Technical University of Denmark

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Publication date:
2015

Document Version
Publisher's PDF, also known as Version of record

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The synopsis part of this thesis is available as a pdf-file for download from the DTU research database ORBIT: http://www.orbit.dtu.dk

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Printed by:	Vester Kopi June 2015
Cover:	Torben Dolin

Preface

This PhD thesis is a presentation of the work conducted under the supervision of Associate Professor Peter Bauer-Gottwein between 1st December 2011 and 2nd March 2015 at the Technical University of Denmark (DTU) with extensive field work in the Machile-Zambezi Basin in south-western Zambia. The work was funded by the Danish Ministry of Foreign Affairs (DANIDA) under the programme for capacity building for the Zambian Water Sector - Phase II. Co supervisors included Anders Vest Christiansen, PhD (Associate Professor, Department of Geosciences, Aarhus University); Imasiku A. Nyambe, PhD (Professor, Geology Department, University of Zambia); and Flemming Larsen, PhD (Head of Department, Geological Survey of Denmark and Greenland). The first part of the thesis is a synopsis that puts into context the main findings of the PhD project. It is based on the second part which gives a detailed account of the work done in the form of three scientific papers referred to as papers I, II, and III. The titles of the three papers are:

I Chongo, M., Christiansen, A.V., Tembo, A., Banda, K.E., Nyambe, I.A., Larsen, F., and Bauer-Gottwein, P. 2014. Airborne and ground based transient electromagnetic mapping of groundwater salinity in the Machile-Zambezi Basin, south-western Zambia. Accepted for publication in Near Surface Geophysics Journal (in press).

II Chongo, M., Christiansen, A.V., Fiandaca, G., Nyambe, I.A., Larsen, F., and Bauer-Gottwein, P .2015. Mapping localized freshwater anomalies in the brackish Paleo-Lake sediments of the Machile-Zambezi Basin with transient electromagnetic sounding, geoelectrical imaging and induced polarization. Submitted to Journal of Applied Geophysics.

III Chongo, M., Nyambe, I.A., Larsen, F., and Bauer-Gottwein, P, 2015. Coupled hydrogeophysical inversion using a groundwater flow and transport model, and transient electromagnetic and direct current electrical resistivity data. Manuscript.

In this online version of the thesis, the papers are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from: DTU Environment, Technical University of Denmark, Miljoevej, Building 113, 2800 Kgs. Lyngby, Denmark. reception@env.dtu.dk

Acknowledgements

I wish to express my thanks and gratitude to all institutions and individuals that have been instrumental to the successful execution and completion of my PhD studies. It is not possible for me to list each and every one of them due to constraints of space on the paper except for a very select few; nevertheless I am truly grateful to all.

I would like to thank the Danish Government for funding this research through its Ministry of Foreign Affairs and to the Zambian Government through the Department of Water Affairs under Phase II of the programme to build capacity in the Zambian Water Sector. I would also like to thank my principle supervisor Peter Bauer Gottwein (PhD) for the coaching, encouragement and guidance throughout this period. I am equally grateful to my co- supervisors Anders Vest Christiansen (PhD), Imasiku Anayawa Nyambe (PhD) and Flemming Larsen (PhD).

A note of acknowledgement and thanks is also extended to the entire departmental and PhD administration at DTU-Environment and also to the Water Resources Engineering Section faculty members and colleagues. I would also like to appreciate the significant technical support from the Hydrogeophysics group at the Department of Geosciences, Aarhus University with respect to processing and inversion of various geophysical data.

Finally, I would like to thank friends and colleagues who supported me by their companionship during my field work in Sesheke and Kazungula districts in Zambia. This also applies to the management and staff at the University of Zambia School of Mines. Last but not the least; I would like to thank my family for only they know how much water has gone under the bridge and the Lord God Almighty for all his goodness and tender mercies.

Summary

The importance of knowing the current state of groundwater resources cannot be over emphasized in rural areas in the developing countries with limited water resources. As such, innovative geophysical techniques are now part of the norm for quick and effective characterization of groundwater resources worldwide. This thesis presents the application of geo-electrical and electromagnetic methods for the investigation of groundwater salinity in the Machile-Zambezi Basin in south western Zambia, southern central Africa. Aerial and ground based transient electromagnetic measurenments were used to map the spatial distribution of apparent electrical resistivity on a regional scale in order to obtain a regional overview of groundwater salinization based on electrical resistivity correlation. Furthermore, ground based transient electromagnetic soundings and direct current and induced polarization measurements were used to investigate on a local scale, indications of surface water/ groundwater exchange from electrical resistivity anomalies coincident with alluvial fans and flood plains as deduced from the aerial electrical resistivity result. New and innovative geophysical data inversion schemes were also developed and used to gain a better explanation of the data collected. These include a new scheme for the joint inversion of direct current and induced polarization data, and transient electromagnetic data; and a new coupled hydrogeophysical inversion setup to allow for the first time the joint use of direct current and transient electromagnetic data in one optimization.

The result from the regional mapping with transient electromagnetic measurenments showed a spatial distribution of electrical resistivity that indicated block faulting in the Machile-Zambezi Basin. Saline groundwater was found to occur predominantly in the low lying graben areas that are essentially an extension of the Palaeo Lake Makgadikgadi system into south western Zambia. In addition, surface water from the Zambezi River was found to interact with saline aquifers to such an extent that the surficial physical form of alluvial fans and flood plains was visible in the spatial distribution of electrical resistivity from the aerial survey up to a depth of about 40 m.

Interpretation of direct current and induced polarization, and transient electromagnetic data using the new joint inversion scheme revealed a fresh water lens overlying the saline aquifer at Kasaya in Kazungula District, Zambia. The freshwater lens appeared to be in hydraulic contact with the

Zambezi River where it was thickest (60 m) and had the highest electrical resistivity values (about 200 Ωm) which steadily declined to about 30 Ωm whereas the thickness reduced to around 22 m at the end of the 6 600 m long transect line measured perpendicular to the Zambezi River towards the North. The distribution of chargeability along the Kasaya transect line was found to be correlated with the distribution of electrical resistivity thus giving a strong indication of the intrusion of fresh surface water into a pre-existing saline aquifer. It is postulated that the intrusion of fresh surface water in to the saline aquifer was driven by evapotranspiration. Finally, the new coupled hydrogeophysical inversion approach resulted in sharp estimates of hydrogeological model parameters. This was for a coupled flow and solute transport model setup for the Kasaya transect under the forcing of evapotranspiration. Performance of the coupled hydrogeophysical inversion was better with the inclusion of direct current data in comparison to the use of transient electromagnetic data alone.

The broader implications of these findings is that groundwater salinization in the Machile Zambezi Basin is now known to be strongly influenced by the tectonism of the Palaeo Lake Makgadikgadi system and is therefore not expected to increase over time. Rather, surface water tends to interact with the saline aquifers in places to create freshwater lenses that are an important source of clean drinking water. Therefore, the findings of this thesis will need to be augmented with data and further research from other geoscience disciplines such as surface water hydrology, geochemistry, petrology and meteorology in order to come up with sustainable water resources management practices that are applicable to arid and semi-arid sedimentary basins in general and the Machile-Zambezi Basin in particular within the broader context of the Kalahari Basin of southern Africa. This will make it possible to project the effects of climate variability and anthropogenic activities on the water resources with a view of disaster preparedness and mitigation for which this part of the world is particularly vulnerable.

Dansk sammenfatning

Vigtigheden af et kendskab forekomsten af grundvandsressourcens kan ikke overvurderes i landområder i den tredje verden med begrænset vandressourcer. I forbindelse med beskrivelse forekomsten af vandressourcer, er anvendelsen af nye, hurtige og effektive geofysiske metoder et vigtigt element. I denne PhD afhandling præsenteres anvendelse af geoelektriske og elektromagnetiske metoder til undersøgelse saltforekomster i grundvandet i Machile-Zambezi bassinet i Zambia, i det sydlige Afrika. Den rumlige fordeling af jordlagenes tilsyneladende elektriske modstand er målt med anvendelse af luftbåren og landbaseret transient elektromagnetiske målinger med henblik på kortlægning af forekomsten af salt grundvand. Derudover er landbaseret elektromagnetiske sonderinger og elektrisk målinger, sammen med induceret polarisations, blevet anvendt på lokal skala med det formål at påvise overfladegrundvandsinteraktion. Nye og innovative metoder til inversion af geofysiske data er blevet udviklet, og anvendt til at opnå en bedre tolkning og anvendelse af indsamlede data. Dette omfatter blandt andet en ny metode for sammenhængende inversion af elektriske data, induceret polarisations data og transient elektromagnetiske data; samt en ny koblet hydrogeofysisk inversionsmetode, der for første gang gør det muligt at foretage en samlet anvendelse af elektriske og elektromagnetiske data i en optimeringsrutine.

Den regionale kortlægning med den transiente elektromagnetiske metode viser en rumlig fordeling af elektriske modstande, der indikerer blokforkastning i Machile-Zambezi bassinet. Salt grundvand forekommer hovedsagelig i lavtliggende dele af grabenstrukturen, der er en forlængelse af Palaeo Makgadikgadi søen ind i den sydlige del af Zambia. Det er blevet påvist, at interaktionen af overfladevand fra Zambezi floden med salt grundvand er så omfattende, at den kan registreres til 40 meters dybde med luftbårne opmålte elektriske modstand i alluvialfane og flodplan sedimenterne.

Tolkningen af elektriske målinger, induceret polarisationsmålinger og elektromagnetiske data, med anvendelse af den nyudviklede koblerede inversionsmetode, viste, at fersk grundvand ligger over salt grundvand ved Kasaya i Kazaungula distriktet, Zambia. Hvor ferskvandslinsen er tykkest (60 m), ser den ud til at være i hydraulisk kontakt med Zambezi floden, og have maksimale elektriske modstand (200 Ωm), som gradvist aftager til 30 Ωm, hvor tykkelsen af ferskvandslaget er reduceret til 22 m for enden af et 6600 m langt transekt, opmålt fra Zambezi floden og vinkelret mod nord. Fordelingen af sedimenterne kapacitet til elektrisk opladning langs Kasaya transektet korrelerer med dets fordeling af elektrisk modstand, og viser derved en stærk indikation på intrusion af fersk overfladevand ind i salt grundvand, hvor saltdannelsen skyldes evapotranspiration.

