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Geoscientific land management planning in salt-affected areas*

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Abstract. Over the last twenty years, farmers in Western Australia have begun to change land management practices to minimise the effects of salinity to agricultural land. A farm plan is often used as a guide to implement changes. Most plans are based on minimal data and an understanding of only surface water flow. Thus farm plans do not effectively address the processes that lead to land salinisation.

A project at Broomehill in the south-west of Western Australia applied an approach using a large suite of geospatial data that measured surface and subsurface characteristics of the regolith. In addition, other data were acquired, such as information about the climate and the agricultural history. Fundamental to the approach was the collection of airborne geophysical data over the study area. This included radiometric data reflecting soils, magnetic data reflecting bedrock geology, and SALTMAP electromagnetic data reflecting regolith thickness and conductivity. When interpreted, these datasets added paddock-scale information of geology and hydrogeology to the other datasets, in order to make on-farm and in-paddock decisions relating directly to the mechanisms driving the salinising process. The location and design of surface-water management structures such as grade banks and seepage interceptor banks was significantly influenced by the information derived from the airborne geophysical data. To evaluate the effectiveness of this planning, one whole-farm plan has been monitored by the Department of Agriculture and the farmer since 1996. The implemented plan shows a positive cost–benefit ratio, and the farm is now in the top 5% of farms in its regional productivity benchmarking group.

The main influence of the airborne geophysical data on the farm plan was on the location of earthworks and revegetation proposals. There had to be a hydrological or hydrogeological justification, based on the site-specific data, for any infrastructure proposal. This approach reduced the spatial density of proposed works compared to other farm plans not guided by site-specific hydrogeological information.

Key words: airborne geophysics, dryland salinity, farm planning.

Introduction

The assumption that a European style of agriculture would work in the Australian landscape was historically applied without any knowledge of Australian geology and geological history. The change from native vegetation to annual crops and pastures in the wheatbelt of Western Australia has resulted in widespread land degradation due to soil acidification, compaction, erosion, and, in particular, dryland salinity.

The salinisation of land and water in Western Australia has been accelerated by increased recharge of groundwater that has occurred since European settlement. This increased recharge is a result of the replacement of deep-rooted perennial native vegetation with annual crops and pastures that use less water than the native vegetation.

The development of dryland salinity is thus driven by a source of water, a source of salt in the regolith, a mechanism that brings the water and salt together and a mechanism that brings the saline groundwater to the surface.

To prevent or manage the spread of dryland salinity in Western Australia, farmers and land managers have been encouraged to reduce recharge to the groundwater. Widespread tree planting is often the populist approach such as the One Billion Trees Program (Hawke, 1989). Rather than a widespread or even piecemeal reactive approach, many farmers have developed 'farm plans' to guide future land management change. Typically, these plans have used rule-of-thumb guidelines for surface water management (Keen, 2001).

Land management occurs at the paddock scale and farmers acquire their paddock-scale information over many years of observation. They use this paddock-scale information to adapt to landscape niches that provide farming opportunities that suit local climate, soils, and water availability. For the effective management of dryland salinity, less readily observable underground information is also required at paddock scale.

Effective land management planning that deals with the subsurface mechanisms that drive salinity requires a level of information of the subsurface that is not provided by most readily acquired land information, such as regional soil maps, and the limited understanding of groundwater that comes from widely spaced groundwater bores.

In 1995, a group of farmers in the Broomehill area commissioned a study to develop farm plans based on a

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wide range of biophysical data, as proposed by Nulsen et al. (1996). Inherent in this approach is the use of geophysical data. Previous work in Western Australia had shown that airborne geophysics has great promise for revealing subsurface landscape information at a scale close to that needed for on-farm and in-paddock decisions (Street, 1992a; 1992b). Despite this promise, before the Broomehill study, no farm plans had been devised and implemented based on information derived from airborne geophysical data. Spies (2001) noted:

> '*one major issue encountered was that while the data very accurately described the landscape, they could not routinely be used to better define management options.*'

This paper describes the Broomehill process and methodology of land management planning at the paddock scale. It goes on to review the physical and economic monitoring of the fully implemented property plan on a property known as The Meadows.

Previous work

Previous attempts at integrating geophysics into land management decisions at Yornaning, Carnamah, and Kent River in Western Australia were carried out by specialists in narrow disciplines within the broad land-management sphere. Results of airborne geophysical surveys (magnetic data and QUESTEM electromagnetic data) were used for catchment planning on a study area at Boscobel in the south-west of Western Australia. The geophysical data provided a good explanation of the geological and hydrogeological reasons for the surface expression of salinity in this catchment, and provided a guide for some catchment-scale land management recommendations (World Geoscience Corporation and Read, 1992). Anderson et al. (1995) prepared a land management plan for a large property at Frankland in the south-west of Western Australia, also using QUESTEM and magnetic data. This study concluded that the geophysical data, used in conjunction with other datasets, had significantly improved the understanding of hydrogeology in this property and assisted in planning management actions to control salinity.

Method

The Broomehill SALTMAP survey area is shown in Figures 1 and 2. The Broomehill project used a multidisciplinary project team in an approach developed from mineral exploration methodology. Every week, the interpretation and planning team would meet and discuss the project and progress towards land-management recommendations. This required the farmer and planner to learn about geophysics and it required the geophysicists to learn about land management and the types of information products required to inform land management planning.

Dryland salinity was the priority issue to be addressed in the planning, so groundwater processes had to be well understood. Prior to this, property plans were based on surface information, sparse drill-hole data, and extrapolation of this information into crude regolith models.

A literature review process was implemented in order to obtain all available land information pertaining to the study area. The types of information acquired were similar to those described by Nulsen et al. (1996). This meant that at least 14 datasets would be used as an information source for property planning decision-making. With the geophysical and interpretation datasets included, there were 22 different types of datasets and information products (Table 1). These datasets were brought into a digital Geographic Information System (GIS). It was necessary to compare features of one image with those of another at the same location. This required interpretation in the form of lines, points, or polygons that could be displayed over the other images. For example, linear trends in the magnetics image were interpreted as lines. These line data could then be displayed over (for example) an aerial photograph mosaic. Features in the aerial photographs reflected basement geology in some areas, but in other areas they did not. This data comparison identified the strengths and weaknesses of any particular dataset. With this knowledge, use of a particular dataset can be constrained to its strengths. Likewise, features in any dataset can be represented in the form of lines, polygons, or points for comparison with any other dataset. Thus, there are primary datasets and derivative or interpreted datasets. Of the 22 datasets used at Broomehill, 16 were primary and six were interpreted datasets (Table 1).

The airborne geophysical surveys at Broomehill provided information on salt storage and basement depth. This resulted in a better understanding of the effect of surface management actions on groundwater conditions that was for the first time available on a site-specific basis. This information changed the approach to designing surface water-management earthworks, such as grade banks and storage dams. These types of earthworks redistribute surface water that is destined to become either runoff or groundwater. Additional knowledge of the spatial distribution of salt storage alone has a major impact on decisions about where water is collected from and where it is placed.

