An assessment of the ability to derive regional resistivity maps from geological mapping data

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Abstract

There is a requirement to understand the electrical resistivity structure of the near sub-surface, i.e. the upper 10 metres. This is the zone into which infrastructure is buried and electrical systems are earthed. Detailed resistivity surveys are carried out for site specific purposes, but there is a lack of regional data. A synthetic resistivity map has been generated by assigning average intrinsic resistivity values to the superficial and bedrock geology and producing an average resistivity for the top 10 m using the superficial thickness as the weight. In order to test this approach the synthetic map has been compared to the measured resistivity arising from a high frequency airborne electromagnetic survey over the Isle of Wight. Many general features between the synthetic and measured maps are in agreement, but some of the resistivity assignments are too simplistic. A revised synthetic map that takes into account the position in the landscape of the geological units and with revised resistivity ranges informed from the airborne survey has been generated that represents a good first approximation of the near surface resistivity structure. A scheme for generating synthetic maps in the absence of measured airborne data is indicated.

Introduction

The upper 10 m of the sub-surface is the zone of human interaction to which our infrastructures and foundations are connected. The electrical resistivity (or its inverse conductivity) is an important parameter involved in the chemical reactions that lead to corrosivity and is required when designing an appropriate electrical earth. Indeed, in the UK it is a requirement of the Electrical Safety, Quality and Continuity Regulations 2002 that any voltage source on a high voltage network is connected with earth at, or as near as is reasonably practicable to, the source of voltage. It is therefore surprising that the need to have systematic information on the electrical resistivity of this zone has been poorly addressed. In contrast the need for soil resistivity data for agricultural purposes is recognised (e.g. Brunner et al., 2007; Mueller et al., 2003) but this only concerns the top 1.5 m and is the layer most susceptible to moisture and temperature fluctuations. Climate change is likely to lead to more extreme temperature and moisture variations which will directly impact on the shallow sub-surface and hence reinforces the requirement to understand the electrical resistivity of this zone. This short note discusses the feasibility of generating synthetic resistivity maps in the absence of regional scale measured data illustrated with an example from the Isle of Wight.

Measured data availability

Small, detailed electrical resistivity surveys are carried out for site specific purposes (e.g. Sudha et al., 2009; Jackson et al., 2006). Regional scale data are most likely to be generated by remotely sensed surveys such as those conducted from aircraft flying along closely spaced, parallel survey lines. Airborne electromagnetic (EM) surveys generate an electrical conductivity image of the sub-surface where the depth investigated depends on the ground electrical conductivity, the frequency of the EM system and the height above ground of the EM sensors. The only publically funded airborne EM data recorded in the UK is that measured by the Hi-RES programme (e.g. Beamish and Young, 2009). Hi-RES (High resolution airborne Resource and Environmental Survey) was instigated in 1998 by the British Geological Survey (Peart et al., 2003) in order to acquire high resolution magnetic, electromagnetic and radiometric airborne data. The intention was to systematically survey the

UK from a low altitude light aircraft (56-90 m flying height) along closely spaced flight lines (200-400 m spacing).The four frequency EM system operates at frequencies of 912, 3005, 11962 and 24510 Hz, the depth of investigation increasing with decreasing frequency. A full description of the EM system is given by Leväniemi et al. (2009).

At the highest frequency deployed by Hi-RES (24.510 kHz) only the eastern half of Northern Ireland, the Isle of Wight and Anglesey have been surveyed and with no new Hi-RES surveys planned this is unlikely to change for several years. An indication of the depth of investigation of the airborne EM measurement may be given by the skin depth δ (the depth at which the signal is reduced to 37% of its value). The volumetric skin-depths of the EM survey system considered here are discussed by Beamish (2004). Centroid depths (Siemon, 2001) also provide a useful measure of the mean depth of investigation of the measurements. The centroid depths for the resistivities encountered on the Isle of Wight are discussed by Beamish and White (in press). At a frequency of 24.510 kHz, the centroid depths may range from about 8.5 m in conductive (e.g. 5 ohm.m) formations to 25 m in more resistive (e.g. 200 ohm.m) formations. Hence, even at this highest frequency a depth profile of greater than ten metres may be sampled by the Hi-RES airborne EM measurement. Thus where the Hi-RES surveys have been flown the upper frequency EM measurement does generate a measured apparent resistivity of the near surface although the depth investigated will vary and it will usually be greater than 10 metres.

