NERC Connect A Project:

Assessing the viability of complex Electrical Impedance Tomography (EIT) with a spatially distributed sensor array for imaging of river bed morphology: a proof of concept study

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February 2007

Project Code: NE/E522559/1

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ACKNOWLEDGEMENTS

The work contained in this report was funded by the Natural Environment Research Council (NERC) as part of their Connect A grant scheme. Project code NE/E522559/1: entitled 'Assessing the viability of complex Electrical Impedance Tomography (EIT) with a spatially distributed sensor array for imaging of river bed morphology'.

The financial support of NERC is gratefully acknowledged.

ACRONYMS

ERT	Electrical Resistance Tomography
ERGI	Electrical Resistance Ground Imaging
EIT	Electrical Impedance Tomography
ECT	Electrical Capacitance Tomography

EXECUTIVE SUMMARY

This report was produced as part of a NERC funded ‘Connect A’ project to establish a new collaborative partnership between the University of Worcester (UW) and Q-par Angus Ltd. The project aim was to assess the potential of using complex Electrical Impedance Tomography (EIT) to image river bed morphology. An assessment of the viability of sensors inserted vertically into the channel margins to provide real-time or near real-time monitoring of bed morphology is reported. Funding has enabled UW to carry out a literature review of the use of EIT and existing methods used for river bed surveys, and outline the requirements of potential end-users. Q-par Angus has led technical developments and assessed the viability of EIT for this purpose.

EIT is one of a suite of tomographic imaging techniques and has already been used as an imaging tool for medical analysis, industrial processing and geophysical site survey work. The method uses electrodes placed on the margins or boundary of the entity being imaged, and a current is applied to some and measured on the remaining ones. Tomographic reconstruction uses algorithms to estimate the distribution of conductivity within the object and produce an image of this distribution from impedance measurements.

The advantages of the use of EIT lie with the inherent simplicity, low cost and portability of the hardware, the high speed of data acquisition for real-time or near real-time monitoring, robust sensors, and the object being monitored is done so in a non-invasive manner. The need for sophisticated image reconstruction algorithms, and providing images with adequate spatial resolution are key challenges.

A literature review of the use of EIT suggests that to date, despite its many other applications, to the best of our knowledge only one study has utilised EIT for river survey work (Sambuelli et al 2002). The Sambuelli (2002) study supported the notion that EIT may provide an innovative way of describing river bed morphology in a cost effective way. However this study used an invasive sensor array, and therefore the potential for using EIT in a non-invasive way in a river environment is still to be tested.

A review of existing methods to monitor river bed morphology indicates that a plethora of techniques have been applied by a range of disciplines including fluvial geomorphology, ecology and engineering. However, none provide non-invasive, low costs assessments in real-time or near real-time. Therefore, EIT has the potential to meet the requirements of end users that no existing technique can accomplish.

Work led by Q-par Angus Ltd. has assessed the technical requirements of the proposed approach, including probe design and deployment, sensor array parameters, data acquisition, image reconstruction and test procedure. Consequently, the success of this collaboration, literature review, identification of the proposed approach and potential applications of this technique have encouraged the authors to seek further funding to test, develop and market this approach through the development of a new environmental sensor.

1.0 INTRODUCTION

This report represents the main output from a Natural Environment Research Council (NERC) project funded under the Connect A grant scheme. The project set out to undertake a proof of concept appraisal of the viability of complex **Electrical Impedance Tomography** (EIT) with a spatially distributed sensor array for imaging of river bed morphology.

The Connect A scheme facilitates and promotes new partnerships between universities and research institutes and public/private sector science users (industry, business, commerce or public sector agencies). This project represents the outcomes of a new partnership between researchers in the Department of Applied Sciences Geography and Archaeology at the University of Worcester, who have expertise in fluvial geomorphology and ecohydraulics, and Q-par-Angus Ltd, a Herefordshire based (SME) company with an international reputation for work in the field of Radio Frequency (RF), microwave and millimetre/sub-millimetre wave systems (radar, communications, electronic warfare), with emphasis on design and innovation.

1.1 Aims and scope of the report

As identified above, this report summarises a proof of concept study that has examined the potential use of complex EIT to image river bed morphology. In particular, it sets out to detail the viability of using EIT for 2-dimensional imaging of river cross-profiles and sub-surface river morphology using near-real time measurements of complex electrical impedance derived from a spatially distributed array of probes. In order to achieve this, the report defines EIT and summarises it's previous uses, provides an overview of existing methods for surveying river cross-profiles and sub-surface river morphology and assesses whether any can provide near real-time non-invasive data collection, describes the proposed approach and outlines future work.

Therefore, the report is organised into the following sections:-

- Current approaches used to assess river bed morphology (Section 2)
- A summary of the limitations of current approaches and the potential of EIT (Section 3)
- The proposed approach (Section 4)
- Future work (Section 5)
- Potential exploitation (Section 6)
- Conclusions and recommendations (Section 7)

1.2 Previous uses of Electrical Impedance Tomography and associated techniques

Tomography is a generic term applied to imaging techniques that create 'sections' of the entity being analysed. Generic tomographic methodology based upon electrical means includes measurements of resistivity (Electrical Resistance Tomography - ERT), capacitance (Electrical Capacitance Tomography - ECT) and impedance (Electrical Impedance Tomography - EIT).

Essentially, EIT is a technique that allows estimation of the spatial distribution of the electrical permittivity or conductivity within an object from impedance measurements at its boundary using non-invasive techniques (Borsic et al 2005). Normally, an array of electrodes is used to inject a known current, and the resulting voltage drops are measured with other electrodes within the array. The electrodes may be placed around an object, located on either side, or on the surface (Gasulla & Pallàs-Areny 2005). Known physical laws are used to relate the measurements with the object conductivity. Tomographic reconstruction uses algorithms to estimate the distribution of conductivity within the object and produces an image of this distribution.

The advantages of the use of EIT lie with the inherent simplicity, low cost and portability of the hardware, the high speed of data acquisition make it potentially advantageous for real-time or near real-time monitoring and over a large range of scales, sensors can be sufficiently robust to monitor in harsh environments (including wet environments (Church 2003)) and are relatively safe, and the object being monitored is done so in a non-invasive manner. The need for sophisticated image reconstruction algorithms, and providing images with adequate spatial resolution are key challenges.

EIT has been utilised for several applications, the most common being medical imaging and industrial processing, with some use albeit more limited in subsurface or geophysical investigations. ERT was proposed independently by Henderson and Webster (1978) as a medical imaging technique (although the first practical realisation of a medical EIT system was created by Barber and Brown (1984)) and by Lytle and Dines (1978) as a geophysical imaging tool. The physics of the basic sensor probably bears some allegiance to ground based mine-detection techniques from the late 1930s and early 1940's.

