The potential to use electrical resistivity to increase the accuracy of flood prediction.

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Declaration

I certify that all material in this dissertation which is not my own work has been identified and that no material is included for which a degree has previously been conferred on me.

Abstract

Helston, Cornwall periodically experiences flooding, caused by high amounts of surface runoff from the increasingly urbanized catchment flowing into a small and modified channel. The aim of the research was to investigate whether the geophysical investigation technique of electrical resistivity can be used as a low cost method to improve the accuracy of flood prediction. It works on the principle that stored water within soil could alter a soils electrical signature and can be detected by electrical resistivity measuring devices such as an ohmmeter. Soil moisture and subsequent infiltration rates are predominantly influenced by precipitation, temperature and land use. Soil moisture is a highly influential component in catchment hydrology dynamics influencing river levels and subsequently in flood prediction. Primary data collection was carried out over a period of 11 weeks, from June to August at four different sites within the Cober River catchment near Helston, using a Chauvin Arnoux C.A.6470N ohmmeter supplied through Camborne School of Mines. The forcing variables of soil moisture (precipitation and temperature) and river levels were collected from secondary sources, such as the Met Office and the Environment Agency. Results show the methods potential to be able to detect changes in soil moisture conditions, as it was sensitive to changes in all variables, especially precipitation. River level changes often reflected the change in soil resistivity. Whilst correlations and relationships established between resistivity and forcing variables were mostly weak it was concluded that the data set was too small to enable true comparisons. Therefore, further research over a larger geographical area and time period would conclusively show the methods potential to increase the accuracy of flood prediction.

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1. INTRODUCTION

The importance of soil moisture on runoff, infiltration and evapotranspiration is well recognized in the literature (Destouni and Verrot, 2014). Much of the literature acknowledges that soil moisture variability and change in a landscape plays a predominant role in land-climate interactions in the hydrological cycle. It can also play a central role in biological cycling, waterborne solute and pollutant transport and vegetation, ecosystem and agricultural conditions within the landscape (Destouni and Cvetkovic, 1991). There is a need therefore to understand soil moisture conceptually in order to link groundwater conditions to subsurface and surface runoff. It has long been recognized that an analytical framework needs to be further developed in order to quantify soil moisture in the long term. This framework is vital to incorporate into hill slope runoff models in order to increase flood prediction capacity. As the demands on floodplains increase with rapid urbanization, flood prediction is becoming ever more relevant.

The key understanding to flood prediction and management would be the rate at which runoff is generated and delivered to the Cober Valley in Helston. Essential to determining runoff to the channel is the relationship between rainfall intensity and ground infiltration capacity, which determines how the flow will be partitioned between surface and subsurface, and at what rate it will reach the channel. When a soil is saturated and rainfall rate exceeds infiltration, the water will flow overland, increasing the rate and volume at which water reaches the channel. The antecedent soil moisture conditions within a catchment have been shown to be highly influential in predictive flood occurrence due to its effect on runoff processes (Huza et al, 2014). This is especially relevant for smaller catchments, such as the Cober, where water storage is key.

However, it is widely accepted that accurate soil moisture conditions for use in flood prediction can be difficult (Huza et al, 2014), and thus there are different, complementary ways of quantifying soil moisture conditions within a local catchment (Destouni and Verrot, 2014). Electrical resistivity is a geophysical method extensively used to measure the subsurface variation of electrical current flow. It is widely accepted that electrical resistance is directly related to variation within rock or soil types. For this reason, electrical resistivity methods are highly useful for soil investigation 'by enabling qualitative estimate of lateral condition variability in the near surface zone, and potentially producing an assessment of vertical variability' (Kowlczyk et al, 2014).

1.1. The project

The purpose of the project is to investigate the potential to use electrical resistivity as a method of predicting runoff from a soil surface. It is necessary to determine whether the apparent electrical resistivity of a soil can be used as a proxy for spatial and temporal variability of the physical soil properties, such as soil moisture and potential infiltration rates (Samouelian et al, 2004),. The report will assess the feasibility of vertical electrical sounding (VES) as a method of flood prediction by assessing the relationship between soil electrical resistivity, precipitation and temperature. This will be carried out using an Ohmmeter to test the soils resistivity at various sites within the catchment of the Cober River. This will test the methods sensitivity to metrological conditions. Using the Cober River's flow gauge data it will be potentially possible to assess the correlation between catchment soil resistivity and stream flow. This goes further than attempting to correlating simply metrological factors to soil moisture but will assess electrical resistivity as a proxy for whole catchment hydrological processes including runoff and lag time.

If successful the VES method offers a relatively cheap, easy and unobtrusive method to quantify soil moisture conditions in soils. These results could further research into hill slope hydrology and modeling which could increase the accuracy and reliability of flood risk prediction.

1.2. The study area

The Cober River is located in West Cornwall, South West England. The overall catchment size is 53.75km^2, originating in Nine Maidens Downs, along Cornwall's central granite ridge nearly 250m above sea level. It runs through the town of Helston (Figure 1) and eventually discharges into the English Channel via Loe Pool, a freshwater lagoon separated from the Atlantic by a shingle bar (Loe Bar). The location of the catchment is seen in Figure 2.

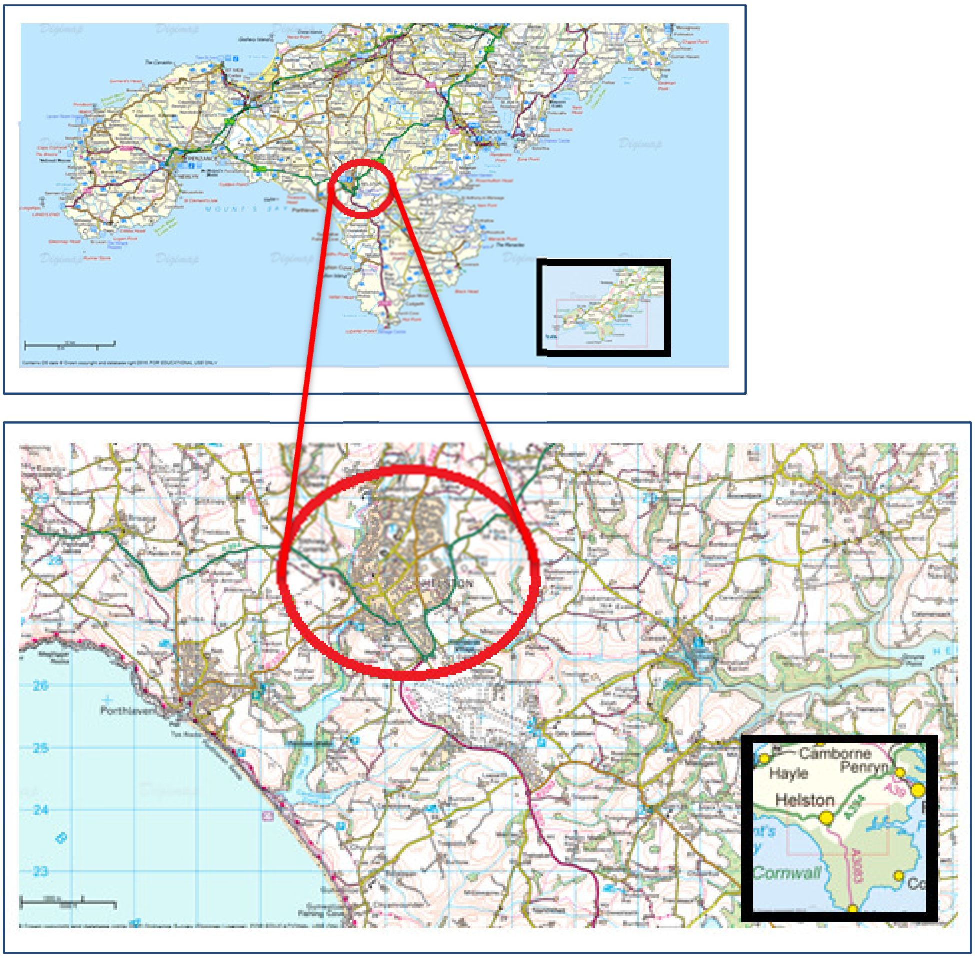


Figure 1.
Location of Helston, a small town located in South West Cornwall, South West England, courtesy of Edina DigiMap (2015)

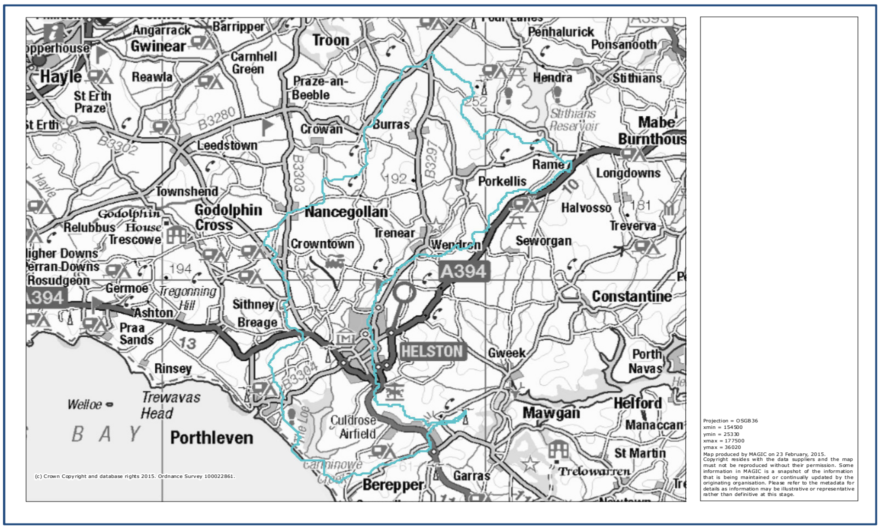


Figure 2
Cober Catchment Location as seen with outlined in blue courtesy of Cornwall Council and DEFRA, via MAGIC Interactive Mapping (2015)

The catchment consists of a varied landscape dominated by tin and copper mining. The geology dates back nearly 600 million years to the Pre-Cambrian period, which has eroded over time to expose tin and copper deposits. For this reason there is evidence of mining from Cornish communities over the past 2000 years. Helston is located to the East of the Tregonning and Gwinear mining district whilst the upper parts of the catchment are located directly within the Wendron mining district, both of which are incorporated into the Cornish Mining World Heritage, as seen in Figure 3. Ore concentrations were lucrative enough to support 30 mines within the Cober catchment until 1939, when the supply and demand within the global market forced closures. Historic mining has resulted in considerable environmental impacts, notably deposition of mine wastes throughout the catchment.

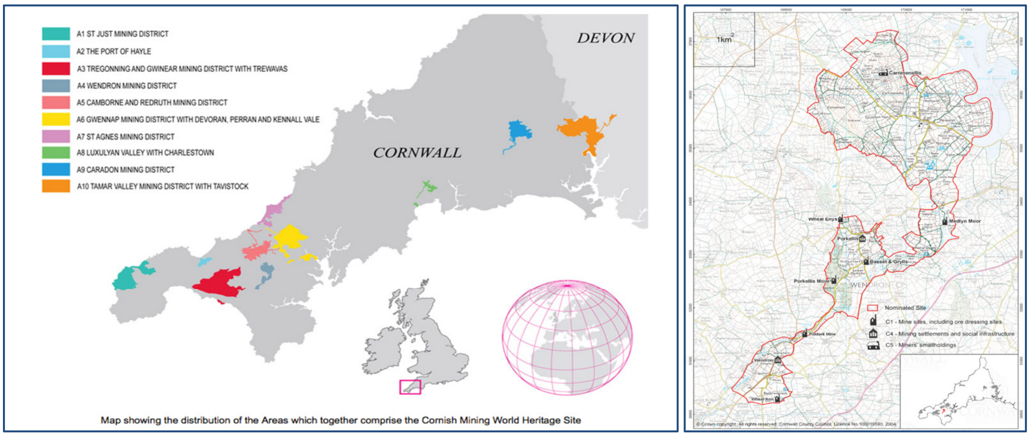


Figure 3
Historic Mining Districts of Cornwall (left) and the Wendron Mining District Location (Right), courtesy of Cornish Mining.net (2015)

Within the catchment, infrastructure wise there are a number of small villages, farm buildings and scattered remains of the former mining industry. A summary of the landscape characterization of the area is seen below in Figure 4.

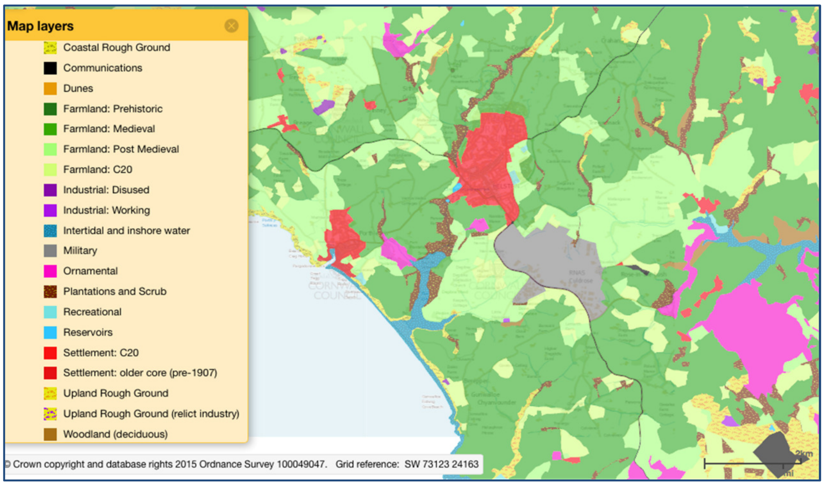


Figure 4
Cober Catchment Land Use Characterization (Helston seen as the red area denoting urban spaces). Courtesy of Cornwall Council (2015)

The upper catchment's land use is still agriculture although it is considered to be less intensive then the lower catchment. This is because the agricultural value of the land is relatively low and farming has to adapt to this. Therefore the upper catchment is predominantly lowland heath, grassland, rush pasture and wet heath supporting dairy and beef farming. There are large stretches were the floodplain has been reclaimed for agriculture. The steep valley sides (as seen in Figure 5) are unsuitable for development and are therefore natural broadleaf forests interspersed with scrub in disturbed areas.

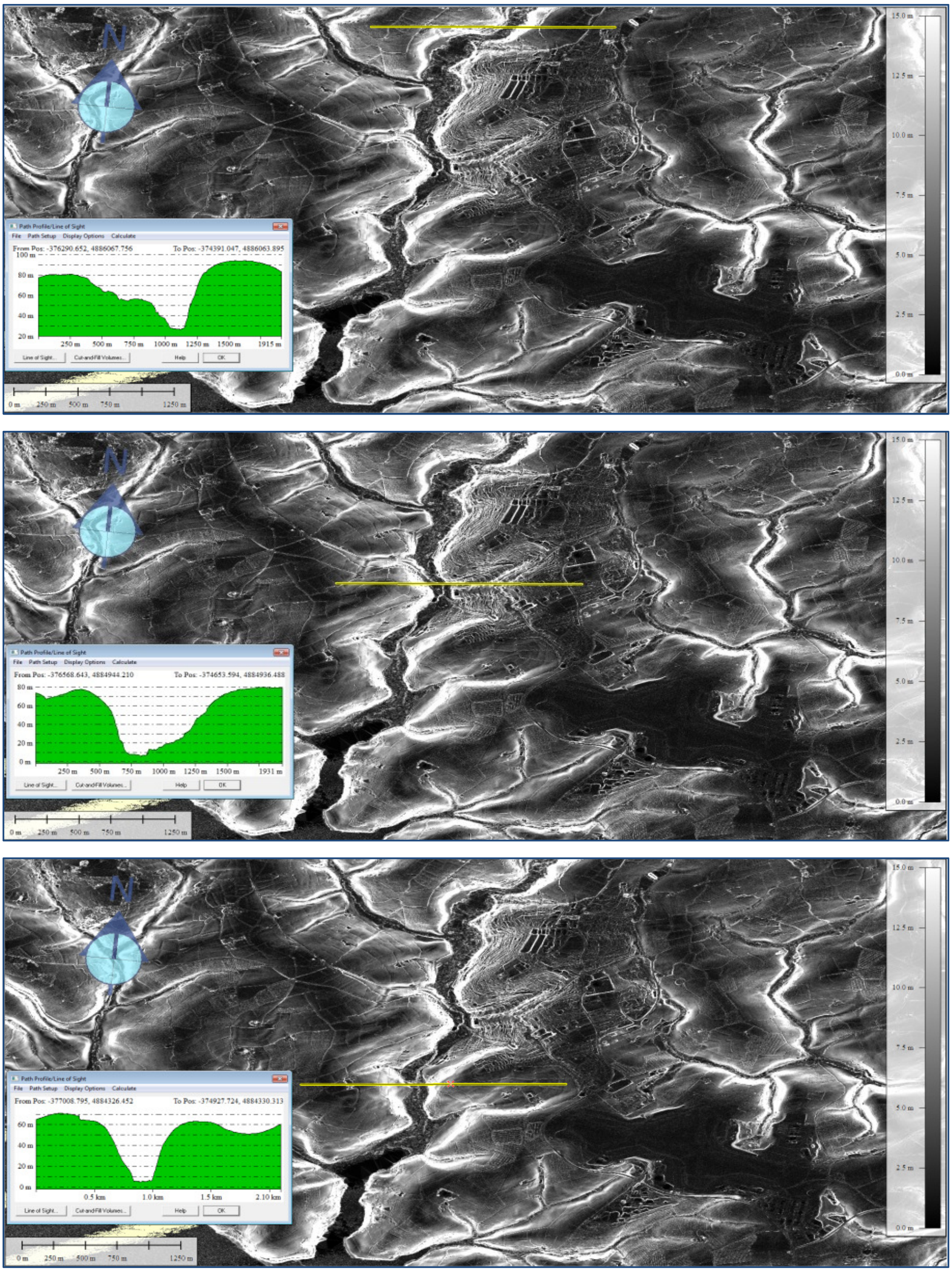


Figure 5

Showing the topography of valley sides along various points of the lower Cober River in Helston. The topographical data is courtesy of LIDAR digital terrain model surveys and screenshots from Global Mapper v.16.0, (Lidar, 2015)

1.3. Flood Risk

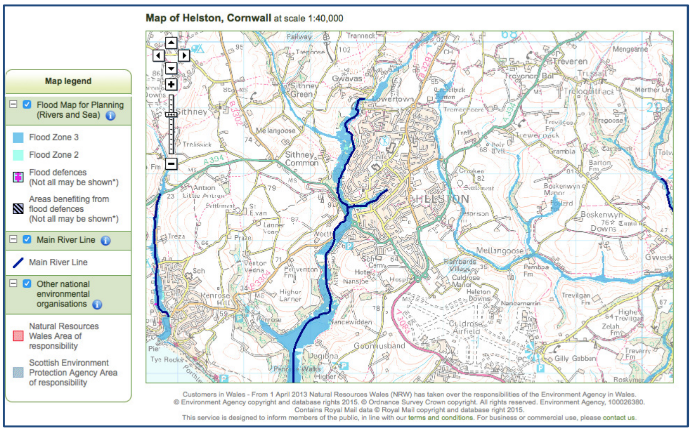


Figure 6
Flood Map for Planning (rivers and sea) for the Cober River in the Helston area. Courtesy of the Environment Agency (2015)

The Environment Agency (EA) offers guidance to the general public on general flood related issues. The image to the left (Figure 6) shows the Flood Map for planning purposes. This indicates the extent of the floodplain, especially to the West of the River Cober and Helston where flood zone 3 extends much further from the river. Flood zone 3 indicates areas which could be affected by flooding if there are no flood defenses. Statistically it implies there is a 1% chance (or greater) of a flood event occurring each year. The upper reaches of the Cober within Helston have no substantial risk of flooding, mainly due to the steep valley sides, hence the effect of urbanization directly up to the floodplain. In the lower reaches of the Cober in Helston however, flood zone 3 areas extend through urban residential areas. Corresponding to the flood planning map would be the flood warning map (Figure 7) (EA, 2015).

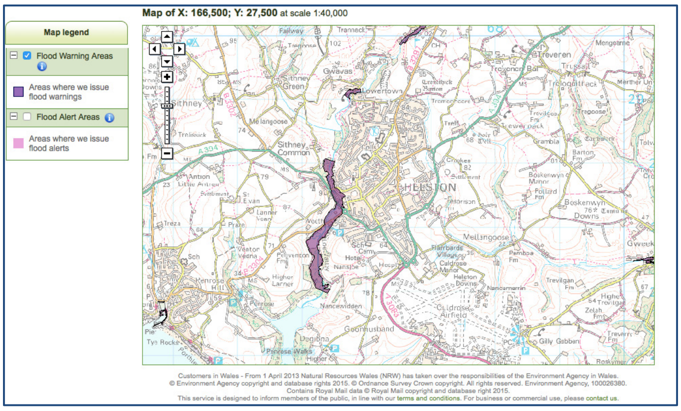


Figure 7
The areas around Helston where Flood Warnings are issued if necessary, courtesy of the Environment Agency (2015).

