Harnessing Spatial Analysis with GIS to Improve Interpretation of Airborne Geophysical Data

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1. Abstract

Modern airborne geophysical surveys are collecting large quantities of high quality data for applications ranging from mineral exploration to environmental problem solving. As a result, there is a growing need for new interpretation methodologies to maximise the amount of information which can be extracted from survey data. This is especially true in the relatively new environmental application areas where interpretation methodologies are not yet well established.

This paper reports on a research project in which spatial analysis with GIS has been adopted as an approach to improve the interpretation of airborne geophysical data for salinity studies. The paper discusses the general and particular interpretation problems for this application; proposes a new methodology for interpretation based on spatial analysis with GIS to address these problems; and concludes with the implications of this work for interpretation of airborne geophysical data for other applications.

Geophysics has long been a field which has made use of leading edge computer-based technology to acquire and process data. However, many areas of the analysis and interpretation of the data are still relying largely on visual interpretation. The advances being in made in computational geography, especially in terms of developing spatial analysis tools on a GIS platform, have the potential to make a significant impact on the interpretation of geophysical data.

2. Introduction

Airborne geophysical data has traditionally been collected for mineral and petroleum exploration studies, but in recent years environmental applications have emerged as an important new application area for this technology. These new applications have in turn driven development of ever more sophisticated data acquisition technology. This has been greatly facilitated by the rapid improvement in computer technology over recent decades.

Geophysical data acquisition and data processing have long been fields which have made use of leading edge computer-based technology, however much of the interpretation of the data still relies largely on visual interpretation skills, albeit with the aid of sophisticated digital image processing. In at least one of the new environmental application areas, that of salinity studies, the interpretation is proving difficult to complete using the traditional approach. The aim of the interpretation is to build a picture of the hydrogeological mechanisms contributing to salt degradation at both catchment and paddock scales, and consequently to develop land management plans which address both existing and possible future salt hazard sites. However, the sheer quantity of data to be examined and interpreted presents a significant challenge. A new approach to interpretation is required to meet this challenge and enable effective and efficient extraction of information from the large multivariate geophysical surveys which are typically collected for these studies.

This paper reports on a research project in which spatial analysis with GIS has been adopted as an approach to improve the interpretation of airborne geophysical data for salinity studies. The background to using geophysics for salinity studies will be introduced, and then the interpretation problems which have arisen with multivariate airborne geophysical data sets will be discussed. In order to address these problems, a new interpretation methodology based on spatial analysis with GIS will be proposed. Finally, the implications of this work for interpretation of airborne geophysical data for other applications will be discussed.

3. Salinity and Geophysics

In recent years, salt degradation of Australia's land and water resources has been widely recognised as a significant environmental problem, although the causes of human-induced (secondary) salinisation can be traced back to widespread clearing of native vegetation post European settlement. Wood (1924) was one of the first researchers to report observations of a link between clearing of native vegetation and land and stream salinisation in the formal scientific literature. Wood (1924) stated that over the 30 year period prior to publication of his paper he had observed several instances of land and stream salinisation developing after adjacent tracts of land had been cleared.

Since those early observations, a vast body of research has given us a much better understanding of the causes of salinisation. Secondary salinisation can be classified into two general types depending on the absence or presence of a groundwater system (Williamson, 1990). The former type occurs where over-grazing causes erosion and the saline or sodic subsoils are exposed. The latter type can occur under both irrigated and non-irrigated farming regimes, but in both cases groundwater is a key element for the development and maintenance of salinity. Changes to the hydrologic equilibrium cause increased recharge to the groundwater system and this in turn leads to a rising watertable which remobilises salts stored in the sub-surface. The saline groundwater is discharged via seeps and streams, or evaporation occurs in the areas where the watertable is very shallow (within 2m of the surface). The result is an increased concentration of salt in either streams or soils, causing degradation of water resources and productive agricultural land.