1.2.1 Use of tomography for medical imaging:-

EIT has been widely investigated as an alternative medical imaging technique to X-ray imaging, computerized tomography, gamma camera, magnetic resonance imaging (MRI) and ultrasound tomography (UST), partly because of the expensive nature of some of these approaches, and partly because of their adverse health effects. EIT has been successfully used as a non-invasive and relatively cheap alternative method for imaging the thorax and therefore assessing heart and lung function and blood volume changes (Smit et al (2005), brain function (Holder & Tidswell 2005), breast cancer screening (Hartov et al 2005), and gastric function (Soulsby et al 2005). An array of sensors are placed around the area of the body where imaging is required (usually 16 electrodes in a ring) and algorithms used to reconstruct the image of the desired area. The main limitations to it's more widespread use and development lie with the low spatial resolution and sensitivity to noise within the measurements. Therefore EIT is still seen as a research technique rather than receiving routine clinical use (Holder 2005).

1.2.2 Use of tomography for industrial processing:-

Many operations, particularly in the chemical, petroleum and power generation industries involve the transport and mixing of a range of substances within pipelines, including air-water, solid-water, and air-oil and water. Depending on the number of substances involved, these are referred to as 'two-phase' flow or 'multiphase' flow. The need to develop sensors and imaging techniques to enable in situ and on-line monitoring of the mixing process of these substances within pipes is driven by a desire to utilise resources more efficiently, reduce environmental emissions and/or to satisfy more strict product quality standards (Seleghim Jr. & Hervieu 1998, Dodds et al 2004).

Typically, an EIT sensor consists of a set of electrodes mounted around the periphery of the pipeline or tube measuring the impedance between electrode pairs and the reconstruction of cross-sectional images using the measured data and a suitable algorithm (Wang et al 2002). Using this approach, studies have utilised EIT successfully to directly image two-phase flows (Seleghim Jr. & Hervieu 1998, Kim et al 2005), the migration of particles in suspension flowing through a tube (Butler & Bonnecaze 1998, Wang et al 2003), and the density and velocity of solids in hydraulic transport inside a tube for dredging purposes (Ma et al 2002).

In certain cases, electrical tomography is one of the most attractive methods for real-time imaging of industrial processes, because of its inherent simplicity and high speed. EIT can generate a series of cross-sectional images and reveal the flow pattern from the images at some defined location in a pipe or process vessel. The distribution of dielectric materials might represent desired properties, such as density or chemical composition. By obtaining two series of images of a flow at two cross-sections and cross-correlating the elements in the two series of images, the velocity profile may be obtained. This opens a new way for on-line measurement of the volumetric flow rate. The data acquisition rates of an EIT system are fast (temporal resolutions in terms of milliseconds (Kim et al 2005)). An EIT sensor can be constructed to be sufficiently robust to cope with the harsh industrial environments. A drawback of electrical tomography is its relatively low spatial resolution — typically 3–10% of a pipe diameter (Kim et al 2005). However, the resolution should be viewed in the context of the practical industrial applications. With electrical tomography both qualitative and quantitative data needed for modelling a multi-phase system can be obtained. For instance, different flow patterns are characterised, in a qualitative way by using both time and space scales. The qualitative model may be verified by comparison between calculated fields of concentration or velocity and measurement results. As tomographic data provides, in a non-invasive way, cross-sectional profiles of the distribution of materials and/or velocities in a process vessel or pipeline, the results obtained from tomographic measurements can then be applied for process design and process control.

Alongside the developments in the use of EIT, other tomographic tools are being assessed. ECT has been used to quantify low concentration multiphase flows in wet gas separation processes (Yang et al 2004) and mixtures of gas, oil and water in the oil industry (Jaworski et al 2003, Ismail et al 2005). High accuracy (0.05%) and high resolution (10-17F) with changes as small as 1g (water) per kg (air) detected has been achieved (Yang et al 2004). Similarly, ERT has been tested for a range of purposes (Wang 2005) including monitoring the hydrodynamics of bubble columns (Toye et al 2005), two-phase air-water flow pattern and velocity distribution (Wu et al 2005), and suspended solid transport through pipes (Norman & Bonnecaze 2005).

In summary, tomographic imaging is becoming an established measurement technique for investigating the behaviour of multiphase mixtures. EIT, ERT and other process analytical measurement technologies have the advantages of being non-invasive, relatively inexpensive, pose few safety risks, can operate under rugged conditions, and data acquisition is relatively fast making it a valuable imaging tool for rapidly changing processes. However, poor spatial resolution and the need for sophisticated image reconstruction algorithms pose key challenges. Nevertheless, tomographic imaging, including EIT can provide a fundamental understanding of these industrial and manufacturing processes.

1.2.3 Use of tomography for geophysical surveys:-

The use of a range of electrical and electromagnetic methods, including ERT, ECT & EIT, have been applied as part of geophysical and environmental investigations. A recent review by Pellerin (2002) highlighted their use for:-

i) subsurface imaging and finding buried objects in archaeology,
ii) detecting groundwater and soil contamination, saltwater intrusion and leakage from buried waste or landfill,
iii) investigation of subsurface engineering structures, such as pipeline characterisation, leakage through embankment dams, and the effectiveness of subsurface barrier,
iv) hydrological investigations including aquifer mapping and infiltration in the upper soil horizons,

v) geophysical site characterisation at buried waste and landfill sites, geological mapping, and
vi) 'very difficult problems', such as mapping cave systems and landmine detection.

High resolution imaging techniques are therefore being used to capture details of the nature of subsurface properties and processes, and studies often use a combination of geophysical methods to reduce uncertainty in the interpretation of survey results (Guillen & Hertzog 2004). Wu (2000, 2001) has also demonstrated the use of radio ground-wave propogation theory for tomographic ground surface imaging with possible applications in ground surface mapping, remote sensing, target positioning and monitoring and navigation.

There has been widespread use of GPR as part of sedimentological studies to examine past depositional environments and conduct hydrogeological surveys (Neal 2004). Neal (2004) suggests however that the range of approaches to process radar data and subsequent interpretation techniques mean there is little consensus over a common method. GPR has also been applied as part of hydrological, soil science and agronomical research to measure soil water content, but the high sensitivity to soil texture and electrical conductivity reduces the range of soils where GPR can be successfully applied (Huisman et al 2003). Borehole Ground Penetrating Radar (BGPR) rather than the more traditional surface-based GPR has also been applied to examine soil hydraulic properties (e.g. the migration of the wetting front during infiltration and hence calculate hydraulic conductivity) (Rucker & Ferré 2004).

There have also been a growing number of studies apply ERT techniques to detect subsurface anomalies. Often, large, high density datasets using 2D or 3D arrays of electrodes are installed in boreholes to monitor environmental remediation, leak detection and soil water and groundwater transport (Daily & Ramirez 2000, Labrecque et al 2004, Samouëlian et al 2005). Baines et al (2002) used electrical resistivity ground imaging (ERGI) to develop a 2D model of the shallow subsurface (<200m) to map the lithology, stratigraphy and geometry of buried sand and gravel deposits and hence delimit former river channels (i.e. palaeochannels) buried within the floodplain at four study sites located in Canada and Holland. ERT was also applied to determine the internal architecture and infilling dynamics of a sand-filled palaeochannel located in the Rhône Delta in Southern France, suggesting these techniques may also aid palaeoenvironmental reconstruction (Maillet et al 2005). However, difficulties with ERT arise when trying to quantify the reliability of the images, and electrode mislocations can cause systematic data error making image interpretation very difficult (Oldenborger et al 2005).