The EA has a flood warning issuing scheme for areas that are considered particularly at risk. At risk areas are shown in purple in Figure 7. These are areas where the EA will warn residents in advance if the threat of flooding is severe enough.

The general Risk of Flooding from rivers and sea shows the EA's assessment of flooding likelihood. It takes into consideration of flood defenses, predicted flood levels and ground water levels. Risk classification is seen below in Table 1. The risk for the Cober floodplain flooding is predominantly medium to high, Figure 8. The risk of flooding to urban areas of Helston is minimal in the upper reaches, however number of residential properties potentially affected increases in Lower Helston.

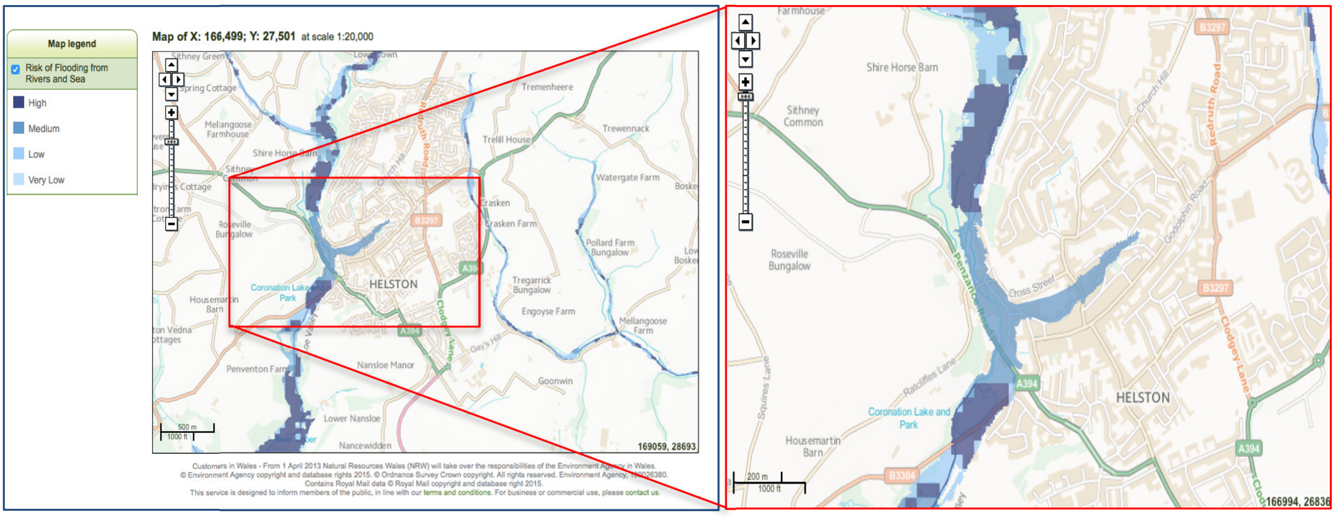


Figure 8
Risk of Flooding (from rivers and sea) along the Cober River, in the Helston area.
Courtesy of the Environment Agency, 2015

Table 1 – Risk classification of flooding (Environment Agency, 2015)

Flood Risk Classification	**Chance of Flooding (in any given year)**
High	Greater than to equal to 1 in 30 chance
Medium	Less than 1 in 30 but greater than to equal to 1 in 100 chance
Low	Less than 1 in 100 greater than to equal to 1 in 1,000 chance
Very Low	Less than 1 in 1,000 chance

1.4. Context

The catchment experiences many inter-related and complex issues however arguably the most pressing is that of flooding, especially within the Helston area. Water level management for flood prevention has been an issue since Loe Bar enclosed the mouth of the Cober. In order to alleviate flood risk the natural course of the river has been extensively altered and managed. Since 1946, the Cober flows through Helston towards Loe Pool in an artificially modified channel. This aimed to deepen and widen the channel therefore increasing the water capacity and decreasing the incidence of flooding. Channelization as a flood management method prioritizes transporting excess water away from Helston and down the valley as quickly as possible. However, serious floods have been recorded in Helston since the initial river engineering in December 1979, November 1984, and January 1988.

As a consequence of historic infilling the gradient of the lower stretches of river is very shallow. Accumulation of deposited material further decreases river gradient. This is because the water velocity drops downstream and material carried in suspension is deposited on the riverbed, making the channel shallower which decreases channel capacity. Further adding to the problem would be the fact that the Cober is artificially channelized through various parts of Helston (Figure 9), separating the river from its natural floodplain. Silt that could be deposited on the floodplain during periods of high discharge are therefore deposited on the riverbed or carried into Loe Pool. Sources of the silt and other suspended material have not fully been identified however urban and agricultural runoff is more than likely to be the main contributors. The low gradient further compounds the issue of flooding in Helston as a decrease in channel capacity and river velocity is ineffective at carrying water through to Loe Pool and therefore leaves Helston susceptible to inundation.

Figure 9
Cober River Artificial Channelization as seen through the area of St. Johns, Helston which is vulnerable to flooding. Here is evidence of work being carried out to clear the river, as velocity drops as the channel is funneled through the bridge deposition occurs. This decreases the channels carrying capacity often leading to blockages in the vicinity (Loe Pool Forum, 2015)

It has been argued that the current flood management strategy does not fully enhance its drainage capacity whilst being expensive to maintain. In December 22nd 2012, issues within the storm water management system lead to areas of Helston being severely inundated with flood waters. After a period of sustained heavy rainfall, the Cober breached its banks in two places in St. John's, prompting Cornwall Fire Service to evacuate 190 people from the area. In total nearly 50 homes in the Cober catchment were flooded (BBC News, 2012). The area worst affected is the low-lying St. John's area of town.

A major factor contributing to the influx in discharge would be the runoff from the increasingly urbanized areas of Helston. Runoff from the center of town combines with the river which has been diverted around the Helston Kennels, flowing into a small unnamed stream (NRA, 1993), which eventually, along with any potential rainwater, drains back into the Cober in the St. John's area. The stream only has a hydraulic capacity of $0.5m3s^{-1}$, considerably smaller than the higher discharges experienced by the Cober that can reach $4m3s^{-1}$.

The Environment Agency (EA) carries responsibility for flood defense and water resource management, among other functions. The EA monitors the Cober via a gauge at the Helston Country Bridge in the St. Johns area as seen in Figure 10. The gauge has a typical range of 1.168m, between levels of 0.232m and 1.400m (GaugeMap, 2015). On December 22nd, 2012 the river gauge indicated water levels in the Cober were at 2.111m after sustained periods of heavy rain prompting the Environment Agency to issue a severe flood warning for various areas within the Cober Catchment, including areas of Helston (BBC News, 2012).

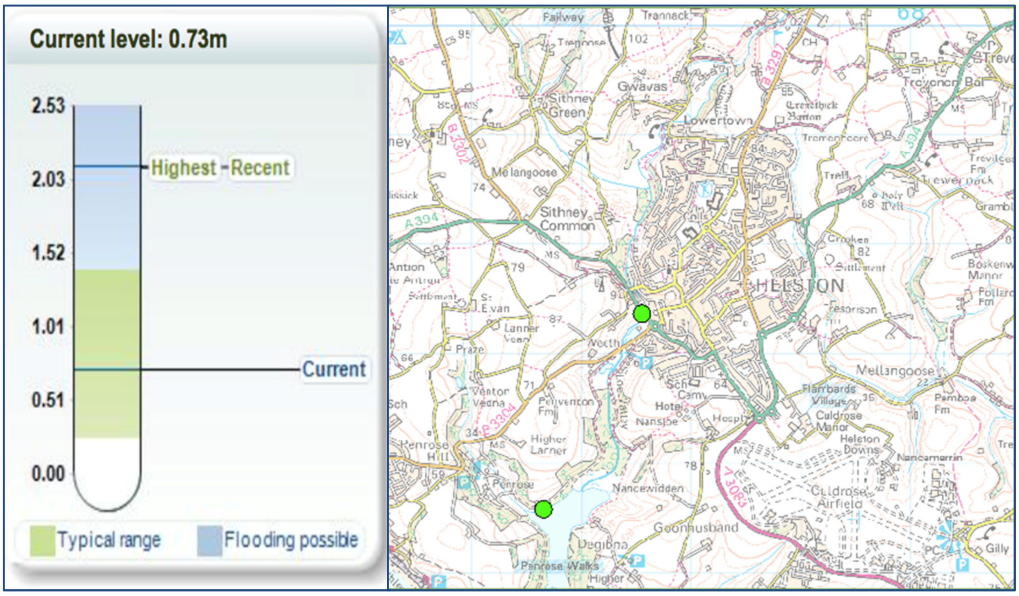


Figure 10
County Bridge River Level (left) and Location (right) . The example gauge reading was taken on the 28th of August. The highest (recent) marking on the gauge was the reading taken on the 22nd of December when the river level measured 2.111m. Courtesy of GaugeMap, 2015.

The Cober River is a complex and dynamic hydrological system, and management strategies need to use integrated knowledge of the catchment and river systems in order to successfully manage the unpredictable and intermittent nature of excess storm water flow. The flooding in 2012 serves as a reminder that the Cober river system is highly influenced by a number of factors which together increase storm water in the channel.

1.5. The aim, objectives and scope

1.5.1. The Aim

To assess the viability of using ground electrical resistivity measurements to find a correlation between meteorological conditions, specifically precipitation and temperature and depth of the River Cober within 4 sites within the catchment. **Overall, the project aims to assess the potential to use electrical resistivity as a low cost tool to increase the accuracy of flood warning systems.**

1.5.2. The Objectives

1. Data sets will be extracted from four sites along the River Cober catchment in Helston, Cornwall. One site is along the flat floodplain with a high risk of flooding whilst the over three are located in steeper sections of the catchment, with a lower risk of flooding representing the vertical profile of the catchment. Land use at each site varies.

2. Electrical resistivity readings will be taken at the same location in each site on days of varying precipitation and river depth.

3. Precipitation, river depth and soil electrical resistivity data sets will be combined and analyzed in order to assess whether correlations exist between data and electrical resistivity.

4. If a correlation is viable, then the ultimate aim is to assess whether it is feasible to use this correlation in order to assess flood predication in the Cober catchment area.

1.6. Justifications of the research

The project aims to act as a comprehensive feasibility study, assessing whether electrical resistivity is a viable method of soil moisture prediction. There is dividing opinion surrounding the use of electrical resistivity to use in soil characterization due to problems of differentiating between the various soil properties which will influence its resistivity. The project takes a more simplistic and holistic approach however when considering soil electrical resistivity and therefore will generalize all factors influencing soil moisture purely focusing on the sensitivity of an Ohmmeter to detect perturbations in soil resistivity due to precipitation.

Therefore the data and equipment required is designed to reflect the simplicity of the project. Primary data collected using the Chauvin Arnoux C.A. 6470N Ohmmeter is made possible by Camborne School of Mines (CSM) in this instance; however the equipment is available to buy for the general public. Secondary data is supplied by the Met Office, on behalf of RNAS Culdrose and The Environment Agency for metrological data and river gauge data respectively.

1.7. Structure of report

The initial section introduces the main aims and objectives of the report whilst explaining the significance and context of the research. As the project is a method feasibility study, the background theory and literature review make up a large portion of the report. Chapters two and three offer a comprehensive understanding of the principles and theory of hydrology, hill slope flood prediction modeling and electrical resistivity, information from which will form the basis of the methodology. The literature review in Chapter four is a synthesis of information from previous research on the various components on the project.

The methodology is outlined in Chapter four which reflects the conclusions drawn from the literature review and background theory. The results of the fieldwork are presented, reviewed and discussed within Chapter five. Discussions include conclusions inferred from the data collection as well as problems encounters and associated limitations within the method. The final chapter summarizes and concludes the findings, answers the initial aims of the research and suggests future research.

2. BACKGROUND AND THEORY

To simplify the complicated topic of hydrology, runoff rate is mainly dependent on three interrelated factors, which combined influence potential flood risk. Firstly, is the rate and extent of water input to the catchment via precipitation. Secondly, the hill slope to channel interface that effects how the water input reaches the channel, and lastly the nature of the channel and valley flow conveyance systems need to be considered. Even small variations in the factors listed above will produce different hydrological conditions within the catchment.

2.1. Catchment Processes

The entire catchment fluvial process is an open system for both energy and matter. This energy output is often referred to simply as stream discharge, which is the rate at which a volume of water passes through a given cross sectional area per unit time. It is the critical discharge stage as which the water surface elevation and velocity means that water rises over river banks and spreads across the floodplain. Often termed overbank discharge, as runoff is supplied to a reach of channel faster than the channel can convey water downstream. The main contributing factors towards over bank discharge include floodplain conveyance and floodplain storage. For society the predominant concern of flooding would be the critical issue of health and safety risks to human life and the potential for infrastructure damage. This is the principle of flooding, although there are multiple definitions depending on the context.

In smaller basins, local patterns of rainfall onto soil mantled hill slope's and water storage are key, therefore hydrographic and hydraulic conditions that contribute to downstream flooding are best understood with the use of hill slope runoff models. Recently there is a greater use of computerized spatial databases of watershed characteristics and satellite records of local weather conditions. However, variable contributions from diverse sources can produce different inundation patterns. Key to successful flood prediction modeling is to therefore to account and quantify all the potential influencing variables. Surface runoff is the most sensitive of the water balance quantities to perturbation. It is generally a small residuum of two much larger processes, evaporation and precipitation and therefore subject to proportionately larger changes.

2.2. Soil Characteristics

Soil is comprised of mineral materials (from the breakdown of underlying rock), organic matter, water and air. A soil profile consists of horizons that can vary in texture and composition. Typical soil horizons are seen in Figure 11 (soil horizon info). Soil is formed by processes that include accumulation of organic matter, dissolved ions and suspended particulates. These particles can also be affected by transformation via capillary action, eluviation which is removal of particles by leaching or translocation by erosion.

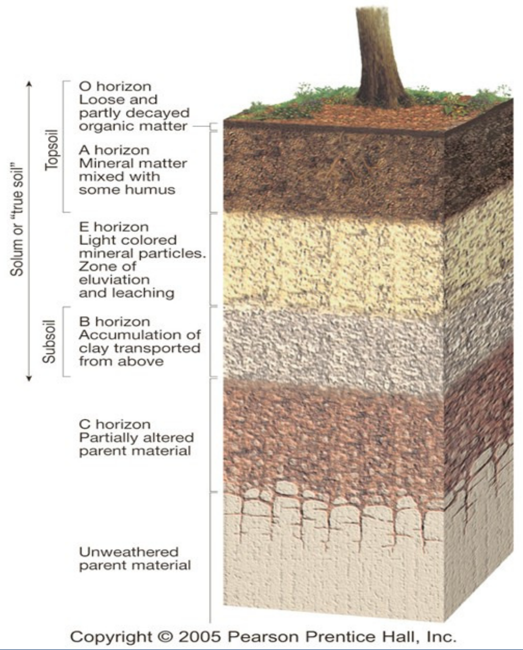


Figure 11
Shows the generic soil horizons associated with a profile depth of soil. These horizons develop over time. Generally, soil is considered a 'natural surficial material that supports life', which is 25% air, 25% water, 45% mineral matter and 5% organic matter (courtesy of Geophysics.ou.edu, 2015)

Soil characteristics depend on numerous factors. Base material depends on local rock mineralogy, as different minerals weather at various rates to produce various soil minerals. The local climate such as temperature and precipitation will influence the weathering and leaching rates of soil whilst surrounding vegetation acts as a source for carbon dioxide and other organic acids. The topography will affect the drainage and erosion patterns, whilst all factors listed above are influenced by time. The ratio of sand to silt to clay within a soil will impact the soils potential infiltration capacity. For example sandy soils are well draining whilst clayey soils drain poorly.

Retention and movement of water in soil is dependent on the potential, kinetic and electrical energy available. Water retention forces include capillary rise, surface tension, polarity, soil suction, soil water potential and osmosis. Key roles of soil water other than controlling runoff, infiltration and storage include supplying vegetation, recharging groundwater storage and movement of pollutants.

2.3. Soil Moisture

Soil moisture has various definitions depending on the context; however soil moisture is most commonly referred to as the conditions within the unsaturated (vadose) zone of soil. This unsaturated zone and ground water table extents are never constant and vary temporally due to forcing by weather and hydro-climatic conditions at the surface, and spatially due to soil distribution and topography (Destouni and Cvetkovic, 1998). Therefore, soil moisture over various points in time and space will reflect conditions in the unsaturated and saturated ground water zones. Soil moisture is of particular importance within hydrological process prediction because antecedent conditions influence the total precipitation input between potential surface and subsurface pathways (Massari et al, 2013).

The overall change in soil moisture storage is the change in recharge to discharge of groundwater. Water is recharged into the ground water system through infiltration of precipitation at the surface, seepage through surface water bodies, groundwater leakage and outflow through aquifers. Discharge however occurs though evaporation, natural discharge from channels or through seepage, groundwater leakage and outflow through aquifers and artificial abstraction in urban areas. Direction and rate of groundwater movement can be calculated from the hydraulic gradient *(ksat*) and hydraulic conductivity (*k*). Hydraulic conductivity is the ability of a given fluid to move through the soil pore spaces (USGS, 2015). There are two main factors affecting conductivity firstly being the fluid characteristics such as density and viscosity. Secondly would be the porous media characteristics, in this case the soil, such as pore sizes, gradients along bedding planes and potential folding or jointing in rocks present.

2.4. Infiltration

If water that is not taken up by vegetation, infiltrates into the ground or evaporates from the surface, it will flow as surface runoff. Factors that affect surface/subsurface flow distribution on a hill slope scale include gradient, form, surface roughness and infiltration capacity. The key factor would be infiltration capacity that is defined as the maximum rate at which water is absorbed into the ground.

Generally, infiltration capacity decreases during rainfall until a stable value has been attained. This value is known as saturated hydraulic conductivity (*ksat*), which is reached when the soil is completely saturated. When soil is saturated and precipitation rate exceeds *ksat* then overland flow known as 'saturation excess' will occur. If rainfall rate simply exceeds infiltration rate and the soil is still unsaturated then the excess rainfall is termed 'Hortonian Overland Flow'.

Therefore, the relationship between the precipitation intensity and infiltration capacity determines not only what type of flow will occur but also importantly how the flow will be partitioned between the surface and subsurface. Soil moisture conditions are of great importance within hydrological process prediction as they can influence the relative proportion of rainfall input over potential overland or subsurface pathways (Massari et al, 2013). The greater the proportion of surface runoff the generally equates to a shorter lag time between precipitation occurrence and an increase in stream discharge. Excess runoff is often a significant factor in flash flooding, as large amounts of surplus water flow into the stream at much higher discharges than normal. The volume of water is often greater as water is not stored within the catchment. Runoff is a considerable factor for flood prediction.

2.5. Runoff

Surface runoff (or overland flow) is when the rainfall rate exceeds the infiltration rate. The runoff will appear within a hydrograph, after initial abstractions of water via infiltration, interception and surface storage. Surface flows often occur during a precipitation event however cease shortly after precipitation has stopped.

There are a number of meteorological and physical factors that influence runoff within a drainage area. As already highlighted infiltration capacity and soil moisture storage are very important when considering the relationship between surface runoff and subsurface water storage. Norbatio et al, 2009 made a link between higher runoff ratio's occurring in relation to higher antecedent soil moisture conditions in a catchment.

2.6. Subsurface Flow

Once water has infiltrated into the ground surface it is known as subsurface flow, which can be partitioned into ground flow or through flow (which can be saturated or unsaturated). Through flow is water that infiltrates the ground surface and then moves laterally though the upper soil horizons. When rainfall occurs and enters the soil more rapidly than it can drain it will flow laterally, in the direction of greater hydraulic conductivity. Groundwater flow is the process where water will percolate through soil to deeper horizons, eventually reaching the channel along layers of varying permeability.

It is often the water held in fully saturated soils and bedrock, meaning pore spaces are completely full and the water pressure is equal to (or greater than) atmospheric pressure. However in the unsaturated zone, the pressure is less than atmospheric pressure creating a transition zone where water moves from high potential to a low potential, towards the groundwater. Groundwater represents the main long-term component of subsurface flow. Therefor the soil and ground are a medium in which water can be stored within the hydrological cycle. Base flow is the steady flow of water from natural storage such as aquifers. This storage component is seldom considered in runoff prediction as it is too long term of a process (USDA, 2004).

Catchment hydrology and drainage basin processes have been summarized above. Clearly soil moisture is a variable controlling a wide array of hydrological processes, importantly the runoff, infiltration and storage ratio of incoming precipitation. The antecedent soil moisture conditions of a catchment have been shown in multiple studies to be highly influential in predictive flood occurrence (Romano, 2014). It is of great importance therefore that initial soil moisture conditions are estimated accurately (Norbiato et al, 2009 and Massari et al, 2013).

