Utilizing Airborne Electromagnetic Data To Model The Subsurface Salt Load In A Catchment, Bland Basin, NSW

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EXTENDED ABSTRACT

One of the important criteria in managing salinity is the ability to quantify the amount of salt stored in the environment. The total amount of salt, including both immobile and mobile salt, is termed salt load. Conventionally, salt load has been calculated from soil and groundwater investigations. In the regolith, salt load is mainly attributed to the volume of saline pore fluid and its salinity. Remotely sensed electromagnetic (EM) systems offer another technique in acquiring information for deducing the salt load. EM systems measure the bulk electrical conductivity (EC) response from various geological materials, including sediments and bedrock, with the latter having a lower EC.

An airborne EM survey, using the TEMPEST time-domain system, with 100 m spaced flight lines, has been carried out in part of the Bland catchment of central NSW, and covers an approximate area of 1,400 km^2. Processed EM data was converted into conductivity depth (CDI) images at the following intervals (0-5, 5-10, 10-15, 15-20, 20-30, 30-40, 40-50, 60-100 and 100-150 m). This dataset, together with petro-physical, chemical and geological information obtained from several drill cores and numerous core cuttings, allows interpretation of 3D sedimentary architecture.

Overall, the area consists of a few hills and ridges, with extensive low lying areas, and sediments up to 70 m thick, burying palaeo-ridges and valleys. The sedimentary fill of the Bland Creek palaeo-valley in the study area can be divided into six depositional units (Units A – F).

Unit A consists of silt-rich mud and mud-rich sand (50-80 % mud) with locally sandier aquifer. Unit B is interpreted as a lake or swamp deposit and is generally muddy (95-100 % mud). Unit C is mostly gravel-bearing sand with minor mud. This unit underlies A or B, but locally extends to surface where there is a good sandy sediment source. Unit D is brown, with massive ferruginous stains, and has interlayer of mud, mud-rich sand and gravel-bearing sand. Unit E represents winnowed fluvial sediment and consists dominantly of sand and gravel-bearing sand. Unit F is locally present at the base of the stratigraphic unit and is sand and mud in varying proportion.

Within aquifer units (i.e. Units A, C and E), preferential flow paths have resulted in less saline groundwater with saltier and older pore water residing in lower permeability materials (mud-rich). However, there is a potential of mixing amongst the pore fluids and groundwater. Salt in the lower permeability units (Units B and D) have limited mobility, except at the interfaces with the aquifer units, where mixing may occur.

For the salt load model, salt load is calculated as:

$$\Phi_{Cl} = Cl \times \theta_v \qquad \text{Eq 1}$$

where Cl is the pore fluid chloride concentration (mg/l) and θ_v was measured as volume of liquid phase of bulk regolith volume.

EC correlates well to the salt load and empirical analytical results show that EC can be derived from salt load via the following equations:

$$EC_a = 0.091\ \Phi_{Cl} + 84.4 \qquad r^2 = 0.85 \qquad \text{Eq 2}$$

where EC_a is the apparent electrical conductivity (mS/m) and Φ_{Cl} is the salt load of chloride.

$$\Phi_{TDS} = 0.0185\ (ECa - 84.4) \times H \qquad \text{Eq 3}$$

where Φ_{TDS} is the salt load of total dissolved solutes (TDS) in tonnes per pixel, H is the thickness of the CDI layer.

Using ArcGIS™ software and the algorithms, salt store grids were created. The model comprises the direct translation of EC into salt store (as tonne of TDS) per voxel (900 m^2 x 5 or 10 m, depending on the CDI thickness) using equation 3. For illustration, salt store images for depth slices 10 – 15, 20 – 30, and 40 – 50 m have been produced. Subsequently the regolith unit maps, interpreted using airborne EM, magnetic and borehole information, were used to aid in visual correlation of salt load and regolith units relationships.

