Journal of Applied Geophysics 123 (2015) 81–92

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Mapping localised freshwater anomalies in the brackish paleo-lake sediments of the Machile–Zambezi Basin with transient electromagnetic sounding, geoelectrical imaging and induced polarisation

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ARTICLE INFO

Article history:
Received 21 January 2015
Received in revised form 4 October 2015
Accepted 6 October 2015
Available online 9 October 2015

Keywords:
TEM
DCIP
Joint inversion
Surface water/groundwater interaction
Zambezi River
Zambia

ABSTRACT

A recent airborne TEM survey in the Machile–Zambezi Basin of south western Zambia revealed high electrical resistivity anomalies (around 100 Ωm) in a low electrical resistivity (below 13 Ωm) background. The near surface (0–40 m depth range) electrical resistivity distribution of these anomalies appeared to be coincident with superficial features related to surface water such as alluvial fans and flood plains. This paper describes the application of transient electromagnetic soundings (TEM) and continuous vertical electrical sounding (CVES) using geoelectrics and time domain induced polarisation to evaluate a freshwater lens across a flood plain on the northern bank of the Zambezi River at Kasaya in south western Zambia. Coincident TEM and CVES measurements were conducted across the Simalaha Plain from the edge of the Zambezi River up to 6.6 km inland. The resulting TEM, direct current and induced polarisation data sets were inverted using a new mutually and laterally constrained joint inversion scheme. The resulting inverse model sections depict a freshwater lens sitting on top of a regional saline aquifer. The fresh water lens is about 60 m thick at the boundary with the Zambezi River and gradually thins out and deteriorates in water quality further inland. It is postulated that the freshwater lens originated as a result of interaction between the Zambezi River and the salty aquifer in a setting in which evapotranspiration is the net climatic stress. Similar high electrical resistivity bodies were also associated with other surface water features located in the airborne surveyed area.

1. Introduction

The interaction between surface water and groundwater has been studied extensively around the world (Milosevic et al., 2012; Shanafield and Cook, 2014; Sophocleous, 2002; Westbrook et al., 2005; Winter, 1999; Zarroca et al., 2015; Zhou et al., 2014) using different approaches, and increasingly geophysical methods are being incorporated into such studies.

Specific examples of studies that have used geophysical data to investigate hydrogeological phenomenon include Bauer et al. (2006) who described the process of salt accumulation on islands within the Okavango Delta, related to the interaction between surface water and groundwater under evapo-concentration using a combination of electrical resistivity tomography (ERT) (which is the same as CVES with respect to geo-electrics) and hydrodynamic modeling; Sonkamble et al. (2014) who evaluated the extent of aquifer pollution from industrial effluent across the flood plain of the Palar River at Ambur Town (India) using 1D and 2D geo-electrics correlated with in-situ water quality data and ground penetrating radar; Shalem et al. (2014) who studied the interaction of the Alexander River with groundwater as it cuts its way across a mostly sandy Quaternary coastal aquifer on the eastern coast of the Mediterranean Sea; and Zarroca et al. (2014) who evaluated coastal discharge processes at the Peníscola marsh on the Spanish Mediterranean coast using electrical resistivity imaging and temperature, salinity and ^{224}Ra, ^{222}Rn tracer tests coupled with petrophysical analysis.

Thus geophysical techniques such as ERT are well suited for gathering data at high spatial resolution in comparison to for example point measurements of hydrogeological parameters at sparsely spaced boreholes (Zarroca et al., 2014). An overall assessment strategy using a combination of different geophysical methods and traditional hydrogeological methods can therefore be advantageous (Brodie et al., 2007; Rubin and Hubbard, 2006). In this regard, TEM (Danielsen et al., 2003; Harthill, 1976; Nabighian, 1991; Xue et al., 2012), direct current geo-electrics (DC) (Aizebeokhai, 2010; Dahlin, 2001; Loke, 1999; Loke

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http://dx.doi.org/10.1016/j.jappgeo.2015.10.002
0926-9851/

et al., 2013) and induced polarisation (IP) (Bertin and Loeb, 1969; Dahlin et al., 2002; Fiandaca et al., 2012; Fiandaca et al., 2013; Titov et al., 2002) techniques are quite suitable for environmental and hydro-geological investigations particularly in sedimentary terrain.

Traditionally, TEM, DC and IP techniques have been deployed separately even for investigations at the same study site (Bauer et al., 2006; Ezersky et al., 2011; Guerin et al., 2001; Nassir et al., 2000; Vaudelet et al., 2011) although it is now common to have instrumentation that measures both DC and IP in the same field setup (Aristodemou and Thomas-Betts, 2000; Marescot et al., 2008). As a result, different types of data sets are quite often generated for the same physical or environmental phenomenon by inverting each type of data set individually. Nevertheless, major benefits can be derived from joint inversion of different types of data that observe the same phenomenon and can lead to more accurate interpretations. Thus many studies have successfully used one form of joint inversion or another such as DC-TEM (Albouy et al., 2001; Christiansen et al., 2007; Danielsen et al., 2007) and MRS-TEM (Behroozmand et al., 2012; Vilhelmsen et al., 2014). Examples of DCIP joint inversions are scarce in the literature with the normal practice being to independently invert the DC and IP data either as separate inversion jobs or in one inversion job but without any of the data sets influencing the other during the inversion process. Furthermore, joint DCIP–TEM inversions have not been reported in the literature before. This paper therefore presents a first case study of joint inversion of DCIP–TEM data.