Derived data

In the absence of regional scale measured electrical resistivity data it is possible to produce a derived data set based on the geology. Geology is heterogeneous, but mapping at 1:50,000 scale is available and provides a framework to which intrinsic resistivity values can be assigned. Intrinsic resistivity is dependent on the quantity and salinity of pore water as well as the resistivities of the component lithologies. For earth materials in which the matrix is resistive it is the pore water that determines the resistivity of the geological unit. Measured values of field resistivities are available from ground electrical surveys. The majority of these comprise resistivity soundings where a linear four electrode array is expanded from a central point resulting in penetration of the electrical current to greater depths. The recorded data comprise apparent resistivities which are weighted averages of the resistivities of the geological layers through which the electrical current has passed. If the geology is assumed to be horizontally layered and homogeneous then it is a simple task to interpret the soundings and assign intrinsic resistivities to the layers. The National Resistivity Sounding Database (Barker et al., 1996) contains the raw resistances from around 8,200 electrical soundings. These have been loaded into a GIS along with the BGS digital 1:50,000 scale bedrock geology (DiGMap-GB50 version 5.18), superficial geology and superficial thickness maps. The geological polygons are identified by their LEX_ROCK code which is a unique rock name and lithology. Thus the resistivity interpretation is at the 50,000 scale and enables, for instance, the differentiation between Triassic arenaceous rocks as sandstone, siltstone and sandstone, pebbly sandstone and conglomerate. It is thus possible to select a representative suite of soundings for each LEX_ROCK code and identify those codes where there are no data. The superficial thickness map indicates the total thickness of superficial cover and thus provides a constraint on the interpretation. These results have been supplemented with data from the BGS Local Geophysical Surveys database that references resistivity interpretations spanning many years that include data to investigate sand and gravel resources and data collected to aid geological mapping.

Synthetic resistivity map

The geological map for the Isle of Wight is shown in Figure 1. There are no electrical soundings from the National Resistivity Sounding Database on the Isle of Wight. It has thus been necessary to use interpretations from subcrops of the same geology in southern England (identical LEX_ROCK codes) or to extrapolate from similar lithologies. Two resistivity values have been derived for each LEX_ROCK code. The first is a mid-range value which is the median and the second is an upper value which is the 75% percentile of the interpretations. These two statistics remove the influence of end members of the population and hence reduces the impact of erroneous interpretations. The initial resistivity attribution for the geology of the Isle of Wight is shown in Table 1.

These resistivity values for the superficial and bedrock geology have been used with the thickness of superficials to produce a weighted average resistivity of the top 10 m of the sub-surface for each node of a 50m grid. The weighting function uses the median resistivity values and determines an average value proportional to the content of the top 10 m. The resulting synthetic resistivity map is shown in Figure 2. A resistivity map generated from the Hi-RES airborne 24.510 kHz electromagnetic data is shown in Figure 3 and, with the limitations described above, can be used to assess the synthetic resistivity map. There are clearly some broad, general agreements; the east-west trending chalk outcrop is clearly delineated and the conductive Palaeogene argillaceous strata on the north side of the island (most notably the Bembridge Marls and the Hamstead Beds) are well matched to the measured data. The thin outcrops of Gault Clay are also well matched between the two data sets as are the mudstones? of the Wealden Group on the southwest coast. However, there are also some mismatches between the synthetic and measured maps, most notably;

- The derived resistivities for the chalk outcrop across the centre of the island are too low, although the value for the West Melbury Chalk in the south is closer to the measured value.
- The ferruginous sands of the Lower Greensand are too resistive in the derived data. These appear as generally, moderately conductive in the airborne data.

- The sand and gravels of the superficial deposits which occur extensively along the north coast appear as resistive features in the synthetic map, but have little impact on the generally conductive values measured in the airborne data. This is partly because several high fly zones (urban areas where the aircraft had to climb to over 200 m above ground level resulting in no EM data) occur along the north coast, but nevertheless the derived resistivities are too high.
- There is a southerly trending band of resistive anomalies in the airborne EM data extending from the chalk outcrop across the centre of the island to the south coast. These are not seen on the synthetic map and do not correlate with the outcropping geology.

