GEOPHYSICAL MAPPING OF SALTWATER INTRUSION IN EVERGLADES NATIONAL PARK

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1. ABSTRACT

The mapping of saltwater intrusion in coastal aquifers has traditionally relied upon observation wells and collection of water samples. This approach may miss important hydrologic features related to saltwater intrusion in areas where access is difficult and wells are widely spaced, such as the Everglades. To map saltwater intrusion in Everglades National Park, a different approach has been used. We have relied heavily on helicopter electromagnetic (HEM) measurements to map lateral variations of electrical resistivity, which are directly related to water quality. The HEM data are inverted to provide a three-dimensional resistivity model of the subsurface. Borehole geophysical and water quality measurements made in a selected set of observations wells are used to determine the relation between formation resistivity and specific conductance of pore water. Applying this relation to the 3-D HEM resistivity model produces an estimated water-quality model. This model provides constraints for variable density, ground-water models of the area. Time-domain electromagnetic (TEM) soundings have also be used to map saltwater intrusion. Because of the high density of HEM sampling (a measurement point every 10 meters along flight lines) models with a cell size of 100 meters on a side are possible, revealing features which could not be recognized from either the TEM or the observation wells alone. The very detailed resistivity maps show the extent of saltwater intrusion and the effect of former and present canals and roadbeds. The HEM survey provides a means of quickly obtaining a synoptic picture of saltwater intrusion, which also serves as a baseline for monitoring the effects of Everglades restoration activities.

2. INTRODUCTION

The Everglades ecosystem encompasses a large area in south Florida extending from south of Orlando to Florida Bay, a distance of over 350 km (Figure 1). Surface-water flows tie these location together starting from the Kissimmee River drainage, which is located north of Lake Okeechobee. Water from the lake drains into the Everglades and then through Everglades National Park to Florida Bay. The building of canals and levees in south Florida over the past century has severely modified the pre-development conditions producing major changes in the ecosystem (Lodge, 1994). As a result of increased understanding of the importance of the ecosystem on water supplies and the economy of south Florida, federal, state, and local governments have been working to reverse some of the adverse effects of development on the Everglades. Restoration activities are aimed at understanding which factors influence the ecosystem, and how modification of water flows to more closely resemble pre-development conditions can improve the viability of the ecosystem while maintaining drinking water supplies and adequate levels of flood protection for developed areas.

One part of the restoration effort involves mapping salt-water intrusion in Everglades National Park (ENP). This information is needed to develop ground-water flow models (Langevin, 1999; Swain, 1999), for use in geochemical studies of ground-water/surface-water interactions (Harvey et al., 1999), and to compare with reconstructions of historic saltwater intrusion based on plant and paleontological studies (Brewster-Wingard et al., 1999; Willard et al., 1999). Figure 1 shows a location map of the study area which encompasses much of the southern tip of Florida.

Saltwater intrusion in coastal aquifers has traditionally been studied using observations wells and water samples. The use of monitoring wells has limited utility in the Florida Everglades where most of the surface is covered by 10-80 cm or more of water, and there are few roads. Another disadvantage of using wells to map saltwater intrusion is that lateral resolution is limited by well spacing, which in turn is controlled by access and economic issues. As a result, subtle features related to changes in geology or human activity are difficult to identify. More recently induction loggers have been used to map the freshwater/saltwater interface (FWSWI) (Sonenshein, 1997).

One approach to address the problem of limited ground access is to use airborne geophysical methods to map resistivity as a function of depth along flight lines. Because the bulk resistivity of geologic formations is highly dependent upon pore-water salinity, geophysical data can give an indirect measure of water quality. There are a number of airborne geophysical techniques that can be employed for this purpose (Palacky, 1986; Fitterman, 1990). In this paper we describe our experience in using helicopter electromagnetic (HEM) surveys and other ground based methods to map saltwater intrusion in Everglades National Park.