Endelig har den nyudviklede, koblede hydrogeofysiske inversionsmetode resulteret i en pålidelig bestemmelse af hydrogeologiske model parametre. Dette blev påvist i en koblet strømnings- og transportmodel for Kansaya transektet, med klimatisk betinget forøgelse af evapotranspirationen. Med anvendelse af den koblede hydrogeofysiske inversionsrutine, blev resultaterne forbedret med indarbejdning af elektriske modstandsdata, sammenlignet med anvendelsen af udelukkende transient elektromagnetiske data.

Den overordnede betydning af disse resultater er den, at forekomsten af salt grundvand i høj grad er påvirket af tidligere tektoniske forhold i området, hvor Palaeo Makgadikgadi søens sedimenter forekommer, er det må derfor forventes, at saltforekomsterne ikke fremover vil blive mere udbredt i området. Tværtimod synes interaktionen med overfaldevand at skabe en linse af ferskvand, der har stor betydning med henblik på etablering af drikkevandsforsyninger. Derfor bør resultaterne fra dette studie uddybes med nye data og yderligere forskning fra andre geovidenskabelig discipliner, såsom hydrologi, geokemi, petrologi og meteorologi for at tilvejebringe generelle, bæredygtige løsninger til god praksis til forvaltning af vandressourcer i aride og semiaride områder, og især i Machile-Zambezi Bassinet og i Kalakari Bassinet i det sydlige Afrika. Dette vil gøre det muligt at belyse effekterne af klimaforandringer og andre antropogene påvirkninger af vandressourcen med det formål at skabe beredskab og forebyggelse i forhold til sygdomsbekæmpelse for en befolkning, der især i denne del af verden, er sårbar.

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1 Introduction

The Earth is a very watery planet considering that about 70% of it is covered by water in addition to occurrences in the atmosphere and subsurface. However, with respect to human habitat and environmental concerns, only a very small percentage is available as renewable freshwater reserves in the form of surface water and shallow groundwater Postel et al. (1996). The renewability of these fresh water resources (and hence their availability for continued sustained use) is very sensitive to climatic variability and anthropogenic activities (Srinivasan et al., 2012; Cassardo, 2014; Collet et al., 2014). Therefore in order to mitigate against the adverse effects of climate change or human socio-economic development on fresh water reserves such as groundwater, it is imperative that the condition of the respective water resources are constantly assessed and the impacts of the various stresses (such as reduced precipitation, pollution or abstraction) on the water resources themselves are quantified. This would then form a basis upon which decision makers can make judgements about the best choices that would ensure sustainability of water resource utilization (Kinzelbach et al., 2003).

1.1 Motivation

Arguably, nowhere is this more important and critical than in arid and semi-arid regions where much of the hydrological cycle oscillates between extremes of precipitation (or flooding) and drought (Buytaert et al., 2012). As a result the dependence on groundwater is increased in such regions (Kinzelbach et al., 2003) like in the Kalahari Basin of southern Africa (McCarthy and Haddon, 2005; McCarthy, 2013). Thus for countries like Angola, Botswana, Namibia and Zambia that have got significant territory and populations within the Kalahari Basin, knowledge of the properties and characteristics of the Kalahari aquifer system is absolutely crucial. Where available, such knowledge could then be used for important planning decisions such as the placement of water points in relation to human settlements or the zoning of new settlements based on the quality and quantity of groundwater reserves.

1.2 State of the art

Various tools and methods have been developed and are still being developed that enable a relatively rapid and cost effective means of characterization of groundwater resources (Kinzelbach et al., 2003). These include ground based and airborne transient electromagnetics (TEM)(Auken et al., 2003;

Christiansen, 2003; Yan et al., 2009; Ezersky et al., 2011; Xue et al., 2012), direct current and induced polarization (DCIP)(Dahlin, 2001; Dahlin et al., 2002; Dahlin and Zhou, 2006; Loke et al., 2013), and hydrodynamic modelling(Rosbjerg and Madsen, 2005; Bauer et al., 2006a; Bauer et al., 2006b). The TEM methods are applied around the world on both regional and local scales and have been shown to be useful for investigation of regional trends on groundwater quality variations and detailed local scale site characterisation (Melloul and Goldenberg, 1997; Bauer-Gottwein et al., 2010; Chongo et al., 2011; Ezersky et al., 2011; Xue et al., 2012; Herckenrath et al., 2013b; Juanah et al., 2013; Podgorski, 2014). On the other hand, DCIP techniques are more suited for detailed local scale investigations since they can only be effectively deployed on ground based systems. However, recent innovations in data acquisition systems has given rise to DCIP instrumentation that combines the benefits of high spatial density, cost effectiveness and the integration of the measurement of both direct current and induced polarization in one field setting (Aristodemou and Thomas-Betts, 2000; Dahlin and Zhou, 2006; Poulsen et al., 2010; Gazoty et al., 2012; Loke et al., 2013). Therefore it is increasingly becoming common to design hydrogeological investigations that incorporate multiple types of geophysical data which can then be incorporated within the context of a hydrodynamic model (Ferré et al., 2009; Hinnell et al., 2010). This then has resulted in a powerful means of evaluating aquifer system behaviour under various stresses such as evapotranspiration and anthropogenic factors like contamination and water abstraction.

1.3 Research objectives

The objectives of the research presented in this thesis were to:

- Gain a better understanding of the occurrence of saline groundwater in the Machile-Zambezi Basin in south-western Zambia related to propagation of the Palaeo Lake Makgadikgadi system through the Okavango-Linyati fault system into Zambia;
- Make a detailed local scale evaluation, at Kasaya in south western Zambia, of high electrical resistivity anomalies (> 100 Ωm) overlying a generally low electrical resistivity (< 13 Ωm) subsurface based on local scale DCIP and TEM measurements using a new DCIP-TEM joint inversion scheme. Areas with such high electrical resistivity anomalies were identified based on the results of the regional scale TEM mapping and appeared to be related to surface water groundwater exchange; and

- Further develop a coupled hydro geophysical inversion framework for application to a river-aquifer solute transport problem under evapotranspiration to enable calibration with both DC and TEM data for the first time.

1.4 Structure of the thesis

As mentioned above this thesis is divided into two parts. The first part is a synopsis that provides a background, context and overview of the research conducted at DTU Environment and extensive field campaigns in Kazungula and Sesheke districts of south western Zambia since December 2011 to date. The synopsis therefore comprises an introduction which briefly outlines the purpose and significance of the research (Chapter 1); a background and context which puts the thesis in the context of recent scientific developments and state of the art (Chapter 2); a description of the study area (Chapter 3); and a short overview of the methods used (Chapter 4). The main findings are presented in Chapter 5 whereas the discussion and conclusion are presented in chapters 6 and 7 respectively.

The second part of the thesis comprises three papers which are a fulfilment of the three overall research objectives stated above respectively. To the best of our knowledge, this study has mapped for the first time the Palaeo Lake Makgadikgadi sediments in the Machile-Zambezi Basin using regional scale ground based and airborne TEM measurements. It has also demonstrated that TEM is effective for mapping groundwater quality (salinity) variations in a sedimentary setting such as that of the Machile-Zambezi Basin (Paper I). Regional scale TEM and local scale DCIP and TEM surveys give evidence of significant groundwater surface water interaction in the Machile-Zambezi Basin. Furthermore, the distribution of electrical resistivity and induced polarization at a study site at Kasaya in Kazungula District, Zambia indicatives recent intrusion of surface water into a pre-existing saline aquifer (Paper II). The intrusion of fresh surface water under evapotranspiration was evaluated using a new CHI that includes both DCIP and TEM data. The CHI showed the evapotranspiration does seem to be the main climatic excitation driving the surface water/ groundwater exchange given the simplifications and consequent limitations in the coupled flow and salinity transport model that was used. The CHI approach was thus shown to have tremendous potential as an effective and cost saving tool for hydrological model validation and geophysical data interpretation (Paper III).

2 Background and context

Hydrogeophysics is a relatively young area of research often classified as a sub discipline of Hydrology even though it has its origins in the fields of mineral and petroleum exploration (Rubin and Hubbard, 2006; Auken et al., 2009a). The increasing interest in the use of geophysical methods as part of hydrological investigations probably stems from the need for a better understanding of how hydrological systems particularly groundwater resources respond to stresses such as climatic variability, pollution and long term abstraction. Furthermore, *classical* methods of groundwater investigation such as pumping tests, slug tests, core sample analysis and geophysical borehole logging can only be conducted as point measurements within a well or a borehole as and as a consequence will usually not be able to adequately capture lateral or spatial variations of hydrological parameters (Rubin and Hubbard, 2006). This lack of spatial data density and variability can potentially be addressed by the incorporation of appropriate geophysical methods into hydrological investigations.

Recent research efforts have therefore been directed at finding ways and means of using geophysical methods to provide accurate and reliable estimates of hydrological parameters such as hydraulic conductivity and porosity in addition to describing hydrological processes like groundwater flow and solute transport (Christiansen, 2010; Dafflon et al., 2010; Pollock and Cirpka, 2010; Christiansen et al., 2011; Busch et al., 2013; Herckenrath et al., 2013b). This has led to rapid developments in geophysical instrumentation, data handling and inversion. Transient electromagnetics (TEM) and direct current and induced polarization (DCIP), which are the main focus of this thesis, are two of the most commonly used geophysical methods for water resource or hydrogeological applications that have been extensively developed and improved in recent years.

2.1 TEM for groundwater applications

TEM systems which are typically deployed as either ground based or airborne have seen the advent of instrumentation that is equally suited for traditional geological exploration as well as for hydrogeophysical applications using a high moment for deeper information and a low moment for shallow information. Furthermore, older instrumentation that is not equipped with the low moment-high moment concept can equally be used for hydrogeophysical applications provided it is calibrated with a just a few accurate ground based

TEM soundings from the survey area (Podgorski et al., 2013). Thus TEM has been successfully used for hydrogeological applications such as regional scale salinity mapping (Guerin et al., 2001; Chongo et al., 2011; Ezersky et al., 2011; Viezzoli et al., 2012)and aquifer characterization (Auken et al., 2003; Auken et al., 2009b; Siemon et al., 2009) and local scale salty water – freshwater interaction studies(Albouy et al., 2001; Bauer-Gottwein et al., 2010; Nenna et al., 2013).