2.7. Hill slope modeling and flood prediction theory

The study of flood prediction and soil moisture modeling has been of growing interest as building on flood plains becomes more common place. With the development of urban areas on flood plains there is a greater risk from flooding, a phenomenon that needs to be predicted accurately and timely more and more. Therefore, there is an increased need to augment meteorological flood forecasting with a quantifiable field method that takes into account local hydrological phenomena. There are many ways of predicting flooding, all often complicated and dependent on quantifying hydrological processes. Discussed below is just one common method of hill slope modeling to achieve a basic understanding of how water flow over a catchment might react to a precipitation event.

Runoff is a principle component of hydrological modeling and is often represented as a Curve Number (CN), which is an index developed by the Soil Conservation Service (SCS) (Halley et al, 2014). The CN is a hydrological parameter which estimated the potential storm water runoff for a drainage area based on land use, soil type and soil moisture. This methodology is widely regarded as the standard hydrological analysis technique in a variety of settings, especially in the United States. As it is a directly derived from soil and land use within the catchment, accurate estimate of the CN involves the mapping of the various soil types and land use categories.

The CN method of runoff potential quantification factors in potential losses such as evaporation and surface storage. Runoff (Q) is dependent on factors such as rainfall (P), maximum water retention (S) and initial abstraction (I_a) (Equation 1).

$$Q = \frac{(P-I_a)^2}{(P-I_a)+S} \qquad (1)$$

The Curve Numbers were assigned using values specifically designed for small urban catchments against the different soil hydrologic groups (Figure 12). This gives an indication of the soils potential infiltration rate. Whilst most soil surveys list the soil types and the hydrological soil grounds, these are only used to estimate the infiltration rate.

Hydrologic Soil Group	Soil Texture	Soil Group Characteristics
A	Sand, loamy sand, or sandy loam	Soils having high infiltration rates, even when thoroughly wetted and consisting chiefly of deep, well- to excessively drained sands or gravels. These soils have a high rate of water transmission.
B	Silt loam or loam	Soils having moderate infiltration rates when thoroughly wetted and consisting chiefly of moderately deep to deep, and moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.
C	Sandy clay loam	Soils having slow infiltration rates when thoroughly wetted and consisting chiefly of soils with a layer that impedes downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission.
D	Clay loam, silty clay loam, sandy clay, silty clay, or clay	Soils having very slow infiltration rates when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission.

Figure 12
Soil characteristics are derived from the Natural Resource Conservation Service, 1986, using soil hydrological groups. Group A has the lowest runoff potential (highest infiltration capacity, whist Group D has the largest runoff potential and the highest water table (lowest infiltration capacity).

Impervious surface percentage is a key part of CN estimation as it defines the land cover of the sub basin with a hydrological runoff perspective, which validates the CN values. Land use distribution can be calculated using planimetric, zoning, parcel boundary maps, aerial photography or already characterized areas on a GIS database. The detail of land use within a catchment is dependent on the accuracy necessary for the modeled output. Land use categories and associated curve numbers are seen in a table extract below (Figure 13). Full tables are tailored to suit the need to the runoff analysis (Halley et al, 2014).

Chapter 2 — Estimating Runoff — Technical Release 55 Urban Hydrology for Small Watersheds

Table 2-2a Runoff curve numbers for urban areas [1]

Cover description: Cover type and hydrologic condition	Average percent impervious area [2]	Curve numbers for hydrologic soil group: A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation) [5]		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c).					

1 Average runoff condition, and $I_a = 0.2S$.
2 The average percent impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition. CN's for other combinations of conditions may be computed using figure 2-3 or 2-4.
3 CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.
4 Composite CN's for natural desert landscaping should be computed using figures 2-3 or 2-4 based on the impervious area percentage (CN = 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.
5 Composite CN's to use for the design of temporary measures during grading and construction should be computed using figure 2-3 or 2-4 based on the degree of development (impervious area percentage) and the CN's for the newly graded pervious areas.

(210-VI-TR-55, Second Ed., June 1986) 2–5

Figure 13
A table used to derive CN values for small urban catchments using land use and different soil hydrological groups. Courtesy of Natural Resources Conservation Service, USDA, 1986.

Curve numbers need to correspond to an antecedent moisture condition (AMC). In this instance AMC is defined as the initial soil moisture conditions prior to a storm event. Within the SCS methodology AMC is based on seasonal limits for precipitation within the 5 day period before the storm event (McCuen, 1982).

For a more comprehensive view of CN values for a catchment it is often easier to create sub basins within a watershed. The CN values can be weighted based on the land use and soil properties within a given drainage sub basin.

The overall equation is as follows:

$$CN_{aw} = \frac{\sum_{i-1}^{n}(CN_i * A_i)}{\sum_{i-1}^{n} A_i} \qquad (2)$$

CN_i is the curve number for each land use soil sub basin, A_i is the area for each land use in each sub basin and n is the number of sub basins which make up each catchment area (Halley et al, 2014).

2.8. Electrical resistivity theory

The general principle of geophysical surveys is the non-intrusive collection of data which is also rapid, efficient and relatively cheap to use therefore allowing the investigation of larger areas (Chapot et al, 2011). The purpose of a soil resistivity surveys is to calculate resistivity distribution and patterns over a volume of soil. In order to achieve this, electric currents are artificially generated and the resulting potential difference is measured. The patterns of measured potential difference provide information on the subsurface heterogeneities (Kearey et al, 2002).

Theoretically, resistivity surveys are based on the use of direct current (DC), as it allows for the greater depth of investigation compared to alternating current. It minimizes problems that arise from the effects of inductance and capacitance of the ground. Although in practice, alternating current (AC) is more frequently used. Direct current electrodes create a polarized ionization field in the electrolytes around them whilst the earth's natural currents and spontaneous potentials induce further unwanted potentials. The use of alternating current reduces the effect of any unwanted superimposed direct currents (EPA, 2015). The majority of resistivity instruments now include an ammeter to verify that the generated current is at an acceptable level between electrodes in order to return a valid result.

For a simple body, the electrical resistivity (ρ, measured in ohms per meter, $\Omega_{-m)}$ R (measured in ohms, Ω) is defined as follows:

$$\rho = R\left(\frac{S}{L}\right) \qquad (3)$$

Where L is the length of cylinder (m) and S is the cross sectional area (m^2).

Fundamental to resistivity theory is Ohms Law, denoting resistance of a given cylindrical body, R, as:

$$R = \frac{V}{I} \tag{4}$$

Where V is the potential and I is the current.

Measurement of electrical resistivity of a soil sample usually involves four electrodes. Two electrodes, A and B, are used to inject the current whilst the remaining two, M and N, record the resulting potential difference. Theoretically there should be no voltage flowing between M and N, the potential electrodes. This is achieved by using either a null balancing galvanometer or high input impedance operational amplifier (EPA, 2015). The electrodes are commonly stakes of bronze, copper and steel and must be driven sufficient into the ground to make good electrical contact whilst remaining stable and upright (EPA, 2015). Theoretically in a homogeneous and isotropic space (the soil medium) the electrical equipotentials are hemispherical from the point source, as seen in Figure 14.

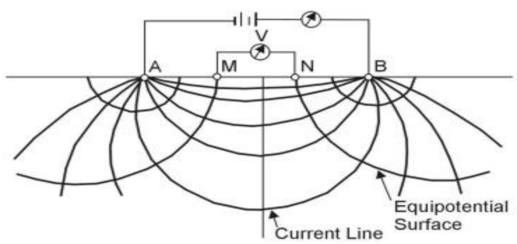


Figure 14
The electrical field generated around the two electrodes (A and B). Equipotentials illustrate the imagery shells surrounding electrodes where the electrical potential is equal everywhere. There are infinitely many paths followed by the current (EPA, 2015).

The potential difference ΔV, is then calculated using the equation below.

$$\Delta V = \frac{\rho I}{2\pi}\left[\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}\right] \quad (5)$$

Where AM, BM, AN and BN represent the distance between the respective electrodes. The overall electrical resistance is then calculated using a geometrical coefficient (K) that is dependent on the electrode arrangement.

Electrical resistivity surveys can be one-, two- and three- dimensional, depending on the required outputs. One dimensional surveys are often used in electrical resistivity calibration processes or for vertical electrical sounding (VES). VES creates a vertical profile of a soil sample by progressively moving the electrodes further apart successively. The results represent the vertical variation of soil resistivity although cannot display this variation horizontally (Loke, 2001). It is normally assumed that the subsurface consists of multiple horizontal layers although no information can be derived from a VES. Bottraud et al, 1984 highlighted the usefulness of VES methods of electrical resistivity to soil science by emphasizing its ability to record vertical discontinuity with various soil horizons. However, for more complex results corresponding to horizontal and vertical changes, both 2D and 3D surveys will render more detailed outputs.

2D surveys involve a multi-electrode array with fixed electrode spacing and current that is moved progressively along a line at the soils surface. This produces a two dimensional vertical sounding image. The inter electrode spacing (a) is dictates the depth of investigation. Depth of a measurement is the distance between electrodes (a), halved. The greater the a values, the greater the depth until maximum electrode spacing has been reached, known as the maximum depth of the investigation, the 'pseudo-depth'. This information is collated to form a 2D pseudo section plot that can display horizontal and vertical resistivity variations of soil (Edwards, 1977).

The geometrical coefficient (K), which derives the electrical difference, is dependent on the array configuration. The most commonly used would be Wenner, Wenner-Schlumberger, dipole – dipole (Figure 15), pole – pole or pole – dipole arrays. Figure 16 summarizes the various characteristics of the array that can have considerable effects of the investigations resolution, sensitivity and depth (Seaton and Burbey, 2002). The various array types have specific advantages and limitations (Samouelian et al, 2005). Hesse et al, 1986 highlighted the potential to use multiple array configurations in order to gain a clearer interpretation of subsurface soil features.

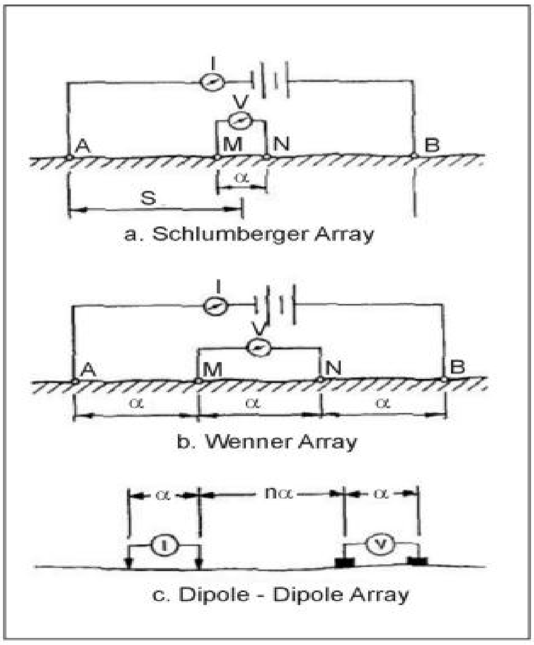


Figure 15
The various deployment patterns of electrodes in a VES are seen above. VES is carried out by increasing the electrode spacing in a systematic manner around a centered point in a method as seen above. Courtesy of Geotec.co.il, 2015

2D surveys can be used in combination to extrapolate data points and form more detailed 3D electrical resistivity image, over a larger area. Reliability issues arise if electrical anomalies are not preferentially orientated to the previous 2D investigations. It widely accepted that several 2D pseudo sections should be oriented in at least two directions, perpendicular to each other (Chambers et al, 2012).

Characteristics of different 2D arrays configurations types

	Wenner	Wenner–Schlumberger	Dipole–dipole	Pole–pole	Pole–dipole
Sensitivity of the array horizontal structures	++++	++	+	++	++
Sensitivity of the array vertical structures	+	++	++++	++	+
Depth of investigation	+	++	+++	++++	+++
Horizontal data coverage	+	++	+++	++++	+++
Signal Strength	++++	+++	+	++++	++

The labels are classified from (+) to (++++), equivalent at poor sensitivity to high sensitivity for the different array configurations.

Figure 16
A summary of the different 2D array configurations and the effects these have on resolution, sensitivity and depth. Courtesy of Samouelian et al, 2005

3. LITERATURE REVIEW

A comprehensive review of current and topical literature was undertaken and the feasibility of different methods of measuring catchment characteristics assessed. Each component of catchment hydrology is incorporated into catchment dynamics and current methods of measuring these components assessed and discussed.

4.1. Electrical resistivity and soil moisture estimation methods in literature

Soil moisture is a variable that is influenced by a wide array of ecological, hydrological, geotechnical and meteorological processes (Romano, 2014). Therefore its existence, amount and the physical, chemical and biological conditions are subject to changes from natural environmental conditions and land management, ultimately leading to changes in storage or soil and soil water across a landscape. Therefore, obtaining representative catchment scale soil moisture measurements can be incredibly difficult due to the dynamic spatial and temporal behavior of soil moisture and its influencing variables (Teuling and Troch, 2005).

In a theoretical study by Ablerston and Montaldo (2003), the influence of parameters including soil, vegetation, precipitation, topography and antecedent conditions on soil moisture dynamics. The results conclusively showed that all the parameters influenced the temporal and spatial dynamics, proving that obtaining soil moisture conditions at the catchment scale can be potentially highly inaccurate, and use in flood prediction is therefore difficult.

3.2. Review of current soil moisture recording methods

Many components of the hydrological cycle including precipitation, stream discharge and runoff are comparatively easy to measure; water infiltration in soils remains more problematic (Huat et al, 2006). Infiltration rates usually decrease with time until a final, constant value is ascertained. There are a few direct and indirect methods which attempt to establish accurate values for infiltration and soil moisture conditions.

3.2.1. Direct methods

Direct methods of infiltration estimation involve processes and equipment that is designed to collect primary data at specific locations. Measurement methods usually include local ground or soil sample measurements at a given depth which then may be extrapolated to represent soil moisture values over a greater area or depth (Destouni, 1991).

Lysimeters are devices which are placed within the ground to collect soil moisture data by measuring the change in mass of water volume in samples. It works on the principle that the mass of soil water will change over time due to evaporation or precipitation, and changes in the two can derive soil moisture conditions. Whilst it supplies viable data on evaporation, lysimeters can be difficult, intrusive and expensive to install and maintain. They are often unreliable when recording soil moisture variability and are therefore not recommended using when assessing temporal changes.

Gravimetric methods are often regarded as the simplest and most accurate. It is a method of quantifying volumetric water content and/or degree of saturation. It can estimate the ratios of water overall water volume and pore water volume to bulk soil volume. Simply the method involves weighing a soil sample when wet, oven drying it and weighing the sample dry to calculate change in water volume. It is possible to take multiple soil measurements that can extend over larger spatial and temporal scales. From these field plots it is possible to extrapolate a larger database of volumetric soil content (Destouni and Verrot, 2014).

Neutron probe is an intrusive method where a radioactive source is lowered into a hole where neutrons collide with the water particles within the soil. Hydrogen ions are a similar size to neutrons and therefore speed up after colliding with the neutron that slows down. If a neutron hits a larger soil particle it will collide with little change in speed. Detectors can therefore measure the scattering of neutrons by the hydrogen atoms which are a function of water content. However, the method has several problems. It is destructive to the soil and the use of radioactive sources involves serious considerations to the environment, health and safety. The method also requires extensive calibration which can be time consuming and expensive.

Time domain reflectivity involves passing a wave of electromagnetic energy through soil. The reflected wave properties are altered depending on the water content. However there is a large problem of data interpretation and often results are only small indications of the actual water content. A good preliminary study however rarely used for conclusive data.

Rainfall simulation is another commonly used method for estimating infiltration based on the principle of spraying water onto a surface (usually below a couple meters squared). Disk infiltrometers are used to measure how long the water takes to drain. The simulation method has had mixed responses in the literature. Podwojewski et al, 2008 found the technique to be useful to estimate the overall infiltration of a soil sample in a variety of environmental contexts. However, several studies have highlighted the fact that the method is often time consuming and expensive. Furthermore it is not suitable for sloping land, as a level artificial soil horizon would have to be created, which potentially interferes with the natural soil properties. Pouring large amounts of water onto a surface artificially has the potential to induce aggregate breakdown due to rapid wetting. This would sharply decrease infiltration and storage (Mamedov et al, 2001). As with any other point sampling methods, observations may not be spatially representative of larger surface areas.

3.2.2. Indirect Methods

Flow nets are an indirect method of estimating soil moisture and subsurface water flow by extrapolating previously collected primary data. It is a method of relating flow distribution to hydraulic/potential gradient. Similar to a contour map the method joins points of equal potential to map the potential distribution of groundwater flow. Groundwater flow corresponds to the maximum gradient of potential indicating the direction of flow and can potentially be used to derive the rate of flow.

Soil moisture models have the advantage of addressing larger temporal and spatial scales in different contexts and environments. For example, a water balance equation may be set up over some hydrologically active soil depth to investigate the soil moisture interaction through the landscape (Botter et al, 2007). However, it is difficult to summarize the problems with individual soil moisture models and a number of generic problems experienced with environmental modeling arise. In many of the hydrology models the cycle isn't closed, instead analyzed as a partial loop of processes that directly influence soil moisture. The loop is driven therefore by estimated precipitation of future rainfall. It introduces huge uncertainties that are the propagated throughout the model. This problem occurs with any estimated parameter in any given model.

Remote sensing data is becoming an emerging source of information to map large-scale soil moisture patterns. The first applications involved remote sensing information for calibration and verification of rainfall-runoff models (Wooldridge et al, 2003). Data is now achieved through various widely used satellite products that can accurately cover large areas. Whilst the method is still under development, it can be used in conjunction with ground measurements are often used to validate the remote sensing products (Cosh et al, 2004). Gautam et al, 2000 argues that as every catchment has its own characteristics remote sensing might be more appropriate for soil moisture monitoring as temporal and spatial resolution may not be suitable for smaller scales (Brunet et al, 2010).

In general, the majority of the in situ techniques can be highly intrusive and potentially very costly. If point observations are available then assessing the spatial variability of soil moisture over larger areas is not fit for purpose. The more indirect methods may not be temporally and spatially accurate for smaller areas. Therefore, alternative in situ techniques are required to predict the spatial and temporal variation of infiltration (Chapot et al, 2011).

3.3. Electrical resistivity and soil moisture in literature

Electrical resistivity measurements of soil have the potential to reflect spatial and temporal variability within the soils moisture content. This is due to the fact that soil materials exhibit electrical properties depending on their physical and chemical properties, including but not exclusive to texture, salinity and importantly water content (Samouelian et al, 2003). In relatively homogenous soils electrical resistivity depends mainly on soil water content, electrical conductivity of pore water (ρ_w) and soil porosity (ϕ) (Archie, 1942). S is the water saturation of the soil whilst a, m and n are empirical coefficients.

$$\rho = a\rho_w \phi^{-m} \; S^{-n} \tag{6}$$

Therefore, by rearranging Eq X, saturation degree can be obtained by (Samouelian et al, 2003):

$$S_n = \frac{a\rho_w}{\phi^m \rho} \tag{7}$$

Archie's equation therefore implies that soil resistivity is dependent on porosity and degree of saturation, both indicators of soils water storage potential (Kowalczyk et al, 2014).

Electrical resistivity has been tested under laboratory conditions to assess the relationship between particular soil parameters and resistivity. Soil type consisted of waterlogged non-cohesive soils to test the hypothesis that the solid particles in non-cohesive soils are non-conductive whilst only the intergranular spaces filled with mineralized water were able to allow electrical current flow. It indicated that the electrical conductivity of soil was dependent on the amount of water, the conductivity of the water and the way the water moves (including spread, porosity, degree of saturation, cementation factor and fracturing)

(Kowalczyk et al, 2014). However, experience has shown that in practice the results are often different to those hypothesized.

The decrease of resistivity can be observed with an increase in soil moisture content (Kowalczyk et al, 2014). The conductivity of the water is especially important to consider as it is noted that water conductivity is mainly electrolytic. The conductance of pore water is related to the size and type of electrolyte. For example, an increase in the salinity of pore water results in a decrease of resistivity (Guyod, 1964). Thus the electrical current depends on the amount and quality of water within soil pores (Chaplot et al, 2011). Moreover, literature indicates that an increase in soil porosity results in higher electrical resistivity (Samouelian et al, 2005), a principle that can be used to differentiate between soil horizons (Robain et al, 1996).

3.4. Advantages

The advantage of geophysical methods is that they are 'non-invasive, non-destructive, relatively rapid and cost-effective' (Kowalczyk et al, 2014). Electrical resistivity surveys are more frequently being used as preliminary and supplementary surveys to soil investigations (Kowalczyk et al, 2014). They can be incredible useful for soil investigation by enabling estimates of lateral variability, especially in the near surface zones. There is the added potential to assess the vertical variability if 2D and 3D electrical resistivity methods are utilized.