The focus of this paper is on local scale electrical resistivity anomalies derived from interpreting regional scale airborne TEM data in terms of surface water/groundwater interaction in the Machile–Zambezi Basin. The objectives were to describe the occurrence of high electrical resistivity anomalies in the low electrical resistivity background environment of the Machile–Zambezi Basin; conduct local scale TEM and direct current-induced polarisation (DCIP) CVES measurements along a transect cutting across an area exhibiting electrical resistivity anomalies; evaluate the benefits of joint inversion of the local scale TEM and DCIP data in comparison to separate inversions; and to evaluate the inverse resistivity section in terms of surface water groundwater interaction taking place at the local site.

2. Materials and methods

2.1. Study site

The study area is in the southern central low lying areas of the Machile–Zambezi Basin on the northern banks of the Zambezi River. The area is drained by three main tributaries of the Zambezi River namely Loanja, Machile (or Kasaya) and Ngwezi. The downstream reaches of the Machile and Ngwezi streams respectively flow across seasonally flooded plains as single channels before entering the Zambezi. However the Loanja stream terminates inland to form an inland delta or alluvial fan. The Loanja alluvial fan and the Simalaha flood plain (bound by Kasaya River to the west and the Zambezi River to the south) were the two local areas of interest for this study. However, the combined TEM–CVES transect is reported only for the Simalaha flood plain (Fig. 1).

2.2. Data collection and pre-processing

Airborne data was conducted along 8 flight lines totalling 1000 line kilometers using the VTEM system (GEOTECH, 2011). Four of the flight lines were oriented southwest to northeast whereas the other 4 were oriented from northwest to southeast (Fig. 1 in Section 2.1). Details about the airborne survey and about the processing, inversion and interpretation of the collected TEM data are given in Chongo et al. (2015). Cross sections of the airborne TEM data along the Loanja and Simalaha profiles (Fig. 1 in Section 2.1) are shown in Fig. 2(a) and (b) respectively. These depict superficial electrical resistivity anomalies in

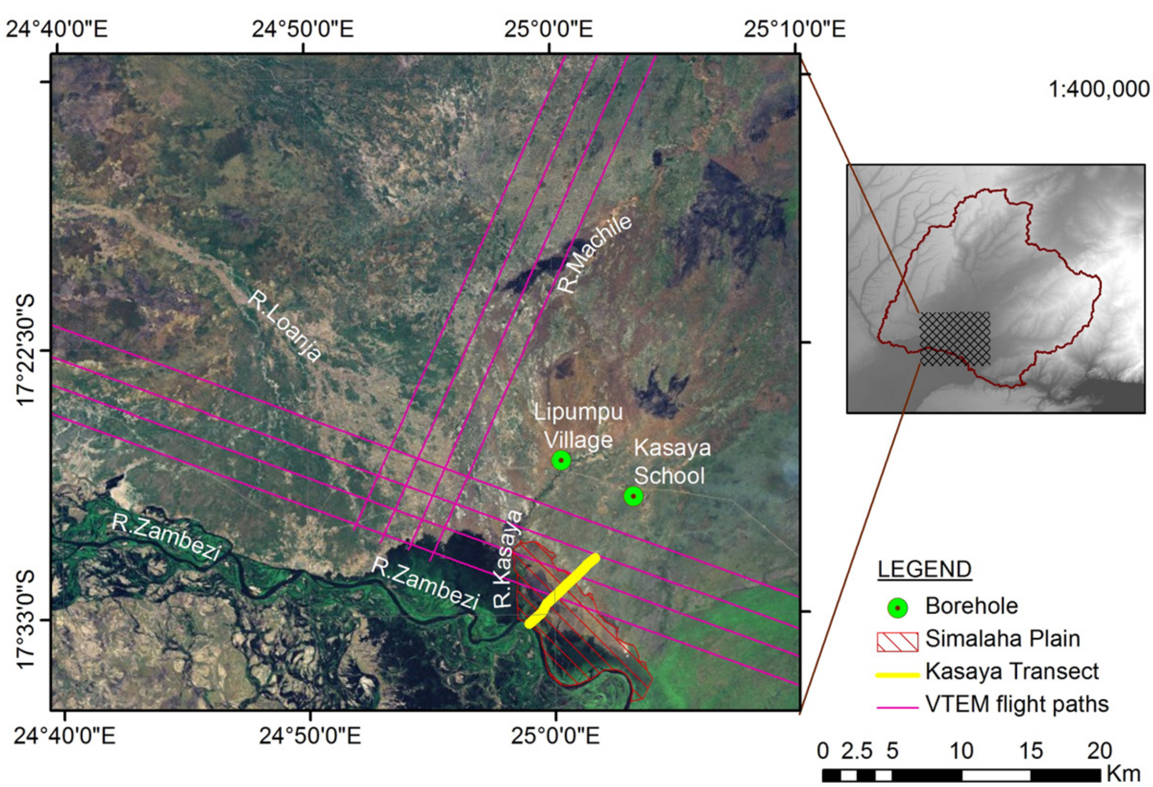

Fig. 1. The study area depicting Loanja alluvial fan, Simalaha flood plain, Kasaya Transect and TEM flight paths. Satellite image courtesy of ESRI (2014). Note that the Simalaha Profile is shorter than the Kasaya Transect since there is no more airborne electromagnetic data outside the flight lines, whereas the CVES and TEM data on the Kasaya Transect extend beyond the flight path where the Simalaha Profile ends up to the Zambezi River.