The basis of the property planning for salinity management at Broomehill was hydrological risk management. For salinity to occur at any particular site there are four primary risk factors, described in Table 2.

The Broomehill area has well defined relief, with slopes in the range of 5 to 3%. The valley floor has a minimum slope of 0.6%.

Table 1. List of datasets and information products used to support property planning decisions at Broomehill.
Those listed in italics are value-added or derivative information products.

No.	Dataset/information product
1	Cadastre/land tenure
2	Topography 10 m interval contours
3	Surface Geology – scanned 1:250000 scale maps
4	Drainage lines
5	Aerial photography – scanned mosaic
6	Satellite imagery – Landsat 7
7	Road and rail networks
8	Vegetation
9	Land use information
10	Climate – rainfall and evaporation data
11	*Soil maps*
12	*Waterlogging prone areas*
13	Digital elevation model from SALTMAP (50 m grid)
14	SALTMAP channel 4–5 conductance (salt storage)
15	Magnetic images
16	*Magnetic interpretation linework*
17	Regolith thickness data processed from SALTMAP
18	Basement (bedrock) topography from SALTMAP
19	*Basement geology interpretation of magnetic data*
20	Radiometric ternary image
21	*Integrated regolith interpretation map*
22	*Salinity (groundwater discharge) hazard map – this was called a hazard map at the time but it is more correct to call it a risk map*

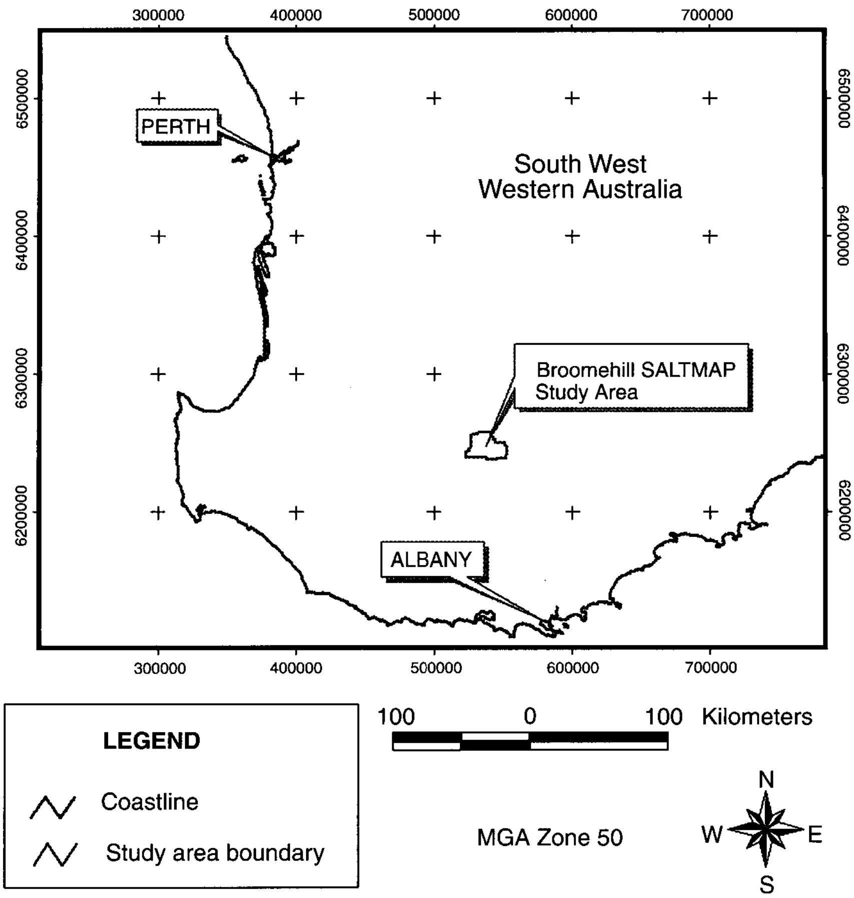

Fig. 1. Location of Broomehill SALTMAP survey area.

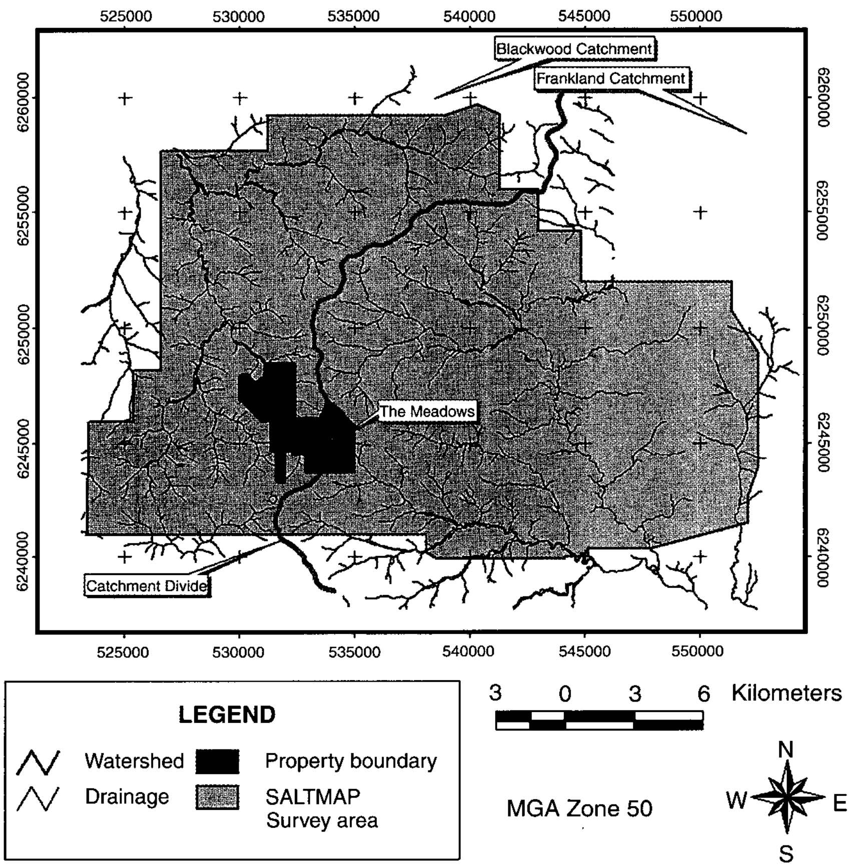

Fig. 2. Broomehill SALTMAP study area and location of The Meadows property.

Table 2. The four primary risk factors for the development of dryland salinity.