Despite soil moisture being highly variable spatially it has been implied that it can show strong temporal stability (Vachaud et al, 1985). This is now referred to as soil moisture rank stability (Chen, 2006). In a review of various soil moisture observations it was shown that rank stability of soil moisture have been recorded under a number of different conditions, at various spatial and temporal scales. The conditions included different soil and vegetation type (Vanderlinden et al, 2012). Martinez et al, 2006 showed that there is relationship between rank stability, climate and soil properties, indicating that electrical resistivity has long term climate monitoring capabilities.

Soil conductivity depends on both the amount, the viscosity of the water and its concentration of dissolved ions, therefore geophysical methods have been used to monitor flow and dissolved ion transport with success (Chaplot et al, 2011). This formed the basis of many studies assessing the preferential flow paths using electrical resistivity changes over time.

Chaplot et al, 2011 presented a study investigating the effectiveness of Rho data when collected with limited information on the soils conditions other than the fact that the soil was classified as being very dry. Rho significantly correlated with soil water content, soil clay content keeping within other literature findings (Samouelian et al, 2005). Correlations were also found with soil bulk density and depth of the 'B' clay horizon however little correlation was found with infiltration. Rho will vary spatially and temporarily with soil moisture content, however it was concluded that mapping infiltration will potentially require further statistical relationships (Chaplot et al, 2011).

3.5. Disadvantages

As soil apparent resistivity (Rho) depends on numerous soil characteristics that can vary simultaneously (Friedman, 2005) direct interpretation of Rho is expected to be unreliable (Chaplot et al, 2011). Rho is often misinterpreted, especially in relation to soil properties including clay, soil water, soil water contents and soil depth. Misunderstandings however are minimized with a better understanding of the relationships between Rho and various soil properties (Chaplot et al, 2011). It is widely thought that there is a lack of accuracy for empirical relationships between Rho and several physical or chemical soil properties (Samouelian et al, 2005). The existence of multiple relationships between Rho confirms the difficulty of using electrical resistivity to record the variations of a single soil property (Corwin and Lesch, 2003).

4. METHODOLOGY

4.1. Preliminary study

As the project is a feasibility study a large part of the preliminary study involved the research of processes key to the proposed method. A full summary of significant concepts on the hydrological processes and electrical resistivity theory is contained within the background, theory and literature review. This was a necessary and important part of the preliminary study as a good understanding of the method enables the user to work more confidently when in the field.

Preliminary methodology was to consider potentially suitable sites to carry out fieldwork in. Helston, within the Cober Catchment was chosen due to previous flooding history, an abundance of public access sits and the accurate meteorological data from the catchment from RNAS Culdrose. Prior to fieldwork it was necessary to contact Culdrose and the Met Office to assess whether data such as daily temperature and precipitation were available. As land was public and the data collection was unobtrusive no further permission was necessary to undertake fieldwork.

4.2. Health and Safety

Health and safety risks to people and the environment were considered minimal for the project.

The largest concern was the use of the ohmmeter. The main problem is that persons could come into contact with the electrodes or wires whilst the ohmmeter is generating electrical current. A similar concern applies for dogs in close vicinity to the fieldwork as the majority of the sites are designed dog walking areas. For this reason, electrodes were set up so that they weren't obstructing space often used by the public such as footpaths.

It was important that the user was alert to the whereabouts of public members when the ohmmeter was turned on. Worst case scenario that someone had come into contact with the electrodes the ohmmeter was generating current at 128 Hz. This frequency is not considered particularly dangerous to humans, although it has the potential to cause mild discomfort.

There are unconfirmed reports that the electrical current within the ground could influence earthworms, which may rise to the surface. However, due to the short period of time that the ohmmeter was recording data it was deemed there would be no detrimental impacts to the environment. The equipment set up left no damage aesthetics of the area.

The weather could be a health and safety issue problem if particularly severe, such as high winds and rainfall. Furthermore, the ohmmeter, whilst being 'weather proof' (a state which means it maintains some durability within a variety of moderate weather conditions), it will not function safely in very wet conditions. Therefore, checking the weather forecast was a prerequisite to site visits.

The equipment was relatively heavy therefore the weight was normally distributed over two people to avoid injury whilst appropriate footwear and clothing was worn. Users wore high visibility jackets so that members of the general public are aware that potentially hazardous activities are occurring in the area. It also identified the user to the public so that any questions or concerns could be addressed.

4.3. Site Locations

All fieldwork sites are located in Helston, in the lower catchment at varying locations in relation to the Cober River. The locations of the sites are seen in Table 2 below, and in Figure 17.

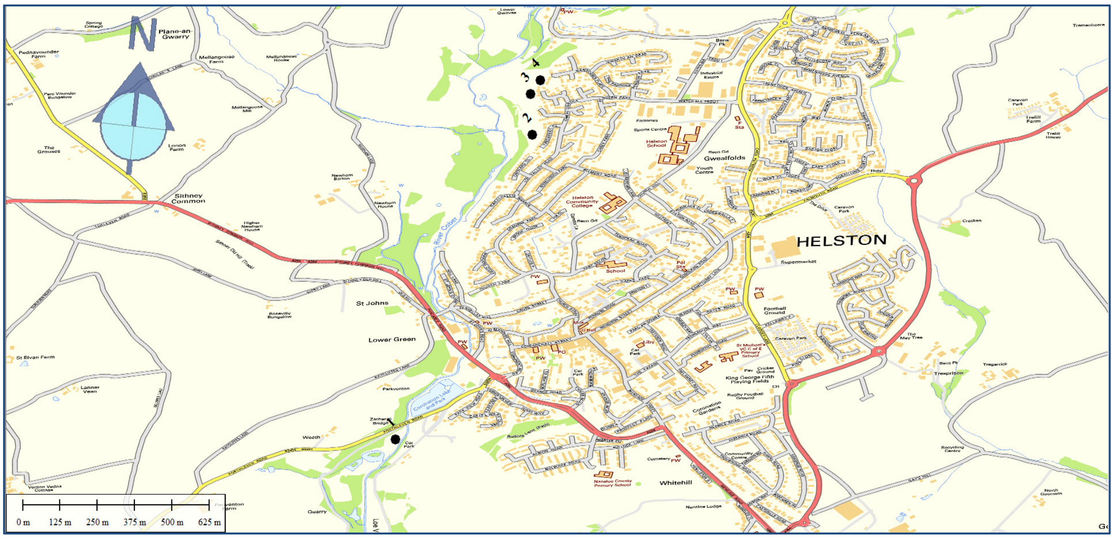


Figure 17
Locations of fieldwork sites in relation to Helston. Sites are labeled chronologically (1 through 4) from South to North. Description of sites locations are seen in Table X. (Edina Digimap, 2015).

	Location (Longitude/Latitude)	Description
Site 1	*50.0963, -5.282665*	Located in a public park along the river Cober. Land use is predominantly grassland, with a few large trees. The B3304 (Porthleven Road) runs to the north of the site, whilst Loe Valley car park and sewage works lie to the south. Towards the east and west is Coronation Boating Lake and Park and other small lakes respectively.
Site 2	*50.11008, -5.27772*	Located in public land space to the west of a residential area off Tregarrick Close. Directly to the east and south lie houses and their gardens, while to the north and west are areas of similar grassland and broadleaf forest. The ground slopes off steeply to the west towards the Cober.
Site 3	*50.1119, -5. 27800*	Located ~200m to the north of site 2 in an area of scrubland and forest to the west of Gweal Wartha, a residential street. Areas of broadleaf forest surround the site on the north and south whilst the River Cober is located to the east, at the bottom of steep valley sides.
Site 4	*50.11253, -5.27760*	Located ~75m Northeast of Site 3. It is an area of grassland with a steep topography located within the same residential area as Sites 2 and 3. The residential street of Nanscober Road is located to the east and south of the site, whilst the rest of the site is boarded by broadleaf forest. The Cober is located to the northwest down steep valley sides.

Table 2 – Descriptions and locations of field work sites.

4.4. Site Characterization

Site 1 is located directly on the floodplain closest to the river whilst the remaining three sites are located further up the valley sides, in more residential areas. All sites are areas of grassland predominantly used for recreational purposes such as dog walking.

The land is very flat and is most likely sediment that has been deposited when overbank discharge occurs. Deposition of sediment will occur when velocity of the water begins to fall, meaning less energy and therefore its capacity to carry suspended load will decrease. Site 1 therefore is expected to drain quickly into the river as material is potentially loosely consolidated sediment. The groundwater table is expected to be fairly high in Site 1 as it's not only the lowest site topographically but its close proximity to the river means that the capillary fringe zone is likely to be close to the surface.

Sites 2, 3 and 4 are located at higher locations on the Cober valley sides, in much more residential environments. The topography is much steeper on a local site scale compared to the much flatter Site 1. The steep topography along the sites reflects the topography of the valley sides, which slope steeply downhill towards the Cober River. The topography for each site is seen in Figure 18. The sites close proximity to residential areas will influence the expected runoff patterns in the local area. An increase in urban areas introduces land uses which have higher runoff rates, as many surfaces are unable to absorb precipitation, such as concrete. As the volume of water travelling via runoff increases, the lag time between water going from precipitation to flowing in the river will decrease. Therefore, it is guaranteed that each site will experience variation within runoff and infiltration processes, so that method sensitivity can be adequately tested.

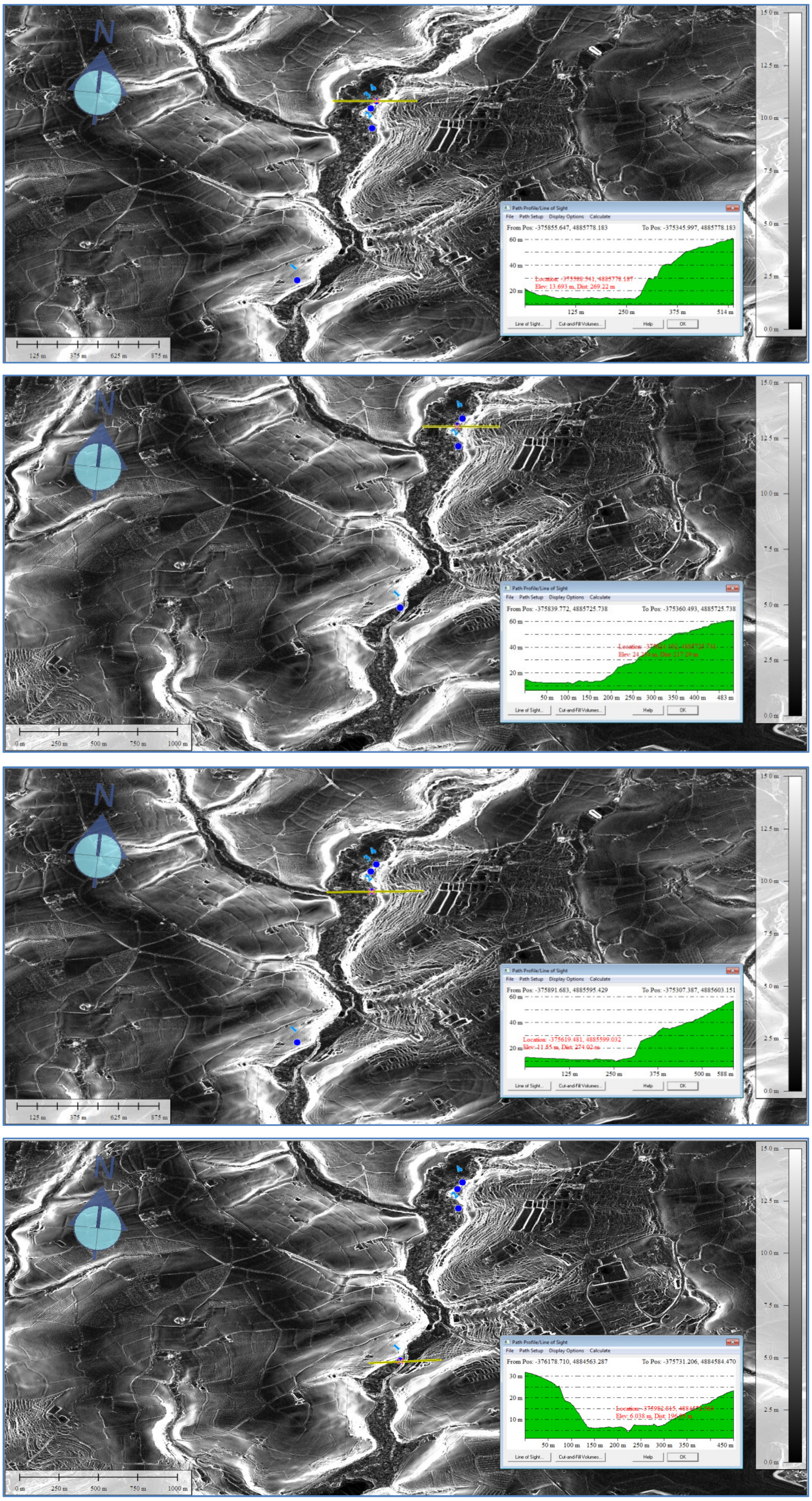


Figure 18
Showing the topography of fieldwork sites along various points of the lower Cober River in Helston. Sites 2, 3 and 4 are much steeper than Site 1. The topographical data is courtesy of LIDAR digital terrain model surveys and screenshots from Global Mapper v.16.0, (Lidar, 2015)

Site 1 is located in an area where the risk of flooding from rivers and sea is termed low to medium. However within close proximity to the site are areas of high risk, including areas around Coronation Boating Lake and St. John's in Helston. Sites 2, 3 and 4 have no classified flooding risk, as they are located much higher than the Cober floodplain. The steep topography of the sites is also not conducive to flooding (EA, 2015).

4.5. Primary data

A suitable point at which to conduct electrical resistivity tests must be located. At each site the measurement location should be easy to find on separate occasions and should not be disturbing the general public. Other considerations include the topography of site and the effect vegetation will have on the soil moisture. Large trees will create areas of lower soil moisture due to uptake by roots, the larger the tree the larger the area in which the roots will extend. Topography will influence soil moisture patterns so it is important that the electrical resistivity array is parallel to the slope, so gradient remains constant over all the electrodes.

Fieldwork was carried out from the 16th of June 2015 to the 22nd of August 2015. Much of the fieldwork was intermittent depending on weather conditions.

A handheld GPS was used to record coordinates for the point at which measurements will be recorded so positions could be mapped. However, the unit had an error of +/- 3m, which meant that the GPS was used as a reference location only and no data collection relied on the coordinates. Location was secured by using reference objects in the site, for example using a fence post and a tape measure extending out a set distance in a set direction. This had the advantage that it was quick and easy to set up the array again on separate occasions, and had higher location accuracy then using a handheld GPS.

Earth resistivity measurements were carried out using a Chauvin Arnoux C.A. 6470N (Figure 19).

Advantages of the system as a whole include a wide measurement range that increases resolution, rejection of interference voltages, and automatic calculation of ground resistivity and recording of results. It operates in an automatic mode for simplicity, where the Rho function is selected on the rotary switch, the distance between the electrodes in input and the start button is pressed. The machine will carry out an earth resistivity measurement at 128 Hz although it accounts for potential interferences voltages and will change the default measurement voltage accordingly. The machine has a full frequency range of 41 Hz to 5,078 Hz.

Figure 19
The Chauvin Arnoux C.A. 6470N, photo courtesy of author

As previously highlighted, measurement of electrical apparent resistivity requires four electrodes and for this experiment they were set up in a Wenner Array. The array is set up with equal space intervals (*a*) between the A, B, M and N electrodes (labeled H, S, ES, E on the Chauvin Arnoux C.A. 6470), which can be increased or decreased by a constant spacing factor. The advantages of the Wenner array would be signal strength and sensitivity of array to horizontal structures, which is ideal for the purpose of this experiment. It was also quick and easy to set up within the field, which reiterates the usefulness of geophysical surveys compared to other methods. The setup and machinery is seen being used within the field in Figure 20.

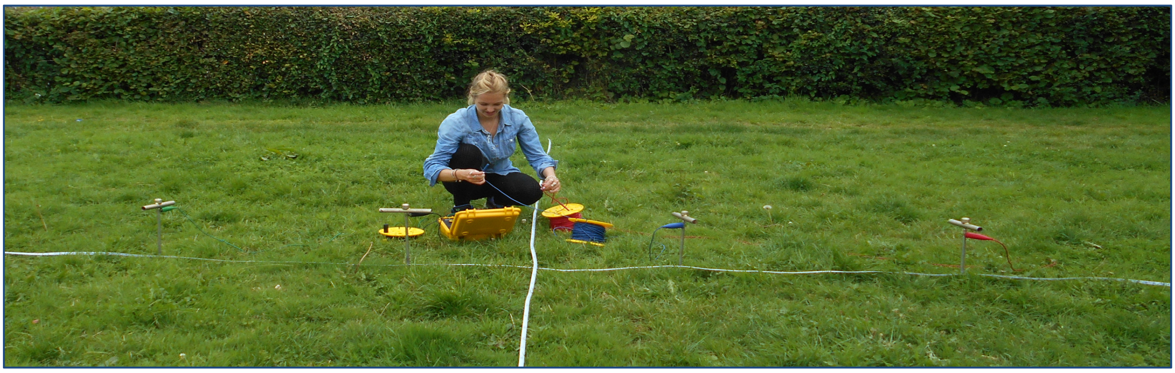


Figure 20
The equipment set up in the Wenner array formation, parallel of hill slopes at site 2, taken on the 12th of August. (Note, set up was a demo only hence the lack of high visibility)

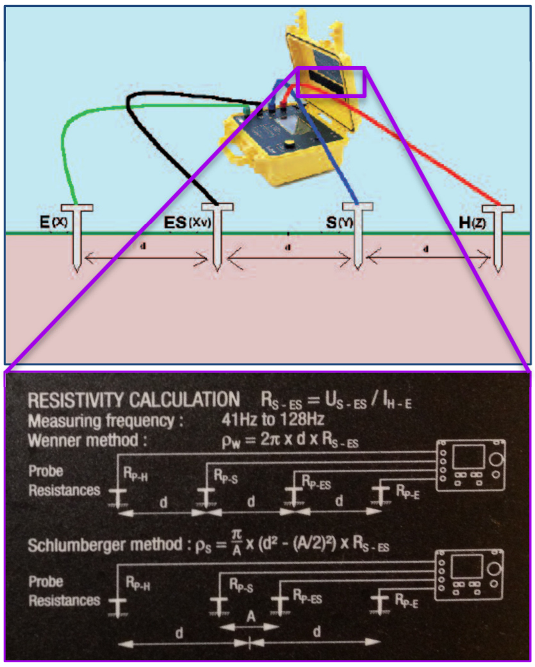


Figure 21
The figure above shows the Chauvin Arnoux in the Wenner array arrangement (Chauvin Arnoux, 2015). The figure below shows the way in which the Ohmmeter calculates Rho (Ω^{-m}) in the Wenner and Schlumberger methods. The figure below is a picture taken from the Ohmmeter machine itself.

The point of measurement occurs equal distance between the two middle electrodes. The C.A.6470 automatically calculates the resistivity of the ground (Rho) per meter although the user must input the electrode spacing (the geometric coefficient, K) and the electrode configuration manually. Thee way in which Rho is calculated for each set up are contained with a diagram on the machine itself, Figure 21. This decreases the possibility for human error due to Rho calculations as these are calculated to a high degree of accuracy on the Ohmmeter. Recording the data in Ω^{-m} allows easier comparisons between the different sites over time.

Two set ups were done at each site to record the electrical resistivity at two different depths. Firstly the electrode spacing was at 1m intervals, which meant that the electrical resistivity was recorded 0.5m under the surface. The spacing was then increased to 2m to gain recordings at 1m under the surface. The electrodes were placed far enough in the ground so that they were stable and able to stand up on their own accord, however less than 10% of the distance between electrodes (*a*). As soil moisture and infiltration rates are most prevalent in the upper most soil horizons there was no need for further data from greater depths.

Data was collected in relation to meteorological conditions. Using deviations from the average weather conditions such as periods of wetter or drier conditions in the area will show the methods sensitivity to input precipitation. Testing the equipment and the potential to measure the electrical resistivity under very wet conditions is especially relevant when assessing the methods potential to be able to predict possible flood circumstances. It may also provide a calibration technique for the method as a resistivity value could correlate to maximum saturation.

4.6. Secondary data

Secondary data necessary for data analysis includes the daily meteorological conditions, such as precipitation and temperature, and the daily river level data from the Cober at Helston.