It is this groundwater driven salinisation which is of interest to this project. In recent decades, a number of researchers have demonstrated the effectiveness of ground geophysics in investigations of this type of salinity. For example, Engel *et al.* (1987b) used geophysics to define recharge and discharge areas associated with dryland salinity in the south-west of Western Australia.

In the late 1980s a group of researchers recognised that the scale of the salinity problem in Australia (and worldwide) could not be effectively addressed by high cost, low areal coverage, ground based studies (Street and Roberts, 1994). Airborne geophysical surveys, whilst sacrificing some of the detail of ground based surveys, could provide regional coverage for comparatively low cost and highlight those areas that required more detailed follow-up on the ground.

The work of Engel *et al.* (1987a, 1987b), Street and Engel (1990) and others, demonstrated that magnetic and electromagnetic measurements provided valuable information about constrictions to groundwater movement and salt storage respectively. Airborne geophysics of this type has traditionally been applied to mineral exploration. Whilst the airborne magnetic technology was immediately applicable to salinity investigations, the same was not true of airborne electromagnetic measurements. The airborne electromagnetic systems in use in Australia in the late 1980s had been designed to probe deep into the earth in search of mineralisation targets such as conductive sulphides. In particular, they had been designed to mask near surface conductivity variations - the very information which is most important in salinity studies.

A collaborative research project (World Geoscience Corporation, CSIRO Division of Exploration Geoscience, CSIRO Division of Water Resources) was established to address this problem. The purpose of the project was to develop a new airborne electromagnetic system, SALTMAP, designed specifically to make high resolution measurements of the electrical conductivity distribution within the regolith.The principal objective was to assist land care specialists to manage planning and implementation of rehabilitation and protection programs in salt-affected areas, by providing cost-effective and accurate information about salt storage and salt hazards at the catchment scale (Street and Roberts, 1994). Development of the SALTMAP system is now complete and further details can be found in Duncan *et al.* (1992) and Roberts *et al.* (1992).

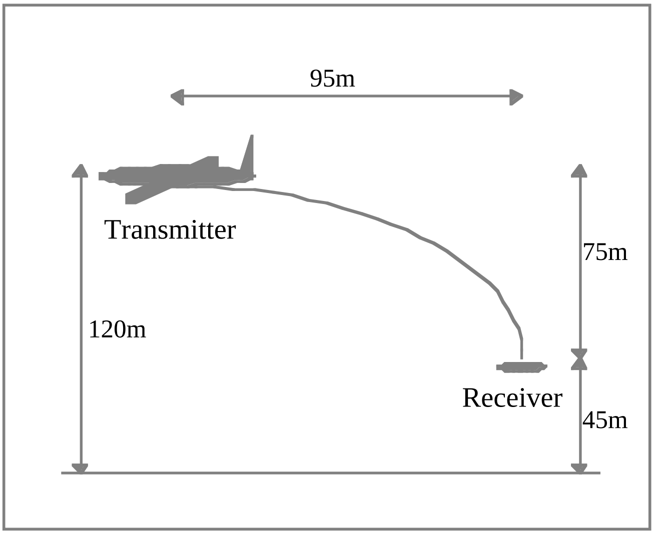

Figure 1: SALTMAP System Geometry (adapted from Roberts et al. (1992)).

3.1 A Typical Airborne Geophysical Survey for Salinity

A typical geophysical survey for salinity will include measurement of three geophysical data sets; electromagnetics, magnetics and radiometrics. The data is collected along parallel survey lines, typically spaced 100 or 200 metres apart with measurements recorded along the line every 10 to 15 metres. Depending on the system being flown, nominal flying altitude is between 60 and 120 metres and survey lines are oriented roughly perpendicular to the strike of the general geology, thus maximising the information content of the data sets. For use, this survey line data (known as located data) is usually transformed to raster format (referred to as grids). In addition to the geophysical data, any available surface information relevant to the study can be collected from the relevant government authority, the local landcare organisation(s), and the local farmers.