3. HYDROGEOLOGIC SETTING

The flow of surface water through ENP come from Shark River Slough and Taylor Slough. Shark River Slough drains into the many tidal rivers flowing to the Gulf of Mexico on the southwestern portion of the study area. Taylor Slough flows southward toward Florida Bay, but it is essentially blocked by the slight elevation rise along the coast called the Buttonwood Embankment. As will be shown, these different flow regimes affect the pattern of saltwater intrusion.

Ground-water flow in our study area is controlled by the general hydrogeologic framework of Dade County, which is described by Fish and Stewart (1991). Three distinct zones characterize the salient features of the hydrogeology: the surficial aquifer, the intermediate confining unit, and the Floridan aquifer system. Of these zones, only the surficial aquifer is of interest to ecosystem studies because of its interaction with surface-water flows. The surficial aquifer is composed of the Biscayne aquifer, a semiconfining unit, the Gray limestone aquifer, and the lower clastic unit of the Tamiami Formation. The Biscayne aquifer contains high permeability (>1000 ft/d) limestone and calcareous sand units. It ranges in thickness from 0 to 80 ft (0-24 m) thick and increases in thickness toward the east.

4. ELECTROMAGNETIC TECHNIQUES

Electromagnetic geophysical techniques were originally developed for mineral exploration, specifically the detection of massive metallic conductors in resistive host rock, such as found in the Canadian Shield. Because this terrain is often difficult to traverse, airborne methods were developed as early as the 1940’s to aid exploration. Over the years many ground-based and airborne geophysical methods have been developed and refined for mineral exploration. The use of electromagnetic techniques for hydrologic studies is relatively new; there has been steady growth in their use over the last decade. Sengpiel (1983) shows the use of helicopter electromagnetic surveys for several ground-water exploration problems, including the mapping of saltwater intrusion on an island. Fitterman and Hoekstra (1984) applied the transient electromagnetic (TEM) sounding technique to the mapping of naturally occurring brine contamination in central Michigan. Stewart and Gay (1986) used TEM soundings to map saltwater intrusion in south Florida. Yang et al. (1999) used both TEM and DC resistivity soundings to map saltwater intrusion in Tawain.

A complete description of the various electromagnetic techniques is beyond the scope of this paper. Very complete descriptions of these methods can be found in Keller and Frischknecht (1966), Nabighian (1988, 1991), Fitterman and Stewart (1986), and McNeill (1990). Suffice it say that all of the techniques used in this study rely upon time-varying magnetic fields from a transmitter to induce electrical currents into the ground. The flow of these currents is controlled by the electrical conductivity of the ground. More conductive zones tend to let the induced currents flow unimpeded, while less conductive zones impede the current flow. The induced currents in the ground produce a secondary magnetic field which is recorded by a receiver coil.

Analysis of the received signals determines how conductivity (or its reciprocal, resistivity) varies with depth and position.

4.1 Helicopter Electromagnetic Surveying

Helicopter electromagnetic (HEM) surveys make use of a system of transmitter and receiver coils housed in a torpedo-shaped tube called a bird. The bird is typically 10-m long and slung 30 m below the helicopter (see Figure 2). During surveying the bird is flown 30 m above the land surface. Using five different frequency-coil-pair combinations, the electromagnetic response is measured every 0.2 s resulting in a measurement point about every 10 m along flight lines. Flight lines are typically 400 m apart. Such a high density of sampling is not economically or logistically feasible with ground-based geophysical measurements or wells.

The electromagnetic response is measured as a function of frequency. Decreasing the frequency increases the depth of exploration. The electromagnetic response consists of two parts, one which is in phase with the transmitted signal and the other which is out of phase (quadrature component) with respect to the transmitted signal. The response is measured in parts per million of the transmitted signal and converted to an apparent resistivity to facilitate comparison of data from different locations. Apparent resistivity is the resistivity of a homogeneous half-space required to produce the measured response. Keep in mind that the response was measured over a heterogeneous earth, hence the use of the term apparent. An apparent resistivity is computed for each frequency.

