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Electrical resistivity and porosity structure of the upper Biscayne Aquifer in Miami-Dade County, Florida

Dean Whitman[a,*], Albert Yeboah-Forson[b]

[a] Department of Earth and Environment, Florida International University, United States
[b] Department of Physical and Chemical Science, Missouri Southern State University, United States

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SUMMARY

Square array electrical soundings were made at 13 sites in the Biscayne Aquifer distributed between 1 and 20 km from the shoreline. These soundings were modeled to investigate how resistivity varies spatially and with depth in the upper 15 m of the aquifer. Porosity was estimated from the modeled formation resistivity and observed pore fluid resistivity with Archie's Law. The models were used to interpolate resistivity and porosity surfaces at −2, −5, −8, and −15 m elevations. Modeled resistivity in the unsaturated zone is generally higher than 300 Ω m with the resistivity at sites with thick unsaturated zones greater than 1000 Ω m. Resistivity in the saturated zone ranges from 30 to 320 Ω m. At many sites in the western portions of the study area, resistivity is constant or increases with depth whereas sites in the center of the Atlantic Coastal Ridge exhibit a distinct low resistivity zone ($\rho < 45\ \Omega$ m) at elevations ranging between −5 and −10 m. At one site near the shore of Biscayne Bay, the resistivity is less than 10 Ω m at −5 m elevation reflecting the presence of salt water in the aquifer. The estimated porosity ranges between 14% and 71% with modal values near 25%. The porosity structure varies both with depth and spatially. Western sites exhibit a high porosity zone at shallow depths best expressed in a NE–SW trending zone of 40–50% porosity situated near the western margin of the Atlantic Coastal Ridge. This zone roughly corresponds in depth with the Q5 chronostratigraphic unit of the Miami Fm. which constitutes the upper flow unit of the Biscayne Aquifer. The highest porosity (>50%) is seen at elevations below −5 m at sites in the center of the Atlantic Coastal Ridge and likely corresponds to solution features. The general NE–SW trend of the resistivity and porosity structure suggests a causal connection with the Pleistocene paleogeography and sedimentary environments.

1. Introduction

The Biscayne Aquifer is a Pleistocene unconfined carbonate aquifer located in southeast Florida and serves as the principal source of water for all of Miami-Dade, Broward, and Monroe Counties (Fig. 1). The properties of the Biscayne Aquifer have been extensively investigated from borehole based measurements including pore fluid sampling, core analysis and geophysical and optical logging (Fish and Stewart, 1991; Cunningham, 2004; Cunningham et al., 2006a, 2006b; Wacker et al., 2014). These studies have demonstrated the micro-scale complexity of the aquifer related to depositional environments and karst controlled secondary porosity. Other studies have focused on the delineation of saltwater intrusion from Biscayne Bay, Florida Bay, and drainage canals cut through the Atlantic Coastal Ridge (Parker et al., 1955; Kohout, 1964; Prinos et al., 2014). Borehole based studies are limited by the expense of installation which results in a relatively sparse distribution of sites within the area. In addition, while borehole based studies provide great detail on the aquifer properties at the site, the complexity of the Biscayne Aquifer as a result of its inherent karst features makes generalizing regional variations in the aquifer problematic.

Geophysical methods such as DC electrical resistivity, and time domain (TDEM) and frequency domain (FDEM) electromagnetic soundings are widely used to provide electrical resistivity (inverse of electrical conductivity) information relating to aquifer and pore fluid properties (Loke et al., 2013). The electrical resistivity of an aquifer depends mainly on groundwater salinity, saturation, aquifer lithology, and porosity (Shaaban, 2002). In general, geophysical methods are both more rapid, less invasive and faster than borehole based methods (Fitterman and Prinos, 2011; Hinnell et al., 2010; Huisman et al., 2010). In addition, because they sample over a relatively larger volume, they provide a more generalized characterization of the aquifer properties than borehole based measurements.

* Corresponding author.

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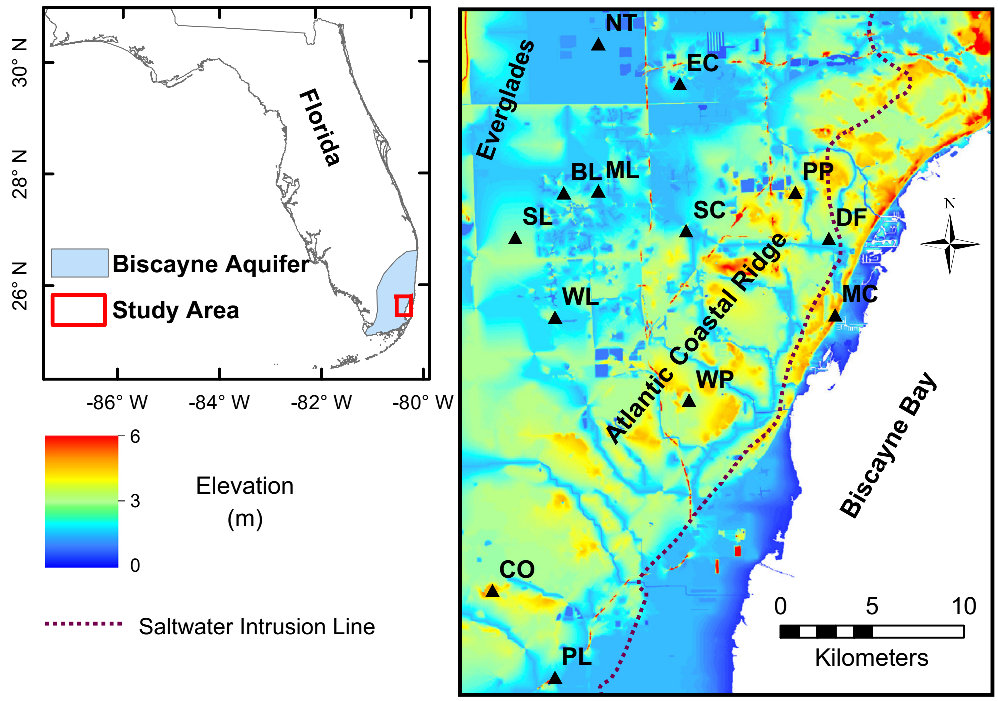