Improved synthetic resistivity map

The assumptions made in assigning the derived resistivities to the synthetic map are simplistic. Geological polygons with the same LEX_ROCK codes across southern England have been assigned the same intrinsic resistivity value which takes no account of regional or local variations. There are a number of factors that will influence the local value of resistivity, most notably;

- Position in the landscape will affect the hydrogeological regime. Locations on slopes or interfluves are more likely to suffer ground moisture deficit than valley bottoms. This will be particularly important for well draining geological units.
- Proximity to ground water will have a fundamental influence on moisture content. Areas of shallow ground water are less likely to dry out and perched water tables may have an important influence, even at elevated localities. It should also be noted that that the Hi-RES data were collected at the beginning of October when the ground is

likely to be dry, whereas the derived data have been compiled from resistivity soundings collected throughout the year.

- More accurate lithological characterisation would take into account the heterogeneity of many geological units. For instance some particle size information is available that would allow a more accurate assessment of clay content and enable sub-classification of many common deposits.

In this short note, further, detailed analysis of the geology have not been undertaken, but based on the factors listed above and the differences observed between the synthetic and measured resistivity maps an improved synthetic resistivity map has been produced.

A digital terrain model of the Isle of Wight has been used in an initial assessment of position in the landscape. The chalk crops out at higher elevations, especially across the centre of the island. Much of this chalk is also folded into a vertical orientation as a result of basin inversion. Hence, even though the chalk matrix generally remains saturated due to the small throat size of the pores it is likely that drainage will occur along the bedding plane fractures which are now vertically orientated. This will lead to a higher resistivity for the chalk across the centre of the island.

Some of the initial resistivity attribution indicated wide ranges in values. For instance, sand and gravel deposits ranged from 200-400 ohm.m, but many of these occur in valleys and are likely to have high moisture contents. Hence, based on landscape position and data from the airborne EM survey the resistivity ranges have been revised and are shown as the final two columns in Table 1.

The resistivity response of the near surface has now been approximated using a revised scheme, similar to the procedure used above. By considering the specific response of the superficial and bedrock units at different positions, spatially varying resistivity values can be determined. These values were calculated using the revised median and upper limits set out in Table 1, scaled as a consequence of elevation. The relative contribution of the superficial and bedrock units was then established from the superficial thickness data and is proportional to the content of the top 10 m. The final synthetic resistivity map is shown in Figure 4.

Discussion

The final synthetic resistivity map has resolved the main mismatches that were observed with the airborne EM data and demonstrates that a regional scale resistivity map can be generated from derived data. The three dominant features of the resistivity map, low resistivities over the Palaeogene argillaceous rocks in the north, the resistive chalk outcrop across the centre of the island and the midrange resistivities over the Cretaceous rocks in the south have been reproduced. Many smaller features are also well resolved such as the outcrop of the Gault clay and the Wealden mudstones in the southwest and east.

There remain two significant mismatches with the measured airborne EM data. At the western tip of the island the clay and silt of the Headon and Osborne Beds would be expected to be conductive, but is of high and variable resistivity in the airborne EM data. Part of this area is associated with urbanisation and two zones of high flight elevations that complicate the spatial integrity of the information (Figure 3) occur here. Additionally, the area contains areas of outcrop of the Headon Limestone which has been determined as a resistive (~100 ohm.m) formation in the work of Beamish and White (in press). There also remains the southerly trending band of resistive anomalies from the centre of the island to the south coast. The sharp, linear, western edge to this band of anomalies suggests that it may be an artefact of the airborne survey as the flight line direction was north-south. Weather conditions have been checked and were generally constant during the survey and do not indicate any significant changes in ground conditions from day to day. An anthropogenic source also appears unlikely as there are no pipelines or power lines along this orientation. A further possibility is that some of the individual anomalies, particularly the most northerly, could be the result of agricultural groundwater abstraction. The sandstones of the Lower Greensand are a shallow aquifer and groundwater abstraction would lead to drawdown resulting in more resistive conditions. The airborne EM data could be sampling to tens of metres depth in resistive ground and may therefore not be representative of the near surface resistivity.