ERT, ECT and EIT are very attractive methods for soil characterisation. Contrary to other methods that may perturb the soil by random or by regular drilling and sampling, these are non-destructive techniques and can provide continuous measurements over a large range of scales. In this manner, temporal variables such as water and plant nutrient, depending upon the internal soil structure are monitored and quantified without altering the soil structure.

EIT has also been utilised as part of geophysical investigations including the assessment of contamination sources, the flow of contaminants and their flow properties. For example, Daily and Ramirez (2003) tested a surface array of electrodes to detect the presence and map the distribution of soil contamination due to the dispersion of a non-aqueous phase liquid (DNAPL) at an outfall site. Other studies have examined the use of EIT with a surface array or electrodes to detect mines buried in the ground by detecting ground conductivity anomalies (Church 2003). A scaled down version was subsequently applied successfully in the laboratory to detect mine-like objects buried at shallow depths in underwater sediments (Church & McFee 2004). A similar laboratory based study demonstrated the potential of EIT as an imaging tool to detect anomalies in sandy samples due to variations in porosity, grain-size distribution and clay content (Borsic et al 2005). Work is also ongoing with respect to the challenge of using algorithms to reconstruct the image based on electrode measurements with sufficient speed to monitor temporal variations in the entity being monitored (Gasulla & Pallàs-Areny 2005).

EIT does not produce direct measurements of the geo-physical properties of solids suspended in water. This can be inferred from measurements of resistivity, capacitance or impedance and then related to the geo-physical properties of solids suspended in water from the work of Archie (1942), the model of Wyllie and Southwick (1954), Hanai (1960), Waxman and Smits (1968), Clavier et al (1977), Sen et al (1981) and Bussian (1983), Garboczi and Douglas (1995), and Chinh (2000) working with complex dielectric can be cited). The reportedly fast development of hardware and software related to EIT allows for the prospect of performing fast tomography acquisition and processing (Barber and Brown (1984), Barber and Seagar (1987) and Xie et al (1993).

1.3. Previous work using EIT for river-based research

To date, to the best of our knowledge only one study has utilised EIT for river-based research (Sambuelli et al 2002). This study surveyed a 5m wide and 1m deep rectangular reinforced concrete sedimentation trap, with 12 sensors (electrodes) located on the channel bottom and 2 positioned vertically on each side. A complete cross-profile survey could be collected and processed within about 10 seconds. The research focused on assessing where sedimentation along the river bed occurred and the results also indicated areas within the water column where particle suspension was evident. Therefore, the Sambuelli et al (2002) study was successful in using EIT to image suspended sediment transport in flowing water and the channel margins in near real-time (see Figure 1 below). The data acquisition system, a Complex Impedance Tomograph (CIT) Mark I, is the same as that described later by Bena (2003) and Borsic et al (2005).

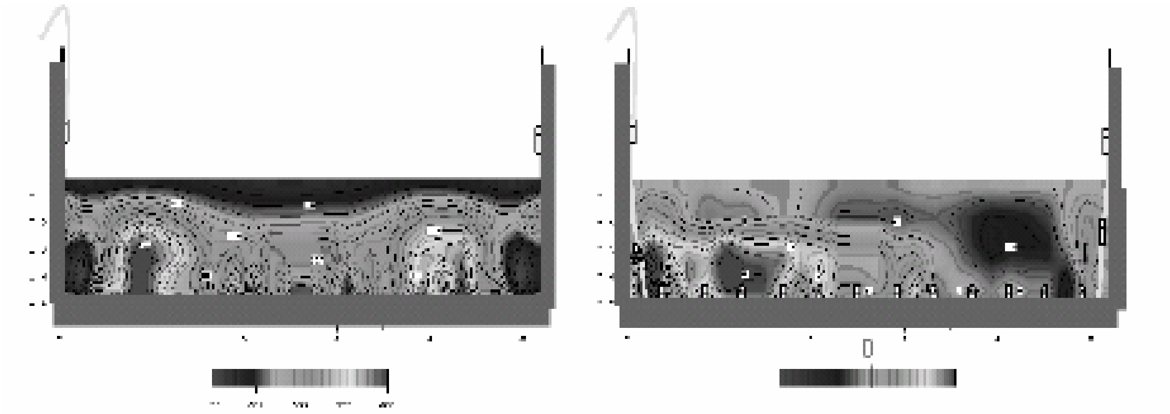

Figure 1.1 Tomographies of the sedimentation trap determined from Wenner array data at 1000 Hz. Background resistivity (left) and percent of resistivity variation after sediment was added to the water (right) (source: Sambuelli et al 2002, p.91).

However, the research did not investigate the role of EIT in imaging changes in river bed topography over time. Furthermore, the equipment design and installation used a sensor array that required electrodes to be placed along the bed of the channel (rather than inserted into the banks on the river margins), and therefore this type of approach is invasive and hence may interfere with the very processes that may also be monitored, i.e. morphological changes due to bedload entrainment, transport and deposition. Therefore, whilst this approach showed great promise for imaging river channel cross-sections, the previous research did not attempt to monitor river bed changes in real-time using a non-invasive sensor array. Therefore we believe that no previous research has examined the potential use of EIT for the purposes proposed by this study.

2.0 ASSESSING RIVER BED MORPHOLOGY: A SUMMARY OF CURRENT APPROACHES

2.1 Why assess river bed morphology?

Understanding river bed forms and their dynamics, channel location and change, and sediment entrainment, transport and depositional processes have long been a fundamental focus of the study of fluvial geomorphology (Simon & Castro 2003). Central to this understanding has been the need to measure and monitor river bed morphology, discharge (or water level) and sediment load in the field. Therefore, the development and application of river bed surveys has been a core area of field data collection and analysis for this subject area. However, the study of such phenomena is not the sole interest of fluvial geomorphologists. Aquatic ecologists study the role of river bed hydraulics due to their influence on macrophyte, macroinvertebrate and fish communities (e.g. Rabeni, & Jacobson 1993, Riis & Biggs 2003, Mérigoux & Dolédec 2004) and the recent development of hydroecology as a new interdisciplinary science often requires bed morphological data to determine river habitat quality (Hannah et al 2004). Civil engineers are interested in river behaviour where it affects new or existing structures, such as the need to monitor scour around bridge supports. River engineers may also wish to monitor river bed dynamics for navigation purposes or to inform the timing and extent of river bed dredging requirements. As a result, an array of methods and techniques have been developed to assess river bed morphology and channel change, in-channel hydraulics, and river bed and suspended sediment dynamics.