1. INTRODUCTION

One of the important criteria in managing salinity is the ability to quantify the amount of salt stored in the environment, and the amount of salt that is mobile, *i.e.* in aquifers or interacting with preferred hydrological flow paths. The total amount of salt, including both immobile and mobile, is termed salt load. Conventionally, salt load has been calculated from soil and groundwater investigations. Remotely sensed electromagnetic (EM) systems offer another technique in acquiring information for deducing the salt load. EM systems measure the bulk electrical conductivity (EC) response from various geological materials, including sediments and bedrock, and the EC is mainly attributed to the volume of saline pore fluid and its ionic concentrations.

The Bland basin in central NSW was chosen as the study area as many datasets are available and the airborne and borehole EM data have been ground validated. The data include geophysics such as EM, radiometrics and magnetics, bedrock geology, stratigraphic framework of the Cainozoic sediment and their physical attributes (e.g. grain size distribution), and hydrogeochemical datasets. In addition, the landscape evolution of the basin has been established by Gibson *et al.* (2002).

2. AIMS

This paper aims to determine the salt store in the sediment and saprolite in part of the Bland Basin, by establishing the EC and salt store relationships derived from statistical examinations of physical attributes of regolith materials, chemistry of pore fluids, and products derived from processed airborne EM data.

3. THE STUDY AREA

The study area is in central NSW, informally known as the Bland Basin, and is one of the sub-catchments of the Lachlan River (Figure 1). The airborne EM survey area is at the western part of the Bland Basin, and consists of several ridges and low lying hills surrounded by low angle colluvial slopes, and alluvium of Bland Creek tributaries. The Bland Creek palaeo-valley is very broad, eroded largely on deeply weathered rocks. Sediment now covers an area of around 6000 km^2, with an alluviated valley floor 125 km long and up to 80 km wide (Gibson *et al.*, 2002). Maximum thickness of sediment is about 80 m, and groundwater quality in the area is mostly poor.

Based on airborne radiometrics, magnetic and EM data, as well as hundreds of borehole lithology logs (mostly from mineral exploration companies), the depositional history and processes of the Cainozoic sediments were established by Gibson *et al.* (2002).

The geology consists of sequences of volcanic and sedimentary Palaeozoic rocks of the Lachlan Fold Belt, which are intruded by felsic igneous rocks. Regional faults trend NNW with some at other orientations due to folding. Most of the volcanic rocks (intermediate to mafic) have been weathered, eroded and buried, and the remaining outcropping ridges are more resistant sedimentary strata. The palaeo-ridges, now buried, are punctuated by gaps through which the original palaeo-drainage passed (Gibson *et al.*, 2002).

4. GROUNDWATER SALINITY DYNAMICS

The bore water and pore waters have been analysed using ICP-OES for Ca, Mg, Na, K, S and Si, ion chromatography for Cl, Br, NO_3, PO_4, SO_4, and refrectometry for TDS. Most pore waters are brackish to saline, with TDS ranging from 10,000 to > 50,000 mg/l (Lawrie *et al.*, 2003).

Based on stable isotope results, Lenahan *et al.* (2004) postulated that rainwater is the primary source of solutes in the groundwater and is concentrated by transpiration in the unsaturated zone. Dissolution of cyclic salts in the unsaturated zone by infiltrating rainwater may constitute up to 30 % of the total solutes present in groundwater. The distribution of salt appears to be dependent on the physical properties of the regolith and proximity to recharge areas (Lenahan *et al.*, 2004). Lower ^{36}Cl/Cl ratio suggests that older, more saline water is residing in lower permeability regolith materials (mud and clay). Within the aquifer, water residing in pore spaces (muddy sand and sandy mud) is saltier than the groundwater. This suggests that groundwater is moving along preferential flow paths, resulting in a heterogeneous distribution of salts within the saturated aquifer unit. Similar ion ratios, despite variation in salinity, indicate mixing between these saline pore fluids and groundwater. As such, these lower permeability regolith materials may represent a significant source of solutes for the groundwater (Lenahan *et al.*, 2004).