Electromagnetic measurements are made by the SALTMAP system mounted on a Britten-Norman Trislander aircraft. The approximate flying configuration is shown in Figure 1. SALTMAP is an active measurement system in which a power source connected to a coil mounted on the aircraft structure forms the transmitter, and three perpendicular coils (X,Y, and Z) mounted in a towed bird comprise the receiver. Technical details of the system are reported in Duncan *et al.* (1992) and Roberts *et al.* (1992). It is sufficient to note here that a measurement consisting of 100 channels per receiver coil (a total of 300 channels) is recorded every millisecond. However, only the X and Z channels are currently used and, depending on the data, the channels can be binned to a more manageable number (perhaps 15 or 20) or only a selected number of channels are retained for analysis.

Electromagnetic measurements respond to changes in the electrical conductivity of the sub-surface. In most landscapes, the mostly highly conductive material is salt (the only exception to this is some highly conductive clays) (McNeill, 1980) and so where salinisation is a problem, it can usually be assumed that the strongest conductors in the landscape are due to salt. For salinisation to occur there must be a source of salt, so this data is used to map the spatial location and extent of salt storage in the landscape.

Magnetic and radiometric data are collected simultaneously on a single aircraft. The system flies at a nominal height of 70m above ground level. Magnetic measurements are made by a cesium vapour magnetometer installed on a rigid boom at the rear of the aircraft and radiometric measurements are made by a gamma-ray spectrometer installed inside the aircraft.

Magnetic measurements respond to subtle changes in the earth's magnetic field caused by the influence of rocks in the sub-surface on the local magnetic field. The magnetic data can be interpreted (in conjunction with the known geology) to produce an interpreted geology map of the survey area. For salinisation to occur there must be a source of salt and a source of water, in this case groundwater. The geology map, in conjunction with a digital elevation model helps to define the likely groundwater flow for the survey area. In particular, magnetics can identify groundwater barriers. These barriers force groundwater to the surface, and if the groundwater is saline an area of salt degradation results.

Radiometric data, unlike magnetics and electromagnetics, measures only surface phenomena. The energy of gamma rays from decaying radioactive elements is measured and thus a relative distribution of these elements can be mapped. The typical channels of radiometrics which are used are potassium, thorium, uranium, and total count. This information can be used to assist in producing an interpreted soils map (Gourlay, 1996) or to characterise the regolith cover. Such information can be used in conjunction with the electromagnetic data to deduce the potential mobility of the salt. It can also be used to better understand the history of the landscape which can have implications for the potential for salinisation.

It is clear then that the final multivariate geophysical data set comprises perhaps several tens of grids, as well as the digital elevation model. In addition, relevant surface data might include stream network, cadastral data, soils map, regolith map, geology map, existing salt degradation, vegetation cover, and waterlogging. With such a large number of data sets, the interpretation becomes unwieldy and extremely time consuming. Also, a significant risk exists that valuable information, particularly relationships between data sets, might be missed. In the following section, the traditional approach to interpretation is discussed and these interpretation problems are examined in greater detail.

4. Interpretation of Airborne Geophysical Data

In its broadest sense, interpretation can be understood to mean the process of transforming the airborne geophysical data into information. However, this is a long and complicated process and masks the various stages which occur in this transformation. For the purpose of this paper, interpretation will mean the process by which meaning is extracted from one or more final data sets. A final data set will be defined as one which has resulted from passing the raw data through a succession of analyses to

1. remove systematic noise and correct for data acquisition errors (eg. varying altitude);
2. present the data in a useful format (eg. transform line data into gridded data); and,
3. present the data as a useful measurement (eg. electromagnetic data might be transformed to conductivity data).

For a typical geophysical survey for salinity studies, these final data sets will be magnetics and radiometrics grids, and electromagnetics transformed to a suite of conductivity grids. The digital elevation model will also be a grid and the surface data sets will be available either in map or digital form depending on the data source.

The aims of the interpretation are

1. to identify the hydrogeological causes of salinisation in the survey area;
2. to predict and rank all sites at risk of salt degradation based on the hydrogeological interpretation; and,
3. to develop a land management plan based on these results.