River level data is collected from Helston Country Bridge, near Site 1 as seen in the catchment characteristics (Figure 10, page 10). It is gathered by the Environment Agency that is published online direct from the gauging station. The EA ensures that 'whilst every effort has been made to ensure the accuracy of the information provided, the EA can be held responsible for any inaccuracies or omissions'.

Precipitation and temperature data was supplied by the Met Office. The station is based at Culdrose (location 50.084, -5.256 and 76m above sea level). It is an automatic weather station meaning that data is collected hourly throughout the day. The station records daily maximum and minimum air temperature and rainfall amount over a 24-hour period (from 10:00 to 10:00 in summer). This data along with various other observations are sent to the central MET Office in Exeter before being post processed and verified. The data acquisition was granted, under a data license for Non-Commercial (Education) Research Use (Appendix A, Page I).

4.7. Accuracy

The specifications for the Ohmmeter include the resolution and range, as seen in the Figure 22. The resistivity average accuracy is +/- 5% of the returned Rho value.

		C.A 6470N	C.A 6471
3P method	Range	0.01 Ω to 99.9 kΩ	
	Resolution	0.01 to 100 Ω	
	Measurement frequency	41 to 512 Hz	
	Coupling measurement	yes	
4P method	Range	0.001 to 99.99 kΩ	
	Resolution	0.001 to 10 Ω	
	Selective 4P	–	yes
Earth measurement with 2 clamps	Range	–	0.01 to 500 Ω
	Resolution	–	0.01 to 1 Ω
	Measurement frequency	–	Auto: 1,367 Hz Manual: 128 Hz, 1,367 Hz, 1,611 Hz, 1,758 Hz
Resistivity	Test method	Wenner and Schlumberger with automatic calculation	
	Range	0.01 to 99.9 kΩ	
	Measurement frequency	41 to 128 Hz	
DC resistance measurement	Type of measurement	2 wires or 4 wires	
	Range	0,12 Ω à 99,9 kΩ	0,001 Ω à 99,9 kΩ
	Measurement current	> 200 mA DC	
Memory		512 memory locations	
Communication		optical / USB link	
Dimensions / weight		272 x 250 x 128 mm / 3 kg	
Electrical safety		50 V CAT IV	

Figure 22
Electrical specifications of the C.A. 6470N. The Resistivity section is the most important to consider within fieldwork.

The accuracy levels for secondary data are unknown. However the Met Office and the Environment Agency are deemed reliable sources therefore any inaccuracy derived from the secondary data can be discounted.

4.8. Limitations

The methodology aims to detect fluctuations within soil moisture conditions, which are directly influenced by meteorological conditions, such as precipitation (and indirectly, such as temperature). Therefore, weather is considered the greatest limitation as it plays such a large role within the methodology outlined above. Whilst it is acknowledged as the greatest limitation, it is completely beyond the user's control. It must be incorporated within the methodology and viewed less as a constraint and more as an essential part of the methodology. Using weather forecasts supplied by the Met Office (Met Office, 2015) variation in weather could be planned and accounted for ahead of time, and fieldwork could be carried out in conjunction to differences in weather patterns. This explains why there was no set structure to fieldwork timings and instead was based on deviations within meteorological conditions over the summer months. Although weather forecasts were used to choose ideal fieldwork timings, heavy precipitation hindered data collection at one site, on one occasion.

Using an automatic Ohmmeter that calculates Rho (in Ω^{-m}) automatically reduces the majority of human errors. Human error within equipment set up was another main concern. Potentials errors included setting up the electrodes with the wrong spacing, inputting the wrong spacing distance onto the machine and using the wrong cable configuration. The advantage of having at least two people carry out fieldwork however was that human errors such as the ones listed could be minimized, as set up configurations can be double checked. The machine had the tendency to return anomalous results in comparison to the general results trend if the set up was incomplete therefore alerting the user to inconsistences within the set up.

4.9. Data Analysis

After both primary and secondary data has been collected, the data sets could be further analyzed in order to establish the potential relationships between data sets. Analysis will be undertaken with two methods, graphically and statistically, which combined will be able to validate the methods ability to improve the accuracy of flood warnings. Data analysis methods are described below.

4.9.1. Graphically

Comparing the data sets graphically involves using daily precipitation and river levels to create a hydrograph for the Cober catchment over the period of fieldwork. This will indicate the channels response to input precipitation. Key points would be the lag time between a rainfall event and an increase in channel flow, and how this affected the overall level of water.

The soil resistivity data sets can also be graphically displayed with meteorological and river level data to assess the general trends between the variables. Graphically represented data might not as quantitatively conclusive as statistical data yet it is none the less an important part of data analysis. General trends can be derived graphically which can then be additionally analyzed further using statistics.

4.9.2. Statistically

All statistics were run using SPSS v21.0, an analysis package specializing in descriptive analysis of scientific data. Before inputting data into SPSS it was important to verify that all data was in a valid format. All the data sets (temperature, precipitation, soil resistivity and river levels) were classified as continuous variable data type within the ratio data category. This is important to consider as data type as it influences how the data is to be examined.

The exploratory statistics will analyze the dispersion of the data sets, including range, variance and standard deviation. Distribution analysis also indicates whether the data is parametric (normally distributed) or non-parametric (not normally distributed) which is imperative to as it will influence what type of explanatory statistical analysis that can be carried out on the data.

Explanatory statistics aim to explain the trend in a relationship between data sets. Correlation tests within data sets will quantifiably show the extent to which one variable influences another separate variable. Correlation tests will be bivariate, with soil resistivity as the dependent variable and either temperature, precipitation and river levels as the other independent variable. Using Spearman's Rank test, the degree of relationship (if any) can be generated and compared.

4.10. Methodology summary

The methods chosen for this study reflect the conclusions drawn from the literature review on current concepts and analysis of hydrological processes and electrical resistivity theory. As a small scale study, the field work that will be undertaken on the Cober Catchment, together with the availability of secondary meteorological data is fit for purpose.

5. RESULTS AND DISCUSSION

The aim of the project is to evaluate the sensitivity of soil resistivity to variations in precipitation and temperature to assess possible correlations with river levels and flood hazards. This chapter aims to summarize results from fieldwork and secondary data obtained from external sources and establish potential relationships. Soil resistivity trends will be presented first followed by analysis of temperature, precipitation and river level data. Then the statistical analysis to determine potential correlation between data sets is described, and finally all results are summarized in graphical form showing all variables. The results section aims to highlight this methods potential feasibility for use as a flood prediction aid by determining if the use of resistivity measurement is sensitive enough to external factors. The discussion will utilize findings from the results section to further analyze the potential for using the method within flood prediction.

5.1. Trends in Soil Resistivity

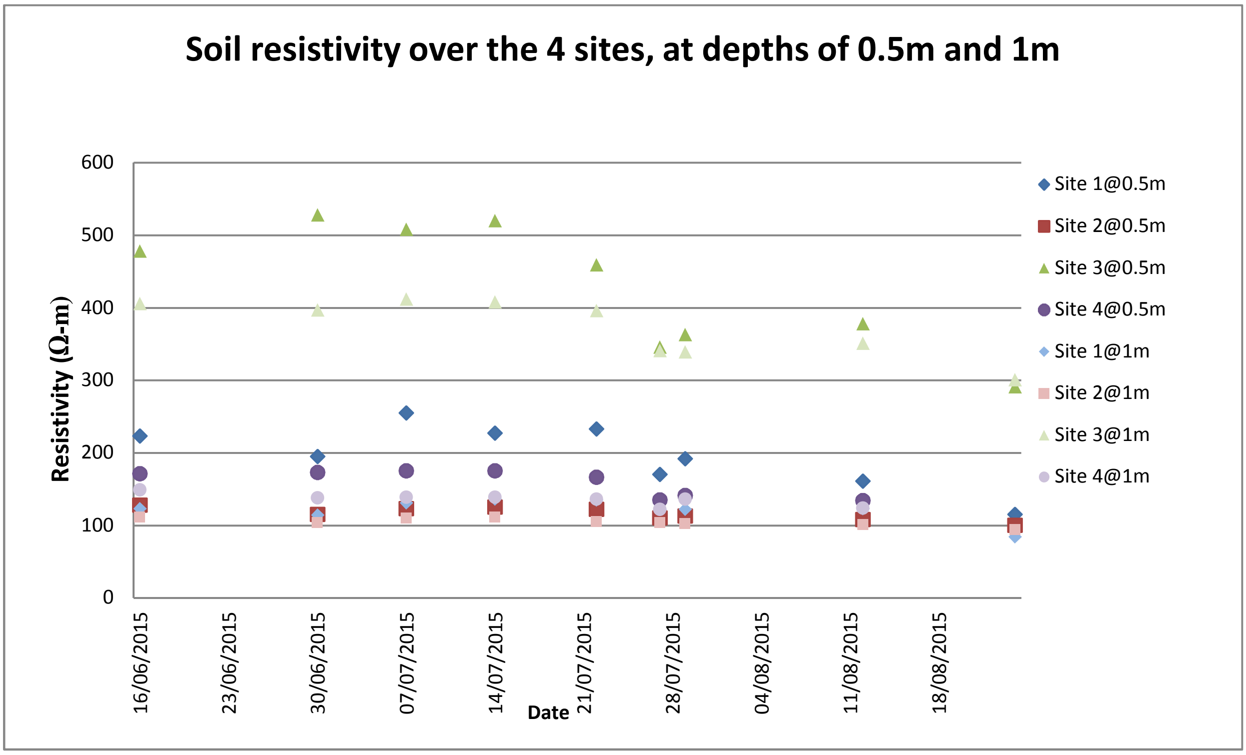
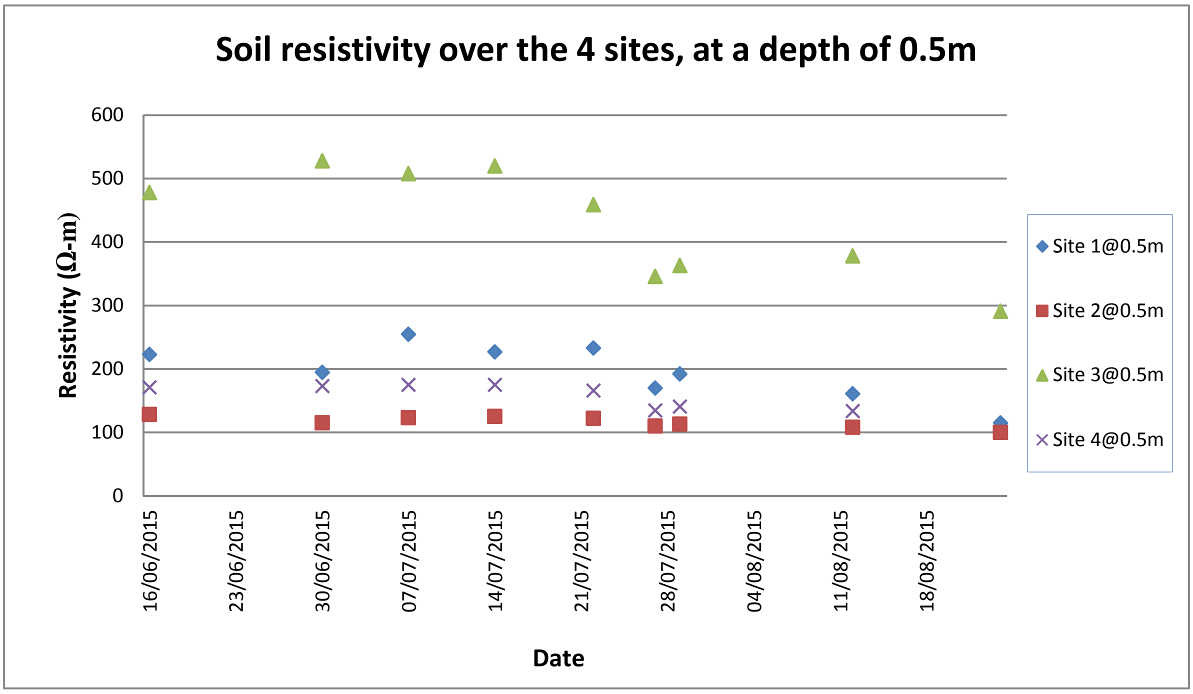


Figure 23
A graph showing the trends in soil resistivity over the 4 sites

Figure 23 shows the resistivity at the 4 sites at both depths, to show general trends over a wider geographical area. Three predominant findings can be derived from the graph, firstly the sites experience different levels of soil resistivity, secondly, that there are similar fluctuations of soil resistivity over the various dates and that the resistivity deviations over depth occur similarly over all sites.

Site 3 experiences much higher soil resistivity in comparison to the other sites, on average the mean was 447.5 Ω^{-m} at a depth of 0.5m. Sites 1, 2 and 4 all experience similar lower resistivity's, with means of 207, 118 and 158 Ω^{-m} at 0.5m depth respectively. The mean resistivity decreases at all sites when depth is decreased to 1m to 125.75, 106, 381.25 and 135.275 Ω^{-m} for sites 1, 2, 3 and 4 respectively. Site 3 has the largest range of measured values, whilst Site 2 and 4 show the least variation. The measurement range is especially prevalent at 0.5m depth. Actual highest and lowest values for each site over depths of 0.5m and 1m are seen in Figure 24.



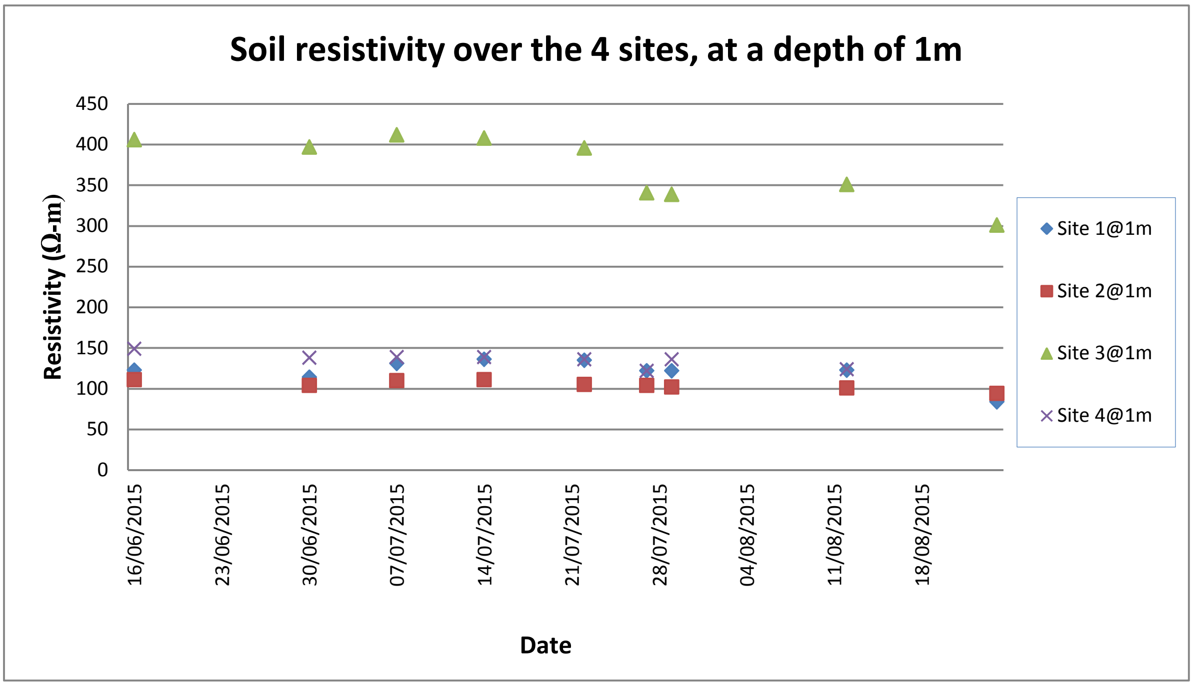


Figure 24
Soil resistivity over 4 sites at both depths

Figure's X also highlights the similar fluctuations over time between the sites. All sites show smaller variation within the first 5 data collections whilst all soil resistivity's readings decrease over the last 4 measurements. Whilst the highest measurements recorded at each site are varied, the lowest resistivity recorded at each site was on 24/08/2015 (apart from Site 4, where no data was collected due to the weather). Highest and lowest measurements for each site (and corresponding date of collection) are seen in Table 3 below for depth at 0.5m and Table 4 at 1m.

Table 3 - At 0.5m depth				
	Lowest (resistivity measurement and date)		**Highest** (resistivity measurement and date)	
Site 1	115	24/08/15	255	07/07/15
Site 2	100	24/08/15	128	16/06/15
Site 3	291	24/08/15	528	30/06/15
Site 4	134	12/08/15	175	07/07/15 and 14/07/15

Table 4 - At 1.0m depth				
	Lowest (resistivity measurement and date)		**Highest** (resistivity measurement and date)	
Site 1	84	24/08/15	136	14/07/15
Site 2	94	24/08/15	111	16/06/15 and 14/07/15
Site 3	301	24/08/15	412	07/07/15
Site 4	122	27/07/15	149	16/18/15

It is worth mentioning the conditions on the last date of data collection, on the 24thth of August. The ground at all sites was visibly saturated and water logged, and there was evidence of runoff in Sites 1 and 2. Observations indicate that the ground was highly saturated, supporting the lower resistivity results for each site.

The difference between site 3 (the highest resistivity) and site 2 (the lowest) is 329.5 at 0.5m depth and 275 at 1m depth. The soil resistivity results decrease with depth. However, the difference in soil resistivity at each site on each date varies considerably between depths. The difference in resistivity between 0.5m and 1 depth are shown in Figure 25. whilst a general trend shows the difference between the two depths decreasing over the time frame of fieldwork, there is no clear pattern otherwise dictating the relationship between the resistivity over the two depths. Analyzing the difference between depths crucially gives a good indication about the soils infiltration rates and the potential to store water under the soils surface. As soil resistivity is lower at a lower depth the ground at 1m is more saturated, which is to be expected.

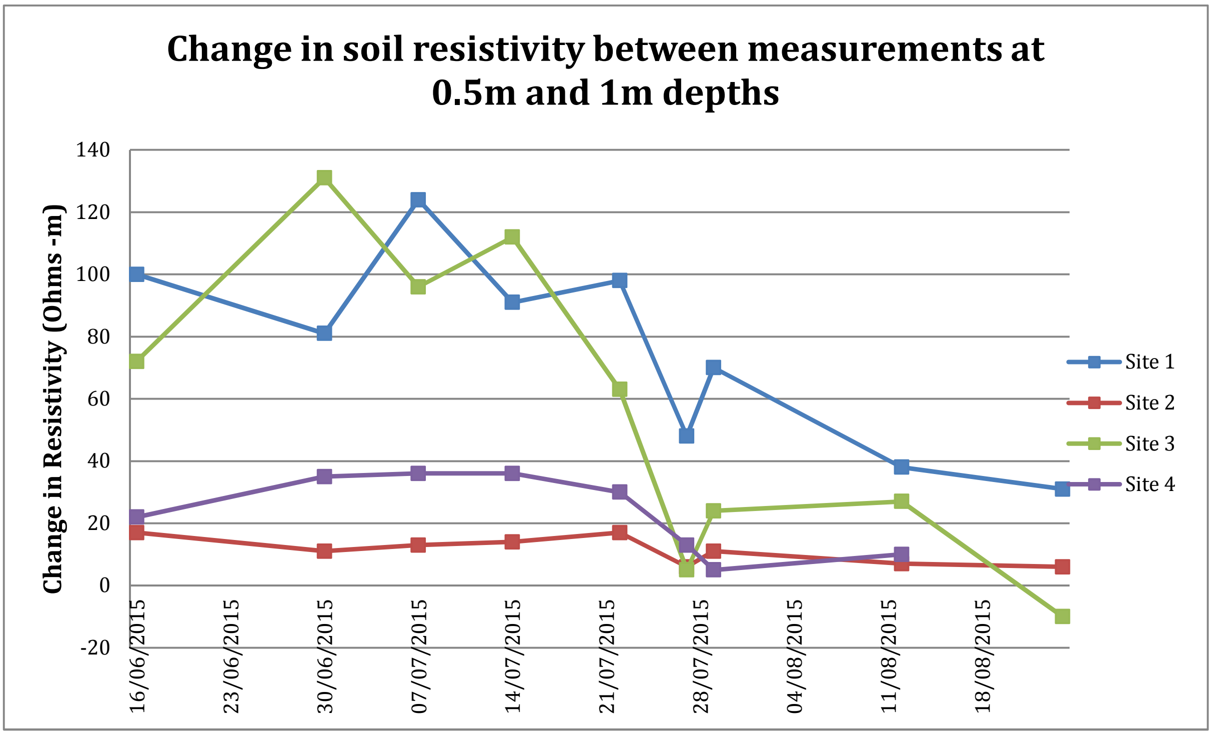


Figure 25
The change in measured soil resistivity values at each site between 0.5m and 1.0m depths

Analyzing the soil resistivity data alone, several key points can be made. Firstly the results are sensitive enough show a difference within resistivity over depth, indicating a change in soil moisture conditions over depth. Secondly, the sites show similar general trends over time potentially shows that the soil is reacting to a change in meteorological factors in the same way. However, variation within resistivity values and a difference within how resistivity changes over depth over sites indicate that there are further factors that are influencing soil resistivity in different ways at each site.