The scale of the synthetic resistivity map is 1:50 000, but its resolution will be less. Geological boundaries are rarely vertical and at sloping interfaces there will be a feather edge effect producing a gradational resistivity boundary. This partly explains the fuzzy appearance of the measured map compared to the synthetic map. In addition both the accuracy and resolution of the superficial thickness map will vary. This is compiled from borehole logs of mainly shallow site investigation boreholes often logged by drillers. Sometimes the interface between the superficial deposit and the underlying, weathered bedrock surface will have been difficult to identify. Superficial thicknesses in areas between clusters of boreholes, which are sometimes quite extensive, have been estimated from a geological model. The intrinsic resistivity assigned to a superficial unit will also vary both laterally and vertically and this also explains some of the fuzzy character of the measured map.

In the absence of regional measured data the synthetic resistivity map produced here is a good first pass representation of the near surface resistivity. Such maps can be of great benefit to those designing grounded electrical earthing systems and for the assessment of corrosive conditions for buried infrastructure. It is clear that a replication of resistivities between similar geological units is an over simplification, but when the principal factors that determine intrinsic resistivity are considered then a suite of representative resistivities can be determined. Temporal changes in resistivity resulting from seasonality and climate change can also be estimated in a derived synthetic map. It should be possible to produce interactive, GIS based maps, in which seasonal weather conditions or the predictions from a climate change model are part of the input scenario. This, when coupled with the ability to produce resistivity maps between any two depths, will produce a powerful ground resistivity prediction tool.

Acknowledgements

This paper is published by permission of the Executive Director of the British Geological Survey (NERC).

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Figure captions

Figure 1. The 1:50 000 scale digital data for the bedrock (top) and superficial (bottom) geology (DiGMap-GB50 version 5) of the Isle of Wight, UK. The geological codes in the legends are explained in Table 1.

Figure 2. The initial synthetic resistivity plot of the top 10 m of the subsurface derived from the median resistivity values in Table 1.

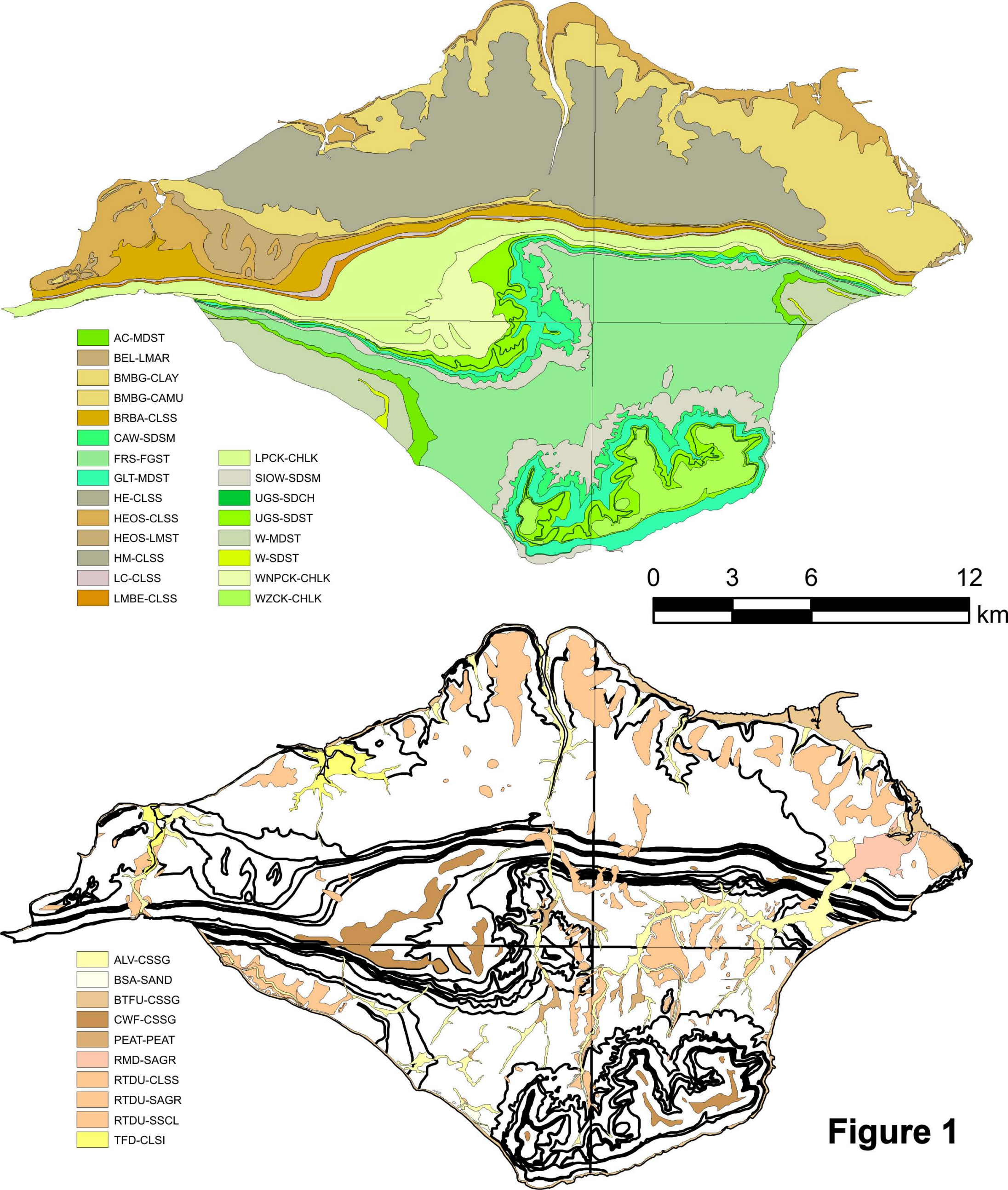
Figure 3. The gridded airborne apparent resistivity data obtained at 24.510 kHz. The red contours denote areas where the survey altitude exceeded 100 m. The polygons with black cross-hatch denote the major urban areas.

