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Review

Current uses of ground penetrating radar in groundwater-dependent ecosystems research

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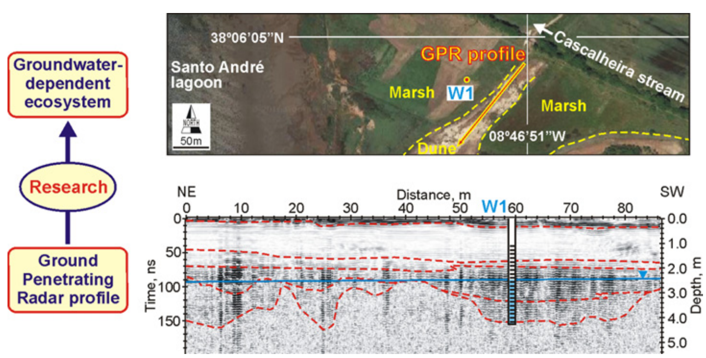
HIGHLIGHTS

- Current uses of GPR in shallow groundwater prospecting and GDE research are reviewed.
- Guidelines for data clustering and interpretation are systematized in a database with 91 cases.
- Common ranges of prospecting depth, water-table depth, and water content are recognized.
- Preferences and gaps of GPR in shallow groundwater and GDE research are identified.
- Several original GPR profiles have been performed to document database classes and gaps.

GRAPHICAL ABSTRACT



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ABSTRACT

Ground penetrating radar (GPR) is a high-resolution technique widely used in shallow groundwater prospecting. This makes GPR ideal to characterize the hydrogeological functioning of groundwater-dependent ecosystems (GDE). This paper reviews current uses of GPR in GDE research through the construction of a database comprising 91 worldwide GPR case studies selected from the literature and classified according to (1) geological environments favouring GDE; (2) hydrogeological research interests; and (3) field technical and (4) hydrogeological conditions of the survey. The database analysis showed that inland alluvial, colluvial, and glacial formations were the most widely covered geological environments. Water-table depth was the most repeated research interest. By contrast, weathered-marl and crystalline-rock environments as well as the delineation of salinity interfaces in coastal and inland areas were less studied. Despite that shallow groundwater propitiated GDE in almost all the GPR case studies compiled, only one case expressly addressed GDE research. Common ranges of prospecting depth, water-table depth, and volumetric water content deduced by GPR and other techniques were identified. Antenna frequency of 100 MHz and the common offset acquisition technique predominated in the database. Most of GPR case studies were in 30–50° N temperate latitudes, mainly in Europe and North America. Eight original radargrams were selected from several GPR profiles performed in 2014 and 2015 to document database classes and identified gaps, as well as to define experimental ranges of operability in GDE environments. The results contribute to the design of proper GPR surveys in GDE research.

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Contents

1. Introduction

Groundwater-dependent ecosystems (GDE), which can be defined as natural terrestrial ecosystems where groundwater is crucial for the wildlife survival (Howard and Merrifield, 2010), represent a large fraction of the terrestrial biodiversity (Hancock et al., 2005; Ribeiro, 2009). In the absence of precipitation, many wetlands and seasonal-water ecosystems reveal their dependence on shallow groundwater for the sustenance of riparian flow, river base-flow, and adequate moisture levels in soil-root and unsaturated zones (Fan et al., 2013; Chambers et al., 2014; Uhlemann et al., 2016). Most of GDE are currently threatened by a combination of global climate forces that extend drought periods and local human-induced pressures such as land-use changes and pollution (Yuce, 2006; Ribeiro, 2009; Kløve et al., 2011; Silva et al., 2012).