An apparent resistivity map alone provides no depth information, however, by comparison of maps made using different transmitter frequencies an idea of how resistivity varies with depth can be formed. To determine true resistivity variation with depth the data must be modeled.

Modeling entails taking data from a measurement point, consisting of the electromagnetic response at several frequencies, and estimating the parameters of a layered-earth, resistivity-depth model that would produce the measured response. This process is called inversion and makes use of nonlinear parameter estimation techniques (Inman, 1975; Deszcz-Pan et al., 1998; Ellis, 1998). Typically parameters for two-, and sometimes, three-layer models can be estimated. Noise in the data, however, often produces large misfits between the measured and observed electromagnetic response, requiring the winnowing of some of the inversion models. Because the geology and hydrologic conditions vary slowly from point to point in the Everglades (Fish and Stewart, 1991), we are justified in using 1-D models. The numerous resistivity-depth models are sliced at specified depths to produce resistivity-depth-slice maps (see Figure 2).

4.2 Transient Electromagnetic Soundings

Unlike the HEM method which has the transmitter on at all times, the transient electromagnetic (TEM) sounding method uses the transition from a steady to zero transmitter current to induce current in the ground. The ground response is measured during the transmitter off-time. We employed a 40-m by 40-m transmitter loop with the receiver coil located at the center of the transmitter loop. The data are converted to apparent resistivity before modeling. Layered-earth model parameters are determined using commercially available nonlinear least-squares inversion software. Because of the large number of data points (typically 25-35) compared to the 10 for each HEM measurement, model parameter estimates are more reliable for the TEM data than the HEM data. The TEM method also has the ability to probe to greater depths than the HEM method. From these data we were able to locate the FWSWI, as well as the depth to the base of the Biscayne aquifer.

Using the TEM method in the Everglades required slight modification of standard methods as most of the soundings were made in water-covered areas. Equipment had to be floated in plastic tubs, and the transmitter wire was strung over saw grass, while the receiver coil was stood on long legs to keep it above the water.

4.3 Induction Logs

At the few sites where we had observation wells (Figure 1), induction logs were measured. The induction tool uses a frequency-domain electromagnetic system to determine the formation resistivity outside the borehole. The borehole must be cased with non-conducting material such as PVC. Induction logs provide very detailed resistivity-depth information within the vicinity of the borehole–about 1 m radius from the well. This information is useful in determining the relationship between formation resistivity and pore water quality (discussed in the next section).

5. ESTIMATION OF WATER QUALITY

Electromagnetic geophysical techniques, such as those described above, provide information on formation resistivity, which depends upon pore-water resistivity and porosity (Archie, 1942; Hearst and Nelson, 1985). When dealing with saltwater intrusion, water quality, which is a property of the pore water alone, is expressed as specific conductance or chloride ion concentration (Hem, 1970; Freeze and Cherry, 1979). If we can relate formation resistivity to pore-water specific conductance and chloride ion concentration, we can use the geophysically determined resistivity model to estimate water quality. To do this we use induction logs to obtain formation resistivity in observation wells, and water samples pumped from wells to determine specific conductance.

Figure 3a shows a scatter plot of formation resistivity as a function of pore-water conductivity from test wells in the study area. The data points represent average formation resistivity over the screened interval in the well and the measured conductivity of water produced from this interval. In some cases a down-hole water conductivity probe was used. Most, but not all, of the points are in the Biscayne aquifer. The linear regression line allows conversion of formation resistivity to specific conductance. To express specific conductance as chloride concentration, we make use of another empirical relationship applicable to surface and near-surface waters in Dade County (A. C. Lietz, USGS Miami, written commun., 1998). The final result is the curve in Figure 3b which shows the relationship between formation resistivity and chloride concentration. While the curve plots as a smooth line, there is an inherent uncertainty in the estimated chloride concentration due primarily to the scatter in the data in Figure 3a. Nevertheless, the chloride concentration is probably correct to within a factor of 2 to 5 based on the scatter in formation-resistivity-specific-conductance data. This relationship will be used to estimate chloride concentration from the geophysical models.