Factor no.	Risk factor description
1	A source of salt
2	A source of water
3	A mechanism that brings the salt and water together
4	A mechanism that brings the saline water to the surface

Even though most of this landscape should be classed as well drained, farmers identified winter waterlogging as a productivity limiting issue. This appeared to be due more to the duplex nature of the soils than to lack of slope. Most soils were loamy sands or sandy loams over heavy clay subsoil. This texture and permeability contrast predisposes duplex soils to waterlogging (Gardner, 1989). Groundwater recharge can occur in any part of the landscape, but the groundwater recharge process is most active in areas of soil waterlogging. In these areas, water is retained in saturated surface soils, and has maximum opportunity to percolate into deeper groundwater via preferential flow pathways (Johnston et al., 1983). Waterlogging-prone areas can be mapped quite accurately from aerial photography, if the photography is captured at the right time of year – in springtime, when differential rates of soil drying are reflected by the condition and maturity stage of crops and pastures. At Broomehill, springtime aerial photography was available. Areas that remained green in spring, relative to those that had senesced and showed more of a straw colour, were the areas prone to winter waterlogging. The aerial photography was interpreted with the assistance of farmers' local knowledge, and used to produce a transparent hatched waterlogging polygon theme in the GIS, as shown in Figure 3. The SALTMAP channel 4–5 conductance image in Figure 4 identifies the distribution of salt storage in the landscape.

By combining the channel 4–5 conductance image with the map of waterlogging-prone areas as shown in Figure 4, it was possible to identify the highest risk areas for the first three requirements for the development of salinity outlined in Table 2. The fourth requirement for the development of salinity is identified by the groundwater discharge mechanisms most commonly found in the granite/gneiss terrain of the Broomehill area, and represented in the form of hydrological models by Street et al. (2006). Any site where groundwater discharge is occurring has a surface water catchment and a groundwater catchment. These catchments often differ from each other in shape and area because impermeable basement topography often differs significantly from surface topography, as can be seen in Figure 5. The main pathway for lateral movement of groundwater in in-situ weathered regolith of the Yilgarn Block in Western Australia is within the saprock zone, which is the interface between fresh, unweathered basement rock and the overlying saprolite clay (George, 1990). The groundwater catchment is determined by basement topography at Broomehill, and this is illustrated in Figure 6. Therefore, basement topography is the principal driver of lateral groundwater movement in this geological environment. The basement topography dataset derived from the SALTMAP data thus filled a major knowledge gap in the information base for land-management planning at Broomehill. The basement topography dataset is a product of a three-layer constrained inversion of the SALTMAP data and represents the surface of the third layer (resistive basement).

The models were the basis for the interpretation of existing and potential saline discharge sites (salt hazards) in the area. The data were interpreted to identify the locations at which the hydrological conditions defined by the models occurred. For example, dolerite dykes are known to present barriers to groundwater movement (Engel et al., 1987). The first pass of this interpretation was manual interpretation using a series of map overlays on a light table.

Salt hazard sites were ranked based on the size and bulk conductivity of the groundwater catchment feeding each site (Street et al., 2006). This produced 18 salt hazard sites on this property. These can be seen in Figure 6. In 1996, three of these sites did not display evidence of groundwater discharge or salinity. There were four existing saline sites on the property that were not identified by the manual interpretation method. At these locations, salinity extended more than 50 m upstream of an identified salt hazard site, and a groundwater discharge mechanism was not identified in the data to explain the full upstream extent of the discharge that was identified by interpretation of satellite imagery. The process of identifying dyke intersections with streamlines and valley floors was later automated in GIS by (Anderson-Mayes, 1997).

Knowledge of basement topography enabled decisions to be made about the diversion of surface and shallow-seepage water to take account of both the surface and the groundwater catchments to the salt hazard sites. It was then possible to design surface water management earthworks that would prevent or substantially reduce waterlogging over high salt storage zones within the groundwater catchments of these sites. This information also enabled the planning of earthworks to be cost-effective. Areas that did not need treatment did not receive treatment. Earthworks infrastructure is expensive both in terms of construction cost and the productive land sacrificed (3.8% of total area of The Meadows property). These earthworks consisted of grade banks and seepage interceptor banks. Grade banks are earth embankments built with a road grader to a maximum height of 0.5 m and intended to collect and divert surface runoff. They are constructed to have a fall of 0.5 m in 100 m which is a gradient of 0.5%. Seepage interceptor banks are cut deeper into the clay subsoil than grade banks, and are designed to intercept shallow seepage water from the interface between the permeable surface soil layers and the less permeable subsoil (saprolite clay). Without the geophysical information, it would have been necessary to design the earthworks in a blanket approach, according to conventional rule-of-thumb guidelines (Keen, 2001). For example, if a slope is x% and soil type is y, then earth banks must be no less than z metres apart. Earthworks designed by rule-of-thumb without geophysical information can, in some instances, aggravate salinity (e.g. Abbott, 2003; Spies and Woodgate, 2005).

Prior to the Broomehill SALTMAP project, a reliable basement topography dataset had not been used in property planning. Basement topography was used in producing a property plan for The Meadows at Broomehill. The mechanisms and pathways of groundwater movement were interpreted and used in decision-making at the paddock scale in this property plan. However, management of mechanisms driving salinity were not the only design criteria. Other design criteria that applied to this planning process include:

- Fencing to soil type,
- Fencing to allow efficient livestock and machinery movement,
- Surface water management to provide all-weather access around the farm,
- Surface water management to control storm water erosion,
- Surface water management to control waterlogging,
- Surface water management to harvest fresh water,

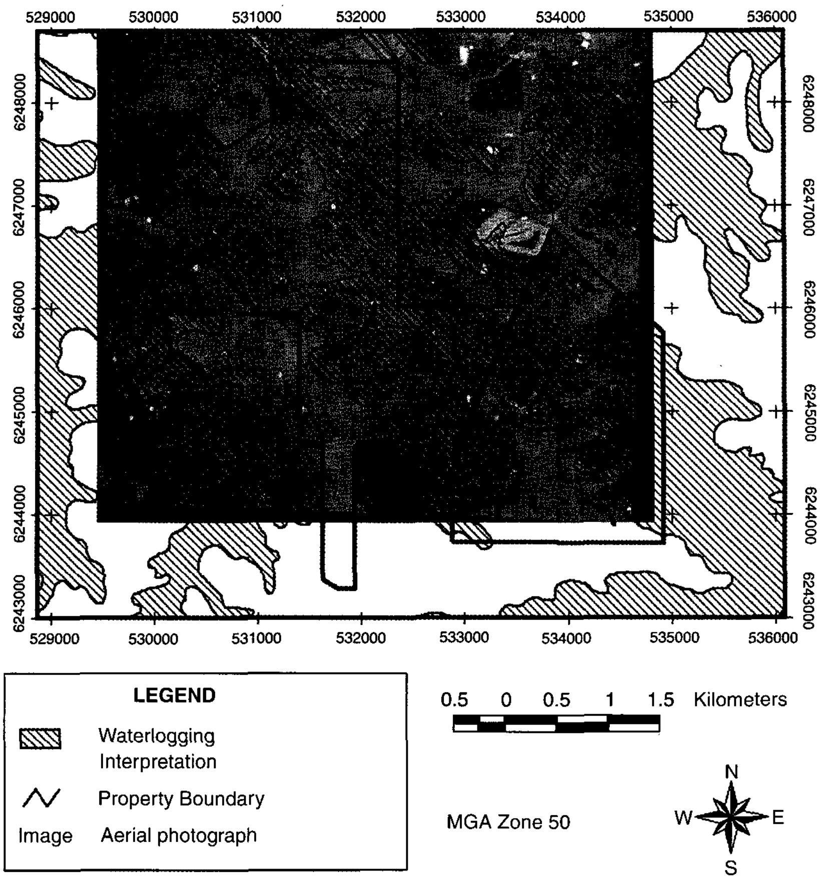

Fig. 3. Aerial photograph interpretation of waterlogging on The Meadows property.