Figure 4. The improved synthetic resistivity plot of the top 10 m of the subsurface derived from the revised median and upper resistivity values in Table 1 and further weighted by the digital terrain data for the Isle of Wight.

LEX_ROCK	LEX_DESCRIPTION	ROCK_DESCRIPTION	Median	Upper	Revised Median	Revised Upper
IoW Superficial Geology						
ALV-CSSG	ALLUVIUM	CLAY, SILT, SAND AND GRAVEL	34	78	30	70
BSA-SAND	BLOWN SAND	SAND	120	400	50	200
BTFU-CSSG	BEACH AND TIDAL FLAT DEPOSITS	CLAY, SILT, SAND AND GRAVEL	34	400	40	200
CWF-CSSG	CLAY-WITH-FLINTS FORMATION	CLAY, SILT, SAND AND GRAVEL	65	300	25	90
PEAT-PEAT	PEAT	PEAT	47	105	50	80
RMD-SAGR	RAISED MARINE DEPOSITS	SAND AND GRAVEL	200	400	30	90
RTDU-CLSS	RIVER TERRACE DEPOSITS	CLAY, SILT AND SAND	30	65	25	50
RTDU-SAGR	RIVER TERRACE DEPOSITS	SAND AND GRAVEL	120	400	20	90
RTDU-SSCL	RIVER TERRACE DEPOSITS	SAND, SILT AND CLAY	80	200	50	120
TFD-CLSI	TIDAL FLAT DEPOSITS	CLAY AND SILT	5	15	5	20
IoW Solid Geology						
AC-MDST	ATHERFIELD CLAY FORMATION	MUDSTONE	15	30	15	35
BEL-LMAR	BEMBRIDGE LIMESTONE FORMATION	LIMESTONE AND [SUBEQUAL/SUBORDINATE] ARGILLACEOUS ROCKS, INTERBEDDED	97	155	15	30
BMBG-CAMU	BEMBRIDGE MARLS	CALCAREOUS MUD	20	40	4	20
BMBG-CLAY	BEMBRIDGE MARLS	CLAY	15	35	3	20
BRBA-CLSS	BRACKLESHAM GROUP AND BARTON GROUP	CLAY, SILT AND SAND	40	75	3	20
CAW-SDSM	CARSTONE (ISLE OF WIGHT)	SANDSTONE, SILTSTONE AND MUDSTONE	40	200	40	70
FRS-FGST	FERRUGINOUS SANDS FORMATION	FERRUGINOUS SANDSTONE	85	400	30	150
GLT-MDST	GAULT FORMATION	MUDSTONE	12	16	8	20
HE-CLSS	HEADON FORMATION	CLAY, SILT AND SAND	30	65	20	50
HEOS-CLSS	HEADON BEDS AND OSBORNE BEDS	CLAY, SILT AND SAND	30	65	4	20
HEOS-LMST	HEADON BEDS AND OSBORNE BEDS	LIMESTONE	120	200	30	85
HM-CLSS	HAMSTEAD BEDS	CLAY, SILT AND SAND	16	22	4	20
LC-CLSS	LONDON CLAY FORMATION	CLAY, SILT AND SAND	16	22	5	20
LMBE-CLSS	LAMBETH GROUP	CLAY, SILT AND SAND	16	60	10	30
LPCK-CHLK	LEWES NODULAR CHALK FORMATION, SEAFORD CHALK FORMATION, NEWHAVEN CHALK FORMATION, CULVER CHALK FORMATION AND PORTSDOWN CHALK FORMATION	CHALK	65	80	75	250
SIOW-SDSM	SANDROCK FORMATION	SANDSTONE, SILTSTONE AND MUDSTONE	40	200	20	50
UGS-SDCH	UPPER GREENSAND FORMATION	SANDSTONE AND CHERT	120	400	20	50
UGS-SDST	UPPER GREENSAND FORMATION	SANDSTONE	90	400	20	60
W-MDST	WEALDEN GROUP	MUDSTONE	18	30	10	30
W-SDST	WEALDEN GROUP	SANDSTONE	90	400	10	25
WNPCK-CHLK	WEST MELBURY MARLY CHALK FORMATION, ZIG ZAG CHALK FORMATION, HOLYWELL NODULAR CHALK FORMATION AND NEWPIT CHALK FORMATION (UNDIFFERENTIATED)	CHALK	46	63	20	150
WZCK-CHLK	WEST MELBURY MARLY CHALK FORMATION AND ZIG ZAG CHALK FORMATION (UNDIFFERENTIATED)	CHALK	20	35	20	66

Table 1. Resistivity ranges derived for the superficial and solid geology of the Isle of Wight. The initial mid-range resistivity is the median value and the upper resistivity is the 75th

percentile from the resistivity range determined from the interpreted electrical soundings. Revised median and upper values have been adjusted after comparison of the synthetic and airborne measured resistivity maps. All resistivities are in ohm.m.


AC-MDST
BEL-LMAR
BMBG-CLAY
BMBG-CAMU
BRBA-CLSS
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FRS-FGST
GLT-MDST
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UGS-SDST
W-MDST
W-SDST
WNPCK-CHLK
WZCK-CHLK
0
3
6
12
km
ALV-CSSG
BSA-SAND
BTFU-CSSG
CWF-CSSG
PEAT-PEAT
RMD-SAGR
RTDU-CLSS
RTDU-SAGR
RTDU-SSCL
TFD-CLSI