6. GEOPHYSICAL RESULTS

6.1 HEM Data

Figure 4 shows a 56-kHz apparent resistivity map from Everglades National Park. Within the central part of the survey most apparent resistivity values are greater than 30 ohm-m with many values exceeding 75 ohm-m. In contrast, near the coast the apparent resistivities are generally less than 5 ohm-m with values below 1 ohm-m not uncommon. This dramatic variation is interpreted as being due to saltwater intrusion in the coastal areas and a fresh-water saturated aquifer further inland. Based on the relationship between formation resistivity and chloride concentration (Figure 3b), the transition from saltwater to freshwater saturation occurs between 10 and 15 ohm-m. As we are dealing with apparent resistivity in this map, the resistivity value of the transition is less certain. Nonetheless, the sharp gradient in the region of Taylor Slough and to the east is caused by the FWSWI. In the western portion of the survey where the boundary corresponds to the terminus of the tidal rivers, the transition zone is more diffuse.

Four depth slices are shown in Figure 5 based on layered earth inversions. These particular maps where chosen because there are significant changes between them. Many features related to saltwater intrusion and the impact of roads and canals on water flows can be seen in them. There is a general decrease in resistivity toward Florida Bay in the south as a result of saltwater intrusion. In the Taylor Slough area (a) the transition between freshwater and saltwater occurs over a short distance. The trace of the interface on the map varies smoothly because the hydrologic conditions do not vary rapidly parallel to the interface. The position and shape of the interface is controlled by the balance between ground-water flow to the south, and evapotranspiration losses and saltwater intrusion. To the west (b), tidal rivers drain the area and allow seawater to move inland a great distance. The result is a less abrupt transition from fresh-water to salt-water saturated zones spread over a greater distance than near Taylor Slough. Parallel the interface there is more variability in the landward extent of salt-water intrusion because of the influence of the rivers.

Several man-made structures have a significant influence on the hydrology as manifested in the resistivity depth slices. Along the main park road (c) there is a four-fold change in resistivity from one side to the other. This feature, which extends to at least 10-m depth, is due to the roadbed blocking the westward flow of freshwater from Taylor Sough. Roads play an important role in controlling the flow of surface water because they are typically raised 1-2 m above the water covered marshes.

Along old Ingraham Highway (d) a conductive feature is seen. This road was constructed between 1915 and 1919 by digging a canal along the side of the roadway and piling up the dredged material. The resulting canal was originally open from Florida Bay near the town of Flamingo all the way to Royal Palm. Seawater migrated inland along this entire section of the canal. The canal was plugged in 1951. We believe that this low resistivity anomaly is due to seawater which remains in the aquifer.

The C-111 canal is a major drainage canal which leads to Biscayne Bay. One of its current functions is to provide water to the southeastern portion of Everglades National Park. This is accomplished through cuts in the spoil piles along the southern bank of the canal from the bend in the canal to highway U.S. 1. In the 5-m and 10-m depth slices a resistivity high (e) is seen to the south of the canal because of freshwater recharge from the canal. This recharge produces a freshwater zone to the south of the main FWSWI location seen in the 10-m and 15-m depth slices. In the 15-m depth slice a cusp in the FWSWI (f) is seen where the C-111 canal crosses the interface. This cusp is produced by water impoundment behind a moveable dam on the canal (control structure S18C).

One issue of concern to studies of Florida Bay is whether or not there are fresh, ground-water flows to Florida Bay. The HEM results indicate that no fresh-water zone exists south of the FWSWI (g). Based on this and other geophysical data, it is highly unlikely that there are fresh, ground-water flows to Florida Bay.