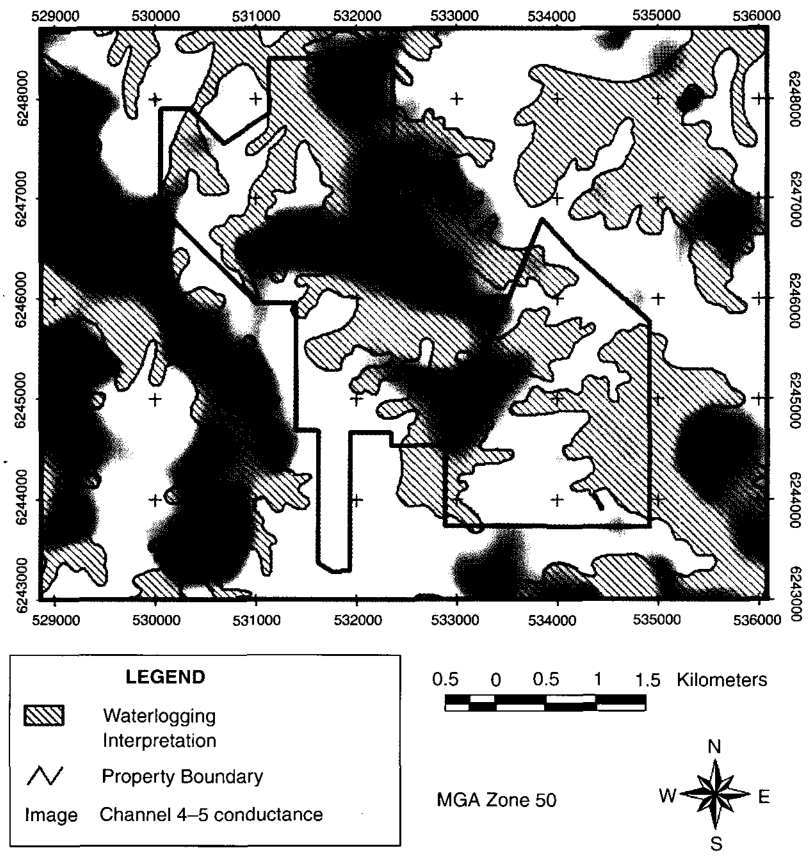

Fig. 4. Water logging prone areas overlaid on SALTMAP channel 4–5 conductance image. High conductance is red/orange, low conductance is blue.

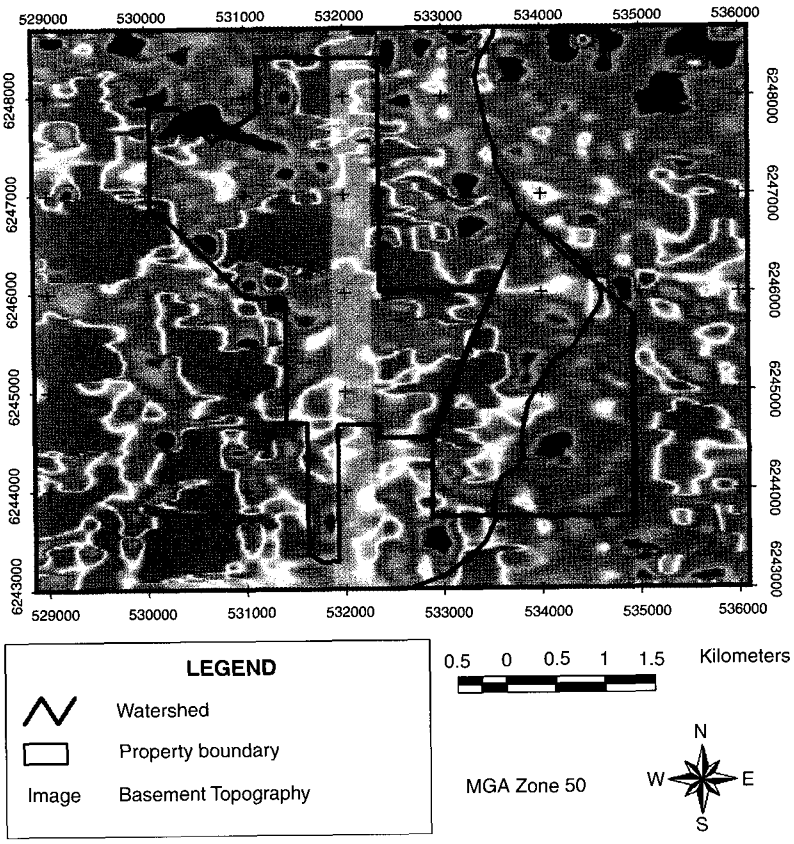

Fig. 5. SALTMAP basement topography image. Note that the basement topographical high (red) is west of the surface topographical high represented by the drainage divide.