5. STRATIGRAPHIC FRAMEWORK OF THE CAINOZOIC SEDIMENT

The sedimentary fill of the Bland Creek palaeo-valley in the study area can be divided into six depositional units (Units A – F), based on grain size and location within the stratigraphic column. Fine grained sediments predominate in the thousands of the sediment samples studied within the project (Lawrie *et al.*, 2003). The study area (sub-catchment) is relatively small compared with the depositional area, *i.e.* Bland Basin, and the sediment units do not form a well-organised bedded fill, but are strongly influenced by local sediment sources (Gibson *et. al.*, 2002). Classification of the sedimentary units is primarily based on texture (Wentworth's scale) and detailed down-hole visual texture estimates (Figure 2).

Unit A was deposited as low angle fan, channel and debris flow deposits, and appears brown (Munsell colour: 10YR5/3) with conspicuous ferruginous mottles in a grey matrix. This unit consists of silt-rich mud and mud-rich sand (50-80 % mud) with locally sandier aquifer. This unit directly overlies Units B and C, but may encompass the entire sedimentary sequence in some areas. Pore fluid salinity is relatively low for the top 10 m but commonly increases to 10,000 mg/l TDS at depth. The salt in this unit is mobile, and may be a source of solute for the underlying Unit C.

Unit B is interpreted as a lake or swamp deposit, and is dominantly grey (2.5Y6/2) with less conspicuous Fe-oxide segregation. This unit is generally muddy (95-100 % mud), with much less sand component and minor gravel (ferruginous pisoliths). Unit B has been sub-divided into 2 parts, upper and lower, based on clay and silt components. The lower part is dominated by coarse silt (16 – 62 μm), similar to Unit A, whereas the upper part is dominantly clay (< 4 μm). The salt hosted within this low permeable unit is likely to be immobile, except at the interface with other units (eg. underlying Unit C).

Unit C was deposited as low angle fan, channel or sheet flow sediment, and is mostly gravel-bearing sand with minor mud. Quartz content in the sand-rich layers may reach above 90 %. This unit underlies A or B, but locally extends to surface where there is a good sandy sediment source. This unit, together with Unit E, are the main aquifers in the area.

Unit D was deposited as debris and sheet flows, or as low angle fan sediment. This unit is brown, with massive ferruginous stains, which grade vertically down into conspicuous mottles. This unit has interlayer of mud, mud-rich sand and gravel-bearing sand, and kaolinite is the dominant clay mineral. Overall, this is a low permeability unit, but the salt may be locally mobile at the interface with Units C or E.

Unit E represents winnowed fluvial sediment and consists dominantly of sand and gravel-bearing sand, the gravel being rounded to sub-angular quartz. This unit is light grey and leached (10YR7/2), and is generally present only in lowest parts of the palaeo-landscape, and is underlain by the saprolite. This unit is one of the main aquifers and occurs in part of the study area.

Unit F is locally present at the base of the stratigraphic unit and is sand and mud in varying proportion. Due to its minor occurrence, this unit is not an important aquifer.

The mineral compositions of the sedimentary units are relatively similar with quartz (as silt and sand) and kaolinite dominant throughout. Occurring in minor amounts are illite/muscovite (as clay and silt), smectite and chlorite. The former two are found in most of the sediments whereas chlorite is present only in Units C and D. The ferruginous mottles are dominantly goethite with lesser haematite. Feldspar is present in low abundance (< 3 %) in some sediment, and albite is the only plagioclase found.

6. ELECTRICAL CONDUCTIVITY AND ENVIRONMENTAL APPLICATIONS

The electrical conductivity (EC), *i.e.* the reciprocal of resistivity) of soils, regolith and rock is dependent on the percentage of conductive minerals or fluids they contain. In some circumstances, this may include magnetite, carbon, graphite, pyrite and pyrrhotite. However, in most cases, EC of bulk materials is dominated by electrolyte (salt) that occurs in moisture-filled pores within an insulating matrix (Lawrie *et al.*, 2003). In this setting, the EC is primarily controlled by concentration of dissolved electrolytes, porosity and the dimension of pore throat (*i.e.* formation factor), degree of saturation, the amount and composition of clays, and temperature (Lawrie *et al.*, 2003).