Figure 1

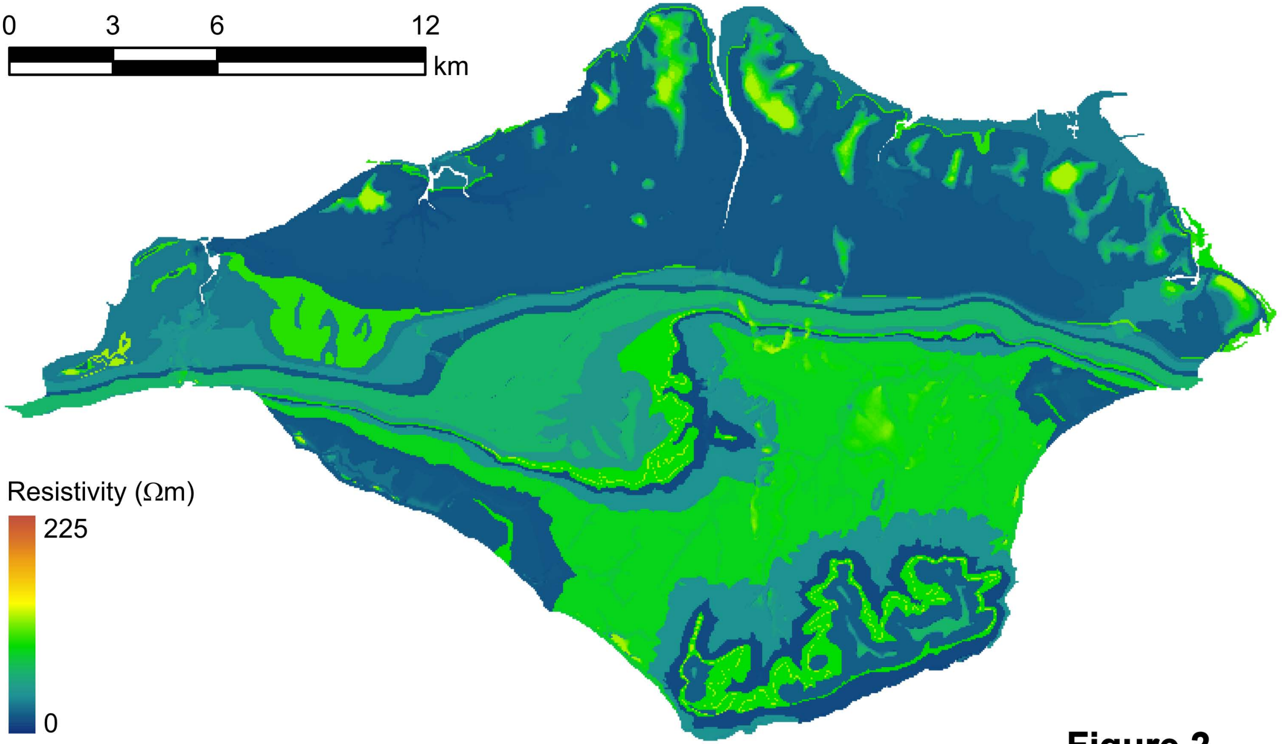

Figure 2