In the European context, GDE are protected by regional legislation (Mendes and Ribeiro, 2014) and international agreements including the RAMSAR convention on wetlands since 1971 [http://www.ramsar.org] and the Water Framework Directive since 2000 (WFD, 2000). According to the WFD, most protected GDE have been catalogued in (1) discharge areas of regional groundwater bodies as permanent springs, freshwater coastal lagoons in the outlet of regional watersheds, and oases in drylands; (2) valleys where the water table is permanent or temporarily intersected by topography favouring temporary springs, surface water bodies, and streams; (3) depressed inland areas (Kløve et al., 2011); and (4) high mountains where snow melting determines seasonal groundwater discharge (Bradford et al., 2009). Most GDE appear in geological environments favouring shallow groundwater such as coastal fluvial (Hardie and Davies, 2007), estuarine (Silva et al., 2012), lacustrine (Félix et al., 2015), inland alluvial (Hardie and Davies, 2007), proglacial moraines (Langston et al., 2011), sand dunes (Adams et al., 2015), oases in drylands (Margat and van der Gun, 2013), high-permeability carbonates (Shapouri et al., 2015), weathered and fissured siliciclastics (Howard and Merrifield, 2010), and crystalline formations (Salvador et al., 2011). Some GDE are the result of local hydraulics favouring shallow groundwater (Salvador et al., 2011) such as the presence of salinity interfaces in the freshwater discharge area of flat coastal aquifers (Hancock et al., 2005; Silva et al., 2012), alpine taluses favouring shallow groundwater drainage (Muir et al., 2011), clay-rich sediments in unsaturated (Howard and Merrifield, 2010) and hyporheic (Henry and Fisher, 2003) zones that favour the water table raising during infiltration events, and human-induced lagoons due to quarries reaching the saturated zone (Molina-Sánchez et al., 2015). Despite this experience, GDE research is still in an early phase which may lead to unsuitable management policies (Kløve et al., 2014) with environmental implications affecting the economy and social habits of the population (Alcalá et al., 2015). The selection of validated techniques to characterize the hydrogeological functioning is a prerequisite for the preservation and conservation of GDE.

Geophysical prospecting techniques have been widely used in groundwater research. Many surveys have combined electrical and seismic techniques to image aquifer geometry (Kirsh, 2009), fracture zones, and caves (Ernston and Kircsh, 2009). Airborne frequency and time-domain electromagnetic techniques have been used to delineate freshwater-saltwater interfaces (Wiederhold et al., 2009). A combination of vertical electric soundings and ground penetrating radar (Khalil et al., 2010) has been implemented to infer 2D near-surface aquifer porosity and groundwater salinity. Resistivity and seismic refraction profiles have been combined to determine 2D near-surface porosity, water saturation, and volumetric water content (Mota and Monteiro dos Santos, 2006; Langston et al., 2011). Binley et al. (2015) pointed out how geophysical techniques have become valuable to study near-surface hydrological processes over multiple spatial scales.

Ground Penetrating Radar (GPR) is a non-invasive, high-resolution geophysical prospecting technique that provides reliable interpretations of near-surface structures and hydrological processes (Sailhac et al., 2009; Doetsch et al., 2012; and references therein) in different geological environments (Cassidy, 2009; Slater and Comas, 2009). The technique is easy to use and requires relatively low maintenance (Grote et al., 2002). Ground penetration varies from a few to dozens of metres, depending on the antenna centre frequency, and the electrical and magnetic properties of geological materials (Bano et al., 2000; Huisman et al., 2003; Slater and Comas, 2009). This makes the GPR suitable for shallow hydrogeological characterizations in general and GDE environments in particular. Experience has been gained in defining near-surface aquifer geometry, volumetric water content of unsaturated and saturated zones (Huisman et al., 2003; Lunt et al., 2005), and water-table depth (Corbeanu et al., 2002; Bowling et al., 2005; Ezzy et al., 2006; Gómez-Ortiz et al., 2009), as basic data needed in numerical groundwater flow and transport models designed to represent the hydrogeological conditions of natural groundwater systems over time (Bowling et al., 2005; Slater and Comas, 2009).

The present paper reviews current uses of GPR in GDE research. For this, 91 worldwide GPR case studies hosting (catalogued or not) GDE associated to the presence of shallow water tables were selected from the literature and classified according to (1) geological environments favouring GDE; (2) hydrogeological research interests; and (3) field