2.2 Summary of current approaches to examine river bed change

The following review provides a broad outline of the most common and relevant approaches that have been used to assess river bed morphology, in-channel hydraulics and river bed dynamics. The most common and traditional approaches are reviewed first, with new technologies that have only been tested in a limited number of applications discussed later. This review is not intended to be exhaustive, but provides a brief overview of the methods and instruments used, commenting on their advantages and disadvantages, and paying particular consideration as to whether the approach has or could be used to provide real-time or near real-time measurements of river bed morphology in a non-invasive manner.

Traditional surveying equipment and instruments that have been used for topographic surveying for many years. ***Surveyor's Levels, Theodolites, and Total Stations*** have all been utilised for the measurement of river bed morphology and concurrent water level surveys. In order to perform river bed surveys, topographic data tend to be collected at individual points across cross-sections from one side of the channel to the other. The surveying instrument is usually set up somewhere on the bankside, and one person operates the surveying instrument from that fixed point. Where the target stream or river is shallow enough to wade, another surveyor manoeuvres the survey staff or pole across the river bed profile. Alternatively, in deeper water the staff or pole may have to be handled from a boat.

In recent years, ***fully motorised total stations*** have been developed that can be operated by one person, with the instrument located on the bankside automatically tracking the survey pole with prism (e.g. Leica TDA5005, or Topcon GTS-810A series). The pole can then be placed in the required positions by the single surveyor and the instrument surveys it's location remotely. Use of these devices increases data acquisition compared to traditional survey instruments, and depending on circumstances may return in excess of 2,500 points per day to an accuracy of 10-20mm (Chandler et al 2002). In a similar way, advances in satellite technology have introduced the viability of using survey grade Real Time Kinematic ***Global Positioning Systems*** (RTK GPS) with sub-centimetre accuracy. RTK GPS instruments can also be operated by one person with the GPS receiver and keypad all mounted on a single survey pole that is manoeuvred between survey points by the surveyor.

Whether using traditional surveying instruments, a motorised total station or a GPS, river bed topography is normally surveyed at individual points and subsequent interpolation between survey points provides continuous 2D cross-profiles (e.g. Sidle & Milner 1989) Some geomorphological studies, for example those interested in volumetric changes in sediment along continuous sections of river, require variations in bed morphology to be surveyed along a river reach, and therefore involve multiple cross profiles being surveyed. These may be spaced either regularly or irregularly along a river section (Paige & Hickin 2000). In addition to the interpolation between points across the profile that is required to produce the 2D results, interpolation between cross-sections in the upstream / downstream direction is carried out to provide the 3D reach topography. Therefore, key decisions need to be made about the number of survey points to use, the number of cross-sections required, and their spacing. A clear trade-off exists between the time required to collect the survey data and the resolution of the cross-profile produced. A greater sampling density leads to improved surface quality but requires more field data collection time.

Studies that are concerned with temporal changes in channel location or bed morphology require repeat surveys, an approach commonly applied to rapidly migrating braided channels in upland or mountain environments (Chandler et al 2002). This is usually performed by installing fixed survey markers on the floodplain on either side of the channel in order to mark out the margins of the survey cross-sections and act as fixed benchmarks so they can be relocated during subsequent surveys (Chappell et al 2003). For example, repeat surveys of cross-sections were carried out over time and superimposed to identify areas of scour and fill on 10 cross-sections covering 5 streams in Alaska (Sidle & Milner 1989). By surveying several cross-sections along a reach and linking these together, volumetric changes can be estimated (Fuller et al 2003). Alternatively, topographic data may be collected at unevenly distributed points spread throughout a reach that mark changes in bed height and breaks in slope and then geostatistical techniques employed to complete the interpolation (Chappell et al 2003).

There are however several limitations in using these traditional approaches. Inevitably errors may be introduced associated with the interpolation process that may smooth out differences in ground heights between survey points. A dense and accurate topographic network of data points is required, appropriately located in space and time to understand geomorphic processes. Interpolation errors can be particularly large in the longitudinal direction, i.e. between multiple cross-sections where these are widely spaced apart (Westaway et al 2000). In fact, Westaway et al (2003) has highlighted the location, spacing and frequency of cross-sections, and individual survey point spacing within cross-sections is often based on cost and practicality in the field rather than being driven by important geomorphological factors.

In addition to the interpolation errors identified above, a more fundamental issue associated with the use of cross-sections to describe 3D reach morphology has been raised. Recent research by Rivas-Casado et al (2004, 2005) compared survey sampling strategies to best describe river bed morphology and hydraulics. This research suggested that random point sampling provided the optimum approach, with cross-profile surveying (as traditionally used in fluvial geomorphological field studies) having the most problems because of the interpolation problem described above.

When considering channel change, rivers are at their most dynamic when discharge is high and therefore sediment entrainment and transport processes have been initiated. The use of traditional survey methods are limited to sites and flow conditions where the survey pole can be safely positioned on the bed of the stream, usually by wading (or less frequently with the use of a boat). This limits work to relatively shallow and slower flowing sites, and makes these methods impractical to use during high flow or flood conditions when in fact these processes are most active. As a result, laboratory flumes have been used to simulate these processes in a more controlled, manageable and safe environment, but the near impossibility of directly monitoring river bed morphological changes in real time has limited our detailed understanding of these processes. Technology that would enable real-time monitoring of river bed morphology with non-invasive instruments would help overcome this limitation.

The approaches outlined above all involve direct contact with the ground and river bed in order to collect topographic data. However, ***remote sensing*** techniques that acquire data about the Earth's surface without coming into contact with it have developed rapidly in recent years. For example, ***airborne laser scanning*** or ***airborne laser altimetry*** (Light Detection and Radar - LiDAR) enables the construction of Digital Elevation Models (DEMs) that are now being used for flood defence planning and hydraulic modelling (French 2003) but the cost is high, and quoted accuracy of 0.15m is considered by some to be overly optimistic (Adams and Chandler 2002). Furthermore, they cannot provide information on bed morphology beneath the water surface.

More recently, ***terrestrial laser scanning*** has also been developed and applied to assess a range of geomorphological environments including sand dunes (Nagihara et al, 2004), glacial outwash plains (Milan et al, in press) and river channel morphology (Heritage and Hetherington, 2007). These relatively new instruments can collect large amounts of data points with greatly improved accuracy and in a short space of time. For example, Heritage et al (2006) conducted a survey of 253,000 points measurements across a point bar with a median spacing of 0.09m and a median error of ~0.003m and this was completed in a few hours. Undoubtedly the use of these instruments will improve the accuracy of DEMs and our understanding of the morphology of landforms and the geomorphological processes that are operating. Their disadvantages lie with the very high cost of the equipment, and their limited ability to penetrate the water surface and map river bed topography below the water. Heritage and Hetherington (2007) suggested that the laser pulse was often refracted off the water surface and no data were recorded unless the water was clear, calm and shallow (<0.1m). Furthermore, where readings were recorded through the water they had a mean error of 0.23m. Huising et al (1998) also reported problems of laser beam reflection on turbulent water surfaces that generated errors when measuring over river channels. Therefore laser scanners are instruments ideally suited to provide rapid and highly accurate surveys of the exposed ground surfaces on floodplains and the margins of river channels, but cannot provide rapid or real-time estimates of bed morphology below the water surface.