2.2 DCIP for groundwater applications

DC and IP have benefited from recent innovations that now make it possible to measure DC and IP in one field setup (hence the term DCIP) using multi-channel instruments that not only greatly reduce the amount of time spent in the field but can at the same time increase the amount of data collected per field setting (Dahlin, 2001; Dahlin and Zhou, 2006; Loke et al., 2013; Singha et al., 2014). Examples of hydrogeological considerations to which DCIP has been applied include groundwater flow and solute transport, groundwater salinization (including salty water freshwater interaction in coastal and inland areas), surface water/ groundwater exchange and groundwater contamination or pollution at landfill or other sites (Aristodemou and Thomas-Betts, 2000; Nassir et al., 2000; Binley et al., 2002; Muller et al., 2005; Bauer et al., 2006c; Muller et al., 2010; Vaudelet et al., 2011; Fernandes et al., 2012; Gazoty et al., 2012; Singha et al., 2014; Van Dam et al., 2014).

2.3 Hydrogeophysical inversion

CHI is one of three approaches that can be used to inform groundwater models with geophysical data. The other two are sequential hydrogeophysical inversion (SHI) in which a groundwater model is setup, parameterised and calibrated based on prior and independently inverted geophysical models; and joint hydrogeophysical inversion (JHI) in which geophysical and hydrological model parameters are inverted at the same time and related through petro physical relations (Herckenrath et al., 2013a). Thus SHI follows the traditional approach with which geophysical data has been used for hydrological purposes whereas CHI and JHI are relatively recent developments that run the geophysical and hydrological inversions simultaneously with exchange of information taking place both ways. Nevertheless they differ in the sense that CHI minimises the difference between hydrological state variables (e.g. solute concentration) and instrument responses through a petro physical transformation of the state variables and subsequent forward response calculation. JHI however inverts for both hydrological model parameters (e.g. hydraulic conductivity) and geophysical model parameters (e.g. electrical resistivity) at the same time; with the hydrological and geophysical parameters being constrained by an appropriate petro physical relationship such as the log-linear relationship between hydraulic conductivity and electrical resistivity.

2.4 Hydrodynamic modelling

Hydrodynamic modelling as applied to water resources in general and groundwater in particular provides an avenue through which scientific theories about hydrological phenomenon and the interplay between different hydrological processes can be tested, validated or disproved. Thus in practice hydrodynamic modelling formulates required hydrological processes in a generic mathematical/ numerical construct which can then be applied to specific hydrological conceptualizations and parameterizations (Rosbjerg and Madsen, 2005; Todini, 2007). Examples of standard mathematical/ numerical constructs applicable to groundwater include MODFLOW (Harbaugh, 2005 ; Hanson et al., 2014) for groundwater flow modelling, MT3DMS for reactive and solute transport modelling (Zheng and Wang, 1999) and SEWAT (Langevin et al., 2007) for coupled flow and reactive transport modelling.

Thus any given model application is at best a parsimonious simplification of natural systems which explains to some degree observed processes and phenomenon. The performance of the model will therefore largely depend on the chosen conceptualization (e.g. layering of the subsurface and stresses in a groundwater model) and parametrizations (e.g. aquifer properties such as hydraulic conductivity and porosity). However there is often a great deal of uncertainty about some or all aspects of the conceptualization and model parameters. A standard approach of dealing with this uncertainty is through the use of in situ data to calibrate and validate the model (Rosbjerg and Madsen, 2005). Quite often the data is very sparsely distributed (e.g. point measurenments of hydraulic head and solute concentration from a limited number of boreholes in a wide geographic area) and because of this, model calibration efforts can often be unsatisfactory. However, geophysical measurenments overcome the limitations on data density since they can be more easily and cost effectively deployed on both local and regional scales. Thus the incorporation of geophysical data into classical and innovative model calibrations should lead to improvements in model parameter estimations and reduced uncertainty (Hinnell et al., 2010).

3 The study area

The Machile-Zambezi Basin straddles Kazungula and Sesheke districts in the Southern and Western provinces of Zambia. It was hydrologically defined for purposes of this research as the catchment area with outlet on the Zambezi River at 17° 50.4’ S and 25°38’E but not exceeding the areal extent defined by latitude 16° - 17° 54’ S and longitude 24° 13’ – 26° 22’ E and within the Zambian territory. Thus it covers an area of about 26, 260 km^2 which includes the northern extent of the Palaeo Lake Makgadikgadi Basin (Okavango-Linyati depression) and the catchment areas of three major streams called Loanja, Machile and Ngwezi. The location of the Machile Zambezi Basin is shown in Fig. 1.

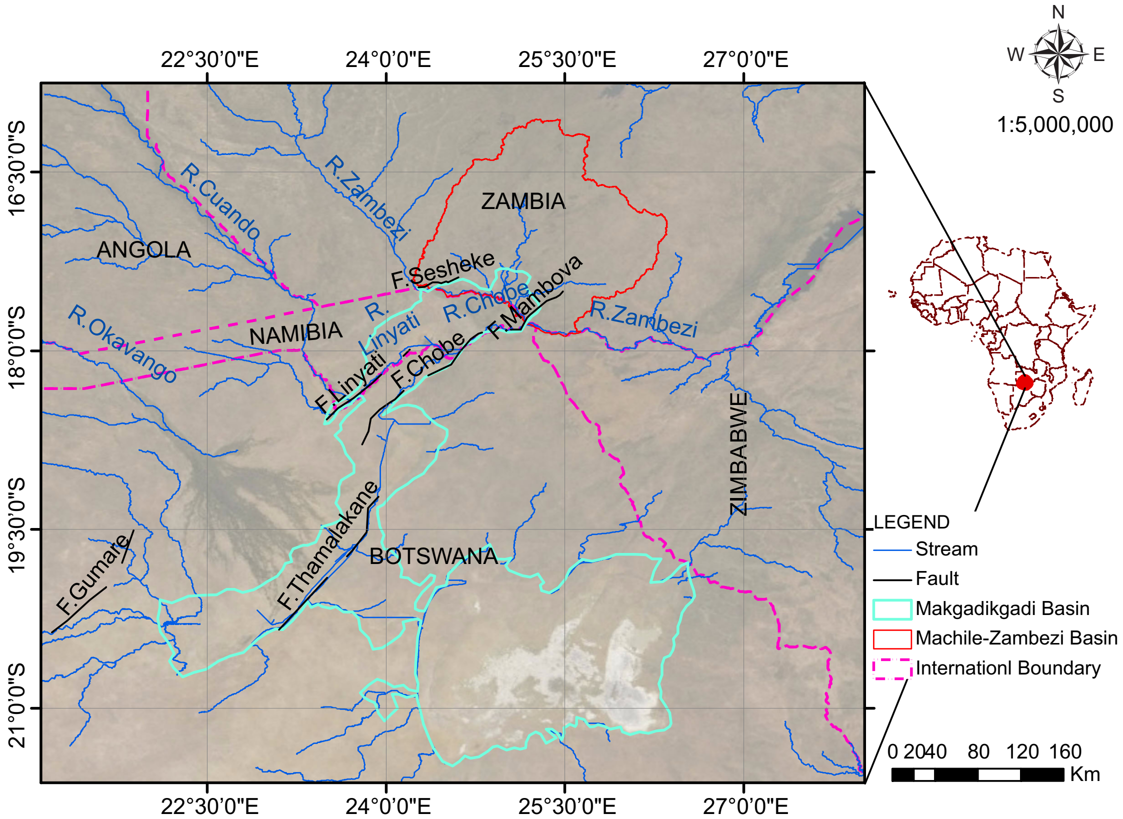

Fig. 1: Location of the Machile-Zambezi in Zambia, southern Africa in relation to the Lake Palaeo Makgadikgadi Basin.

3.1 Geomorphological setting

The landforms and features of the Machile-Zambezi Basin are characteristic of a fluvial sedimentary environment with an intermittent - ephemeral river network that is prone to extensive flooding. This river network is entrenched onto a topography that is broadly divided into upland and low land areas. The upland areas or hilly belt with altitude between 950 – 1150 m above mean sea level surround the low lying areas (935 -950 m above mean sea level) in form of an arc that stretches from the north western extent of the basin through the Machile-Kafue Watershed in the north east until the south eastern extent of the Basin. The Zambezi River forms the northwest to southeast boundary of the Basin into which many of the streams drain whereas others terminate into alluvial fans before reaching the Zambezi River. A topographic map of the Machile-Zambezi Basin which also depicts the surface geology is shown in Fig. 2.

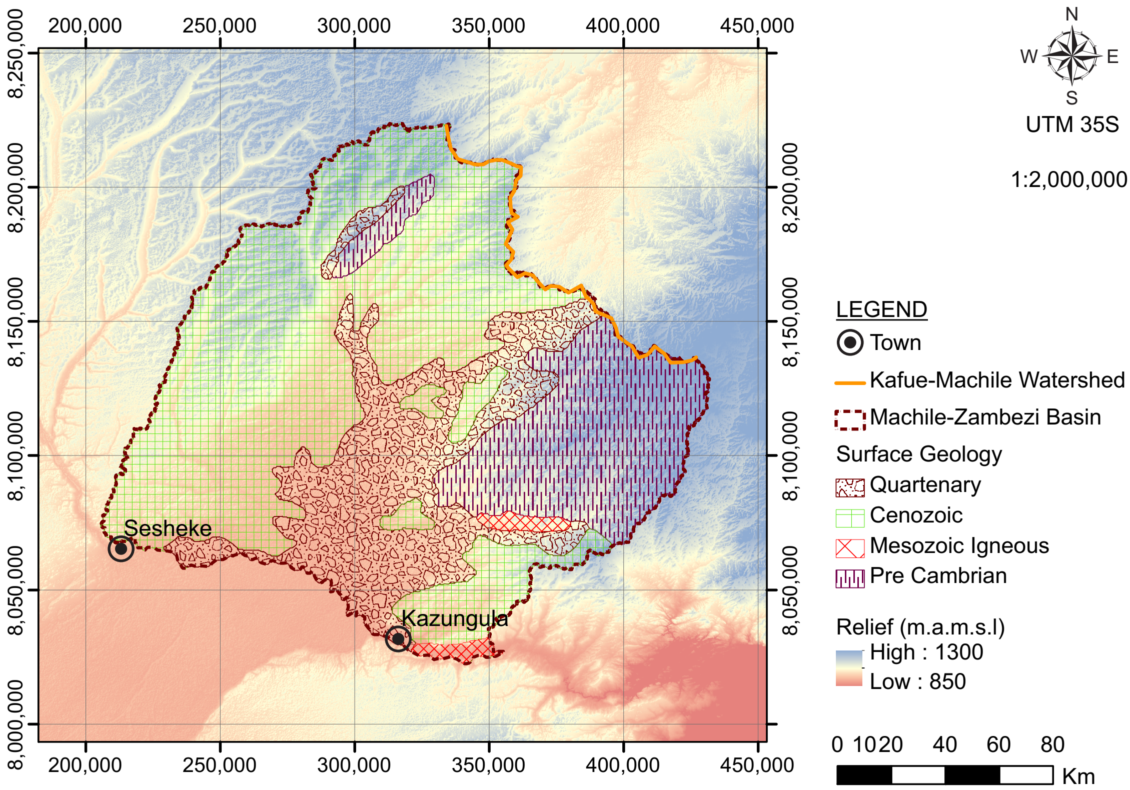

Fig. 2: Topographic map of the Machile-Zambezi Basin also depicting the surface geology.