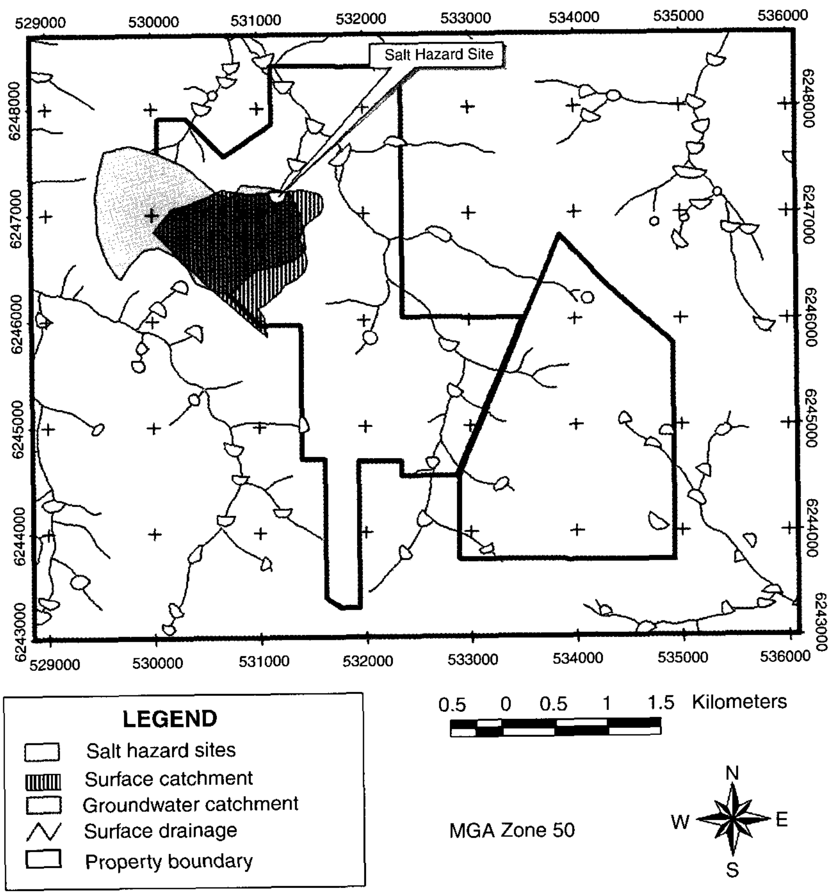

Fig. 6. Salt hazard sites on and surrounding The Meadows property. Note the difference between groundwater and surface water catchments to the marked salt hazard site.

- Surface water management to concentrate waterlogging control over high salt storage areas,
- Revegetation to protect soils from wind erosion,
- Revegetation to dry out subsoil over and upslope of high salt storage areas,
- Revegetation to moderate paddock microclimate,
- Ensuring there is a livestock water supply in every paddock.

Farm planning is a process guided by multiple design criteria of which, in this case, salinity management had a high priority. Another criterion is the need to fence the property according to soil type but there are compromises. For example, it is beneficial to try to locate earthworks close to soil type boundaries, so that fencing follows the earthworks and serves a dual purpose of protecting associated tree belts. This criterion is often compromised by the location of high salt storage and waterlogging areas, because they are addressed as a higher priority. Earthworks must deliver water to predetermined points, such as storage dams, thus requiring further compromise. This means that in the 'low conductance' parts of the property, where salinity management had a lower priority, the other criteria, listed in dot points above, often required infrastructure proposals.

Results

Ten years after the Broomehill SALTMAP project five key results can be noted. They are:

1. The plan for The Meadows, including fencing, earthworks, roadworks, revegetation and construction of new water storages was fully implemented, driven by the landholder's conviction that the proposals in the plan were based on the most comprehensive set of supporting data available at that time. This is significant because less than 5% of the hundreds of property plans prepared in Western Australia were implemented. This was reported by Robinson et al. (1996).
2. The property became water efficient. Prior to implementing the plan, the landholder frequently had to cart water for stock during summer. He has not carted water since, even in the face of declining average rainfall, because runoff and shallow seepage water that was previously causing degradation or going to waste is now directed into storage dams.
3. The plan was a catalyst for changing the way the farm was managed. It is now ranked in the top 5% of properties in the regional farm productivity benchmarking group.
4. Implementation of the plan was followed up by independent economic assessment and physical monitoring. The economic analysis by Chamarette and Robinson (1999) examined the cost benefit of the implementation of the plan. The physical monitoring continues in the form of monitoring of piezometers by the Department of Agriculture.
5. The implemented farm plan was economically more profitable in terms of its internal rate of return on investment than property plans in the same region utilising similar biophysical strategies but different land information base (Chamarette and Robinson, 1999).

Visual examination of the property plan for The Meadows (Figure 7) reveals no obvious difference to any other property plan using similar strategies. To discover if there was a significant difference in the average spatial distribution of works due to the use of the SALTMAP data, the property was coarsely classified into 'high conductance' and 'low conductance' areas as shown in Figure 8. It was then possible to measure the amount of farm plan infrastructure (hectares of revegetation and kilometres of earthworks) in the 'high conductance' and the 'low conductance' areas respectively. The farm plan infrastructure is shown overlaid on the conductance classification in Figure 9.

As can be seen in Table 3, the distribution of farm plan infrastructure is quite even between both classes. When measured on a per hectare basis there is no difference between the 'high conductance' and 'low conductance' areas in the average spatial density of earthworks, but the high conductance areas are still favoured for revegetation.

The Department of Agriculture Western Australia undertook a comparison of this property plan with two other property plans that used similar biophysical strategies in the same region (Chamarette and Robinson, 1999). The implemented plans were compared on the basis of Benefit Cost Analysis (BCA). This took into account implementation costs, estimates of the productivity benefit resulting from implementation of the farm plan, the likely decline in arable area, and the gross margin if no farm plan was implemented. The Benefit Cost Ratio (BCR) was calculated for each property. If the BCR< 1, the costs exceed the benefits. If the BCR >1, the benefits exceed the costs. The most profitable farm plan was that of The Meadows, as shown in Table 4.

Table 3. Farm plan infrastructure per hectare by SALTMAP conductance class.

	Revegetation (ha/ha)	Earthworks (km/ha)
High conductance	0.065	0.021
Low conductance	0.054	0.021

Table 4. Benefit cost ratios of the three properties examined by Chamarette and Robinson (1999).

	The Meadows	Property A	Property B
BCR	1.41	0.89	0.08

This was because the cost per hectare of implementation was the lowest of the three properties. In the absence of site-specific regolith information to support planning on properties A and B, the 'better be safe than sorry' principle led to the use of deep excavated grade banks costing twice as much per kilometre as those on The Meadows. The property plan for The Meadows had the lowest implementation cost per hectare because the use of information from geophysical data facilitated a strategic approach to the location, quantity, and specifications of proposed works. There had to be a hydrological or hyrogeological justification, based on the site-specific data, for any infrastructure proposal.

If the earthworks costs for The Meadows are doubled, its BCR comes to 1.0, which is break-even. Thus, we can attribute to the use of the geophysical data the difference between a negative cost benefit and breaking even. In gross margin terms this equates to approximately $3 per hectare per year on-going benefit for a one-off additional cost of $3.25 per hectare for acquisition and interpretation.