Photogrammetry has a long history of utilising information from analogue photographs to produce topographic maps. However, it suffers from many of the limitations of laser scanning because of the expense of chartering flights to acquire the vertical aerial images (Chandler et al 2002). The recent development of ***digital photogrammetry*** using images acquired from high resolution digital cameras coupled with ground survey has been used to monitor changes in bed morphology using both vertical images (Lane 2000) and using terrestrial based oblique images (Chandler et al 2002). The latter has advantages of being cheaper due to the images being acquired from a suitable ground-based vantage point rather than from the air (although this may still be problematic in many environments, e.g. level or heavily wooded terrain). When applied to monitoring river bed morphology, this approach can provide survey data for large expanses of exposed river bed at low flow much more quickly than traditional ground based surveys (Westaway et al, 2000, Westaway et al, 2003). However, in common with laser scanning, this approach does not survey beneath the water surface and hence to develop complete maps of river bed topography, this method has to be combined with traditional survey methods using surveyor's levels, theodolite or a total station bringing the potential errors and limitations already outlined above. Therefore, automated digital photogrammetry cannot provide data on real-time changes in river bed morphology.

Another development in recent years has seen the application of ***airborne multispectral and hyperspectral remote sensing*** to assess stream morphology (Gilvear et al, 2003) including water depths ('bathymetry') (e.g. Winterbottom & Gilvear 1997, Fonstad & Marcus 2005, Carbonneau et al

2006), flow type and river habitats (Whited et al 2002, Marcus et al 2003) and particle size measurements on dry exposed areas of the river bed (Carbonneau et al, 2004, 2005) and shallow wetted areas with coarse substrate (Carbonneau et al, 2006). Whilst these approaches are still in their infancy and show promise in terms of broad spatial coverage and rapidly improving resolution, they are limited by the cost of obtaining the airborne imagery and the difficulties of collecting data over short temporal scales to detect rapid changes in river environments. More importantly, current state-of-the-art for depth estimates have been estimated to +/- 15cm with a $4m^2$ spatial resolution (Carbonneau et al 2006), and the method will not work when the river is obstructed from view from above (e.g. from clouds or riparian tree cover), heavily shaded (e.g. from steep banks, incised valleys and/ or low sun angles) or where the water is turbid. These deficiencies mean that at present, remote sensing is not suitable for the detection of small scale changes in river bed topography, or for real-time monitoring.

A host of other new technologies and monitoring devices have been developed to detect channel change, the initiation of river bed sediment erosion, transport and deposition and river bed scour. For example, Hürlimann et al (2003) describe the combined use of ***ultrasonic devices, video cameras, a radar device and geophones*** to detect high magnitude debris-flow events in the Swiss Alps in real-time. The ultrasonic and radar devices measure flow depth, video cameras record pictures of the debris flow as it occurs, and the geophones record measure ground vibration produced by the passing debris flow which also trigger similar monitoring devices further downstream. Whilst the combined use of these various devices at different locations along the channel helped elucidate the nature and dynamics of the debris-flow, the ultrasonic and radar devices only record water surface level. The authors postulate that there was probably a significant amount of channel bed erosion during the peak flows and hence total water depth at that time would have been greater than estimated, but these devices cannot measure river bed erosion. Therefore discharge estimates could also contain significant inaccuracies. Itakura et al (2005) provide an overview of the wide range of devices used to monitor debris flows and whilst many may operate in real-time, none provide real-time images of the channel bed profile.

Fluvial geomorphologists and hydraulic engineers alike have directed huge efforts over many decades to understand the complex interaction between river bed sediment entrainment, transport and deposition, discharge, hydraulics, sediment supply, grain size variability, embeddedness and compaction (Dollar 2004). Field studies have utilised a wide range of approaches to understand particle movement, including the use of ***'tagged' or 'labelled' particles*** that are placed on the stream bed at known locations and then relocated after being transported downstream by a high flow or flood event sufficient to initiate particle entrainment. Radioactive tracers (Sayre & Hubbell 1965), fluorescent dyes (Yasso 1966), magnetic tracers (Hassan et al 1999) labelling with paint (Lenzi et al 2006) and the use of high frequency radio-tagging (Habersack 2001) have all been used to 'mark and recapture' bed sediment particles and help explain the interaction between sediment transport and river morphology. Estimates of bedload can be gained from portable devices or ***bedload samplers*** that are lowered onto the streambed containing collecting baskets that 'catch' material as it moves downstream, such as the Helley-Smith pressure difference bedload sampler. However, these are notoriously difficult to manoeuvre into position particularly when most bedload occurs during high flows, small differences in design and shape seem to have large effects on the amount of material collected, and only involve point sampling when bedload may vary significantly over short distances across the channel (Ryan & Porth 1999).

Alternatively, ***bedload traps*** consist of open troughs installed on the river bed, and bedload falls in to the trough as it passes over the opening. Some contain moving belts within them to deposit the material into a sump usually installed in the bank and so the trough does not overfill (Leopold & Emmet 1976, Harris & Richards, 1995). These devices are inherently expensive to install and maintain, and by placing an aperture on the river bed they reinforce and therefore alter the environment where the sampling occurs. Some bedload will bounce or saltate along the river bed and therefore issues of sampling accuracy are also a limitation.

Marked sediment particles, bedload samplers and bedload traps have helped elucidate some issues relating to sediment movement in the field, but they do not involve direct monitoring of the entire cross-section in real-time and therefore provide important but only partial information relating to bed morphological changes during the phases of entrainment, transport and deposition.

Acoustic Sensors have been tested and proven successful to monitor the bedload transport of uniform sand-sized particles in laboratory flumes in real-time with a resolution of +/- 0.5mm (Kuhnle et al 1998). However, field testing has not been reported, and nor indeed has measurement of other particle-sizes such as silt, clay, gravel, cobble or mixed particle sizes more commonly found on river beds. Subsequent research has tended to concentrate on the use of this technology to estimate suspended sediment rather than bedload sediment transport (Wren et al 2000). ***Photography and videography*** has also been used to record particle movement, although this approach requires high water clarity to make observations and therefore will always be restricted in its application to a small number of suitable sites or more commonly in laboratory flumes (Drake et al 1988).

Acoustic Doppler Current Profilers have been developed that float on the surface and are pulled across the water via a tag line (or manipulated remotely via a radio control device), transmitting ultrasound frequency sound waves into the water column to provide data on water depth and water velocity profiles across the entire cross-section (Cheng & Gartner 2003). A discharge calculation can be made from these data. At present these instruments are expensive, and whilst they represent a huge improvement in the time required compared to current meter surveying to provide discharge estimates (approximately 3 minutes compared to 30 minutes), they are not capable of providing real-time measurements of the entire profile at any point in time.