Fixed wing TEMPEST time-domain system was flown across the study area (Lawrie *et al.*, 2003) and products derived from the processed EM data include layered earth inversion (LEI) and conductivity depth slice indices (CDI), the latter depicts the conductivity responses at various depth intervals. Electrical conductivity logs were also obtained from numerous boreholes and these have been used to calibrate the airborne EM data as wells as for correlation amongst the salt load, pore fluid salinity, water content of regolith materials and their textures.

7. DERIVING ALGORITHMS FOR SALT STORE

Salt load is proportionate to the amount of fluids contained in a regolith material and its salinity (ionic concentrations), and can be calculated using the equation:

$$\Phi_{Cl} = Cl \times \theta_v \qquad \text{Eq. 1}$$

where Cl is the pore fluid chloride concentration (mg/l) and θ_v was measured as volume of liquid phase of bulk regolith volume.

EC correlates well to the salt load (Figure 3a) and empirical analytical results show that EC can be derived from salt load via the following equations:

$$EC_a = 0.091\ \Phi_{Cl} + 84.4 \qquad r^2 = 0.85 \qquad \text{Eq. 2}$$

where EC_a is the apparent electrical conductivity (mS/m) and Φ_{Cl} is the salt load of chloride.

The total amount of salt is also positively correlated to the chloride content:

$$\Phi_{TDS} = 1.87\ \Phi_{Cl} \qquad \text{Eq. 3}$$

Each pixel is 900 m^2 (30 by 30 m), and chloride concentrations are in milligrams. Thus, converting salt load into tonnes per voxel and the equation becomes:

$$\Phi_{TDS} = 0.0185\ (EC_a – 84.4) \times H \qquad \text{Eq. 4}$$

where Φ_{TDS} is the salt load of total dissolved solutes (TDS) in tonnes per pixel, and H is the thickness of the CDI layer.

8. PRODUCING SALT STORE IMAGES

The processed, micro-levelled, CDI data were imported into ERMapper™ software and converted to '.ers' files (*i.e.* ERMapper™ raster datasets). These datasets were then imported using ArcGIS™ software, and the salt load grids were created using the Spatial Analyst Raster Calculator. The following algorithms were used for the depth intervals of 10-15 m, 20-30 m and 40-50 m respectively:

slt_ld10_15 = ([cdi10_15m.ers] - 84.4) * 0.092;

slt_ld20_30 = ([cdi20_30m.ers] - 84.4) * 0.185; &

slt_ld40_50 = ([cdi40_50m.ers] - 84.4) * 0.185.

These salt store grids were classified into classes using standard intervals as shown in the legends (on Figures 4a-c). The values of each salt store image depict the amount of salt stored in the regolith as tonnes (of TDS) per voxel (900 m^2 x 5 or 10 m thick).

8.1. Mapping of regolith units

Using the airborne EM and magnetic data, and borehole information, Czarnota (2004) has mapped the Cainozoic sediments, saprolite and saprock for various CDI depth slices (except for the shallowest, i.e. 0-5 m, 5-10 m). These polygons provide a visual correlation to the salt store and regolith relationships, and 3 examples of the regolith unit maps corresponding to the three salt store images are shown in Figures 4 d-f. Confidence maps for the regolith interpretation have been produced by Czarnota (2004). Most interpreted regolith polygons have medium to high confidence, except for the north-west corner of the survey area where there is a lack of borehole information.

9. SALT STORED IN THE REGOLITH UNITS

At a given salt concentration in the pore fluid, the amount of salt stored in regolith material is controlled by the porosity at saturation. Porosity can be grouped into 3 types; total or physical porosity, effective porosity and chemical porosity (Aplin *et al.*, 1999). Total porosity refers to the volume of a material that is not occupied by mineral grains, and includes isolated pores. Effective porosity is the volume of connected pores where fluids are able to move through. Permeability in this case is mainly defined by the dimension of the pore throat. Chemical porosity includes micro-pores, nano-pores and isolated pores where the movement of fluids in and out of these pores is minimal.