In all of the depth slices a high resistivity zone associated with Taylor Slough (h) is seen. Taylor Slough is the major source of water to the central portion of Everglades National Park. From the HEM interpretation this zone is seen to extend to a depth of at least 40 m.

6.2 TEM Data

The TEM sounding data from two representative locations are shown in Figure 6. (See Figure 1 for sounding locations.) Sounding EG108 is from a region seaward of the FWSWI as determined from the HEM data, while EG111 is landward of the interface. Both soundings are east of Taylor Slough and south of the C-111 canal. The measured apparent resistivity is shown as a function of time after transmitter-current turn off. Also plotted is the computed apparent resistivity of the model which best fits the data. The apparent resistivity for sounding EG111 decreases with time, approaches a steady value near 55 ohm-m, and then decreases further at later time. Sounding EG108 has a much more dramatic decrease at early time, an easily recognized minimum of about 5.5 ohm-m, and a final increase in apparent resistivity. The apparent resistivities of sounding EG108 are consistently lower than those of sounding EG111.

The model resistivities in Figure 6b confirm the general behavior of the apparent resistivity curves. At site EG111 the resistivity decreases monotonically with depth. The thick second layer (109 m) has a resistivity of 43 ohm-m and produces the steady value seen in the middle of the apparent resistivity curve. Sounding EG108 has a resistivity minimum of 2.8 ohm-m between 11 m and 29 m depth which produces the apparent resistivity minimum.

A histogram of interpreted layer resistivities for all of the TEM soundings (not shown) exhibits a natural division of interpreted layer resistivities of those less than 10 ohm-m from those that are greater. This division corresponds to the transition from fresh to saline water and provides a basis for using the TEM results to map the FWSWI.

7. DISCUSSION

Figure 7 shows the results from the three data sets used to map the FWSWI. The TEM locations have been plotted with symbols color coded to indicate if the interpreted resistivity of the surficial aquifer is greater or less than 10 ohm-m. Resistivities less than this value are considered to be saltwater intruded. Using the TEM data a line representing the FWSWI has been interpolated between the sounding locations. Similarly the locations of the observation wells have been color coded and plotted. Wells with specific conductances of greater than 3000 µS/cm are considered to be saltwater intruded. A line showing the FWSWI based on the well data is also plotted. Last, the interpreted-resistivity, 10-m depth-slice map from the HEM data is shown. In this map the interface occurs around 10 ohm-m, which corresponds to an estimated chloride concentration of about 2100 ppm.

Comparison of the three interpretations of the FWSWI show, as expected, that the data set with the highest spatial sampling density, the HEM data, shows the most detail. The TEM derived FWSWI has pretty good agreement from the bend of the C111 canal to the western limit of Taylor Slough, but becomes less detailed to the west as sampling density diminishes. The well-derived FWSWI misses several major features such as the southward extent of the FWSWI in the middle of Taylor Slough, the old Ingraham Highway canal anomaly, and the effect of the tidal rivers to the west. If ground access were not an issue, a more detailed picture of the interface could have been obtained through the use of carefully chosen TEM soundings. However, it is unlikely that TEM soundings alone could match the detail of the HEM data. Using wells to achieve a similar results would be very difficult if not impossible.

8. CONCLUSIONS

Ground and airborne electromagnetic methods have been shown to be an effective method for mapping saltwater intrusion in Everglades National Park. The results of these surveys and well measurements are in agreement. The HEM data with its high sampling density presents a detailed picture of saltwater intrusion that, in turn, allows identification of factors influencing the location of the FWSWI. The interpreted resistivity maps, when combined with well log data to determine the formation-resistivity-chloride-concentration relationship, provide a means of developing a three-dimensional water quality model that can be used in ground-water modeling studies.