Discussion

The objective of the Broomehill SALTMAP project – at the request of the principal clients and stakeholders – was to produce 'better' farm plans. The term 'better' refers to how well the farm plans address the salinity risk. Reviews of the project focussed on the technology in their criticisms and did not review the farm planning outcomes. They focussed on how well the SALTMAP data matched data models from other sources such

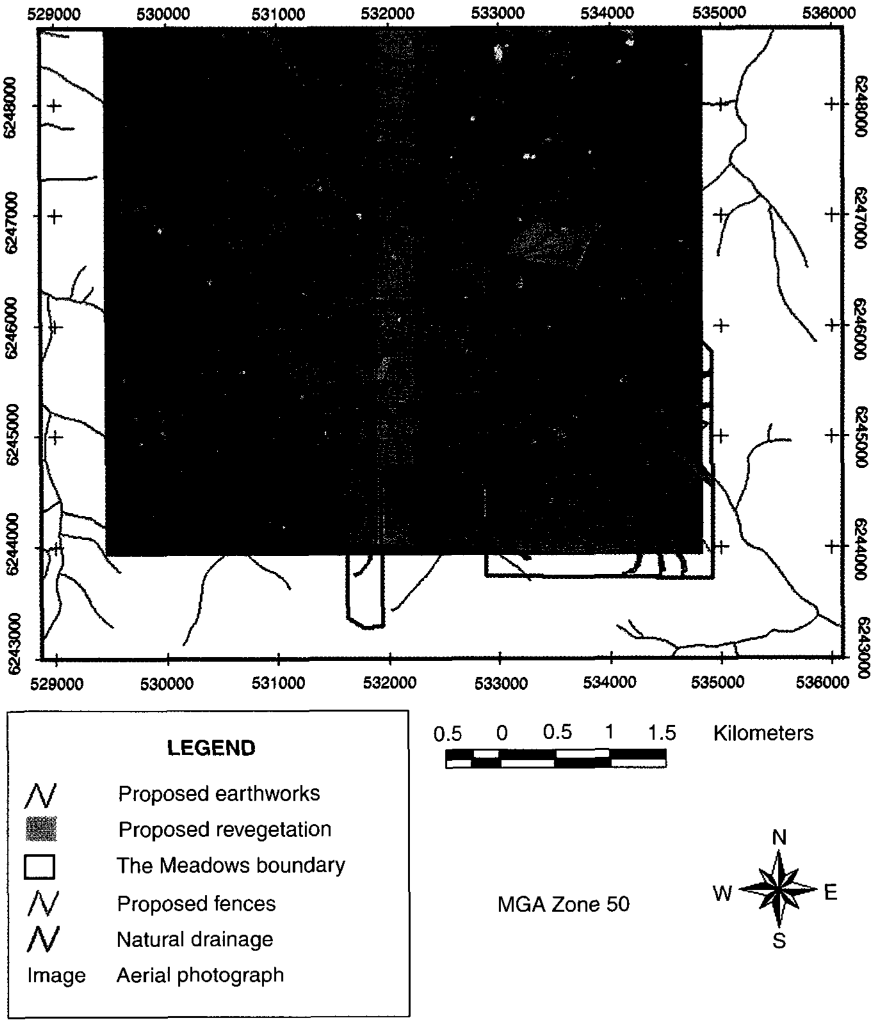

Fig. 7. Plan showing proposed works on The Meadows property.

as boreholes. It did not match very well at all. It provided a different kind of information that addressed the primary weakness of borehole data – its spatial distribution. It was agricultural economists Chamarette and Robinson (1999) who eventually reviewed the farm planning, who made no reference to airborne geophysics, and possibly had no knowledge of its use in the farm planning process.

The usefulness of airborne geophysical data at Broomehill was questioned by Leonhard (1999), because although there was a good correlation across the study area between salt storage, bedrock depth, and groundwater conductivity against Broomehill SALTMAP channel 4–5 conductance, there was a variance about the mean of 40% when comparing individual borehole measurements against individual Broomehill SALTMAP data points. This is because the SALTMAP data is an averaged measurement of a 'footprint', sampling area in the order of a hectare of land, whereas the borehole is sampling a very small (1 m^2) area in a highly variable landscape. Nevertheless, Leonhard (1999) concluded, *'However Broomehill SALTMAP survey channel 4–5 conductance displays a positive and close association to bedrock depth, groundwater salinity and salt storage.'* This was precisely the information required to manage salinity risk. There is more information provided by the spatial pattern revealed in the data than there is in the actual number measured at any particular point.

In his report on the use of geophysical data at Broomehill, O'Brien (1998) notes that the salt hazard sites were identified at least as effectively by experts during field inspection using the 'Bunbury rules' (George and Smith, 1998). These were a set of rules designed to quantify hydrological knowledge of the causes of dryland salinity, devised at a workshop in Bunbury, Western Australia, in 1994. How these sites are identified is not as important as whether or not they are identified. The automated interpretation of salt hazard sites is cost-effective compared to detailed on-ground assessment by experts. It is a means of applying expert knowledge over a large area without requiring the expert man-hours. The important point is that these sites need to be identified because they determine the groundwater and surface water catchments that are the foci for management actions.

The Department of Agriculture produced a technical report that examined the effectiveness of farm planning at the Byenup Hill catchment using a groundwater model (Raper and Guppy, 2003). The Byenup Hill catchment is situated in the western part of the Broomehill SALTMAP study area (Figure 2). This study used a smoothed and generalised regolith model based on soil/landform units. Raper and Guppy concluded that modelling the implementation of farm plans resulted in a reduction of only 1% in the area of land at risk from salinity by 2012. They also noted that the impacts of farm plan implementation would be localised and at a spatial scale that would not be well represented by the model. This indicates a mismatch between the functional scale of the model and the scale of the impacts it was attempting to assess.

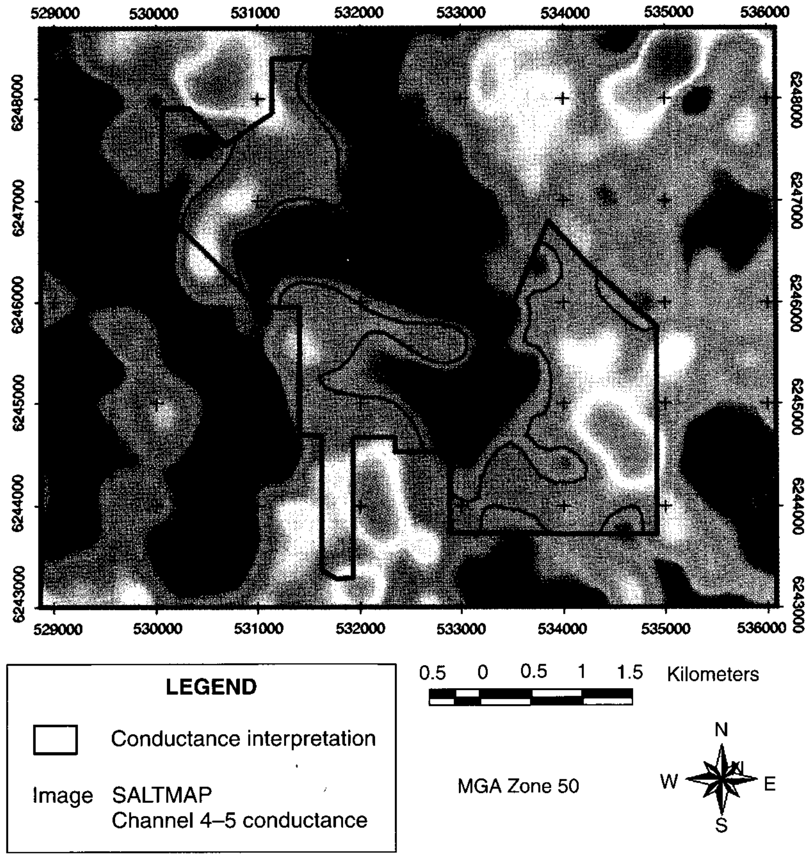

Fig. 8. Manual classification of conductance image into high conductance and low conductance classes.