Coarse materials such as sand have higher effective porosity than fine textured mud and clay, and hence higher permeability. In contrast, the mud and clay have higher chemical porosity, which also results in higher total porosity than sand. Thus, at a given salinity at saturation, mud and clay have a higher salt load than sand due to higher total porosity.

From the 10-15 m salt store and regolith unit images, the salt load has been halved compared to the other 2 depth slices due to its thickness (5 m instead of 10 m). The highest salt load occurs in the undifferentiated unit (the lacustrine Unit B predominant). In contrast, the saprock has low salt load, due to low total porosity and moisture content. Moderately low salt loads (11 to 40 tonnes/voxel) occur in the units A, C, D and saprolite, with smaller areas containing higher salt load (up to 60 tonnes/voxel).

The 20 – 30 m salt load image shows large area of the undifferentiated sedimentary unit contains high salt loads (up to 120 tonnes/voxel). Similarly, the saprolite of the volcanic rocks also contains high salt loads due to its clay-rich nature and high total porosity. In contrast, the sand-rich Unit C holds lesser salt load (41 – 80 tonnes/voxel) owing to its lower total porosity.

The regolith units present in 40 – 50 m depths are mostly saprock and saprolite. The saprock holds low salt load (< 10 tonnes/voxel) whereas the saprolite contains high salt loads (61 – 120 tonnes/voxel). The gravely-sand palaeo-drainage sediment (Unit E) is also present associated with moderate salt loads (< 40 tonnes/voxel). The sandy colluvium Unit C also contains low to moderate salt loads (< 60 tonnes/voxel).

9.1. Limitations of the Models

This study shows that the spatial distribution of salt loads can be ascertained through well calibrated and processed EM data and chemical attributes (salinity concentrations) of regolith materials. However, heterogeneity of materials at a local scale makes the mapping of regolith units difficult, and locally the thickness of each unit varies and may overlap laterally. Thus interpreting the salt load and regolith association is carried out on a broad scale only. Besides, variation in pore fluid salinity and degree of saturation of the materials may produce outlier data/voxel. The accuracy of the salt load model is associated with the airborne EM system, which is less accurate in detecting the conductivity response of near surface (0-5m) materials. In such cases, ground-based EM techniques or frequency domain system will be better suited to delineate the conductivity of soils and near surface sediments (Lawrie *et al.*, 2003).

9.2. Future work

Following the determination of the amount of salt stored in the Bland sub-catchment, it is necessary to determine the amount of salt which is mobile, *i.e.* can be transported or exported out of the sub-catchment. For example, high salt store associated with the mud-rich lacustrine sediment (Unit B) is likely to be relatively immobile (sediment behaves as an aquitard with low permeability). Thus, it is necessary to determine quantitatively the range of permeability for the Cainozoic sediments, saprolite and saprock. The regolith polygons will be assigned the permeability values, and the transmissivity polygons depth slices will be calculated. These images will portray the connectivity of the aquifers and help better define the locations of low permeable units, which could be significant sources of solutes for the groundwater.

10. CONCLUSION

Due to potential mixing between saltier pore fluids and the groundwater in aquifer units A, C and E, calculating the salt load is essential in determining the salinity risk in the area. This exercise demonstrates the use of airborne EM as an alternative for modelling salt load and potential salt mobility within a catchment. The raster data and the capability of the EM system to sensed EC responses at depths provide an advantage of calculating the salt load more accurately than using conventional methods from widely spaced observations and borehole information.