Because the HEM data were collected in less than five days, the results essentially provide a snapshot of the entire aquifer. At present, there is no other way to obtain an equivalent synoptic picture. Equally significant, this survey can be used as a baseline against which future surveys can be compared. Such comparisons are a means of assessing the effects of ecosystem restoration activity on saltwater intrusion beneath the Everglades.

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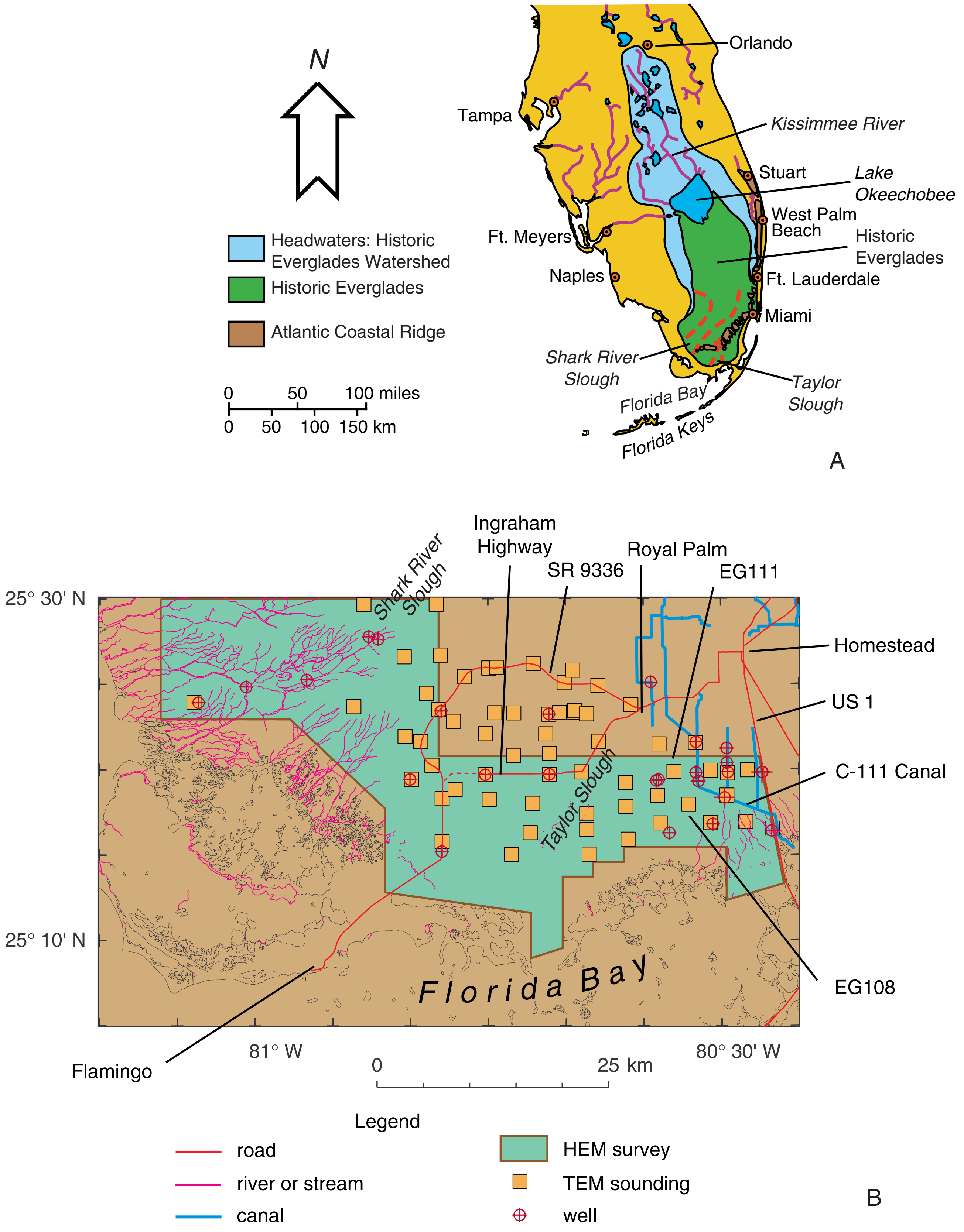

Figure 1 a) Map of south Florida and the historic Everglades.
b) Location map showing the December 1994 HEM survey, TEM soundings, and observations wells in and near Everglades National Park used in this study. Note the location of TEM soundings EG108 and EG111.