Attempts to assess the erosional and depositional processes that occur around bridge supports has led to the development of further river bed monitoring devices. Some studies have utilised ***ground penetrating radar (GPR)*** (e.g. Olimpio 2000, Park et al 2004) to assess the extent and depth of existing and infilled scour thickness, streambed substrate properties, and the pre- and post-scour surfaces at bridge piers. The GPR was reported to penetrate between 2m and 8m of subsurface sediments, with the depth of sediments assessed largely affected by the depth of the water above. The study by Olimpio (2000) indicated that shallow water (<1m) had a small effect on signal penetration of stream bed materials, but deep water (>3m) attenuated the signal and stopped signal penetration beyond 30-70cm. Also, the nature of the bed material exerts an influence on signal penetration, with cobble and boulder-sized particles stopping any signal penetration. The studies performed pre- and post-flood and scour event surveys to examine the extent of bridge scour and hence there was no real-time or continuous monitoring element to these studies.

Lin et al (2004) used ***optical fibre sensors*** to monitor the same problem, i.e. bridge scour, but with the added advantage of providing real-time data. This system measured scour depth and variations in water level successfully but concluded that additional work was required on the sensor housing and location to avoid damage during the floods from the high impact forces that occur from sediment in transport in the water during these events. In other words, because this device is invasive and requires fixing within the water column it is prone to damage. This system also suffers from the limitation of providing point measurement data at the sensor location rather than cross-profile information.

Microwave Doppler radar combined with GPR have also been utilised in a small number of studies in the US to provide non-invasive measurements of stream discharge (Costa et al 2000, Haeni et al 2000, Melcher et al 2002, Cheng et al 2004, Costa et al in press). A pulsed-Doppler radar system was used to collect water surface velocity data, whilst the GPR instrument was suspended above the water via a cableway and slowly pulled across the river to identify the river bed topography and water surface and hence calculate cross-sectional area. Whilst this confirms the use of GPR to identify river bed / water boundary similar to the bridge scour studies identified above, the GPR measurements took approximately 8 minutes to cross a 183m wide river, required a cableway to suspend the instrument, and was suggested to be less reliable in turbid water conditions.

In summary, a wide range of surveying instruments and monitoring devices have been utilised to assess river bed morphology for numerous purposes. However, non appear to provide measurements of entire cross-sections in real-time or near real-time. No reported studies were found that had applied EIT to this issue, and therefore the approach proposed appears to provide a novel use of this relatively new technology.

3.0 LIMITATIONS OF CURRENT APPROACHES FOR REAL-TIME, NON-INVASIVE MONITORING OF RIVER BED MORPHOLOGY AND THE POTENTIAL OF ELECTRICAL IMPEDANCE TOMOGRAPHY

3.1 The limitations of current approaches

As described in the previous section, assessments of river bed morphology are carried out to provide field data sets for a variety of different purposes, such as describing the habitat quality of rivers, hydraulic modelling, studies of sediment entrainment and transport, channel dynamics and change, discharge estimations and assessing scour extent around bridge supports.

Table 1 below summarises the range of approaches used and their advantages. The final column comments on their use or viability to provide real-time, non-invasive measurements of river bed morphology and hence highlights whether any of the existing approaches can meet the proposed objectives of EIT.

Table 3.1. Summary of approaches used to monitor changes in river bed morphology

Technique / Approach	Advantages	Limitations for providing real-time, non-invasive measurements of river bed morphology
Traditional surveying using levels, theodolites or total station with point measurements collected across transect(s)	Relatively low cost of instruments Most common approach enables comparisons with other studies	Time consuming Interpolation errors between points and cross-sections Difficult to survey deep and or fast flowing rivers Health and safety issues Not real-time
Terrestrial laser scanning	High resolution Rapid collection of large number of data points	High cost of instrument Does not penetrate water easily therefore cannot image river bed in turbid, turbulent or moderately deep water (<0.1m)
Digital photogrammetry	Potentially large and continuous spatial coverage	Cannot penetrate water surface to image river bed

Technique / Approach	Advantages	Limitations for providing real-time, non-invasive measurements of river bed morphology
Hyperspectral remote sensing	Potentially large spatial coverage Applied to measure stream depth, water velocity, substrate size	High cost of data acquisition Inadequate spatial resolution Problems with shading, tree cover on banks, turbid water Not real-time
Remote sensing - Airborne laser scanning (e.g. LiDAR)	Rapid collection of large number of data points	High cost of data acquisition Cannot penetrate water surface to image river bed Inadequate spatial resolution
Combined use of ultrasonic and radar devices, video cameras and geophones	Detect initiation and movement of debris-flows in mountain torrents	Cannot measure river bed morphology or detect real-time bed changes
Tracers, bedload samplers and bedload traps for sediment transport studies	Measure extent of sediment transport and size of particles entrained	Difficulty locating tagged sediment after event Bedload samplers measure at fixed points and may induce or interfere with process they are measuring Bedload traps are difficult and expensive to install and monitor at one point location No real-time monitoring
Photography and videography	Records particle entrainment and transport	Restricted to sites with high water clarity, usually limited to flume experiments
Acoustic Sensors	Monitor bedload transport accurately in real-time with high resolution in flumes	Only used on sand-sized particles and not tested in field conditions
Acoustic Doppler Current Profiler	Measures water depth and velocity profile whilst traversing stream surface. Enables rapid measurement of discharge	High cost of instrument Not continuous or real-time as requires device to traverse water surface

Technique / Approach	Advantages	Limitations for providing real-time, non-invasive measurements of river bed morphology
Ground Penetrating Radar	Used to monitor scour thickness below bridge supports in pre-and post-flood studies	Less effective as water becomes deeper Not real-time monitoring and only used at fixed points
Optical fibre sensors	Used to monitor scour below bridge supports and changes in water depth in real-time	Only provides measurements close to sensor, i.e. at fixed points Needs to be in water and therefore is invasive and prone to damage from water and sediment transport
Microwave Doppler radar combined with GPR	Radar used to measure surface water velocity and GPR used to image river bed profile, hence calculate discharge in a non-invasive manner	GPR cross-profile survey requires cableway to traverse above stream surface Not real-time

This overview illustrates that a wide range of methods and techniques have been utilised to monitor and measure changes in river bed morphology. These range from the more traditional approaches using surveyor's levels, theodolites and total stations, to more recent developments using surface, airborne or satellite-based remote sensing with radar, LIDAR, electro-optic (EO) and acoustic sensors.

3.2 The potential of Electrical Impedance Tomography

The potential advantages of EIT to the measurement of riverbed morphology are stated as follows:

- Low cost (Toye et al 2005)
- Simple construction
- No mechanical moving parts
- Rapid data measurement with low latency allowing real-time processed image presentation
- Does not depend upon the optical properties of the water and suspended solids
- Portable
- Does not perturb the region of measurement

4.0 PROPOSED APPROACH

The proposed approach is to bury a set of vertically disposed electrodes on opposite sides of the water course. Electrical measurements will then be made between all combinations of the electrodes. Using algorithms derived from existing tomographic imaging techniques a cross section of the river bed will be derived.