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12. ACKNOWLEDGEMENTS

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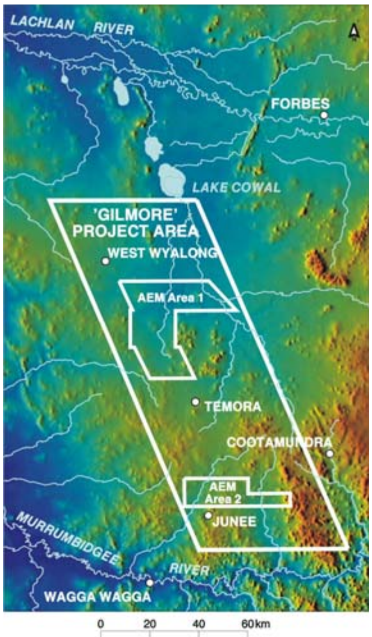


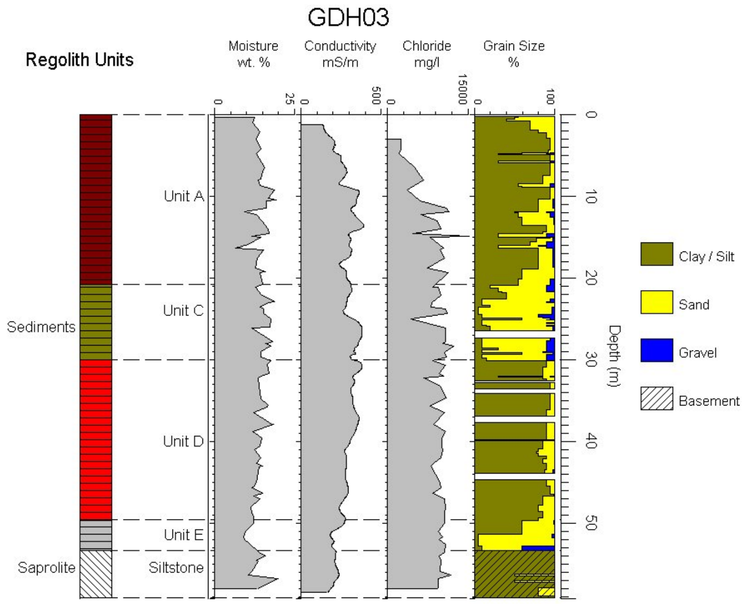
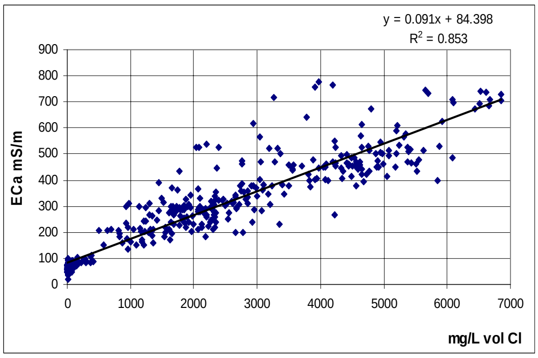


Figure 1. The study area (AEM area 1) is part of a catchment of the Lachlan River, NSW.

Figure 2. Visual display of drill log information of core hole GDH03 showing the stratigraphic units, geophysical logs and regolith attributes.