The first two interpretation tasks are the focus of this paper as they involve direct interpretation of the airborne geophysical data. For the first, each data set is examined in turn, and from it information relevant to the hydrogeology of the area is extracted. In the case of magnetics, this will involve a full geological interpretation based on the magnetic data, the known geology, and the interpreters own experience and knowledge of the area (Isles *et al.*, 1994). On the other hand, only the areas of high conductivity (delineating interpreted salt storage) and low conductivity (delineating areas of potential recharge) might be of interest in the electromagnetic data. Alongside these individual interpretations, interpretation of integrated data sets will seek relationships between the data sets in order to build up a picture of the hydrogeological regime operating in the area. For example, if regions of high conductivity consistently appear up-slope of magnetic lineaments, then these lineaments (eg. dolerite dykes in Engel *et al.* (1987a)) are interpreted as acting as groundwater barriers which cause a deposition of salt on the up-slope side of the lineament.

The process of identifying and assessing all potential salt hazard sites is much more specific. A number of researchers have examined methods which can be used to predict/ assess salinity risk (see for example Caccetta and Kiiveri (1996)), however, most use surface data sets such as satellite imagery which fail to examine the sub-surface causes of salinity. When geophysical data is incorporated into the prediction/assessment process, salt hazard sites are sought on the basis of specific hydrogeological models which are known to cause salinity in the survey area. For example, if salinisation is known to occur up-slope of dykes in the survey area, then first, all sites where groundwater flow intersects these groundwater barriers need to be found. Second, the hydrogeological regime up-slope of the intersection needs to be examined to determine whether the intersection poses a salt hazard, and if so, the severity of the potential hazard.

These interpretation tasks are traditionally completed manually based on visual cues. A suite of hardcopy images and maps are the interpreter's data set and tracing paper or clear film, pens, and a light table as the interpretation tools. The first stage of interpretation involves identifying boundaries and lineaments in the data set and interpreting these in geological terms. The degree of complexity in this task depends on the information being extracted from the data set. For example, under the assumption that regions of high conductivity define salt storage, the interpreter derives the salt storage map by simply tracing the boundaries of high conductivity regions off a hardcopy image. This involves a simple visual assessment of colour level for a single target variable, salt storage. By contrast, the interpretation of magnetics is much more complex and relies on a visual assessment of colour level, image texture, and extraction of lineaments, which are interpreted in terms of both lithology and structure.

The second stage of interpretation is an integration task. Interpretations from the first stage are combined to build up a more complete interpretation. The integration of data sets might confirm the existing interpretation; it might lead to new insight being added to the interpretation; or it could identify regions of inconsistency leading to a revision of the original interpretation.

Depending on the application, the final stage of interpretation will usually involve some target identification or recommendation for further action. In salinity studies, this stage involves identifying the spatial location of potential salt hazard sites based on some model (eg. intersection of saline groundwater with a barrier) and then determining the potential severity of that site.

Three key areas of inadequacy arise when the interpretation methodology just described is applied to geophysical surveys for salinity studies.

1 Whilst complex data sets such as magnetics can only be interpreted using a manual/visual approach, some of the simpler interpretation tasks (eg. deriving the salt storage map) could be more accurately and efficiently performed using a computational approach.
2 The large quantity of data available in a typical salinity study renders the integration stage of interpretation cumbersome and difficult to complete effectively. A significant risk exists that potentially important relationships between data sets will be missed using the traditional interpretation methodology.
3 The target identification process is currently missing salt hazard sites (as reported by farmers using the existing interpretation for the Broomehill district, Western Australia). A more systematic approach to identifying the salt hazard sites might solve this problem, and it would alleviate the extremely subjective nature of current salt hazard severity rating.

5. A New Methodology for Interpretation

In order to address some of the interpretation limitations discussed above, a new methodology based on a GIS platform is proposed. The GIS platform has been chosen because it offers

1. a data storage/management facility suitable for storing both raster and vector data;
2. access to a range of spatial analysis techniques which can be tailored to suit the particular requirements of this problem; and,
3. a map-making environment with which modern geoscientists will be comfortable.