4.1 Electrical Impedance Tomography (EIT)

The electrical measurements will be made to measure either the complex impedance of the path between the electrodes or simply the resistive component. In the case of the complex impedance the measurement will comprise the resistive component, the imaginary component and the phase angle between them. It is suspected at this stage that the imaginary component will be mainly capacitive since the measurements will be largely through the water and water has a high dielectric constant. In salt water the situation may be different because of the predominantly high conductivity of the water.

For simplicity we suggest that the study should address resistance tomography in the first place, then move on to electrical impedance tomography. In this way the importance or otherwise of the complex components of impedance can be assessed.

4.2 Modelling and validation

In order to make an initial assessment of the technique it is proposed that a resistance network is made with resistance values that mimic the cross section of the river bed to be imaged, this cross section having been previously measured using traditional techniques. Using a simple multimeter to measure across the resistance network a data table will be compiled. The data will then be processed in the same way as the measurements from the river situation and the results compared. Figure 4.2.1 shows the resistance network. Later in the project the resistance network could be connected to the measuring system that will have to be designed for these measurements in order to achieve real time river bed cross section images. These procedures will give confidence that the technique is working.

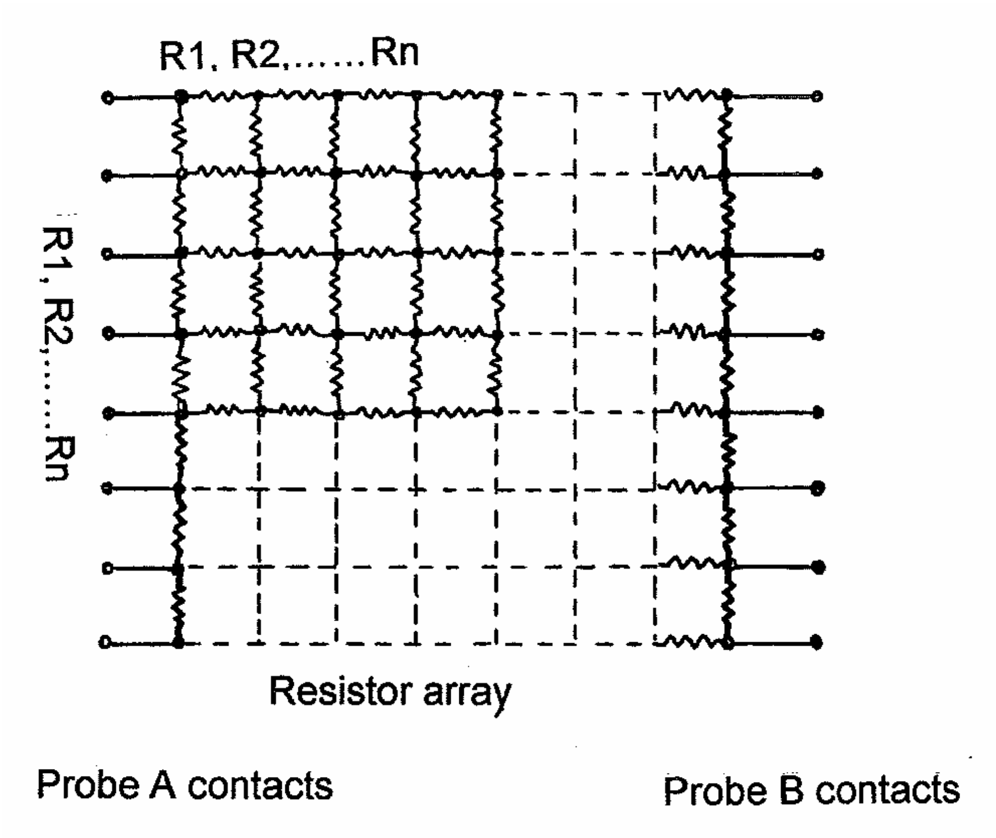

Figure 4.2.1 Array of resistors

4.3 Probe design

The probes will consist of a linear array of contacts insulated from one another with contact wires that are brought to the surface for connection to the measuring system. Ideally the probes should be as deep as possible and have as many contacts as possible in order that sufficient of the river bed is imaged in detail. In order to deploy the probes it is proposed that a hole is cored out on each side of the river bed. If the extracted cores are kept intact they will give further information about the strata in the region of the banks of the river. Fig.4.3.1 shows the probe construction.

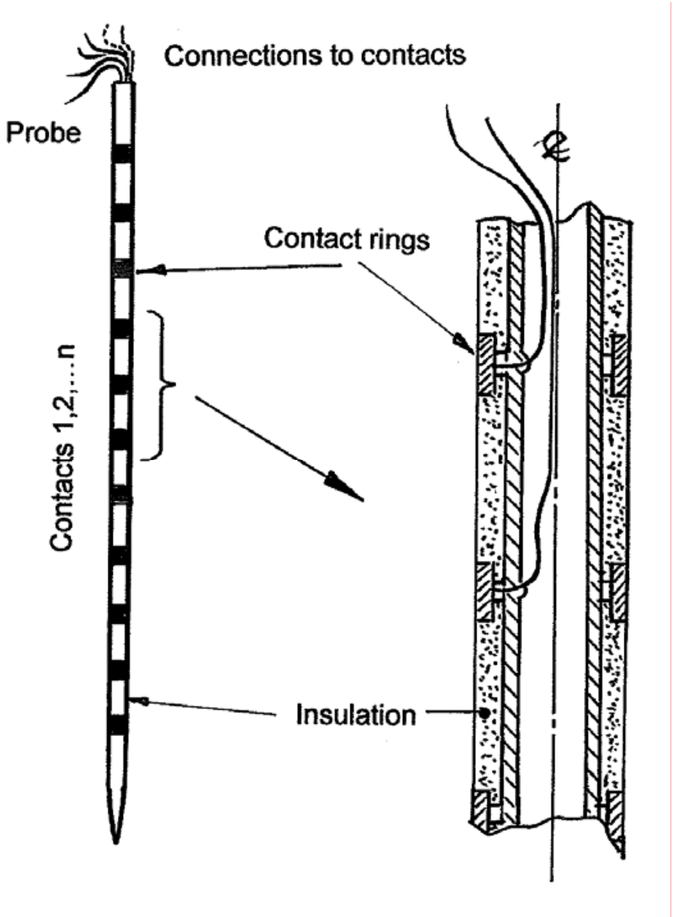

Figure 4.3.1 Probe construction

4.4 Array parameters

Figure 4.4.1 shows a simple array of 13 elements per side. Measurements will be made between all combinations of elements and this is represented by the lines shown in the figure. It is obvious that the greatest resolution will occur where the density of crossing lines is greatest. The image is derived by solving a series of simultaneous equations to define the values of an equivalent network of resistors.