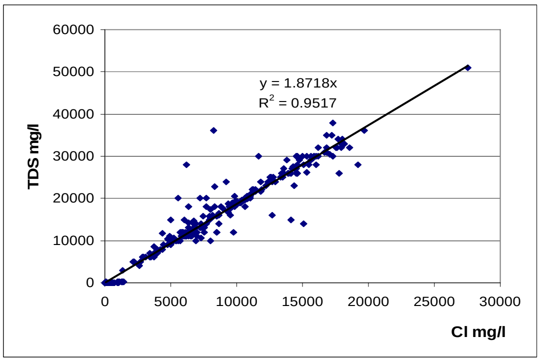
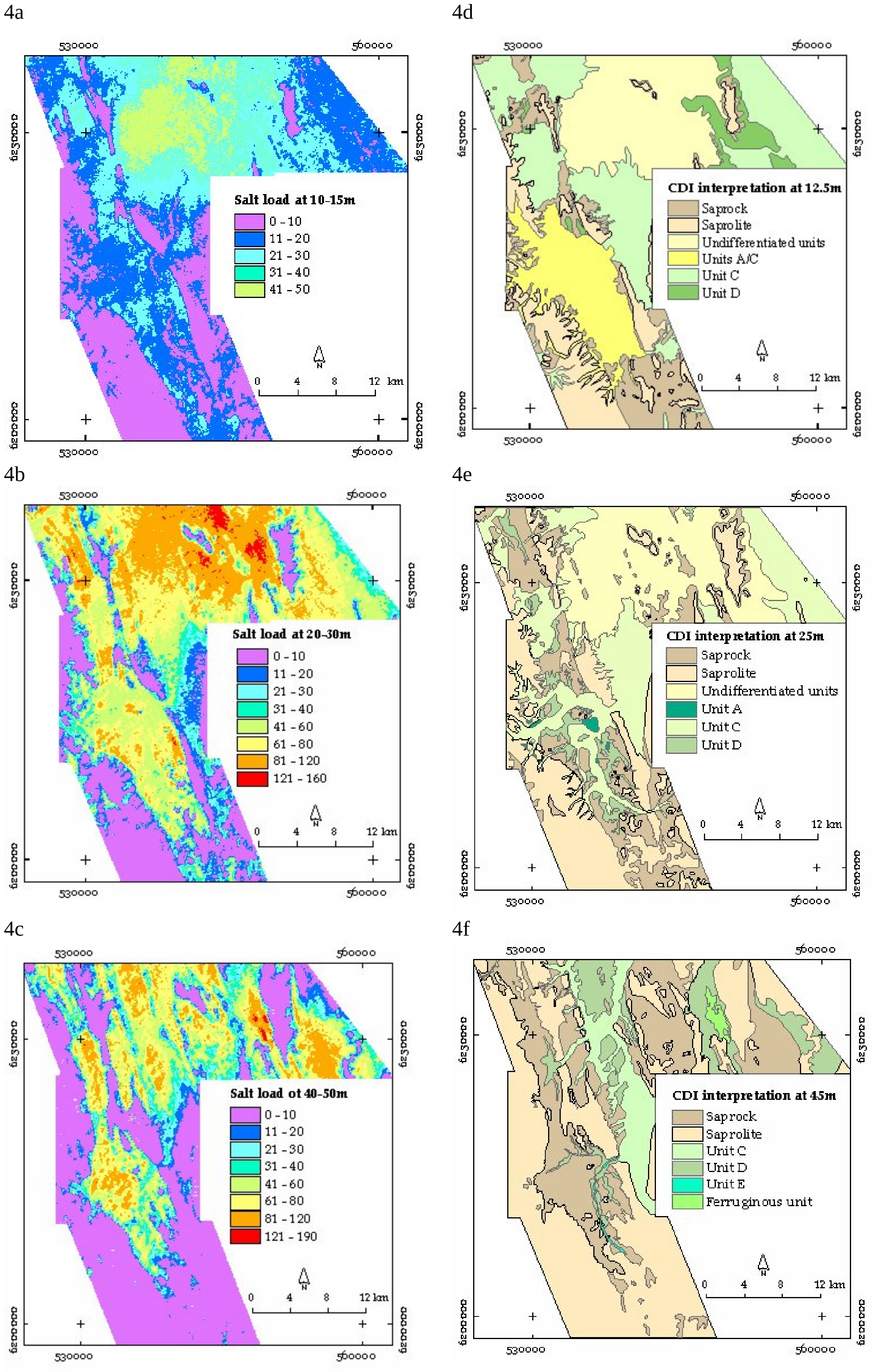


Figure 3a. Positive correlation between apparent electrical conductivity and salt (chloride) load.

Figure 3b. Positive correlation between total dissolved solutes and chloride concentrations in the pore fluids.



Figures 4 a – f. Salt load models and their corresponding regolith units across the same depth intervals.