3.2 Geological setting

The low lying areas occupy a position that appears to be a continuity in the form of a topographic depression that extends all the way down and across the Zambezi River then into the Okavango-Linyati depression (McCarthy, 2013). This depression, which is a remnant of the Palaeo Lake Makgadikgadi, is controlled by the Okavango-Linyati fault system whose genesis is the propagation of the East African Rift System through the Tanganyika-Mweru-Upemba-Kabopmbo Gorge axis (Moore et al., 2012) . The tectonic activity responsible for the creation of the Okavango-Linyati Depression is said to be still ongoing and has been responsible for evolution of landforms and drainage patterns in the entire Kalahari Basin (Moore et al., 2012). The low lying areas are thus underlain by sediments that have in-filled a graben structure often referred to as the Machili Graben or the Machili Basin (Main et al., 2008; Moore et al., 2012; McCarthy, 2013).

The stratigraphy of the Machile-Zambezi Basin is a variant of the general stratigraphic setting of the entire Kalahari Basin and comprises a Kalahari Supergroup sand member as the uppermost unit. This in turn is typically underlain by a Kalahari Supergoup sandstone member or in its absence any sequence of stratification ranging from Karoo to Basement Complex. The blanket of sand varies in thickness from place to place and is generally thinnest on the outer northwest and southeast fringes of the basin particularly close to the Zambezi River where outcrops of Basalt and Basement Complex rocks respectively are clearly visible. A map depicting the surface geology of the Machile-Zambezi Basin is shown in Fig. 2.

3.3 Hydrological setting

As has been mentioned above, the Machile-Zambezi Basin has three main streams of which the Machile and Ngwezi flow directly into the Zambezi River whereas the Loanja terminates in a seasonally flooded alluvial fan adjacent to the Zambezi. The upper reaches of the stream network originate in the forested hilly belt and are characterised by narrow flood plains and intermittent to perennial flow. On the other hand, the lower reaches traverse the low lying areas as they head towards the Zambezi River and are characterised by very wide flood plains and an ephemeral flow regime.

Annual precipitation is around 808 mm whereas the actual and potential evapotranspiration are in the order of 616 and 1718 mm per annum (JICA/MEWD-B, 1995). Groundwater recharge has been estimated at 5 % of annual precipitation or around 40 mm per annum. The groundwater regime is predominantly characterised by unconsolidated sand and sandstone aquifer units that have a moderate yield of 3 – 10 l/s and hydraulic conductivities in the order of 1.05 m/day (Chenov, 1978; JICA/MEWD-D, 1995).

3.4 Socio-economic aspects

The Machile-Zambezi Basin is a vast rural area with sparse population whose main centres are the towns of Kazungula and Sesheke. The main economic activity is trading with nearby towns like Livingstone in Zambia, Kasane in Botswana and Katima Mulilo in Namibia. Agricultural activity is mostly for subsistence (although some commercial agriculture does take place in the

Kazungla area) and involves staple crop production and animal husbandry. A thriving commercial timber industry used to exist in the area but this has now been reduced to small scale operators due to depletion of the timber stock over time.

3.5 Wildlife

There exists a great variety of plant and animal species in the Machile-Zambezi Basin. The vast majority of the animal species are confined to the game management areas which are a buffer zone between the Kafue National Park in the northern fringes of the basin and human settlements in the central and southern areas. The Machile-Zambezi Basin also is home to the Machile and Simungoma Important Bird areas given the unique and diverse bird species that live there. Furthermore a new wildlife sanctuary has been established in the Machile Flats (the Machile Graben area) called Simalaha Community Conservancy (SCC). It is an important wildlife sanctuary in the Kavango-Zambezi trans-frontier wildlife conservation area that seeks to re-establish wildlife populations and their migratory routes between the Chobe National Park in Botswana and the Kafue National Park in Zambia. SCC also aims at improving the economic outlook of the local people through tourism and wildlife development (Peace-Parks, 2015).

Fig. 3: Sable Antelope grazing in the dry season on the southern fringes of the Kafue National park interfacing with the northern areas of the Machile-Zambezi Basin.

The main vegetation types are deciduous tall canopy trees and flood plain and dambo grass. The major tree species include Mopane (Veenendaal et al., 2008; Smit, 2014) and Baikiaea plurijuga locally known as Mukusi or Zambezi Teak (Childes and Walker, 1987; Richer, 2008). The Mukusi is prominent in the hilly belt whereas the Mopane thrives in the low lying areas of the Basin that are close to the Zambezi River. The tall flood plain and dambo types of grass are primarily found in flood plains and dambos (local scale seasonally flooded pans) (Fanshawe, 2010).

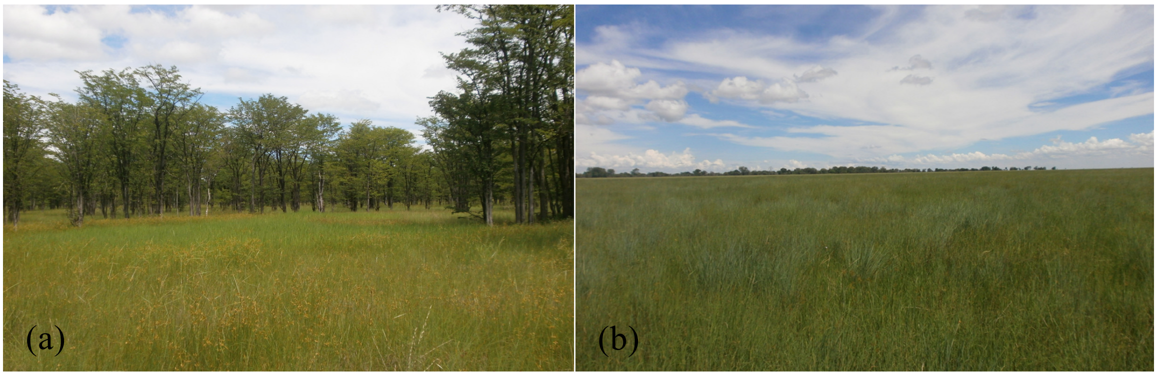

Fig. 4: (a) Typical vegetative cover during the rainy season in the low lying areas of the Machile-Zambezi Basin in south-western Zambia. (b) Vegetative cover in a typical flood plain in the Machile-Zambezi Basin in south western Zambia during the rainy season. In the background is the tree line denoting the beginning of the forested area shown in (a).

3.6 Data archive

During the course of the research reported in this thesis, a large amount of old and new data was gathered and processed. This includes old ground based TEM data from Chongo et al. (2011) and new DCIP and TEM data (aerial and ground based) from this work. Furthermore, a large amount of new data was created in the form of intermediary TEM and DCIP data files required for inversion in addition to the final inverse models. A significant number of C++ and Matlab scripts were also produced or modified in order to support and implement the innovative inversion schemes herein described. Furthermore, geospatial data for the study area was created and managed in two geographic information systems. These were:

- ArcGIS (ESRI, 2015) for general spatial data processing and management; and
- Aarhus Workbench (HGG, 2014) for processing and inversion of aerial TEM data and spatial visualization of aerial and ground based TEM inverse models.

This archive comprising raw data, processed data, programming scripts and geospatial databases is contained in an electronic appendix as out lined in Chapter 9 (Appendix). It may be accessed by contacting:

DTU Environment
Technical University of Denmark
Miljøvej, Building 113
2800 Kgs. Lyngby
Denmark
reception@env.dtu.dk

4 Materials and methods

4.1 Airborne and ground based transient electromagnetic measurements

The TEM (Nabighian, 1988; Nabighian, 1991; Danielsen et al., 2003; Kirsch, 2006) method was used on both local and regional scale for mapping of electrical resistivity variations in the Machile-Zambezi Basin. The regional scale TEM was deployed on both airborne and ground based systems for mapping of the entire basin whereas the local scale TEM was conducted using only ground based TEM equipment on a 6.6 km transect line on the northern bank of the Zambezi River at Kasaya in south western Zambia. The instrumentation that was used for the airborne TEM measurements was the VTEM system from GEOTECH (GEOTECH, 2011) whereas the instrumentation for the ground based TEM comprised WalkTEM (ABEM(b), 2014) and ProTEM equipment. However, data from the ProTEM equipment is not discussed in this thesis. This is because more data was collected with the WalkTEM instrument. In addition, at locations where measurements were collected with both instruments, similar responses were obtained with slightly better measurements from the WalkTEM.

The regional TEM survey was designed with two objectives in mind. These were:

- To cover as much area of the Machile-Zambezi Basin as possible given the constraints on time and resources; and
- To capture as much geological variations as possible.

Therefore with the constraint of 1000 line kilometers for the airborne measurements, the aerial survey was designed with two sets of four flight paths. One set was oriented northeast to southwest whereas another was oriented southeast to northwest.