Key variables that influence soil resistivity over the sites include soil type, topography and land use within the local area. Sites 2 and 4 had the smallest resistivity and the least variation and yet had the steepest topography and were located within the most urban areas. Runoff might have been greater within these sites, leading to less infiltration and therefore less variation in soil resistivity. Variation within Site 1 could be linked to its location on the floodplain whilst the other sites are located at steeper sections of the valley. The soil type and location of the ground water saturated zone is likely to be considerably different, which could explain the variation in soil resistivity. As the values were much greater in Site 3 it is quite possible that a further external factor is increasing the soil resistivity that is not in effect at the other three sites. Without further research on each sites physical characteristics, the reason why the soil resistivity is so variable over the sites is unidentifiable

5.2. Trends in forcing variables

Further analysis on the influencing factors such as precipitation and temperature can be carried out using correlation tests. The influence on these factors on river level can also be assessed. These data sets are much larger, spanning the entire fieldwork period (87 days). Using SPSS v21, descriptive statistics were used to show data distribution and results are summarize below.

The mean daily mean temperature was 14.845 °C, with a maximum of 19°C and a minimum of 10.9°C. The mean daily precipitation was 2.885mm, with a maximum of 42.2mm and a minimum of 0mm. The mean river level was 26.391cm, with a minimum of 18cm and a maximum of 94cm. It should be noted that flood warnings were issued (by the EA) on two occasions during fieldwork, on the 22/08/2015 and the 25/08/15. Flood alerts were given for given for rivers within West Cornwall, from the Environment Agency in conjunction with the Met Office. A flood alert means that ‘flooding is possible, be prepared’ it advises those effected to monitor local water levels and future precipitation forecasts (Met Office, 2015).
The precipitation and river level for that week are seen below to put into perspective what conditions constitute a flood risk in the Cober catchment (Table 5).

Table 5 – precipitation and river level data (flood alerts issued = *)

Date	Precipitation (mm)	River Level (cm)
21/08/2015	14.8	31
22/08/2015*	21.2	61
23/08/2015	3.8	72
24/08/2015	10.4	51
25/08/2015*	19.0	69
26/08/2015	1.2	94
27/08/2015	0	62
28/08/2015	Not available	58

The lag time between precipitation and an increase is shown within the table to be ~1 day. This is the time it takes the high levels of precipitation on the 22nd and the 25th of August to generate rises in river levels, in this case a day later on the 23rd and 26th respectively. The levels of precipitation experienced within the week prior to the flood alert was not the highest levels of precipitation measured during the fieldwork period. The flood alert takes into consideration the antecedent soil moisture conditions and infiltration capacity within the catchment on river levels. This can explain why flood alerts were given during a week of sustained rainfall instead of just one off rainfall events. Flooding is more likely to occur when the catchment is already saturated with water, as was the case for the flood alerts within the last week of August for the Cober. The river levels reiterate this sensitivity to periods of sustained rainfall.

Data distribution is shown in histograms (Appendix B, p.IV). The Shapiro-Wilk test of normality was used in this case as it handles data sets of this size better than the Kolmogorov-Smirnov test. The results are seen below in table derived from SPSS. If the significant figure is greater than 0.05 then the data is considered to be normally distributed (parametric), otherwise the data is not normal (non – parametric). Significant figures for each data set are seen in Table 6.

Table 6 – significant figures from the Shapiro-Wilk test of normality

River Level (cm)	0.000
Temperature (°C)	0.087
Precipitation (mm)	0.000

Therefore the only data set that is parametrically distributed is mean daily temperature. Daily rainfall and river level is non-parametric. This is necessary to know before commencing correlation tests as it influences the type of test that can be carried out.

5.3. Forcing Variable Correlations

Spearmans Ranks was used to determine correlation between data sets. The correlation coefficients for each data set are seen in Table 7, and fully in Appendix C, p.VI. Values can range on a scale from 1 to -1, denoting the strength of the relationship. The closer values are to each end of the scale the stronger the relationship meaning that the two variables influence each other strongly. If the value is positive, then the correlation is positive and if the value is negative then the correlation is negative.

	River Level	Precipitation	Temperature
River Level (cm)		0.230	-0.281
Temperature (°C)	0.230		0.243
Precipitation (mm)	-0.281	0.243	

Table 7 – Correlation coefficients for forcing variables

Generally, none of the variables are strongly correlated to each other, as correlation coefficient values are all very low.

Research into the relationship between precipitation and temperature suggests that a negative correlation should exist however, often due to the fact that higher temperatures accompany lower precipitation amounts (IPCC, 2007). Dry conditions favour more sunshine and a decrease in evaporative cooling. However, the relationship is highly influenced seasonally, especially within temperate climates such as the UK. Within winter months the positive correlation is expected as the atmospheres increased capacity to hold water in colder conditions limits precipitation. In warmer winter conditions, warmer air advection occurring in cyclonic storms usually results in increased precipitation. These trends are expected to be strong over larger spatial and temporal scales (IPCC, 2007).

Therefore, the weak positive correlation between temperature and precipitation over the Cober valley in summer is unexpected. It should be noted that the Cober catchment is relatively small in comparison to the much larger regional areas that the trends proposed above are derived from. Smaller local scale weather conditions could be influencing the overall correlation between precipitation and temperature that are not accounted for in larger studies. The size of the sample should also be taken into account. The 87 days that the meteorological data was collected and recorded does not offer a particularly large sample group to analyze, especially when comparing against long term seasonal trends. Without long term meteorological data for the area comparisons of seasonal trends are unadvisable due deviations from the mean summer conditions are unknown at this point.

The negative correlation between temperature and river level is anticipated. An increase in temperature increases the potential for evaporation that can influence river levels directly and indirectly. Direct evaporation from the rivers surface and an increase in evaporation from surfaces within the catchment indirectly reduces the amount of water within system. Evaporation occurs from all surfaces, however does depend on the amount of water available. More water will evaporate from surface water (such as lakes or puddles) then drier mediums such as soil. Adding complexity to the matter is the prevalence of evaporation of vegetation surfaces, termed evapotranspiration.

Water is drawn upwards from the soil by roots and transported towards the leaves which is then lost to the atmosphere via evaporation from pores on the leaves surface. This is termed transpiration and can be a considerable factor in evaporation calculations (Water and Climate Change, 2015). Transpiration rates increase in higher temperatures. The valley sides along the Cober are all woody areas dominated by broadleaf forests and therefore the influence of evapotranspiration is likely to reduce the amount of water that is supplied to the river.

The positive relation between precipitation and river levels is anticipated although the correlation was expected to be stronger. However, this trend can be explained by the role of water storage within the catchment. As already highlighted within the literature review, not all water flow from precipitation is runoff; much of the water is stored either within the surface or subsurface. It not only decreases the amount of water available for channel flow, but also introduces lag time between an increase in precipitation and corresponding river levels. The time that water is stored is variable, from days in the upper soil horizons to potentially decades in ground water or aquifers. Lag time is highly dependent on antecedent catchment conditions. Therefore correlation is potentially better viewed graphically instead of statistically, which could give a much better indication on how long the lag time actually is for the Cober catchment. The comparatively small sample size means that long-term trends and correlation cannot be derived from the data set.

The strengths of the correlations have been discussed above, however due to the small sample size (n=87) therefore correlations are purely inferential of wider processes. Therefore inferential statistical tests were completed to assess the significance of the suggested correlations.

Tests were set at the 0.05 level (2-tailed), meaning that when the significant value was less than 0.05 the data was considered significant. If significant the null hypothesis (H_0) can be rejected, meaning that there is less than a 5% chance that the relationship established between variables is by chance. The H_0 is that there is no association between the two variables (within the population).

The significant figures for between each variable are seen in Table X (and again in Appendix C).

	River Level	**Precipitation**	**Temperature**
River Level (cm)		0.032	0.008
Temperature (°C)	0.032		0.385
Precipitation (mm)	0.008	0.385	

Table 8 – Significant figures for Spearman's rank between forcing variables

Correlations between river level and precipitation and river level and temperature are therefore significant, whilst the inferred relationship between temperature and precipitation is not significant. This indicates that the sample size was too small to deduce a relationship.

5.4. Soil Resistivity Correlations

Using SPSS, the Shapiro-Wilk test for distribution indicated that soil resistivity data at 0.5m and 1m depth is non-parametric (Appendix D, p.VII). Spearman's Rank was used to establish a correlation between soil resistivity and the external factors, as seen in Table X.

	Soil Resistivity at 0.5m	Soil Resistivity at 1.0m
River Level (cm)	-0.205	-0.195
Temperature (°C)	0.089	0.062
Precipitation (mm)	-0.080	-0.052

Table 9– Correlation coefficients for forcing variables against soil resistivity

Generally, the correlations between the soil resistivity values are very weak and therefore relationships inferred should be taken with caution. However, broad trends can be deduced such as whether correlations are positive or negative and the differences that variable have on soil resistivity at different depths. It is useful to reiterate within the discussion, that an inverse relationship between soil resistivity and soil moisture exists.

The weakly positive relationship between temperature and soil resistivity is expected, as an increase in temperature often leads to a decrease in soil moisture. This is due to an increase in evaporation from soils surface and therefore a decrease in water available for infiltration. This increase in infiltration produces a matric potential within the soil medium, which could draw water up from the more saturated zones deeper within the ground.

The weaker correlation between soil resistivity and temperature at a lower depth indicates that there is little relationship between the two variables. A tentative conclusion can be drawn that the soil is potentially wetter deeper down. A negative correlation would indicate wetter soil with an increase in temperature, and a lower correlation value at a lower depth could potentially indicate that this is the case. However, it could also be interpreted that the soil resistivity at a lower depth in the soil has less of a relationship. This is understandable as temperature will have much less of an influence at greater depths. The only way of gaining further understanding on the proposed relationship would be to gain further readings to increase sample size.

The correlation between precipitation and soil resistivity is also very weak. The correlation that exists indicates the relationship is negative; this is to be expected as an increase of water within the soil (due to infiltration and subsurface flow) results in a decrease in resistivity. The relationship between precipitation and soil resistivity is even weaker at the lower depth of 1m. One explanation could be that lower soil depths will be less sensitive to precipitation inputs. The process of infiltration decreases the velocity of water, often creating a lag time as water flows through the soil, hence the concept that soil plays a vital role within water storage. Subsurface pathways closer to the soil facilitate a greater movement of water. Vegetation plays a major role as roots create larger channels for water to flow downwards, thus infiltration rates are much quicker and there is no lag time. Soil is more compacted at deeper horizons decreasing infiltration capacity, which could explain the decreases sensitivity of soil resistivity to precipitation at a greater depth. A similar pattern is shown within the correlation between river level and soil resistivity.

The negative correlation between river level and soil resistivity is anticipated, showing that as river levels increase soil resistivity will decrease. This is caused by a precipitation event leading to an increase in soil moisture conditions and ultimately in river levels. Whilst comparatively, the correlation between river level and soil resistivity is the strongest out of tested variables, the correlation is still considered rather weak. This could be explained by the difference in flow partitioning of water after a precipitation event largely dependent on antecedent soil conditions and type of precipitation event. The greater the amount of runoff equates to an increase of river levels over a shorter time lag. This could potentially increase the amount of water runoff due to lack of storage in the ground. The lag time could therefore be much longer, if water is able to infiltrate into the ground and slowly percolate towards the river. Whilst antecedent soil moisture conditions drive the infiltration process, it is also relational to the type of precipitation. More runoff will occur in a heavy rainfall event, then in a lighter shower. Therefore, a high correlation is not to be expected when purely comparing the river level and the soil resistivity on a day to day basis.

Further research between river levels and antecedent soil conditions would be very beneficial.

Table 10 shows the significant figures for the correlation tests. The level of significance remained at 0.05 (2 tailed) level. Values less than 0.05 are considered significant, full data available in Appendix E, p.VIII.

	Soil Resistivity at 0.5m	Soil Resistivity at 1.0m
River Level (cm)	0.238	0.260
Temperature (°C)	0.610	0.725
Precipitation (mm)	0.647	0.768

Table 10 - Significant figures for Spearman's rank between forcing variables and soil resistivity

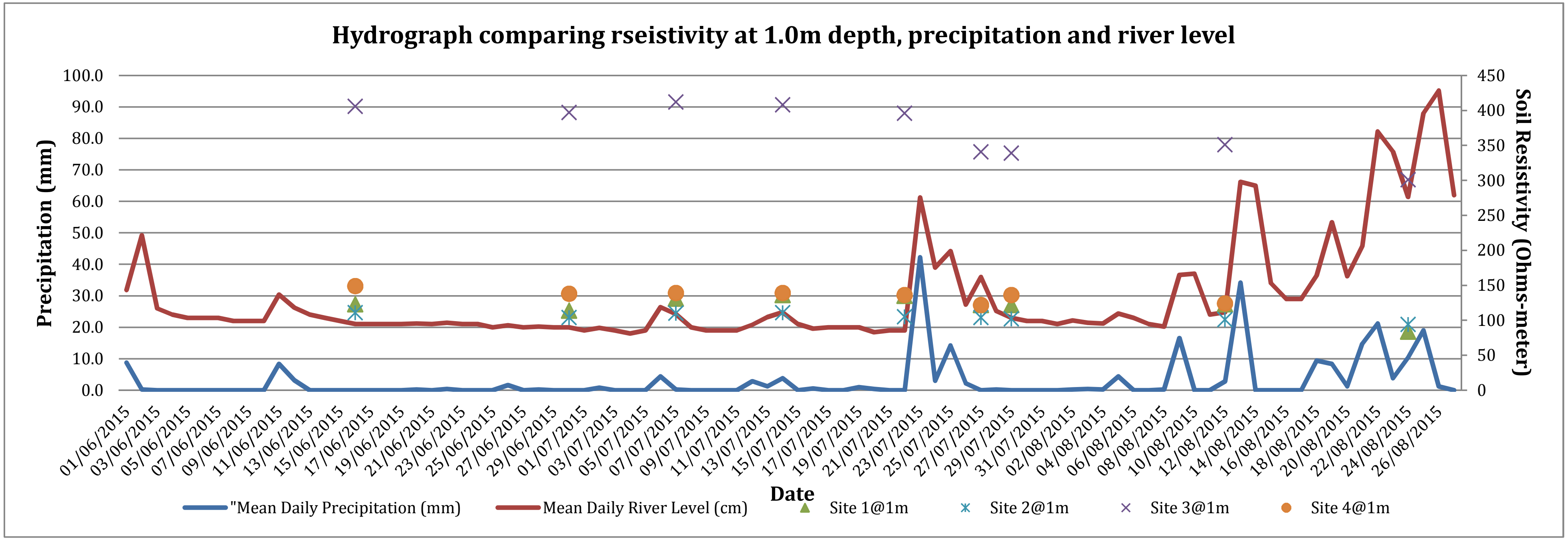
None of the correlation tests between soil resistivity and external variables are significant. However this is most likely down to the limited size of the data set that does not contain enough data points to fully establish the nature of the relationship. Therefore, further research is recommended before forming a conclusion on variable correlations.

5.5. Graphical Analysis – a hydrograph

By analyzing the results graphically, a much better indication of the sensitivity of the method to external influences can be shown. Results for each site, over both depths are seen in Figure 26, comparing soil resistivity, mean daily river levels and mean daily precipitation in a hydrograph. The precipitation and river level follow similar patterns as described above. The soil resistivity values respond to fluxes within precipitation values indicating that the method is sensitive enough to detect such atmospheric changes. The trend shows an overall decrease is soil resistivity from the 14th of July onwards as precipitation increases.

The lag time between the two variables is between 1 – 3 days, depending on the size of the rainfall event. Smaller rainfall events have a smaller lag time, although the style of rainfall will influence lag time just as much as the amount of rainfall.
The influence of saturated ground conditions is clearly visible, especially within the month of August towards the end of the fieldwork. The river levels rise to their

highest peak on the 26th of August of 94cm. However the precipitation amounts for the day was only 1.2mm. Even with a proposed lag time of around 2/3 days the recorded precipitation was 3.8, 10.4 and 19 mm over the three days whilst being a substantial amount is not the highest recorded over the fieldwork period. However, it is worth noting that previous to river levels surging to 94cm, rain had been measured on 8 consecutive days (totaling nearly 90mm). The soil in the catchment was therefore was becoming increasingly saturated and unable to store water. This subsequently increased the prevalence of runoff and the river level rose dramatically. The impact of antecedent conditions only confirms the necessity to further research valid methods of soil moisture environments.



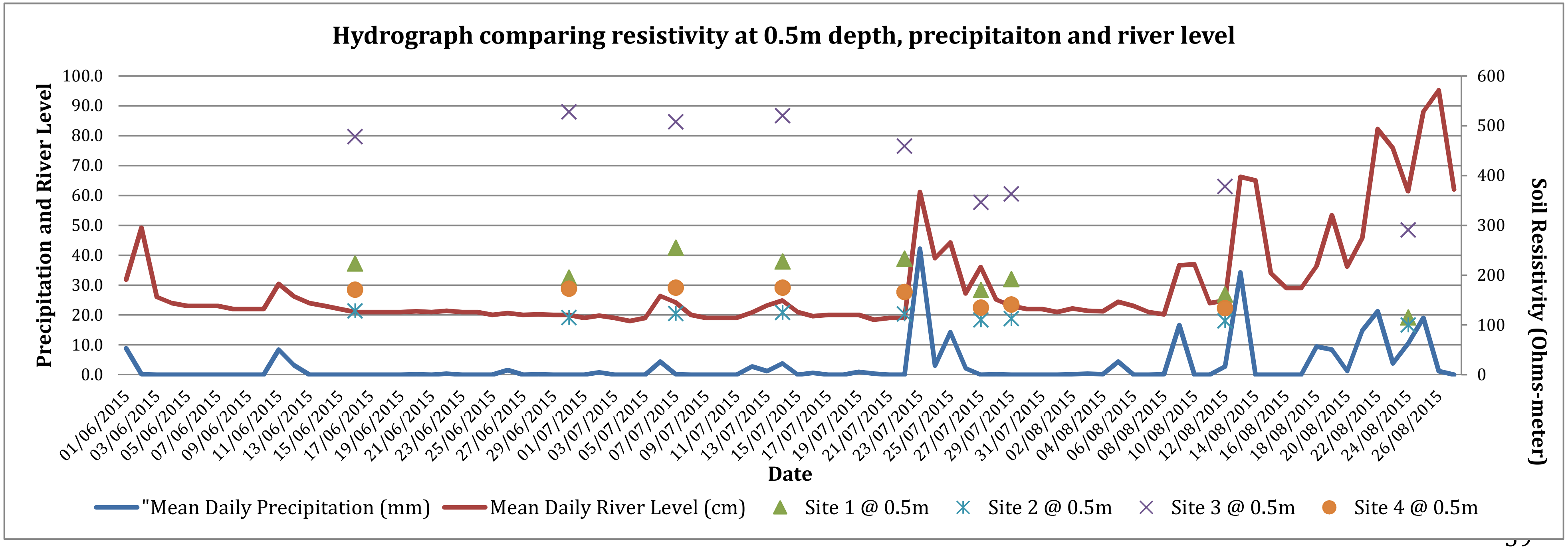


Figure 26 – hydrograph showing precipitation and river levels with soil resistivity measurements (at 2 depths)

5.6. Antecedent conditions

A common theme between soil resistivity and external forcing factors would be the need to consider the antecedent soil conditions. Whilst this introduces the concept of further research and analysis, a provisional look at the precipitation conditions could indicate further relationships between variables that have to be considered before conclusions are drawn. Within the scope of the fieldwork carried out, little information can derive on antecedent conditions directly.

Catchment response time can be indirectly inferred from graphical plots of rainfall, river level and soil resistivity. The lag time has already been established as 1 day (although can range up to ~ 3 days). Quantifying a time period to represent antecedent soil moisture is difficult as the conditions are cumulative over long time periods. An indication of soil moisture conditions could be the collective precipitation over the days prior to soil resistivity measurements. Graphs showing soil resistivity in relation to 2 and 5-day cumulative rainfall totals prior to soil resistivity measurements are seen in Appendix F, p.XI. The regressions between the two variables are seen in Table 11 for 2 day cumulative total and Table 12 for a 5 day cumulative total.