The new methodology will be a four stage iterative process. It is designed to achieve a balance between the important aspects of the traditional approach (in particular, the importance of spending time familiarising oneself with the data) and the time saving and effectiveness of automating interpretation tasks in the GIS environment. The methodology, shown schematically in Figure 2, is designed to be used in applications other than salinity studies, but the discussion which follows concentrates on the salinity application. Figure 3 shows an example of the interpretation methodology applied to a typical salinity study.

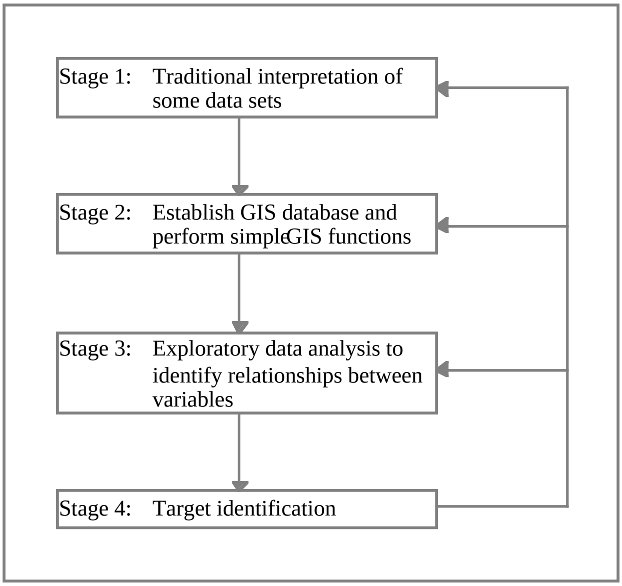

Figure 2: Schematic representation of the proposed GIS-based interpretation methodology

5.1 Stage 1

Firstly, the traditional, manual interpretation approach will still be required on some data sets, most importantly the interpretation of magnetics to produce a geology map. As noted earlier, interpretation of magnetics requires an assessment of several different image properties (colour level, texture, extraction of lineaments) which need to be interpreted in terms of both lithology and structure from the perspective of the interpreter's understanding and knowledge of the area. It is this latter component, the interpreter's knowledge, which makes automated interpretation of this data so difficult. Within the context of this new methodology, interpreting magnetics in the traditional way serves an important purpose - it allows the interpreter to become familiar with the geology of the area (Isles *et al.*, 1994). This enables the interpreter to understand the context into which results from later work can be fitted.

5.2 Stage 2

The second stage of the methodology involves establishing the entire data set in the GIS. This will involve importing data in both raster and vector formats, and may involve some digitising of data. Also, simple GIS manipulations might be used at this stage to extract simple property maps from some data sets. For example, a salt storage maps needs to be derived from the electromagnetic data. This can be obtained by slicing off the high end of the conductivity at some threshold value, dependant on the knowledge of the area. These simple GIS manipulations partially replace the tracing paper phase of the traditional approach.

5.3 Stage 3

In the third stage, relationships between multiple variables are sought. This might be done for two reasons. Firstly, in some applications, an interpreter knows that a particular combination of geophysical signatures will give him/her areas within the data set on which he/she must focus. Secondly, the interpreter will want to gain insight into how the various geophysi-