In order to extend the coverage of tem measurements beyond the 1000 line kilometers of the aerial survey, the regional ground based survey was designed to conduct spatially distributed TEM measurements at a spatial density of approximately 25 km^2 taking into account the survey objectives mentioned above. The ground based survey was conducted only on the eastern half of the Machile-Zambezi Basin because spatially distributed TEM sounding on the western half of the basin were available from Chongo et al. (2011). The locations of the flight paths and all TEM soundings considered in this thesis are shown in Fig. 5. Further details about the regional TEM mapping including calibration, processing and inversion of the airborne TEM data are given in Paper I**.**

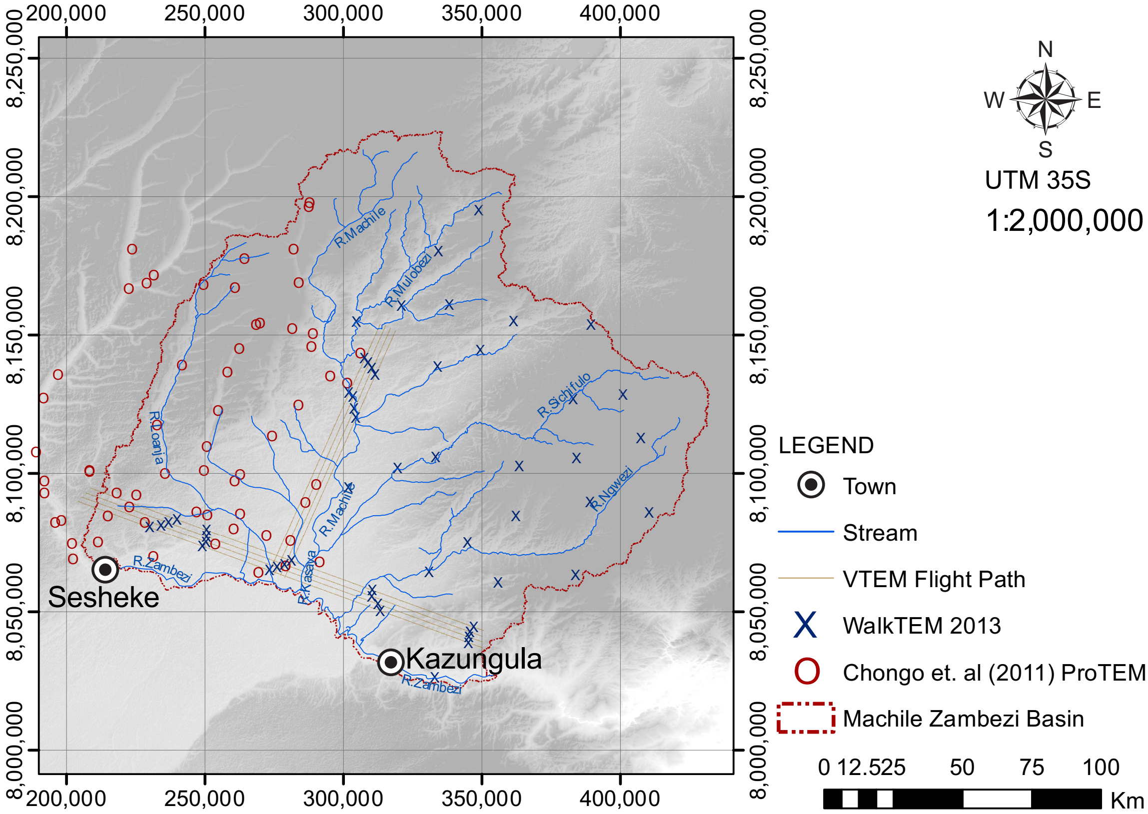

Fig. 5: Map showing the location of VTEM flight paths and ground based TEM soundings in the Machile-Zambezi Basin. The ground based TEM soundings coincident with the flight paths were used to calibrate the VTEM signal for amplitude and time shift error.

The local scale TEM measurements were collected together with DCIP measurements on a transect line at Kasaya in the Machile Zambezi Basin as described in Section 4.2. Sixty-four TEM soundings were thus collected on the transect line at an approximate spacing of 100 m.

4.2 Direct current and induced polarization measurements

DCIP (Binley and Kemna, 2006)measurements were conducted on a 6 600 m transect line across the Simalaha flood plain at Kasaya in the Machile-Zambezi Basin. The Terrameter LS (which is an innovative data acquisition system for self-potential, electrical resistivity and induced polarization) (ABEM(a), 2012) was used for the DCIP measurements in a roll along continuous vertical electrical sounding (CVES) setup (Loke, 1999; Loke et al.,

2013) with 5 m electrode spacing. The gradient array (Dahlin and Zhou, 2006) protocol was used in order to take advantage of the multi-channel capabilities of the instrument. This resulted in significant reduction in the amount of time spent in the field but with data quality as good as traditional electrode configurations such as the Wenner and Schlumberger arrays (Dahlin and Zhou, 2004). Location of the Kasaya transect within the Machile-Zambezi Basin is shown in Fig. 6. The site was chosen based on electrical resistivity anomalies from the aerial TEM survey that were indicative of surface water groundwater exchange. Another site that showed similar traits is the Loanja alluvial fan. However this is not treated in this thesis.

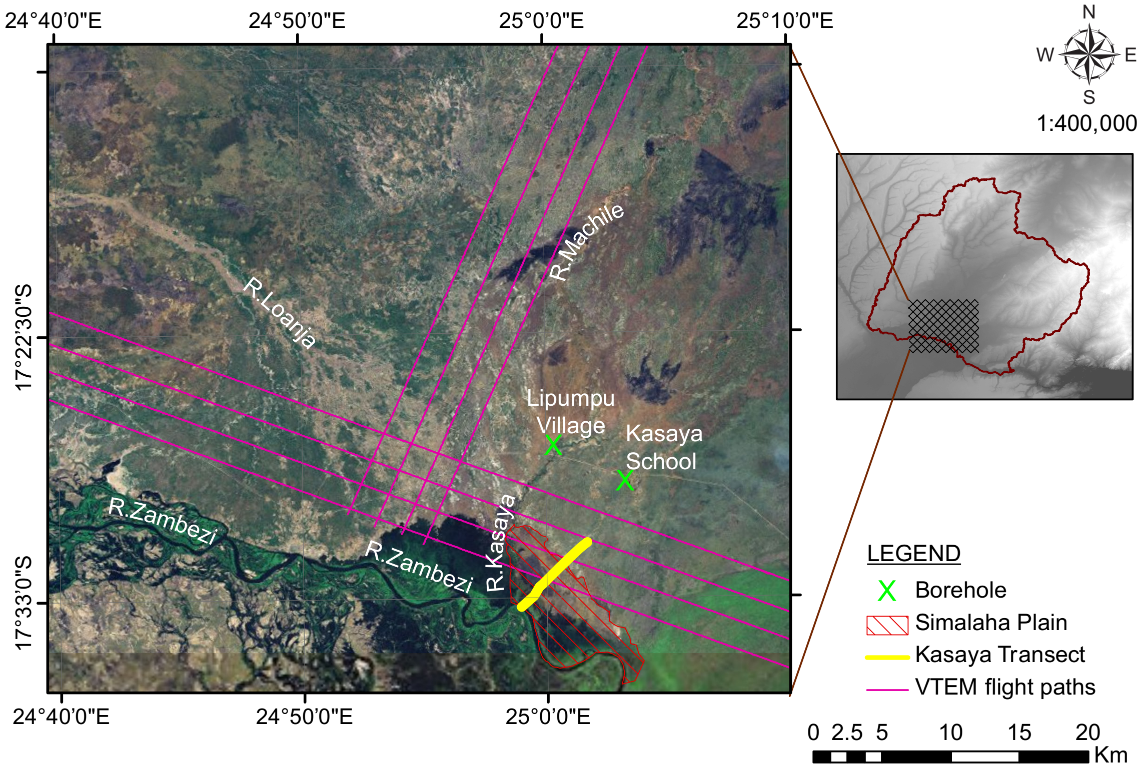

Fig. 6: Location of the Kasaya Transect across the Simalaha Plan in the Machile-Zambezi Basin. Also note the termination of the Loanja River into an alluvial fan which was another area investigated but is not reported for purposes of this thesis.

More information about the Kasaya Transect including details about how the data collected was processed in an innovative DCIP-TEM inversion scheme can be found in Paper II.

4.3 Processing and inversion of TEM and DCIP data

4.3.1 Data processing

The electromagnetic data from the aerial survey was presented in the form of a geo-database by GEOTECH (GEOTECH, 2011). This was imported into the Aarhus Workbench (HGG, 2014) for processing and inversion. The aim of the processing was to remove data affected by coupling and systematic noise and to supress random noise by averaging of the electromagnetic data into soundings. The processing also comprised filtering and averaging of geographic position and altitude data and removal of soundings exceeding a roll or pith angle of 25 degrees. This was followed by visual inspection and editing where required (HGG, 2011). Calibration parameters (Sørensen et al., 2011; Podgorski et al., 2013) for correction of amplitude and time shift errors were added to the data at the processing stage. The calibration parameters (time shift and amplitude shift factor) were derived from calibration of the VTEM signal with corresponding ground based WalkTEM soundings (Paper I). Ground based TEM data was processed for removal of data points affected by noise and coupling using SiTEM-SEMDI (HGG, 2001) and sometimes manually with a text editor after download from the WalkTEM instrument. Unlike the airborne electromagnetic data, the ground based TEM data was processed on an individual sounding basis because the data was collected one sounding at a time at different locations. Finally DCIP data was also imported into the Workbench for automatic processing followed by visual inspection and manual editing (Paper II).

4.3.2 Data inversion

Following processing, the airborne electromagnetic data was inverted in the Aarhus Workbench using the laterally constrained inversion (LCI) (Auken et al., 2005) approach on a flight line by flight line basis. This was followed by spatially constrained inversion(Christiansen, 2008; Viezzoli et al., 2009) of the whole aerial dataset in one inversion job. Ground based TEM data collected for the regional survey was inverted separately for each site using AarhusInv (Auken et al., 2014). However the inverse models were imported into the Aarhus Workbench for synchronization with the aerial TEM inversion result. This facilitated the creation of mean horizontal electrical resistivity maps at various depth intervals for the Machile-Zambezi Basin (Paper I).

DCIP and TEM data collected for the Kasaya transect was inverted using AarhusInv under various schemes. These included separate LCIs of DCIP and TEM data; mutually and laterally constrained inversion (MCI)(Christiansen et al., 2007) of DC and TEM data; and finally an innovative MCI of DCIP and TEM data. Details about the inversion of DCIP and TEM data on the Kasaya Transect are given in Paper II.