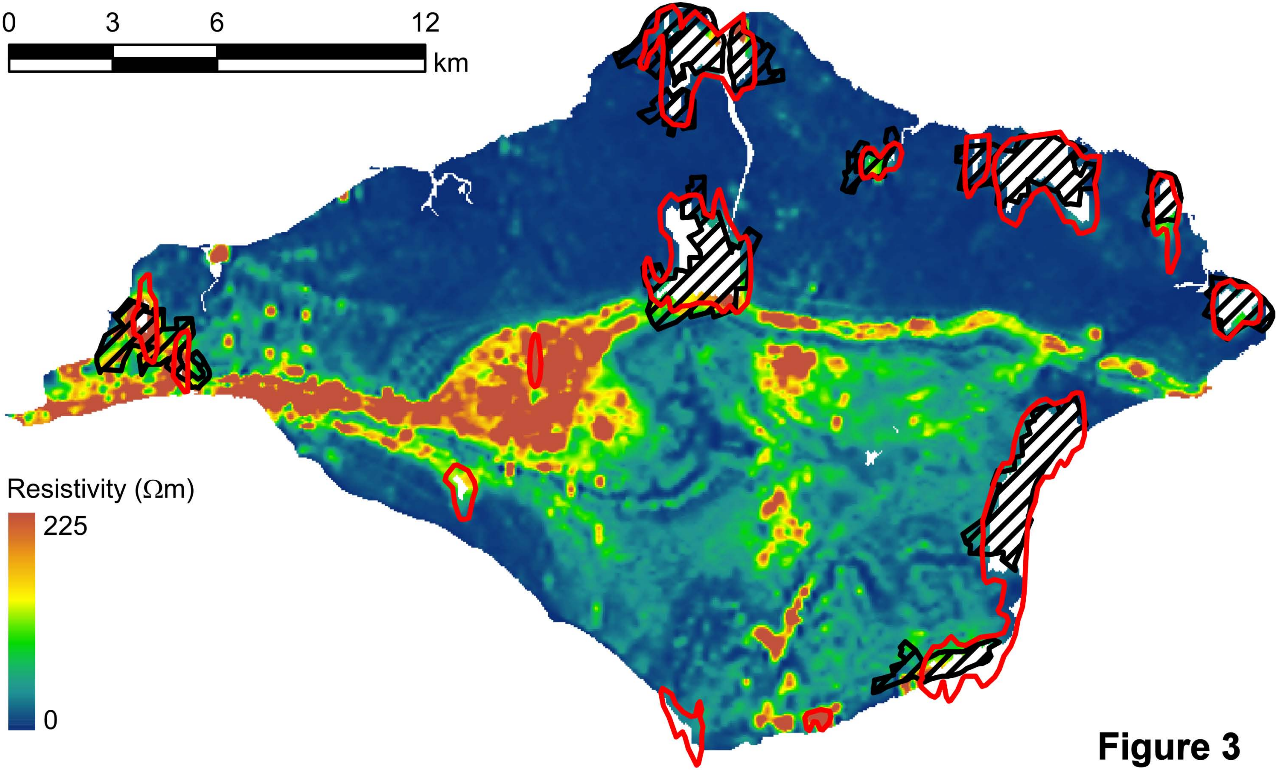

Figure 3

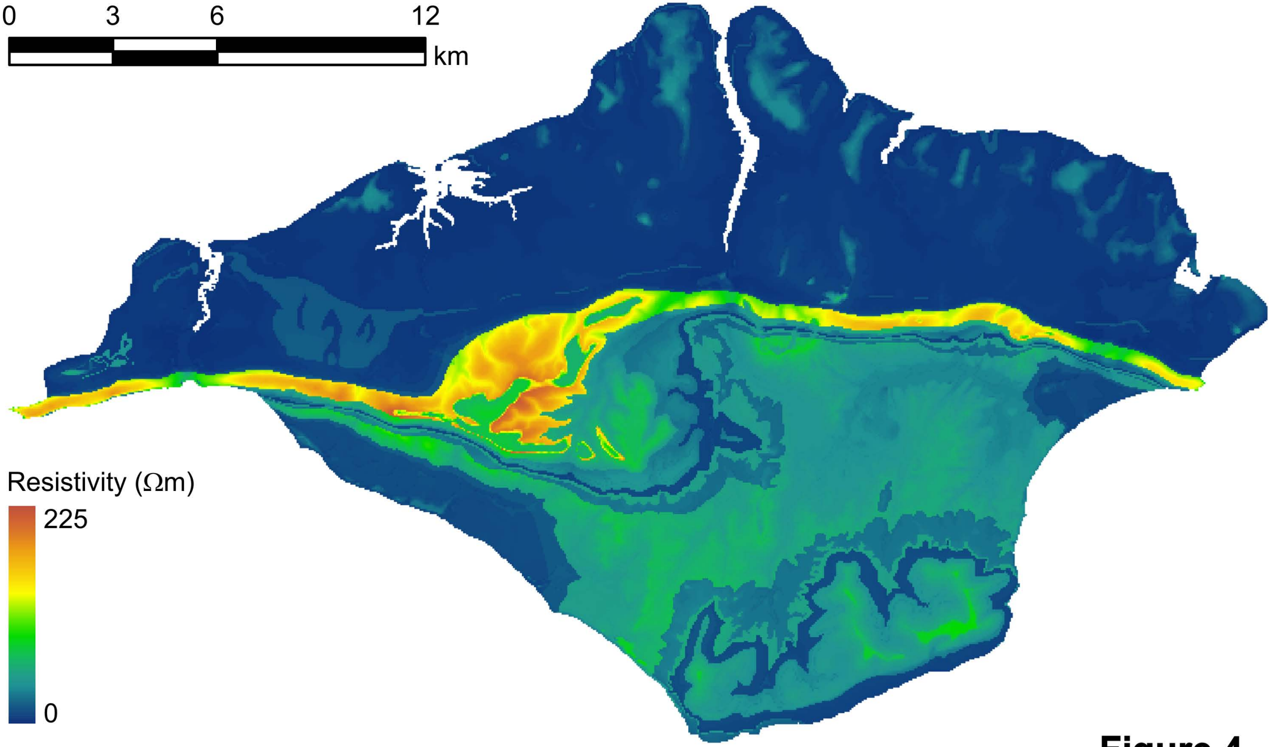

Figure 4