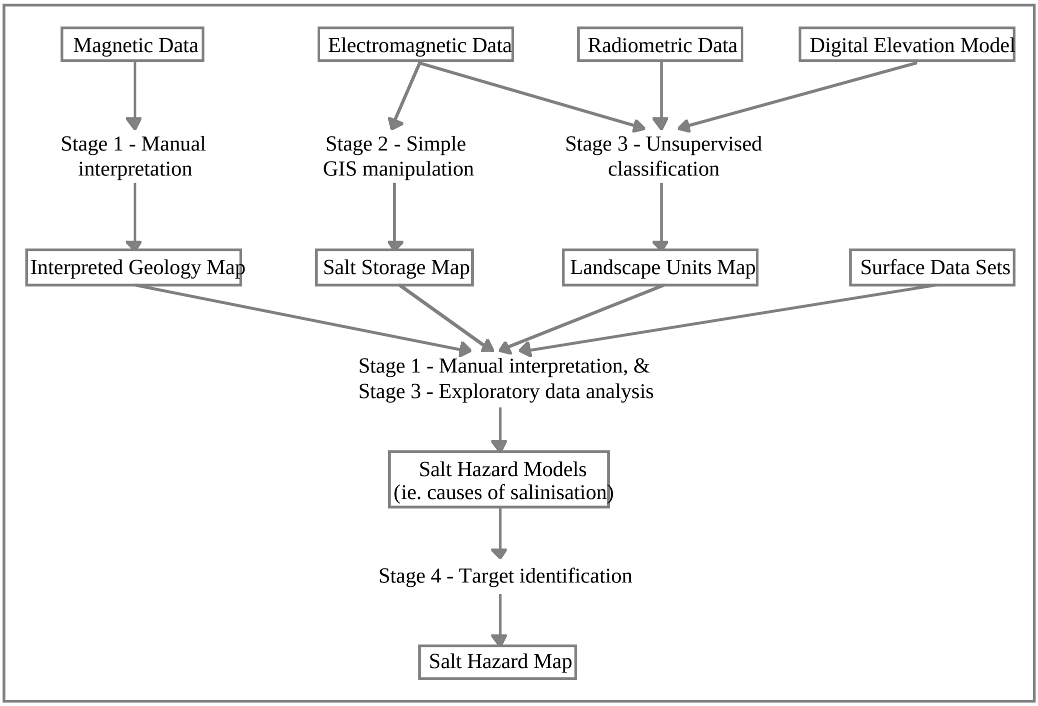

Figure 3: Schematic representation of the application of the proposed methodology to a typical salinity interpretation.

cal data sets relate to each other, and this will lead to a better understanding of the geological processes which have shaped the landscape to its present state. Exploratory data analysis, such as classification, principal components analysis, and decision tree analysis provide avenues for the structure of a multivariate data set to be elucidated. This work replaces using the light table to overlay multiple data sets, and improves on it by placing quantitative values on the relationships between variables.

5.4 Stage 4

The final stage is target identification. This is the only part of the methodology which is application specific, and its successful automation depends on the degree of complexity in the target identification process. If this methodology is to be adopted in applications beyond salinity studies, it will require a commitment of resources to translate the expert knowledge about the targets into the appropriate code. Two possible avenues exist for target identification - data driven and knowledge driven. An example of the data driven approach is decision tree analysis, where areas of known salt degradation are used to "train" the decision tree to find all other sites of salt hazard potential. This follows the exploratory data analysis of Stage 3. The knowledge driven approach requires the expert knowledge about the causes of salinisation in the study area to be translated into a series of rules. Stages 1 through 3 should have enabled the interpreter to identify the hydrogeological causes of salt degradation and define conceptual salt hazard models for the survey area. These salt hazard models can then be used to produce maps of ranked salt hazard sites for the survey area.

6. Confidence in the Proposed Methodology

In examining this proposed new methodology, the question will naturally be asked, "Why have confidence that it will work?". First, as noted previously, a GIS platform meets the technical requirements of the problem (spatial data storage, analysis, and visualisation) whilst offering a user environment which allows the interpreter to perform digitising and overlay operations analogous to the tasks he/she performed on the light table. This should ensure that the technology transfer of this methodology is achievable.