4.4 Coupled hydrogeophysical inversion

Coupled hydro-geophysical inversion was performed using the Gauss-Marquardt-Levenberg parameter estimation approach (Doherty, 2005) for a simple coupled flow and solute transport model using TEM and DC data. The model was setup for a case of freshwater intrusion into a saline aquifer under evapotranspiration with a fixed river head boundary. SEAWAT (Langevin et al., 2007) was used to implement this hydro-dynamic model which was first calibrated using TEM data and then with an innovative combination of TEM and DC data. The PEST (Doherty, 2005) implementation of the Gauss-Marquardt-Levenberg algorithm (Marquardt, 1963) was used for the minimization of square differences between transformations of simulated SEAWAT concentrations and apparent electrical resistivity from TEM and DC measurements. Thus Archie’s law (Archie, 1941) was used to transform the simulated concentrations into simulated electrical resistivities. The electrical resistivities were then sampled at locations corresponding to the location of respective geophysical data and used for calculation of forward instrument responses or apparent resistivities using AarhusInv (Auken et al., 2014). The optimization was thus performed on the SEAWAT model parameters (e.g. hydraulic conductivity and porosity) and petro-physical parameters (e.g. Archie’s exponent and cementation factor) but evaluated based on the sum of squared differences between the calculated forward responses and measured geophysical data. Further details about the calibration of the SEAWAT model with TEM and DC data are given in Paper III.

5 Main findings

5.1 Regional electrical resistivity variations

Regional aerial and ground TEM electrical resistivity variations in the Machile-Zambezi Basin reflected the tectonic setting of the Okavango-Linyati fault system and Palaeo Lake Makgadikgadi extension into south-western Zambia. A regional graben-horst system with a northeast to south-west strike was outlined. The horst regions were characterized by resistivities values greater than 100 Ωm on the eastern and western flanges of the basin. However, the graben region was characterized by an area than can be considered to be a full graben in the low lying southern central portions of the basin and an expanse that dips into the full graben from the north east to the south-west. The full graben was found to be characterized by electrical resistivity values less than 13 Ωm whereas the dipping expanse had electrical resistivity values ranging between 10-100 Ωm. The low electrical resistivity values in the graben are attributed to the Palaeo Lake Makgadikgadi sediments. A map depicting the spatial distribution of electrical resistivity values for the deep sub subsurface(80-100 m) is shown in Fig. 7.

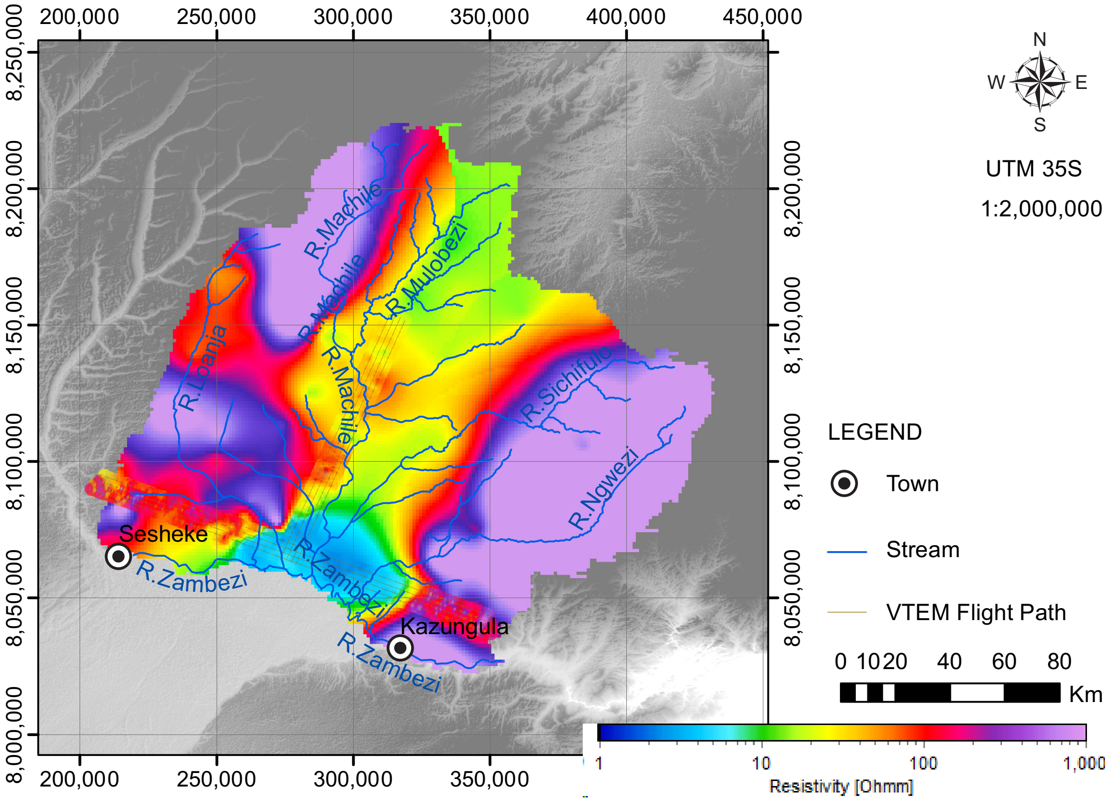

Fig. 7: Mean horizontal electrical resistivity distribution at depth interval 80-100 m for the Machile-Zambezi Basin from aerial and ground TEM measurements.

5.2 Localised freshwater/ groundwater interaction

The drainage network of the Machile-Zambezi Basin is such that streams originate in the high elevation areas on the north-western to north-eastern peripheries of the basin. As they flow southwardly towards the Zambezi river, they cross the low relief full graben area. At this stage, some of the streams form very wide flood plains whereas others terminate into alluvial fans. At several locations within the basin, the flood plains and alluvial fans make an imprint onto the electrical resistivity distribution in the shallow subsurface (0-40 m) by anomalously high resistivities (greater than 13.2 Ωm) that are coincident with these surface water features in an otherwise low electrical resistivity subsurface. This was indicative of intermediate to local scale surface water groundwater exchange. A satellite image showing the coincidence of an alluvial fan and flood plain with anomalously high electrical resistivity values in the Machile-Zambezi Basin is shown in Fig. 8.

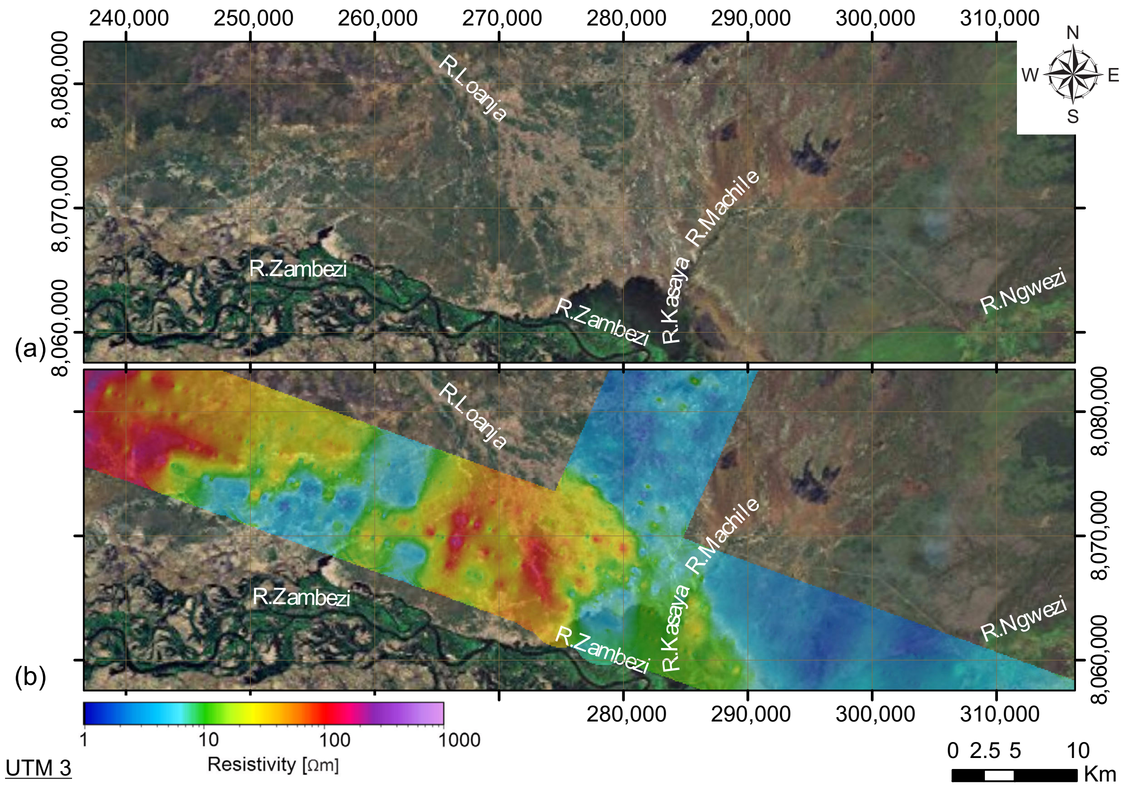

Fig. 8: (a.) Alluvial fan and flood plain features for the Loanja River and the Kasaya River as it enters the Zambezi River respectively. (b.) Overlay of 0-20 m electrical resistivity map depicting the imprint of the alluvial fan and flood plain features onto the shallow subsurface.

5.3 Freshwater intrusion into saline aquifer

Local scale evaluation of the anomalous superficial electrical resistivities mentioned in Section 5.2 using DCIP and TEM measurements at Kasaya, depicted a layer with variable high end electrical resistivity distributions and thickness. This layer exhibited electrical resistivity variations from about 200 Ωm at the beginning of the transect (at the edge of the Zambezi River) to about 30 Ωm at the end of the transect line (total distance 6,600 m). It in turn was overlain by a thin low resistivity layer (less than 12.6 Ωm) and underlain by the low electrical resistivity (3.59 Ωm) subsurface and was 60 m thick at the beginning and 22 m thick at the end. In addition, the spatial distribution of chargeability from joint inversion of DCIP and TEM data was more or less correlated to that of the electrical resistivity. This strong correlation between induced polarization and electrical resistivity is a strong indicator of freshwater intrusion into a pre-existing saline environment. The electrical resistivity and chargeability cross sections for the Kasaya Transect are shown in Fig. 9.