Table 11 – Cumulative rainfall total for 2 days

	0.5m Depth	1m Depth
Site 1	-0.32461	-0.49046
Site 2	-0.30697	-0.28365
Site 3	-0.29030	-0.29033
Site 4	0.01250	-0.04176

Table 12– Cumulative rainfall total for 5 days

	0.5m Depth	1m Depth
Site 1	-0.59063	-0.33460
Site 2	-0.57073	-0.38730
Site 3	-0.60239	-0.67612
Site 4	-0.55840	-0.58976

It echo’s the general trends as outlined within the correlation statistical tests, however there is a much stronger relationship between cumulative precipitation and soil resistivity values. This shows that the cumulative precipitation amount has a much stronger influence on soil moisture conditions; especially over longer time periods as the 5 day total often has much higher regression. All trends for the 5 day cumulative total show a strongly negative correlation (as precipitation total increases, resistivity total decreases). The trend is reiterated in the 2 day cumulative total for Sites 1, 2 and 3, however for Site 4 at 0.5m depth the trend is positive. This however could be an anomaly as regression is very weak.

The trends are stronger in the upper soil depth of 0.5m. Hence why a catchments antecedent soil moisture conditions are so important to flood risk prediction, as it is the soil closest to the surface is more sensitive to changes in cumulative precipitation.

The strength in the relationships between cumulative rainfall totals indicate that the research into antecedent coil moisture conditions and soil resistivity is vital to continue. Within the results derived from the field work, relationships between cumulative rainfall and soil resistivity offers the most conclusive evidence that the method is able to accurately measure soil moisture conditions.

5.7. Final Discussion

Both advantages and disadvantages of using soil resistivity to determine soil conditions have arisen throughout fieldwork and are evident within the results. The crucial question that needs to be considered is whether the measurement of soil resistivity offers the potential to increase the accuracy of flood prediction.

Results indicate that the method was sensitive to changes in precipitation. As precipitation and river levels increase, the soil resistivity at all sites over all depths decrease, representing an increase in soil moisture as highlighted in much of the existing literature on the matter. This relationship is shown both statistically and graphically within the results. The proposed method can hypothetically establish a relationship between soil resistivity within a catchment and river levels which is a key factor to consider within the science of flood prediction. Therefore the method of using an Ohmmeter to determine soil moisture conditions and degree of saturation could be considered feasible. This offers the possibility of further analysis to derive infiltration rates and water storage potential in a given area.

However, it is difficult to show conclusively to what extent relationships resulting from measurements taken in the Cober valley, over the course of the fieldwork are significant without further research. Although the soil resistivity appear sensitive to changes in precipitation it also raises further questions about the other factors potentially influencing the soil resistivity which are not considered within the scope of this report. Realistically, summer is not the best time period to be analyzing the models sensitivity to fluxes in precipitation or river levels. Precipitation is sporadic over the summer months, which may not be an accurate representation of how soil moisture reacts in times where precipitation is more consistent such as winter. It should be noted that all recent major flooding events in Helston have occurred in November and December, and therefore predicting flooding using soil moisture resistivity should be a long-term investigation.

It is important however to consider whether this method would be viable to quantify soil moisture in a format that would allow the measurement of soil resistivity to be used further within flood modeling and prediction. The fact that the method is low cost, unobtrusive and quick and easy to set up should also be factored into decision of method feasibility. To fully discuss the potential for the method to produce accurate soil moisture conditions to use within flood prediction further research is essential.

6. LIMITATIONS

The main discussion has emphasized that measurements of resistivity are sensitive to changes in catchment processes. However, clearly the method has inherent errors and limitations, which are briefly outlined below.

As highlighted within the literature review, interpretation of soil resistivity can be difficult. This is the main limitation of using a VES 1D method that the return of a single calculated value had to be interpreted using the users knowledge. Although the topic had been well researched, the relationship implied throughout the project that soil resistivity directly equates to soil moisture may not be completely correct. The method described cannot offer a holistic approach to soil science and a direct quantification of soil moisture to derive infiltration rates.

The weak or non-existent results to correlation testing indicate insufficient data was available, thus the true nature of these relationships is difficult to determine. There were two possible limitations with the data, which in turn could have influenced whether the data was statistically significant. Firstly is the size of the data set, a much greater sample size would have minimized the potential for correlations to be inferred by chance. Secondly, would be that the data collection occurred in summer, arguably the most inappropriate time to analyze precipitation, river levels and antecedent soil moisture conditions. Major flooding events are unexpected in summer in the UK. Precipitation events leading to a rise in river levels were likely anomalies over the time frame of summer and therefore analyzing these potential anomalies meant that correlations may be based on events that don't fully represent catchment conditions. Therefore, further research is outlined below.

7. FURTHER RESEARCH

Having highlighted the necessity for further research it is practical to recommend for further continuous surveys and to consider how recorded data could be used within other investigations. Further research includes repeated investigations over a longer time period. Different and complementary methods of soil moisture analysis can be carried out to calibrate and validate the use of resistivity as a flood prediction method. Eventually the way in which the soil resistivity data could be used within flood prediction models needs to be considered.

Statistically it has been shown that correlations are very weak, due to the lack of data and that the summer months are not an ideal season to carry out resistivity fieldwork. The summer offers a lack of continual precipitation and relatively small fluctuations in river level and therefore strong significant correlations aren't to be expected from the fieldwork carried out. For a more comprehensive study and definitive results to aid flood warning, the study period needs to extend over a whole year to assess seasonal variation. A prolonged study period would reveal how the catchment recharges its ground water table and the subsequent impacts on soil resistivity, which are unable to be detected within a short-term study. For example if major recharge to ground water table occurs in autumn then the flood risk is expected to be higher in the winter months. The methods sensitivity to changes in the saturation zone (and indirectly soil moisture) therefore has yet to be assessed. A long-term study would measure the cumulative effect of precipitation much better then over one summer. By researching the change in soil moisture dynamics over the year, the method could be used to accurately predict at what rainfall level a flood warning needs to be issued depending on how much water is already stored in the soil.

Further research into the other variables that influences soil resistivity should be carried out to calibrate the method. Once a greater understanding into other processes driving changes in resistivity is gained then the actual soil moisture content could be isolated. This could offer a solution to the difficulties involved with accurately measuring soil moisture content in relation to forecasting infiltration rates. Key variables that should be further investigated include topography, soil type, underlying geology, organic matter content and evapotranspiration potential over the catchment.

Once the method has been calibrated and can successfully isolate the soils sensitivity to fluxes in moisture then its capacity to predict floods is improved. Ideally, what is required from the methodology is a ‘tipping point’ – denoting a point in time in which the soil is too saturated to store any more water. When the tipping point has been reached, any further rainfall will flow directly as runoff, increasing the risk of flash flooding. Using tipping points and future meteorological forecast in conjunction with each other offers a valuable and accurate method of flood prediction. A point of saturation may have already been found in the study, as observations from the field on the 24th August showed water logged soils and evidence of runoff on sites. However, river levels remained at a level that did not pose a flood threat. By continuing the research this tipping point threshold can be further analyzed in wetter conditions.

So after proposed further continuation of fieldwork and subsequent validation and calibration of the method, it can be used for flood prediction. The method potentially offers a method of soil moisture and infiltration rate quantification that can be used within hill slope runoff models. This parameterization of infiltration can increase hill slope model accuracy, as current methods are often based on qualitative soil moisture estimations. This reduces a significant amount of human error introduced to flood prediction modeling.

Ultimately, the method has the potential to be able to provide a cheap and quick alternative to soil moisture measurements. This can be fine-tuned to use within flood prediction modeling, but also has potential practical applications within the construction and insurance industries.

8. CONCLUSIONS

The aim of this investigation was to assess the feasibility of a method that used electrical resistivity testing to measure soil moisture and infiltration, which could eventually be used in flood prediction. Soil moisture is intrinsically complicated to quantify and measure due to the individually complicated nature of each catchment and specific study site. However, results from field work indicate that soil resistivity is sensitive to fluctuations in precipitation, temperature and can correlate with river levels within the catchment. Therefore, it is concluded that the method is a potentially feasible method of increasing the accuracy of flood prediction whilst lowering the cost.

The method has the benefits that it was reproducible, compact, portable, non-invasive and relatively inexpensive, fulfilled health and safety requirements and can be used by a sole operator. It can be deployed quickly over different catchment conditions and changing weather situations. The research has shown that this type of electrical resistivity field work may work on a larger scale and over a longer period of time, to obtain a comprehensive and accurate assessment of other river catchments and to incorporate these methods into flood prediction modeling.

Whilst the research does not offer fully conclusive results on the relationships between soil resistivity, precipitation, temperature and river level, it showed promise that with further research and method refinement the results could be highly valuable and influential within approaches to flood prediction.

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APPENDIX

Appendix A

Met Office Licence Reference:	**010067213**	**Licence**	08/11/2015

Licensee Details

Name and Address:	**Contact:**
Bea Webb	**Telephone:**
	Email: mailto:bw269@exeter.ac.uk

Met Office Details	**Main Contact: Joan Self**
Telephone No:	**Email: metlib@metoffice.gov.uk**

Description of the Data	**Licence Term**	**Price**
Culdrose daily data 13/7/15 to 25/8/15	1 year	

Price (Excluding VAT)	£0
Total Price (Including VAT @ 20%)	**£ 0.00**

Payment terms:	30 days from date of invoice

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Non-Commercial Research Use	YES	NO

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[Describe the reason why the Data is being licensed to the Licensee, for example, for writing an article for a scientific journal on the impact of increased rainfall in

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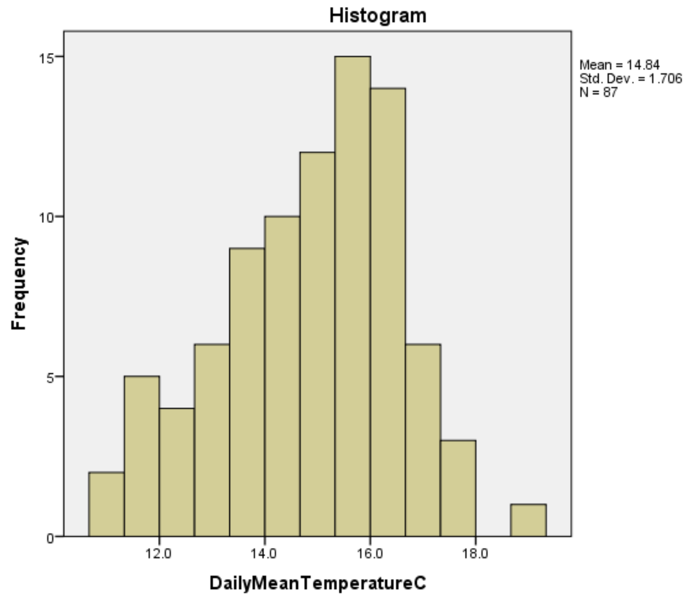
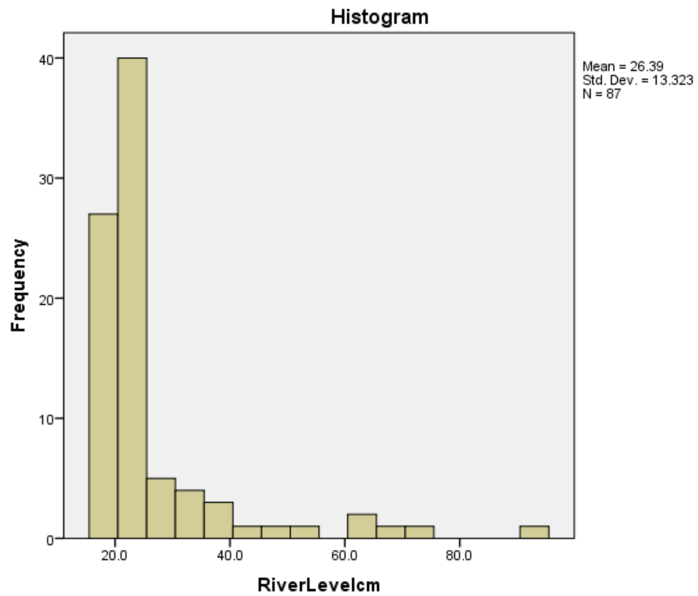
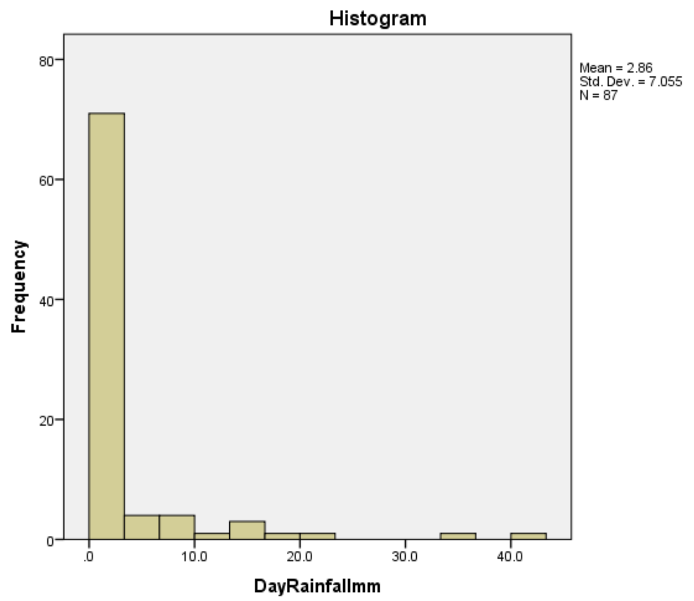
Appendix B







Distribution histograms for daily temperature, river level and daily rainfall (top to bottom)

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
DailyMeanTemperatureC	.081	87	.200*	.975	87	.087
DayRainfallmm	.343	87	.000	.469	87	.000
RiverLevelcm	.318	87	.000	.573	87	.000

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Shapiro Wilk test for normality (forcing variables)

Appendix C

Correlations

			DayRainfallmm	RiverLevelcm
Spearman's rho	DayRainfallmm	Correlation Coefficient	1.000	.230*
		Sig. (2-tailed)	.	.032
		N	87	87
	RiverLevelcm	Correlation Coefficient	.230*	1.000
		Sig. (2-tailed)	.032	.
		N	87	87

*. Correlation is significant at the 0.05 level (2-tailed).

Correlations

			RiverLevelcm	DailyMeanTemperatureC
Spearman's rho	RiverLevelcm	Correlation Coefficient	1.000	-.281**
		Sig. (2-tailed)	.	.008
		N	87	87
	DailyMeanTemperatureC	Correlation Coefficient	-.281**	1.000
		Sig. (2-tailed)	.008	.
		N	87	87

**. Correlation is significant at the 0.01 level (2-tailed).

Correlations

			DailyMeanTemperatureC	DayRainfallmm
Spearman's rho	DailyMeanTemperatureC	Correlation Coefficient	1.000	.243*
		Sig. (2-tailed)	.	.023
		N	87	87
	DayRainfallmm	Correlation Coefficient	.243*	1.000
		Sig. (2-tailed)	.023	.
		N	87	87

*. Correlation is significant at the 0.05 level (2-tailed).

Spearmans Rank Tests for correlation between forcing variables

Appendix D

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
SoilResistivityat1m	.224	35	.000	.804	35	.000
SoilResistivityat2m	.370	35	.000	.693	35	.000

a. Lilliefors Significance Correction

Shapiro Wilk test for normality (soil moisture) (Soil resistivity is measured in electrode spacing)

Appendix E

Correlations

			SoilResistivityat 1m	RiverLevelcm
Spearman's rho	SoilResistivityat1m	Correlation Coefficient	1.000	-.205
		Sig. (2-tailed)	.	.238
		N	35	35
	RiverLevelcm	Correlation Coefficient	-.205	1.000
		Sig. (2-tailed)	.238	.
		N	35	35

Correlations

			RiverLevelcm	SoilResistivityat 2m
Spearman's rho	RiverLevelcm	Correlation Coefficient	1.000	-.195
		Sig. (2-tailed)	.	.260
		N	35	35
	SoilResistivityat2m	Correlation Coefficient	-.195	1.000
		Sig. (2-tailed)	.260	.
		N	35	35

Spearman's Rank Tests for correlation between soil moisture and river level (Soil resistivity is measured in electrode spacing)

Correlations

			SoilResistivity at1m	DayRainfall0900 2100mm
Spearman's rho	SoilResistivityat1m	Correlation Coefficient	1.000	-.080
		Sig. (2-tailed)	.	.647
		N	35	35
	DayRainfall09002100mm	Correlation Coefficient	-.080	1.000
		Sig. (2-tailed)	.647	.
		N	35	35

Correlations

			DayRainfall09002100mm	SoilResistivityat2m
Spearman's rho	DayRainfall09002100mm	Correlation Coefficient	1.000	-.052
		Sig. (2-tailed)	.	.768
		N	35	35
	SoilResistivityat2m	Correlation Coefficient	-.052	1.000
		Sig. (2-tailed)	.768	.
		N	35	35

Spearman's Rank Tests for correlation between soil moisture and daily rainfall (Soil resistivity is measured in electrode spacing)

Correlations

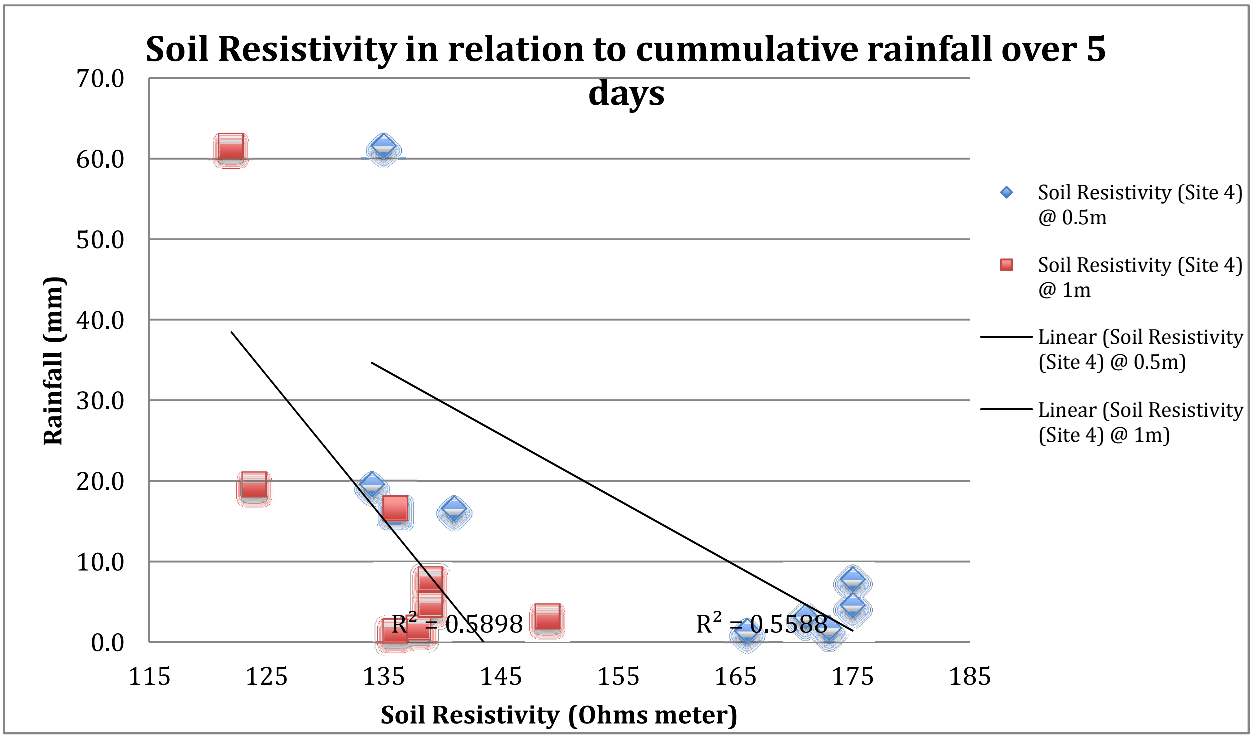
			DailyMeanTemperature09000900C	SoilResistivityat1m
Spearman's rho	DailyMeanTemperature	Correlation Coefficient	1.000	.089
		Sig. (2-tailed)	.	.610
		N	35	35
	SoilResistivityat1m	Correlation Coefficient	.089	1.000
		Sig. (2-tailed)	.610	.
		N	35	35

