heavy Metals in the Environment*, September 1985, Athens. CEP Consultants Ltd., Edinburgh, UK, pp. 700–702.

Perez, P., Dray, A., White, I., LePage, C., and Falkland, A. (2003). AtollScape: simulating freshwater management in Pacific atolls. Spatial processes and time dependence issues. In: *Proceedings MODSIM, International Congress on Modelling and Simulation, Integrative Modelling of Biophysical, Social and Economic Systems for Resource Management Solutions* (14–17 July 2003, Townsville, Australia). Modelling and Simulation Society of Australia and New Zealand, Inc., Canberra, Australia, pp. 514–518.

Pons, L.J. (1973). Outline of the genesis, characteristics, classification and improvement of acid sulphate soils. In: Dost, H. (ed.) *Proceedings of the International Symposium on Acid Sulphate Soils,* 13–29 August 1972, Wageningen. IILRI Publication No. 18, Vol. 1, International Institute for Land Reclamation and Improvement, Wageningen, Netherlands, pp. 3–27.

Roling, N. (1988) *Extension Science: Information Systems in Agricultural Development.* Cambridge University Press, Cambridge, UK.

Sammut, J., Melville, M.D., Callinan, R.D. and Fraser, G.C. (1995) Estuarine acidification: impacts on aquatic biota of draining acid sulphate soils. *Australian Geographical Studies* 33, 89–100.

Sammut, J., White, I. and Melville, M.D. (1996) Acifidication of an estuary due to drainage from acid sulfate soils. *Marine and Freshwater Research* 4, 669–684.

Simpson, H.J. and Pedini, M. (1985) *Brackish Water Aquaculture in the Tropics: the Problem of Acid Sulphate Soils*. FAO Fish Circular No. 791. FAO, Rome.

Smith, J. (2000) An assessment of the spatial variations in actual acidity at McLeods Creek. BSc Honours thesis, School of Geography, the University of New South Wales, Sydney, Australia.

Teakle, L.J.H. and Southern, B.L. (1937) The peat soils and related soils of Western Australia, II. A soil survey of Herdsman Lake. *Journal of Agriculture Western Australia* 14, 404–424.

Thom, B.G. (2002) *Environmental History and Decision Making*. Keynote address, 5th International Acid Sulfate Soils Conference, Tweed Heads, NSW, Australia, 26–30 August 2002. ASSMAC, Wollongbar, NSW, Australia.

Thom, B.G. and Harvey, N. (2000) Triggers for late twentieth century reform of Australian coastal management. *Australian Geographical Studies* 38, 275–290.

UNESCO (2002a) Wise practices for managing conflict situations. In: *Continental Coastal Regions*. *Results of a workshop on 'Wise Practices for Coastal Conflict Prevention and Resolution'*, Maputo, Mozambique, 19–23 November 2001. Coastal region and small island papers, UNESCO, Paris.

UNESCO (2002b) Wise practises for conflict prevention and resolution in small islands. In: *Results of a Workshop on 'Furthering Coastal Stewardship in Small Islands'*, Dominica, 4–6 July 2001. Coastal region and small island papers 11, UNESCO, Paris, 70 pp.

Walker, P.H. (1972) Seasonal and stratigraphic controls in coastal flood plain soils. *Australian Journal of Soil Research* 10, 127–142.

White, I. (2002) Swelling and the hydraulic properties and management of acid sulfate soils. In: Lin, C., Melville, M.D. and Sullivan, L.A. (eds*) Acid Sulfate Soils in Australia and China.* Science Press, Beijing, China, pp. 38–62.

White, I. and Melville, M.D. (1993*) Treatment and containment of potential acid sulphate soils: formation, properties and management of potential acid sulphate soils*. Report for Roads and Traffic Authority, NSW. CSIRO Centre for Environmental Mechanics, Canberra, Australia, Technical Report T53.

White, I., Melville, M.D., Wilson, B.P., Price, C.B. and Willett, I.R. (1993) Understanding acid sulphate soils in canelands. In: *Proceedings of the National Conference on Acid Sulphate Soils,* Coolangatta, Australia, 24–25 June 1993. NSW Agriculture, Wollongbar, Australia, pp. 130–148.

White, I., Melville, M.D., Sammut, J., Wilson, B.P. and Bowman, G.M. (1996) Downstream impacts from acid sulfate soils. In: Hunter, H., Eyles, A. and Rayment, G. (eds) *Downstream Impacts of Land Use*. Department of Natural Resources, Brisbane, Australia, pp. 165–172.

White, I., Melville, M.D., Wilson, B.P. and Sammut, J. (1997). Reducing acid discharge from estuarine wetlands in eastern Australia. *Wetlands Ecology and Management* 5, 55–72.

White, I., Macdonald, B.C.T. and Melville, M.D. (2001) Modelling groundwater in soft, sulfidic, coastal sediments. In: Ghassemi, F., Whetton, P., Little, R. and Littleboy, M. (eds) *Proceedings of MODSIM, International Congress on Modelling and Simulation*, 10–13 December 2001, Australian National University, Canberra, Australia. Vol. 2, Natural Systems (Part 2), Modelling and Simulation Society of Australia and New Zealand, Inc., Canberra, Australia, pp. 567–572.

White, I., Smiles, D.E., Santomartino, S., van Oploo, P., Macdonald, B.C.T. and Waite, T.D. (2003) Dewatering and the hydraulic properties of soft sulfidic soils. *Water Resources Research* 39, 1295, doi:10.1029/2002WR001324.

Willett, I.R. and Walker, P.H. (1982) Soil morphology and distribution of iron and sulphur fractions in a coastal flood plain toposequence. *Australian Journal of Soil Research* 20, 283–294.

Williams, J. (2002) Acid sulfate soils. In: *OECD Workshop on An Interdisciplinary Dialogue: agricultural production and integrated ecosystem management of soil and water*, Balina, Australia, 10–16 November 2002, OECD, NSW Agriculture, University of New South Wales, Sydney, pp. 114–122.

Wilson, B.P., White, I. and Melville, M.D. (1999) Floodplain hydrology, acid discharge and water quality associated with a drained acid sulfate soil. *Marine and Freshwater Research* 50, 149–157.

Woodward, H.P. (1917) *Investigation into the cause of mineralisation of the 'seven-mile' swamp at Grassmere, Southwest Division*. Western Australia Department of Mines Annual Report, pp. 49–57.

WRI (World Resources Institute) (2000) *World Resources 2000–2001. People and Ecosystems: The Fraying Web of Life.* World Resources Institute, Washington, D.C., 389 pp.