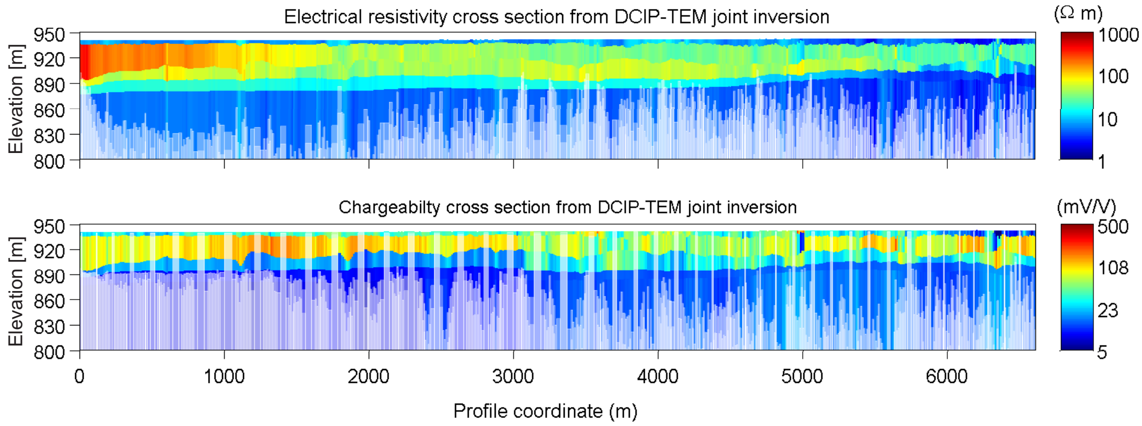

Fig. 9: (a.) Electrical resistivity cross section and (b.) chargeability cross section from DCIP-TEM joint inversion for DCIP and TEM data collected at Kasaya, Southern Province, Zambia.

The mechanism governing the intrusion of freshwater from the Zambezi River into the salty aquifer at Kasaya is unknown. However, evapotranspiration seems to be a key process. Evaluation of the evapotranspiration hypothesis conducted using an innovative coupled hydro-geophysical inversion of a SEAWAT model with DC and TEM data added credence to the hypothesis. Nevertheless, processes such as seasonal recharge/ flooding, infiltration and percolation, and through flow could possibly have had an impact on the model outcome and could have helped to obtain a better explanation for the DCIP and TEM data.

5.4 Utility of electrical and electromagnetic methods

TEM and DCIP are effective methods that can be used for quick characterization of groundwater resources particularly in sedimentary terrain. Major benefits can be drawn from innovations in instrumentation and data processing or inversion. Thus aerial TEM systems originally designed for mineral exploration such as the VTEM system can now be used for hydrogeological applications provided they are calibrated with accurate and precise ground based measurements. Similarly, innovative data processing schemes such as DCIP-TEM joint inversion can be used to take maximum advantage of recent and innovative data acquisition systems that enable the simultaneous collection of electrical resistivity and induced polarization measurements. Furthermore, TEM and DC data can now be jointly used to inform or calibrate coupled flow and solute transport models to such an extent that reliable estimates of parameters can be achieved as within sharp confidence intervals.

5.5 Coupled hydrogeophysical inversion with combined DC and TEM data

An implementation framework for the calibration of hydrodynamic models (SEAWAT freshwater intrusion model in this case) was successfully developed. Model output in form of solute concentrations were transformed through a series of steps into simulated instrument responses and used in the parameter estimation process. Thus the Gauss-Marquardt-Levenberg algorithm implemented in PEST was used to minimise the difference between the simulated instrument responses and the measured TEM and DC data. This implementation approach has demonstrated the benefits of using multiple datasets in terms of both type and quantity by the improved sensitivities and reduced uncertainty in parameters and parameter estimates. In addition, the developed framework id flexible enough to incorporate any data type (hydrological or geophysical) for as long as it can be related to model variables (e.g. solute concentration and hydraulic head) using either direct or empirical relationships).

Qualitative evaluation of the CHI for a simple coupled flow and solute transport problem yielded a simulated electrical resistivity profile from the distribution of solute concentrations that is a close approximation of the electrical resistivity distribution obtained from joint inversion of DC and TEM data.

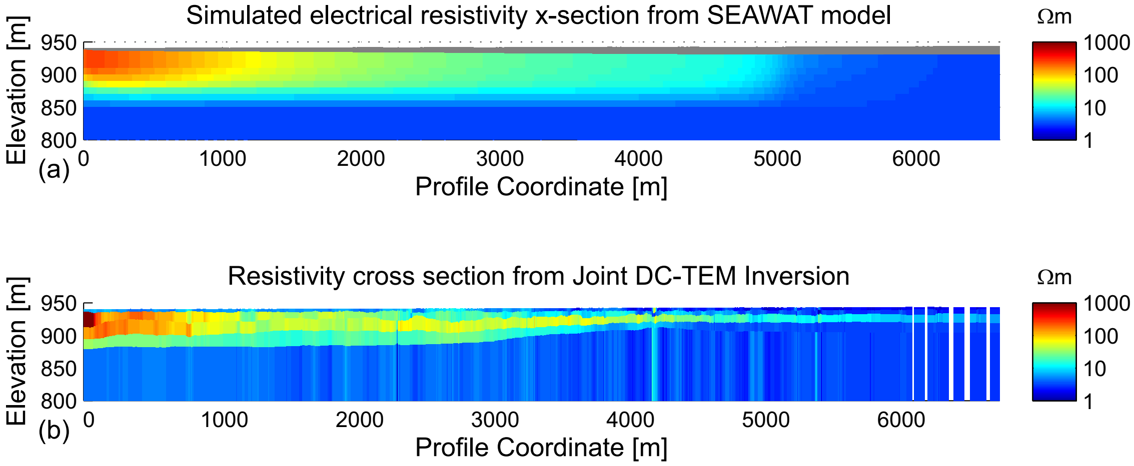

Fig. 10: (a.) Simulated electrical resistivity cross section generated from solute concentration output of a SEAWAT excited by evapotranspiration at Kasaya, south-western Zambia. (b.) Electrical resistivity cross section from joint inversion of DC and TEM data.

It is envisaged that the main limitations to the CHI is the simplicity of the hydrodynamic model that was used. Improved process descriptions and parameterizations in the model would lead to a closer match between the CHI resistivity cross section and the DC-TEM joint inversion cross section.

6 Discussion

Electrical and electromagnetic methods are an effective means of evaluating groundwater resources particularly with respect to groundwater salinity variations and aquifer delineation in sedimentary basins. This is because of the sharp electrical resistivity contrasts between fresh groundwater and salty groundwater, and between aquifers and the background geology (Nobes, 1996; Albouy et al., 2001). Thus using a combination of both aerial and ground based deployment, regional trends in groundwater salinization can be cost effectively mapped. A typical regional survey would therefore begin with a ground based reconnaissance survey at appropriate sample spacing, followed by a more targeted aerial survey to gain finer resolution of regional features of interest as detected by the preliminary ground survey. In this way a balance can be struck between the need for high data density, reduced uncertainty in model interpretations, spatial coverage and costs associated with aerial surveys (Sapia et al., 2014). Furthermore, ground based measurements are more amenable to deployed for finer scale investigations such as site characterization and they can also be used for quality control checks and calibration of aerial measurements (Podgorski et al., 2013). Thus geophysical measurenments offer the possibilities of determining hydrological parameters for a broad range of scales(Rubin and Hubbard, 2006) particularly when used in conjunction with traditional means of hydrological exploration such as core recovery, pumping tests and groundwater sampling (Danielsen et al., 2003; Auken et al., 2009b; Ruggeri et al., 2014).

However there are a number of significant challenges that hinder the use or incorporation of geophysical methods into hydrological investigations. These include terrain/geology specific suitability or appropriateness; requirement for sophisticated interpretation algorithms; general association of geophysical methods with mineral and petroleum industries; very high initial costs of instrumentation; and measurement of other physical earth properties than the hydrological parameters of interest (Rubin and Hubbard, 2006; Kirsch, 2009). Consequently, DCIP and TEM measurenments are not suitable for use in all geological environments. They are very effective in sedimentary systems because of the relatively high electrical resistivity contrasts between targets of interest and their host materials (e.g. clay lenses embedded in sand or fresh water lenses overlying salty aquifers) (Nassir et al., 2000; Guerin et al., 2001; Bauer et al., 2006c; Gazoty et al., 2012). This is in contrast to igneous or metamorphic geology in which groundwater occurs predominantly in the superficial weathered zone and in deeper fractures (Raju and Reddy, 1998) which may not exhibit a sufficiently high electrical resistivity contrast to have a meaningful distinction between aquifers and their host environment. This is in addition to the high electrical resistivity nature of such environments which typically results in very low signal to noise ratios. Furthermore, geophysical datasets that are collected for surveys beyond a certain size (e.g. aerial surveys of more than a few 100 km^2 or ground based transects of more than 1 km) often demand excessive computer memory and calculation speeds that cannot be met by ordinary computers. As a result, a significant investment in appropriate computer technology and expertise is often required if DCIP and TEM data are to be interpreted and used in a meaningful way. This comes with the requirement for complicated data handling software and inversion algorithms that are often proprietary as a result of many years of expensive research that go into their production. The fact that the same geophysical principles and methods as are used for hydrological applications can also be used for mineral and petroleum exploration does not help matters either. The mineral and petroleum industries are in general more willing and able to pay for geophysical instrumentation, data interpretation algorithms and the innovations thereof for as long as they can be shown to improve their operations and productivity. Therefore the laws of supply and demand dictate that the water and environmental sectors are at the losing end of the geophysical supply chain and would thus rather use alternative methods that fit their funding profiles in order to answer the pertinent hydrological questions. Many would go on to further argue that after all, geophysical methods do not measure the properties that are of most interest to hydrologists. For example, DCIP and TEM methods measure the chargeability or the electrical resistivity of the subsurface whereas hydrologists are interested in the aquifer properties such as porosity and hydraulic conductivity. There is no direct relationship between most geophysical parameters and hydrological parameters of interest except for the use of empirical relations such as Archie’s Law and hydrogeophysical inversion.