Second, the structure of the methodology is completely analogous to the interpretation structure which the interpreter is already using. References on the art of interpretation of geophysical data are few, although a multitude report the results of interpretation. However, a set of course notes on interpretation from Isles *et al.* (1994) states the following:

As with all data sets, the interpretation should be regarded as dynamic - it will change as new evidence and ideas come to light. It is most important, therefore, to be able to retrace the interpreter's steps back to the original data so that if necessary it can be recycled. (Pg. 7)

The flexible structure of the proposed methodology ensures that this important criteria is met. In addition, the interpreter's knowledge is valued at all stages of the methodology. Researchers in the growing field of knowledge discovery consider this point to be central to the success of using computers to extract knowledge from data. Brachman and Anand (1996) state that "knowledge discovery is a *knowledge-intensive* task consisting of *complex interactions*, *protracted over time*, between a *human* and a (large) database, possibly supported by a *heterogeneous suite of tools*". At the centre of many knowledge discovery systems are similar analysis techniques to those suggested for this application - classification, regression, clustering, decision tree analysis (Fayyad *et al.*, 1996). The main application areas for these systems are currently large financial and health care databases which are not primarily spatial. However, the parallels between knowledge discovery and the interpretation methodology described here, suggest that the human-centred, interactive approach which has been adopted here is likely to be successful.

Finally, the spatial analysis techniques which have been selected to underpin this methodology are already widely used on similar data sets. Stage 3 of the methodology identifies classification and principal components analysis (PCA) as important spatial analysis techniques. Both of these are widely used on satellite remote sensing imagery, which is similar in many ways to airborne geophysical data. A general property of PCA is that the result demonstrates the true dimensionality of the data set, thus potentially reducing the amount of data which needs to be analysed. Also, Singh and Harrison (1985) reported that PCA applied to raw remote sensor data might yield images which are more interpretable than the original data. Both of these results would be useful in the context of interpreting airborne geophysical data for salinity. Classification, by contrast can be described as a process which transforms data into information (Jensen, 1996). In the remote sensing arena, spectral signatures for identified classes are used to tie the imagery to features on the surface (eg. different types of land cover). A completely analogous process can be used with airborne geophysical data, but spectral signatures are replaced by groups of physical properties. For example, the relationship between radiometrics, conductivity, and topography could be used to give an indication of the type of regolith. Classes with high potassium and high conductivity at the bottom of a hill would be identified as depositional areas, whereas areas of shallow bedrock would be identified by classes exhibiting very high potassium and very low conductivity on hills or slopes (pers comm G Street, 1996).

Stage 4 of the methodology refers to the use of cartographic modelling. This technique is described extensively by Bonham-Carter (1994) for use in producing maps of mineralisation potential. The approach is based on developing mineral potential models (using expert knowledge or derived from decision tree analysis) using a suite of geological, geochemical, and geophysical data. The development of salt hazard models is completely analogous to this process, although with a much stronger emphasis on geophysical data. Also, salt hazard sites will normally be specific sites, whereas mineralisation potential maps are usually regions rather than point sites. But, the success of a cartographic modelling approach to these problems, gives us confidence that this will be a successful approach to identifying salt hazard sites.

7. Conclusions

This paper has presented a new methodology for interpretation of large multivariate airborne geophysical surveys for salinity studies. However, the methodology has been constructed on principles which apply equally to interpretation of airborne geophysical data for other applications. For example, the development of a new generation of electromagnetic technology is providing mineral explorers with a new geological mapping tool. In the past, electromagnetics was used by mineral explorers to seek deep, conductive targets (likely hosts of mineralisation), but the new generation of electromagnetic systems is providing them with geological mapping information which will complement that currently obtained from magnetics and radiometrics. It is certain then that mineral explorers will soon meet identical interpretation problems to those discussed in this paper for salinity studies. This methodology provides a framework to address those problems. Resources will need to be committed to meet the development of application specific analysis modules, especially in Stage 4 of the methodology, but the overall framework is completely portable.

The strength of this methodology lies in the fact that it incorporates a "natural" approach to geoscientific interpretation with a range of spatial analysis techniques which have already proved successful in similar problems. Users of geophysical data can look forward to a future which moves beyond the use of leading edge computer-based technology for data acquisition and processing, to the use of such technology to enhance interpretation.

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