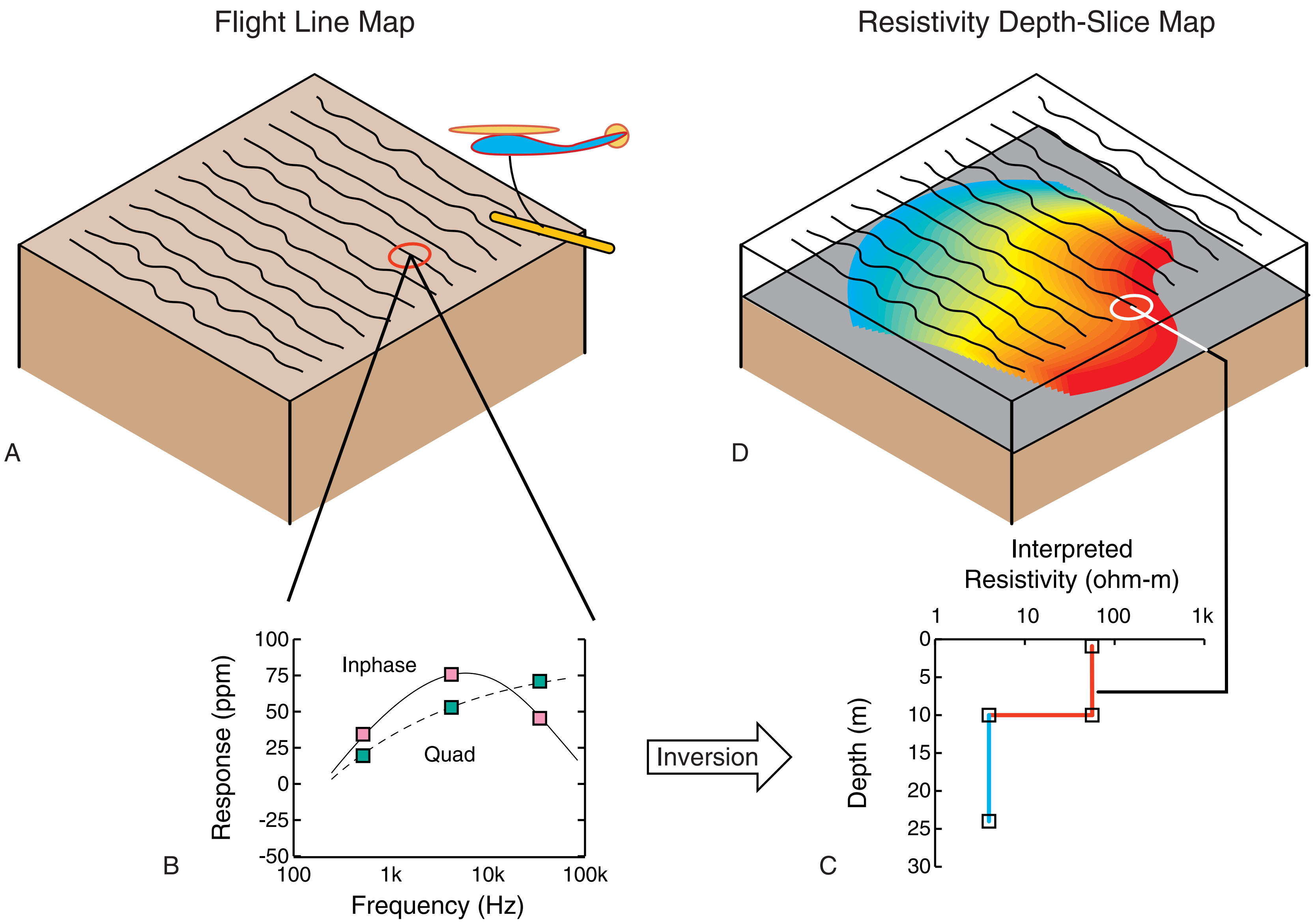

Figure 2 Schematic representation of HEM data collection and interpretation. a) Flight lines are flown along parallel lines spaced 400 m apart. b) The bird measures the inphase and quadrature electromagnetic response at several frequencies. c) The measured response is used to determine the resistivity-depth function by a process called inversion. d) The