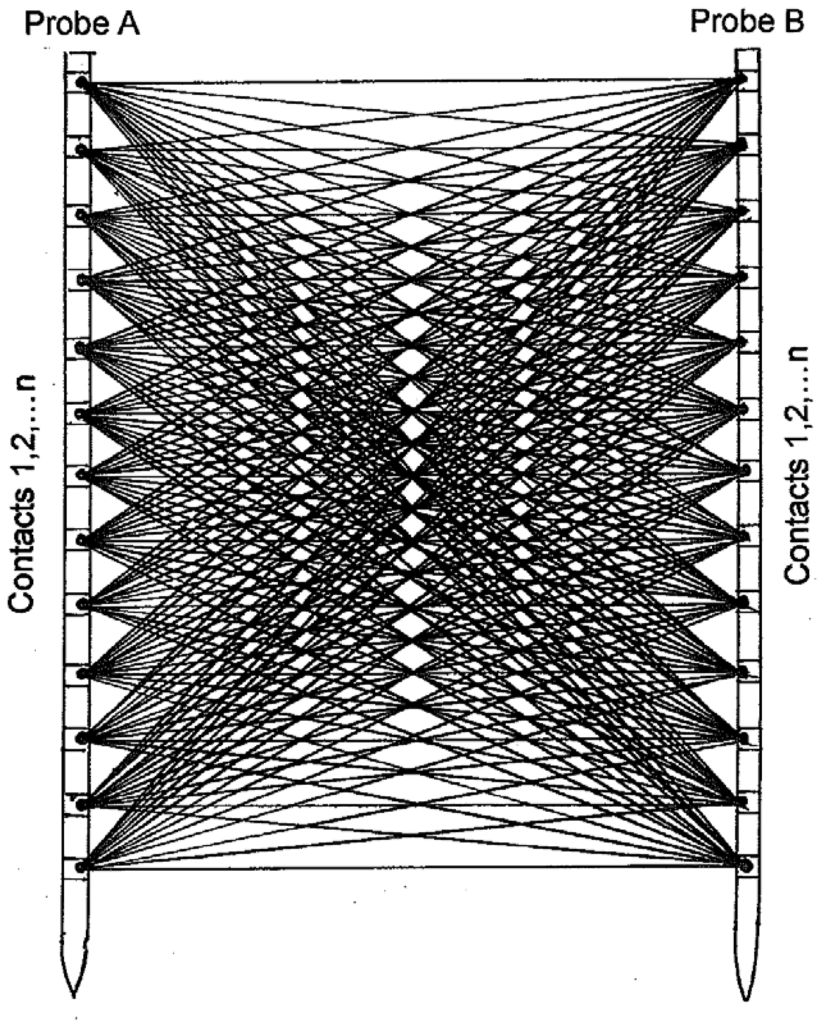

Figure 4.4.1 Electrical paths between probe contacts

4.5 Data acquisition

In a real instrument as opposed to an experimental set-up the resistance or complex impedance will be measured and logged automatically with a purpose designed measurement and data logging system. This will also be capable of showing a visual representation of the river bed cross section in near real time.

4.6 Test site

The Leigh Brook (which is known as the Cradley Brook in its headwaters) rises on the western flank of the Malvern Hills in Worcestershire and forms a tributary of the River Teme, which joins the River Severn just downstream from the City of Worcester. The area is largely rural, interspersed with a few small villages, and land-use is dominated by improved grassland for agricultural use and woodland. In it's lower reaches, the brook flows through the Knapp and Papermill Nature Reserve managed by the Worcestershire Wildlife Trust. The catchment area upstream from this location is approximately 80km^2. Within the reserve, the brook flows through an incised wooded valley. The channel is tree-lined and displays a wide variety of morphological types including riffles, glides, pools, and bars (lateral, mid-channel and diagonal); features associated with a natural gravel bed river. Within the reserve, the active channel is approximately 10-15m wide and 2-3m deep from streambed to bankfull.

Previous research (Maddock and Lander 2002) involved a detailed morphological survey of a 198m stretch of the brook described by 199 cross-sectional surveys spaced 1m apart and assessed with 5429 survey data points. This previous and work can be used to guide site selection within this reach. Therefore, we propose to use this site for field testing for the following reasons:-

- The previous research means we have existing detailed morphological data than can be used to identify a suitable reach to carry out field testing.
- The brook has a relatively varied morphology. This would enable us to select multiple cross-sections spread along a short stretch of river to test the approach over a range of different bed morphologies.
- The brook is a reasonable scale to test the approach, and manageable size to work in, with wading possible along most of it's length.
- The University of Worcester runs a permanent hydrological monitoring site on the brook within the reserve, and therefore concurrent measurements of water level (and water quality) will also be recorded as part of the routine monitoring. These data can be used to compare flow conditions during different field trials.
- The proximity of the site is convenient, lying part way between the University of Worcester and Q-par-Angus. The previous and ongoing monitoring means we have a good relationship with the landowners

and permission has very kindly been granted by Worcestershire Wildlife Trust to carry out the previous research and ongoing monitoring. Further permission would need to be sought to conduct the proposed research.

5.0 FUTURE WORK

This will involve a program of practical measurement, electrical design, numerical techniques and measurement interpretation and validation. It is seen as an ideal cooperative University / Industry project that should result in a product with a substantial worldwide market that benefiting not only the industrial partner but providing revenue for the University.

6.0 EXPLOITATION

EIT has become established in recent years as tool used for imaging in the areas of medical analysis, industrial processing and geophysics. This study has investigated the potential viability of using EIT to provide a low cost, portable, real-time or near real-time assessment of variations in river bed morphology. Subject to successful construction, development and field testing, applying EIT to image river bed morphology may have potential benefits for a range of new exploitations. These include:-

Fluvial Geomorphological and Ecohydrological Research:-

- Cross-profile surveys that require temporal monitoring
- Bed morphological surveys
- If a 3D image can be produced, then reach surveys may be used to develop Digital Elevation Models (DEM)
- Bedload transport studies, particularly monitoring bedload entrainment initiation in real-time or near-real time
- Assessing spatial and temporal variations in suspended sediment transport if images can be calibrated accurately
- Cross-profile measurements, when coupled with velocity readings, may be used to calculate discharge

Civil engineering exploitation

- EIT may provide real-time or near real-time images of river bed erosion around structures, e.g. bridge supports. This could be coupled to an alarm system when critical bed incision around supports occurs.

Navigation

- Sensors could monitor changes in bed morphology across sites used for navigation but are also susceptible to sedimentation. Data could be used to inform the timing and extent of dredging requirements.

7.0 CONCLUSIONS & RECOMMENDATIONS

Our conclusion from this Connect A project is that Electrical Impedance Tomography has a valuable place in imaging river bed morphology. This is not only from a research standpoint but for monitoring river bed cross section for civil engineering applications; for example in the region of bridge structures. Our recommendation is that this topic is worthy of further research with a view to commercialisation. Considerable effort has gone into the bibliography in section 9.0 which has helped to identified the unique application of tomography to river bed morphology.

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