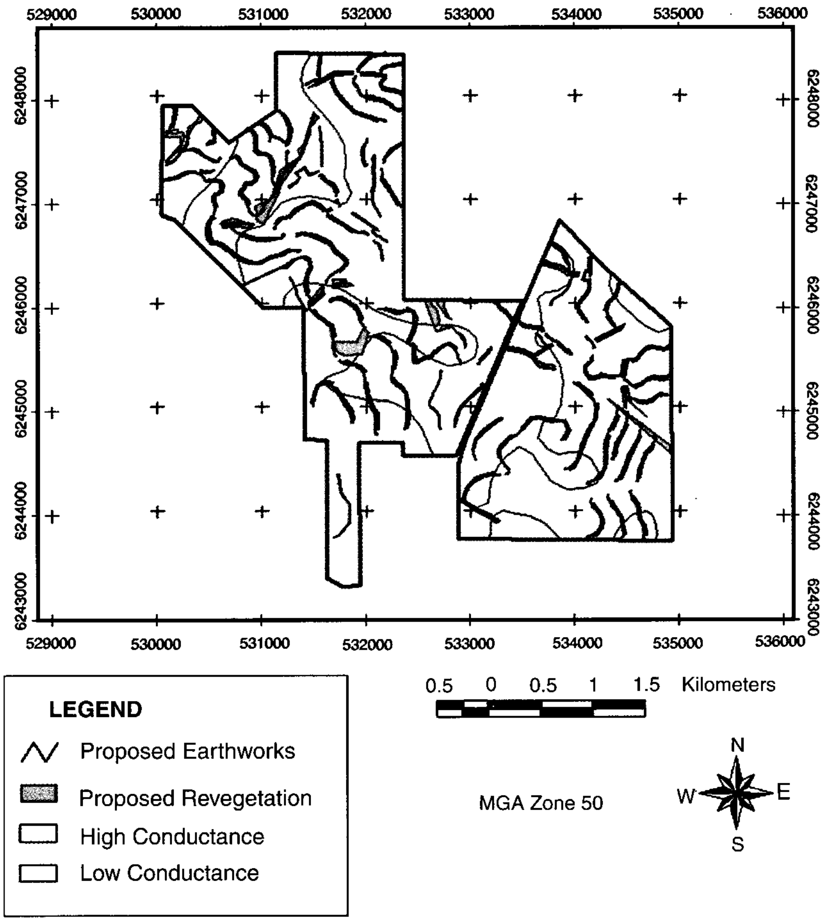

Fig. 9. Farm plan infrastructure allocated to either high conductance or low conductance class.

The Broomehill study has accomplished in real life what modelling attempts to achieve numerically, but instead of generalisations and assumptions, measured paddock-scale regolith parameters derived from airborne geophysical data were used to plan land management actions. These land management measures have been fully implemented, and actual results have been measured at the same paddock scale, by the farmer and independently assessed by the Department of Agriculture.

The main influence of the SALTMAP data on the property plan was on the quantity and location of earthworks and revegetation proposals. There had to be a hydrological or hyrogeological justification, based on the site-specific data, for any infrastructure proposal. Once the salinity risk had been addressed, for example, by a proposed grade bank, the water harvesting requirement was often satisfied as well. Where there was no requirement for earthworks for salinity management, water harvesting, or erosion control, no earthworks were proposed. This approach reduced the spatial density of proposed works compared to other property plans not guided by site-specific hydrogeological information.

George and Smith (1998) recorded the results of a field workshop where expert participants examined salt hazard sites in the field and assessed their own use of airborne geophysical data in devising management proposals to address salinity risk at those sites. They concluded that AEM data was used in only 55% of the sites, and that its use improved management. A piecemeal focus on individual salt hazard sites would not allow any leveraged benefit from integrated planning where items of infrastructure address salinity risk for more than one salt hazard site. Measurement of the costs and benefits of a fully integrated farm plan that has been implemented on The Meadows by Chamarette and Robinson (1999) shows a 37% greater benefit-cost ratio than the nearest comparable property (property A) (Table 4).

The Meadows farm plan cost $96 per hectare (including the cost of acquisition and interpretation of airborne geophysical data) to design and implement. The SALTMAP airborne geophysical data cost $3.25 per hectare to acquire and interpret. This is the average cost over the whole study area and it is unlikely to be cost-effective to acquire airborne geophysical data over a single property or small number of properties. $3.25 per hectare is 3.4% of the cost of design and implementation. This extra 3.4% cost returned a 37% additional benefit relative to a comparable farm plan not using geophysical data. If we accept George and Smith's 15% benefit this is still a significant improvement for a 3.4% additional cost.

A subsequent drilling program at Broomehill cost $4.38 per hectare. This is based on 35 boreholes in 40 000 ha costing $175 000 (Leonhard, 1996). This drilling project did not yield information suitable for farm planning. To understand the strengths and weaknesses of these information sources, the minimum grid distance necessary to reproduce the same salt storage distribution information represented in the classification in Figure 9 using (for example) boreholes, was assessed. The smallest spatially significant class variations occurred over a distance of ~150 m. A smaller grid spacing than this would be needed to map it accurately, but if 150 m is accepted as the conservative minimum resolution or maximum grid spacing, then it would require 530 boreholes to basement on this property to provide equivalent information on the spatial distribution of salt storage. To achieve this on The Meadows would require a drilling project costing $2 204 per hectare (based on drilling costs above). This is an unfair criticism – requiring that drilling provide the same type of data as airborne geophysics, just as reviewers of the Broomehill project criticised airborne geophysics for not providing the same type of data as drilling. This is a fruitless argument. The information technologies and their datasets are complementary, and neither can be used to its full potential without the other.

Conclusions

The strategies employed in The Meadows property plan were not new, nor did they require massive revegetation and changes in farm enterprises. The infrastructure proposed in the plan was, however, site-specifically targeted. In designing the plan there had to be a hydrological or hyrogeological justification, based on the site-specific data, for any infrastructure proposal. Property planning using airborne geophysics at Broomehill was an education process for the landholder, the planner, and the geophysicists. Everyone involved felt the discomfort of setting aside familiar ways of doing things. This is why previous attempts at using airborne geophysical information for land management planning had failed. The geophysical images were handed over to people who had specialist expertise in some aspect of land management and they were asked to use them to design management options. In the absence of an interactive learning process, the experts retreated to their familiar areas of expertise and the geophysical information was not used. Due to the rigour of this methodology in designing the property plan for The Meadows, independent economic analysis of the implemented plan has demonstrated that the landholder has obtained an acceptable biophysical and economic return on an profitable level of investment.