Notwithstanding, the advantages of incorporating geophysical measurements into hydrological investigations are increasingly being recognised. A case in point is the characterisation of regional and local scale subsurface features in the Machile Zambezi Basin using DCIP and TEM measurenments. Standard aerial and ground based TEM measurenments were used to for the first time visualise the extent of the propagation of the Okavango-Linyati Fault System (OLFS) into the Machile-Zambezi Basin in south-western Zambia. The OLFS is considered to be an important structural control on the extent of groundwater salinization in the Machile-Zambezi Basin as it relates to the spatial extent of the Palaeo Lake Makgadikgadi sediments. Thus a block faulting system was inferred in the Machile-Zambezi Basin whose main feature is a northeast to southwest oriented graben structure which is deepest at its south western extent. Salinized groundwater was found to occur predominantly in this graben structure particularly at the deepest end in the southwest (Paper I). One implication of this is that saline groundwater was created at the time of deposition of the Palaeo Lake Makgadikgadi sediments and that as a consequence, further salinization of groundwater is not taking place (Banda et al., 2014). Indeed as indicated from the aerial TEM data, significant surface water\ groundwater exchange based on high electrical resistivity values that were found to be coincident with surface water features appears to be taking place, leading to the creation of freshwater lenses that are an important source of clean drinking water. A combination of DCIP and TEM measurements indicated that the high electrical resistivity anomalies were as a result of intrusion of fresh surface water into a pre-existing saline aquifer (Paper II). However a more detailed understanding of the surface water / groundwater exchange indicated by the geophysical data is still needed. This can only be achieved by conducting further research that will integrate geochemical, hydrological, petrological and meteorological data around the new knowledge that has been brought out by the geophysics as closely as possible under hydrogeophysical inversion approaches similar to those presented in Paper III. This will of no doubt be useful to water resource managers and planning authorities who have to weigh societal and environmental interests with respect to scarce freshwater resources particularly where decisions have to be made with the aid of groundwater models. Thus better estimates of pertinent hydrological parameters and processes can result from new formulations that incorporate as much geophysical data as is available in addition to data from other geoscience disciplines such as petrology, geochemistry, hydrology and meteorology. Furthermore, model outcomes will be more reliable and better able to predict system behaviour for as long as the model faithfully represents the natural system under consideration and this requires an integrated multidisciplinary approach.

7 Conclusion

The main conclusions that have been arrived at with respect to the research reported in this thesis are as follows:

- Saline groundwater in the Machile-Zambezi Basin in south-western Zambia was found to occur in a northeast to southwest oriented graben structure related to propagation of the Okavango-Linyati fault system stretching from Botswana in the south into south-western Zambia. The graben structure is deepest at its south-western extent where the observed low electrical resistivity values have been attributed to Palaeo Lake Makgadikgadi sediments and associated saline groundwater. This marks the first time that the northern extent of the Paleo Lake Makgadikgadi system (including the associated fault structures) extending into Zambia has been mapped using TEM methods;

- Considerable surface water/ groundwater exchange takes place in the Machile-Zambezi Basin as indicated by the coincidence of high electrical resistivity anomalies (> 100 Ωm) in a low electrical resistivity (< 13 Ωm) geological setting with surface water features such as alluvial fans and flood plains. One such feature, the Simalaha Flood Pain, was investigated at a local scale at Kasaya in Kazungula District, Zambia, using a combination of DCIP and TEM measurenments. Evaluation of the measurenments under a new DCIP-TEM inversion scheme revealed a freshwater lens with high electrical resistivity values (30-200 Ωm) overlying a Saline aquifer with electrical resistivity values 3.59 Ωm and below. The correlation of electrical resistivity and chargeability from the DCIP-TEM inversion result indicates intrusion of fresh surface water into a pre-existing saline environment; and

- An innovative coupled hydro geophysical inversion framework was developed to enable the calibration of a coupled flow and transport model with both DC and TEM data for the first time. When tested for a river-aquifer exchange problem under evapotranspiration for the Kasaya Transect in Kazungula District, Zambia, the CHI resulted in sharp parameter confidence intervals and reasonable estimates of parameter values. The estimated parameters also exhibited strong sensitivity with respect to model outcomes.

- Finally, the practical relevance of the findings is that there is now new knowledge on a regional scale about the spatial distribution of saline groundwater in the Machile-Zambezi Basin including local scale surface water/ groundwater exchange in places. This knowledge will be useful in planning for new water points or human settlements taking into account the location of fresh and saline aquifers. Furthermore, these findings have an important impact on the management of the water resources not only of the Machile-Zambezi Basin, but of the entire Kalahari Basin in Southern Africa and other similar semi-arid sedimentary settings around the world. This is because standard transient electromagnetic and geoelectrical (direct current and induced polarization) methods have been shown to be effective means of groundwater characterization in a semi-arid sedimentary environment. In addition, the findings have also shown that the data requirement for groundwater models which are an important water resources management tool and decision support can be effectively complimented by using geophysical data.

8 Outlook and Perspectives

The hydrogeophysical characterization of groundwater salinization reported in this thesis is an important outcome for water resources management in arid and semi-arid environments particularly in the Machile-Zambezi Basin. However is does not represent the whole picture from the hydrogeological point of view because by and large the geophysical data was not integrated with other data such as geochemical (e.g. prevailing groundwater types and their evolution), petrological (e.g. laboratory determinations of rock and sediment properties like porosity and cementation) and hydrogeological (e.g. hydraulic conductivity and hydraulic head) data due to a lack of it. The few such data available in the study area were mostly not coincident with the geophysical data. Therefore there is still a strong need to conduct further geochemical, petrophysical, sedimentological, hydrological and hydrogeological research to generate data that can help to strengthen and or validate the outcomes from the hydrogeophysical investigation reported in this thesis.

Furthermore, it is highly likely that given the nature of the propagation of the East African Rift Valley system into southern African, there could be other graben structures in the western parts of Zambia similar to the Machile graben that are hidden by the extensive Kalahari sand cover but nevertheless harbour salinized groundwater as a result of palaeo lake systems. One such palaeo lake system that could be investigated in the future is the area around the Barotse Flood plains which has been designated as Palaeo Lake Bulozi by Moore et al. (2012). The Barotse flood plains are an important wetland on the course of the Zambezi River and are protected under the Ramsar Convention on conservation of wetlands of international importance. Thus in order to come up with measures that mitigate against the adverse effects of climate variability such as floods and droughts, and to develop water resource management and development practices that maintain the heritage status of the Barotse Flood plains whilst sustaining the requirements of the local people, the need for ongoing and integrated multi-disciplinary water resource related research cannot be over emphasised. Such research will need to integrate surface water and groundwater evaluation using multiple data from remote sensing and airborne geophysics to ground based geophysics and sedimentological, petrological, groundwater and geochemical sampling.

A recommended research strategy with respect to the Kalahari System of western Zambia would therefore be to:

- Use satellite data for a preliminary description of the hydrology of the Zambezi River system and design of a network of permanent hydrological monitoring stations;

- Conduct preliminary ground based TEM measurements in a 25 x 25 km grid in order to gain a regional perspective of ground water salinization based on electrical resistivity correlation. Geochemical sediment sampling could also be incorporated into the preliminary TEM survey in order to have an initial basis for relating geological mineralization to electrical resistivity variations;

- Design and develop a ground water monitoring network based on the preliminary TEM and geochemical sampling survey mentioned above with a rough spatial density of one monitoring borehole per 500 km^2. The hydrogeological, petrological and geochemical data derived from these boreholes could then be integrated with the geophysical data using various geostatistic and inversion approaches to interpolate and extrapolate parameters of interest. It is recommended that the monitoring boreholes should have a minimum depth of 500 m in order to capture all relevant geological history and not only that of the relatively recent Kalahari Supergroup;

- Design and conduct site specific airborne TEM surveys based on areas of interest identified by the preliminary ground based TEM and geochemical sampling surveys mentioned above, followed by detailed local scale surveys that integrate different geoscience disciplines in order to gain a comprehensive picture about the ecosystem and water resources particularly with regards to the impact of climatic variability and anthropogenic activities; and

- Create an electronic and online database that integrates local and international multi-disciplinary data. This database should go together with coordinated environmental and water resources related research across the international boundaries of the southern African countries with significant territory in the Kalahari Basin.

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10 Appendix Inventory of electronic material

Electronic materials associated with the production of this thesis are listed below. They could not be placed in a CD as is usually the practice due to the requirement for large storage space (63.9 gigabytes). The containing folder is called Chongo_Thesis_Electronic_Materials and maybe obtained by contacting the following:

DTU Environment
Technical University of Denmark
Miljøvej, Building 113
2800 Kgs. Lyngby
Denmark
reception@env.dtu.dk

The contents of the electronic appendix are as follows:
Raw data items

- Geotech db/dt aerial data
- Kasaya transect DCIP data
- Kasaya transect differential GPS files
- Kasaya transect TEM data
- Kasaya CHI setup
- Machile-Zambezi ground based TEM (raw and processed)

Processed data items

- Machile-Zambezi Aarhus workbench workspace for aerial and ground based TEM data
- Kasaya transect Aarhus workbench processed DCIP data files
- Kasaya transect TEM data (.usf and .tem files)
- Kasaya transect DCIP data (RES2DINV format and electrode coordinates)
- DCIP_TEM_Joint (Folder containing the DCIP-TEM joint inversion scheme)
- Joint_DC_TEM_Inversion (Folder containing the joint DC-TEM inversion scheme)

Databases

- Sesheke GIS
- Endnote references

Scripts

- C++ CHI Scripts
- Matlab CHI Scripts

Documents

- Thesis
- Papers I-III

11 Papers

The scientific papers that form the basis of this thesis are:

I Mkhuzo Chongo, Anders Vest Christiansen, Alice Tembo, Kawawa E. Banda, Imasiku A Nyambe, Flemming Larsen, Peter Bauer-Gottwein, 2015. Airborne and ground based transient electromagnetic mapping of groundwater salinity in the Machile-Zambezi Basin, south-western Zambia. Accepted for publication in Near Surface Geophysics Journal (in press).

II Mkhuzo Chongo, Anders Vest Christiansen, Gianluca Fiandaca, Imasiku A Nyambe, Flemming Larsen and Peter Bauer-Gottwein, 2015. Mapping localized freshwater anomalies in the brackish Paleo-Lake sediments of the Machile-Zambezi Basin with transient electromagnetic sounding, geoelectrical imaging and induced polarization. Submitted to Journal of Applied Geophysics.

III Mkhuzo Chongo., Nyambe, I.A., Larsen, F., and Peter Bauer-Gottwein, 2015. Coupled hydrogeophysical inversion using a groundwater flow and transport model, and transient electromagnetic and direct current electrical resistivity data.

In this online version of the thesis, the papers are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from:

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The Department of Environmental Engineering (DTU Environment) conducts science-based engineering research within four sections:
Water Resources Engineering, Urban Water Engineering,
Residual Resource Engineering and Environmental Chemistry & Microbiology.

The department dates back to 1865, when Ludvig August Colding, the founder of the department, gave the first lecture on sanitary engineering as response to the cholera epidemics in Copenhagen in the late 1800s.

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