Fig. 1. Map of azimuthal resistivity survey sites and topography. Topographic source USGS 30 m DEMs. BL-Bird Lake Park; CO-Camp Owaissa Bauer; DF-Dante Fascell Park; EC-FIU Engineering Center; MC-Montgomery Center; ML-Miller Pond Park; NT-North Trail Park; PP-Palmer Park; PL-Palmland Park; SC-Snapper Creek Well Field; SL-Sun lake Park; WP-West Perrine Park; WL-Wild Lime Center Park. Saltwater Intrusion line from Prinos et al. (2014).

In SE Florida, several studies have applied airborne FDEM, ground based TDEM and borehole electromagnetic induction logging to map the location and extent of the saltwater interface in the Biscayne Aquifer (Fitterman et al., 1999, 2012; Fitterman and Deszcz-Pan, 1998; Fitterman and Prinos, 2011). Since these geophysical data were concentrated along the saltwater interface near the shores of Biscayne and Florida Bay, few geophysical measurements have been collected at inland sites and little is known about the regional variation of resistivity and porosity in the aquifer.

Yeboah-Forson and Whitman (2013) applied azimuthal square array measurements at 13 sites within central Miami-Dade County to map regional variations in electrical anisotropy within the Biscayne Aquifer. In that study, variations in anisotropy were presented spatially and in terms of an effective depth proportional to the array size, but the data were not inverted to real earth models. In this study, the azimuthal square array data is averaged at each square size, converted to an equivalent Wenner array spacing and inverted to resistivity depth models in order to explore the regional variation of resistivity with depth in the upper (0–15 m) Biscayne Aquifer. The specific objectives of the study are to (a) determine the spatial variation of resistivity at different sites and depths within the aquifer through resistivity modeling, (b) estimate the porosity of the study area through application of Archie's law, and (c) interpolate these measurements to create continuous surfaces of these resistivity and porosity across the aquifer. Mapping the regional variations in resistivity and porosity in the saturated zone will play a useful role in effective water protection and management of the Biscayne Aquifer.

2. Geologic setting

The surface elevation in the study area range from around 1 m above sea level on the eastern margin of the Everglades to as much as 6 m on the Atlantic Coastal Ridge (Fig. 1). The Atlantic Coastal Ridge (ACR) is a NE–SW trending feature which is cut by a number of NW–SE trending valleys known as the transverse glades. Many of the transverse glades are occupied by canals cut during the mid 20th century to allow drainage of water from the Everglades. The Ridge was formed in the late Pleistocene as a high energy ooid shoal. This shoal was traversed by tidal channels which later formed the transverse glades (Hoffmeister et al., 1967).

The rocks in the study area are composed of the Miami Limestone at the surface underlain by the Fort Thompson Formation. The Miami Limestone, formed during a sea level high stand associated with the Sangamonian/Eemian Interglacial, is the predominant unit found at the surface and is subdivided into oolitic and the bryozoan facies (Hoffmeister et al., 1967). The oolitic facies is present beneath the Atlantic Coastal Ridge and can be grouped into cross-bedded and bioturbated facies. The bryozoan facies is found underneath the Everglades and consists of sandy fossiliferous rocks which were formed in lagoonal environments west of the Atlantic Costal Ridge. The Miami Limestone thickens from 4 m in the western parts of the study area to 9 m near Biscayne Bay. The Fort Thompson Formation is made up of intercalated fresh and marine limestone and underlies the Miami Formation in Miami Dade County (Fish and Stewart, 1991). Recent work has characterized the structure of the Miami and Fort Thompson formations in terms of chronostratigraphic units, Q1 through Q5 (Perkins, 1977) or high frequency cyclostratigraphic cycles (Cunningham, 2004; Cunningham et al., 2006a). These units represent distinct depositional environments which relate to vertical variations in lithofacies, porosity and permeability within the Biscayne Aquifer.

Detailed discussions of the hydrogeological setting of the Biscayne Aquifer can be found in Parker et al. (1955), Fish and Stewart (1991), Cunningham et al. (2006a, 2009) and Cunningham and Florea (2009). Water levels in the aquifer are higher to the west in the Everglades and decrease towards the southeast and south. The thickness of the aquifer in the study area ranges from 20 m in the west to 40 m near the shore of Biscayne Bay (Fish and Stewart, 1991). Porosities in the aquifer range from