The analysis of the spatial distribution of property plan infrastructure showed that, contrary to what might be expected, there was no significant difference in average distribution between high conductance and low conductance areas. This is a consequence of the multiple design criteria that apply to the property planning process. If an element of infrastructure is not required for the first priority it is often required for the next but not necessarily in the same place.

In a short article on the history of airborne electromagnetics in Australia, Spies (2001) noted:

> *'one major issue encountered was that while the data very accurately described the landscape, they could not routinely be used to better define management options.'*

This was true in a large part due to the disconnection between scientists and land managers. In his overview of the Broomehill SALTMAP project, O'Brien (1998) made this comment:

> *'A major strategic and technical challenge which appears largely in default is filtering of land elements through layers of different methodology to yield reliable and cost effective land management outcomes.'*

The interactive learning that took place in the multidisciplinary team at Broomehill overcame that technical challenge. The property plan for The Meadows is a demonstration that the strategic and technical challenge referred to by O'Brien was met and reliable and cost effective outcomes were achieved.

The Broomehill project demonstrates that the application of airborne geophysical information to land management is not a technical issue but a people issue. It has shown a positive cost benefit at the paddock and farm scales. The technology for interpreting and producing information products from airborne geophysical data has developed greatly since the Broomehill project. The benefits of disciplined, interactive interpretation of an integrated land information base facilitated by GIS technology have been demonstrated in the Broomehill project. The people issue is one of training and teamwork and extends to demonstration of due diligence in acquiring and using appropriate land information to guide management recommendations.

The reason that little reliable and cost effective land management resulted from airborne geophysical data in the past is there was not the methodology to overcome the gaps in understanding between disciplines involved in land management. The methodology employed at Broomehill is a model for land management planning projects utilising airborne geophysics that can demonstrate due diligence and produce reliable and cost effective land management outcomes.

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塩害地域における地球科学的土地管理

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要 旨： 過去20年にわたって西オーストラリアの農家は，農地への塩害を最小限にとどめるために，土地管理方法変更してきた。変更を実行するための指針として，農場経営計画がしばしば用いられる。たいていの農場経営計画は，地表水流のみの最低限のデータと理解に基づいている。しかし，そうした農場経営計画は，土地の塩害のプロセスに対して，効率よく対処できない。

西オーストラリアの南西部，ブルームヒル（Broomhill）のプロジェクトでは，地表および地下の風化層の特徴を測定した多くの空間データを使う方法が採用された。さらに，気候や農耕の歴史などのデータも取得された。この方法の根幹は，調査対象地域における空中物理探査データの収集である。このデータには(1) 土壌を反映する放射線データ，(2) 基盤地質を反映する磁気データ，および(3) 風化層の厚さと電気伝導度を反映する"SALTMAP"による電磁データが含まれる。

データ解釈にあたっては，塩害プロセス進行のメカニズムに直接対応する計画を農場全体（広域）と各牧場区画単位（比較的狭域）の両方で決定するために，エアボーンによる地質および水文地質学的情報が牧場区画単位スケールで他のデータセットに加えられた。築堤や漏水防止堤のような地表水の管理構造物の位置と設計には，空中物理探査データから導かれる情報が用いられることが多い。この計画の有効性を評価するために，一つの農場全体の計画が 1996 年以来，農業省によってモニターされている。この計画の実行に当たっての費用対利益比は正であり，その農場は現在，その地域の生産性基準（ベンチマーク）グループの上位 5%に入る高利益比をあげている。農場経営計画策定に当たって，空中物理探査データが最も利用されるのは，土木工事と植生再生計画の場所選定である。

現地で取得されたデータに基づいた水文学と水文地質学的に正しい解釈は、あらゆる社会基盤の整備計画において必要である。このアプローチによって，その土地固有の水文地質学の情報を使わない他の農場計画に比べて，地域内で計画される作業の量の軽減が可能である。

キーワード：エアボーン物理探査，農場管理計画，乾燥地塩分濃度

염기화된 지역에서의 지구과학적 토지 관리 계획

Simon Abbott[1], David Chadwick[2], Greg Street[3]

요 약: 지난 20 년 동안, 서부 오스트레일리아 농부들은 염분이 농토에 미치는 영향을 최소화하기 위해 토지 경영방법들에 변화를 주기 시작했다. 농지 계획은 자주 농기구 변화의 지침서로 활용되어 왔으나, 이제까지의 대부분의 계획들은 지표수의 흐름과 최소한의 자료에 기초하여 세워져 왔다. 따라서 농지 계획은 토지의 염기화를 야기하는 과정을 효과적으로 설명해 주지 못하였다.

서부 오스트레일리아 남서쪽에 위치하는 Broomhill 에서 수행된 연구과제에서는 표토층의 지표와 지표하부의 특성을 측정하여 얻은 일련의 대규모 지질학적 자료를 이용하는 접근방법을 시도 하였다. 또한 기후나 농업의 역사 등과 같은 다른 자료들도 연구 되었다. 이 접근법의 근간은 전 연구지역에 대한 항공지구물리 자료의 획득에 있다. 이 방법은 토양의 특성을 반영하는 방사선탐사자료, 기반암의 지질을 반영하는 자력탐사자료, 그리고 표토의 두께와 전기전도도를 반영하는 SALTMAP 전자기탐사자료를 포함한다. 해석 단계에 있어서, 이러한 자료들에는 지질학과 수리지질학적인 목장규모 (paddock-scale)의 정보가 추가되게 되는데 이는 염기화 과정을 유도하는 메커니즘과 직접적인 연관이 있는 농장이나 목장에서의 결정을 내리기 위함이다. 항공지구물리 탐사자료로부터 얻어진 정보들은 농수로나 누수차단댐 등과 같은 지표수 관리를 위한 구조물들의 설계 및 위치 선정에 중요한 영향을 주었다. 이러한 계획의 효과를 평가하기 위하여 1996 년부터 농업농민부는 한 농장 전체에서 수행된 계획을 모니터링 해왔다. 실행된 계획은 긍정적인 비용-이익비를 보여 주었으며, 이 농장은 현재 지역생산 벤치마킹 단체 중 상위 5%내에 드는 성과를 보였다.

항공지구물리 자료는 토목공사의 위치 선정이나 다시 식물은 재배하기 위한 제안서 작성에 중요한 영향을 미친다. 현장특성에 맞는 수리학적 또는 수리지질학적 검토는 사회간접자본 건설을 위한 어떠한 계획안을 세우더라도 필수 불가결한 요소이다. 이 연구에서 제안한 접근법은 현장 특성에 기초한 수리지질학적 정보에 기인하지 않은 농지 계획법들에 비해 제안된 작업들의 공간적인 밀도를 줄일 수 있는 방법이라 하겠다.

주요어 : 항공지구물리학, 농지 계획, 건조지역 염도

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