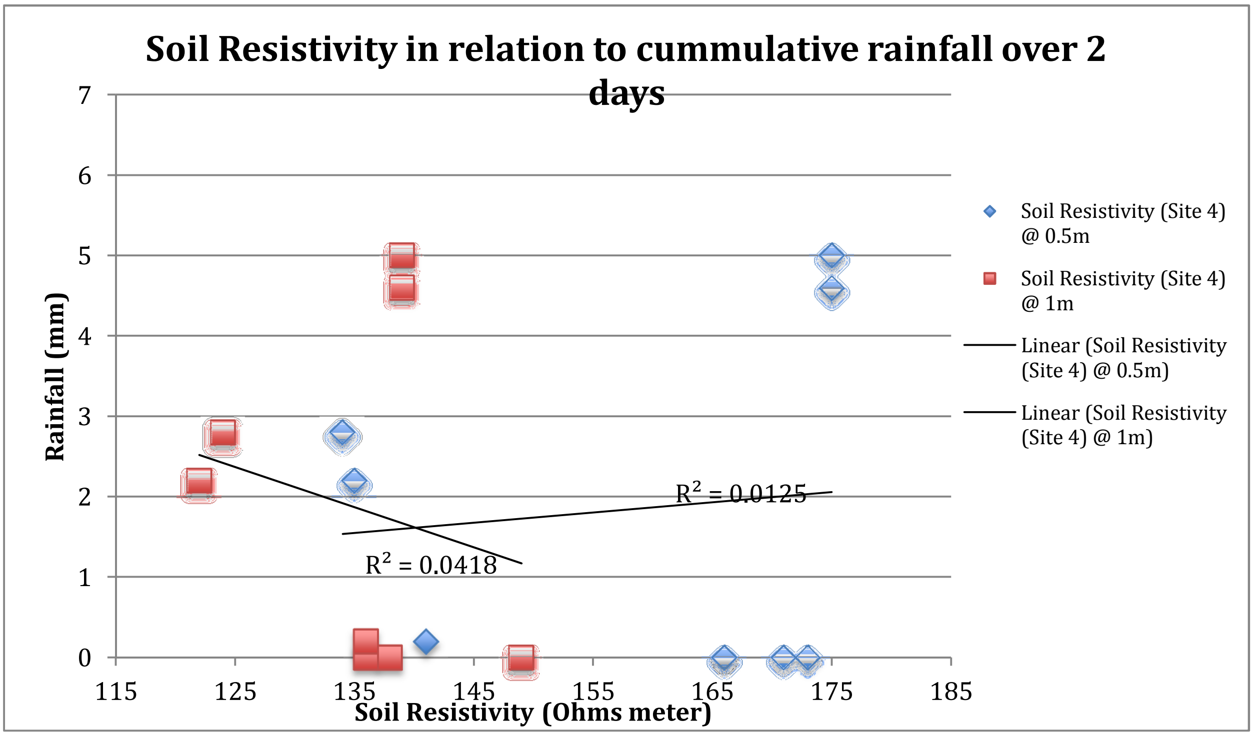
Correlations

			DailyMeanTemperature09000900C	SoilResistivityat2m
Spearman's rho	DailyMeanTemperature	Correlation Coefficient	1.000	.062
		Sig. (2-tailed)	.	.725
		N	35	35
	SoilResistivityat2m	Correlation Coefficient	.062	1.000
		Sig. (2-tailed)	.725	.
		N	35	35

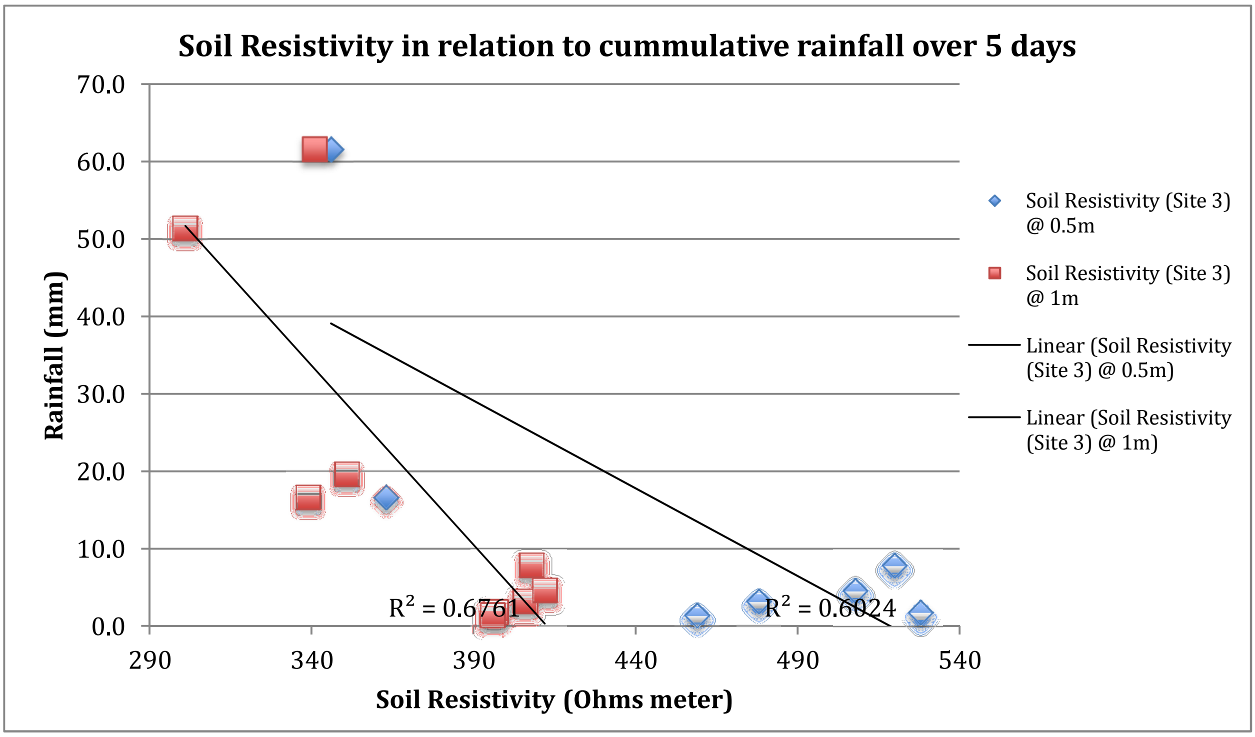
Spearman's Rank Tests for correlation between soil moisture and daily temperature (Soil resistivity is measured in electrode spacing)

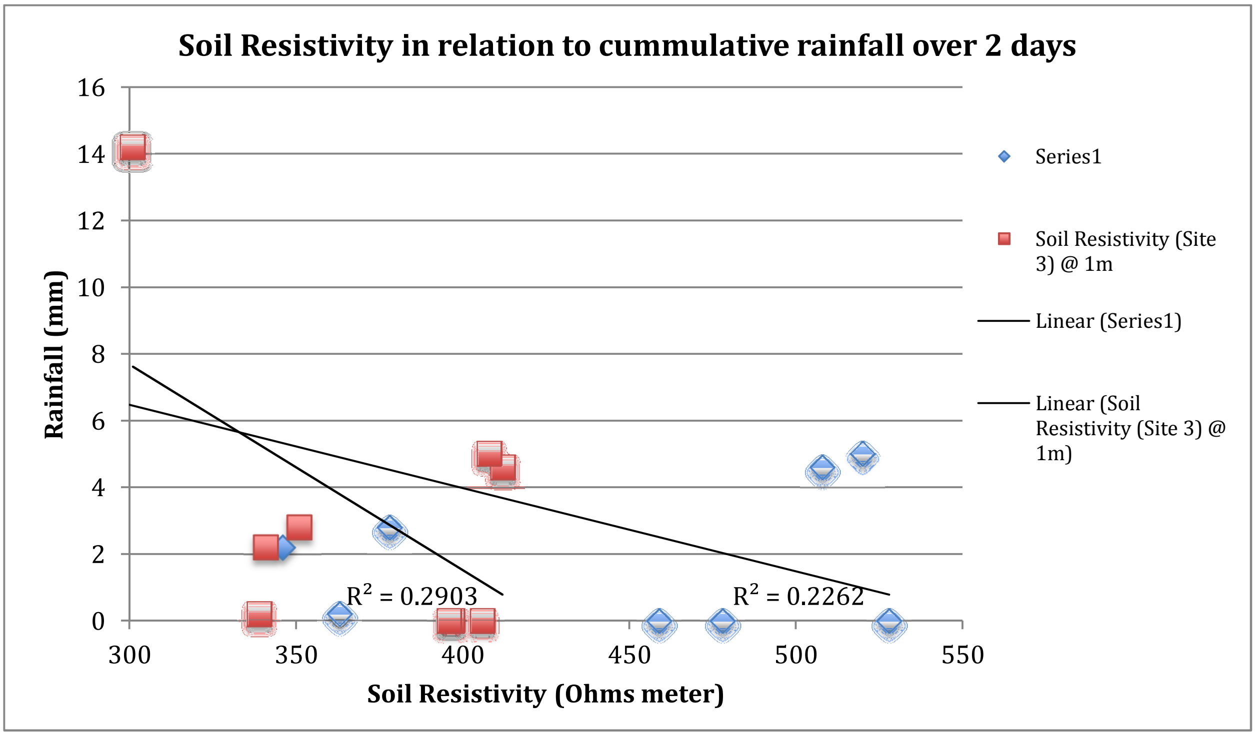
Appendix F



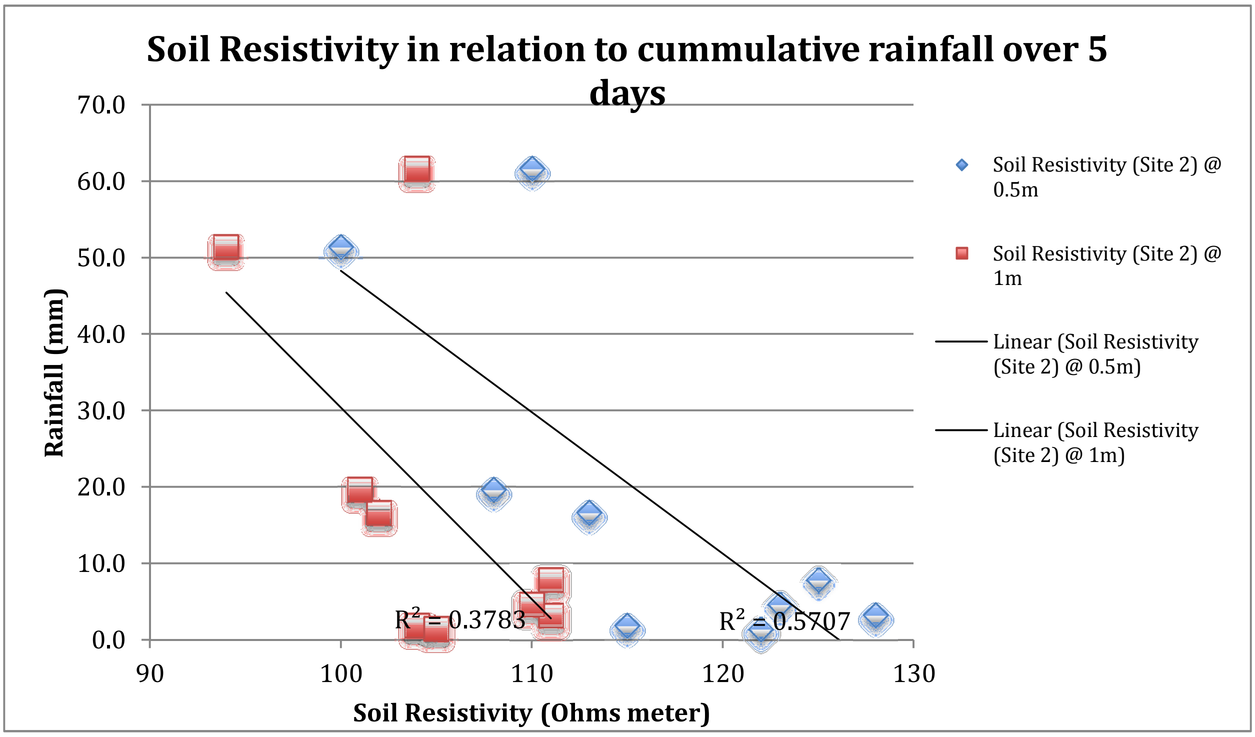


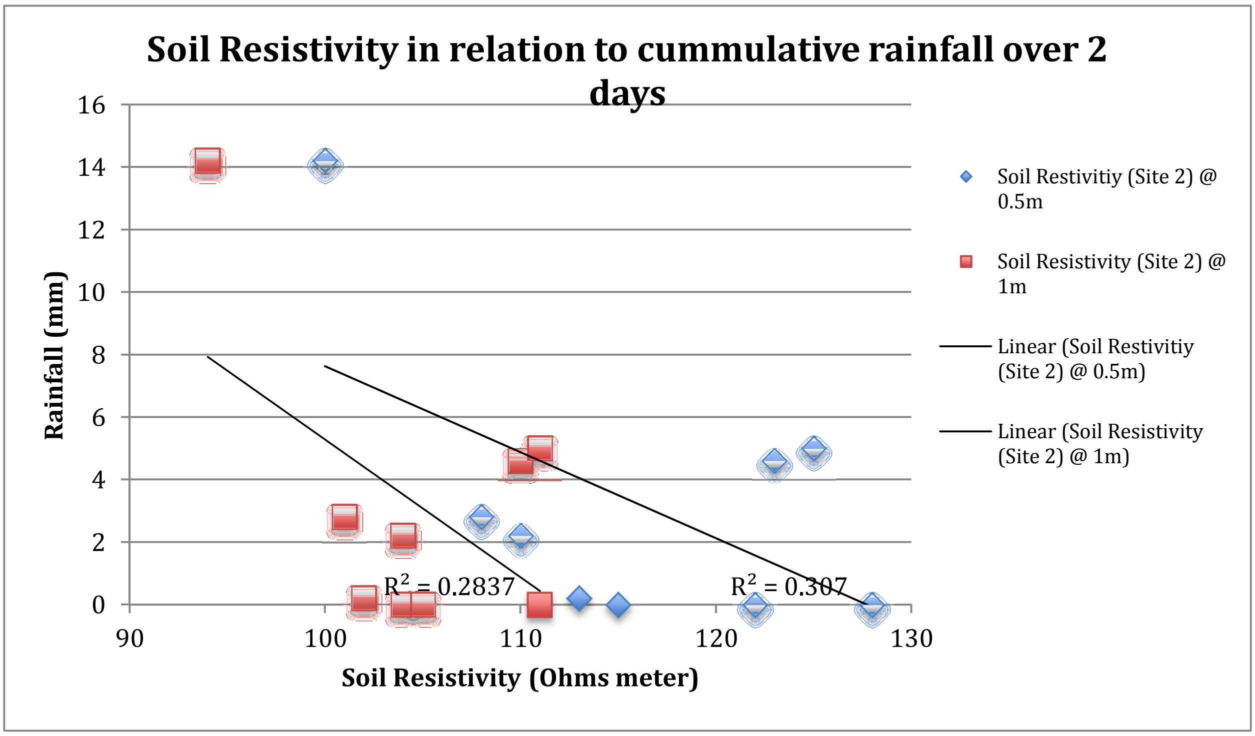
Regression between cumulative precipitation and soil resistivity values at Site 4



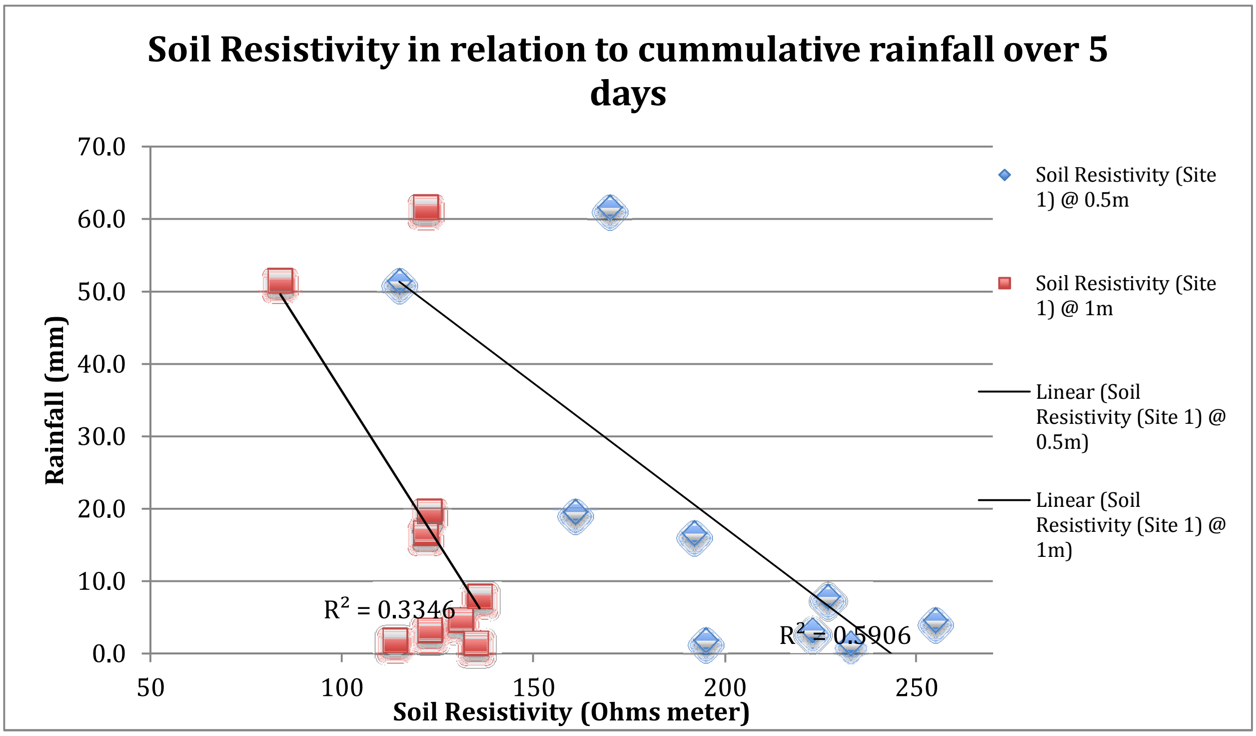


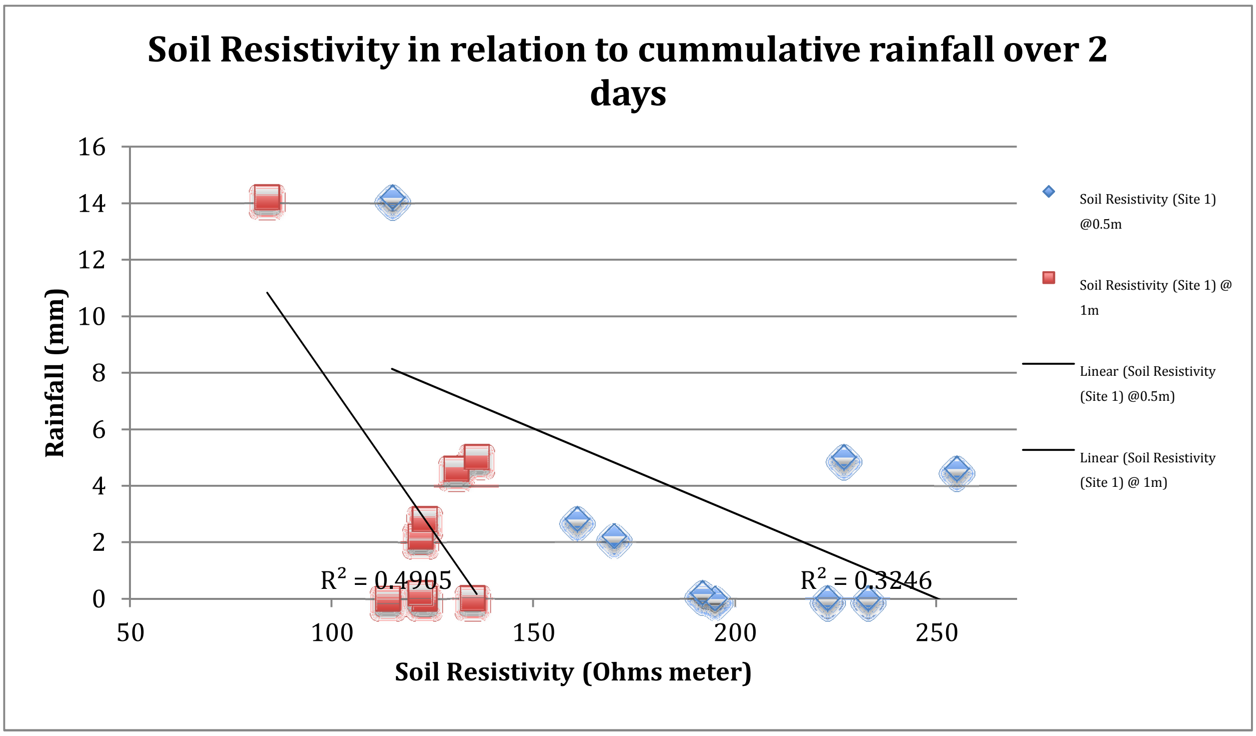
Regression between cumulative precipitation and soil resistivity values at Site 3





Regression between cumulative precipitation and soil resistivity values at Site 2





Regression between cumulative precipitation and soil resistivity values at Site 1