resistivity-depth functions are combined to produce an interpreted resistivity depth-slice map.

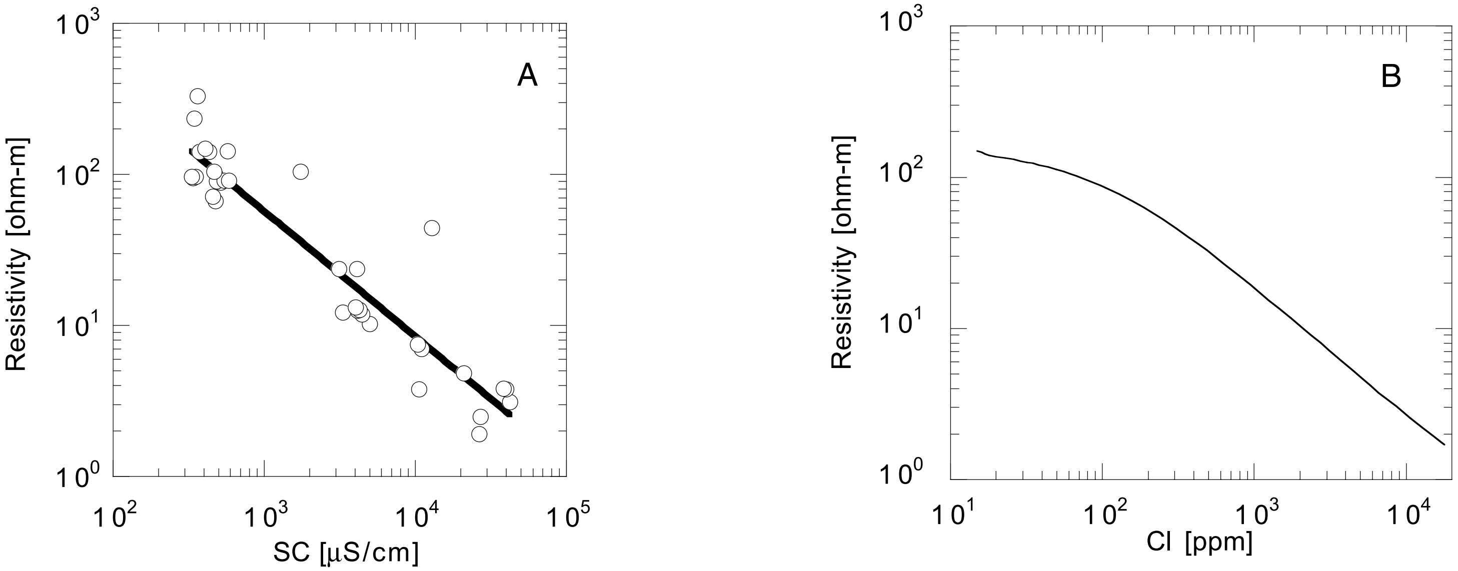

Figure 3 a) Formation-resistivity-pore-water conductivity relation from induction logs and water samples. The solid line is the power-law relation which best fit the data.

b) Derived formation resistivity-chloride relationship for the surficial aquifer in the study area.

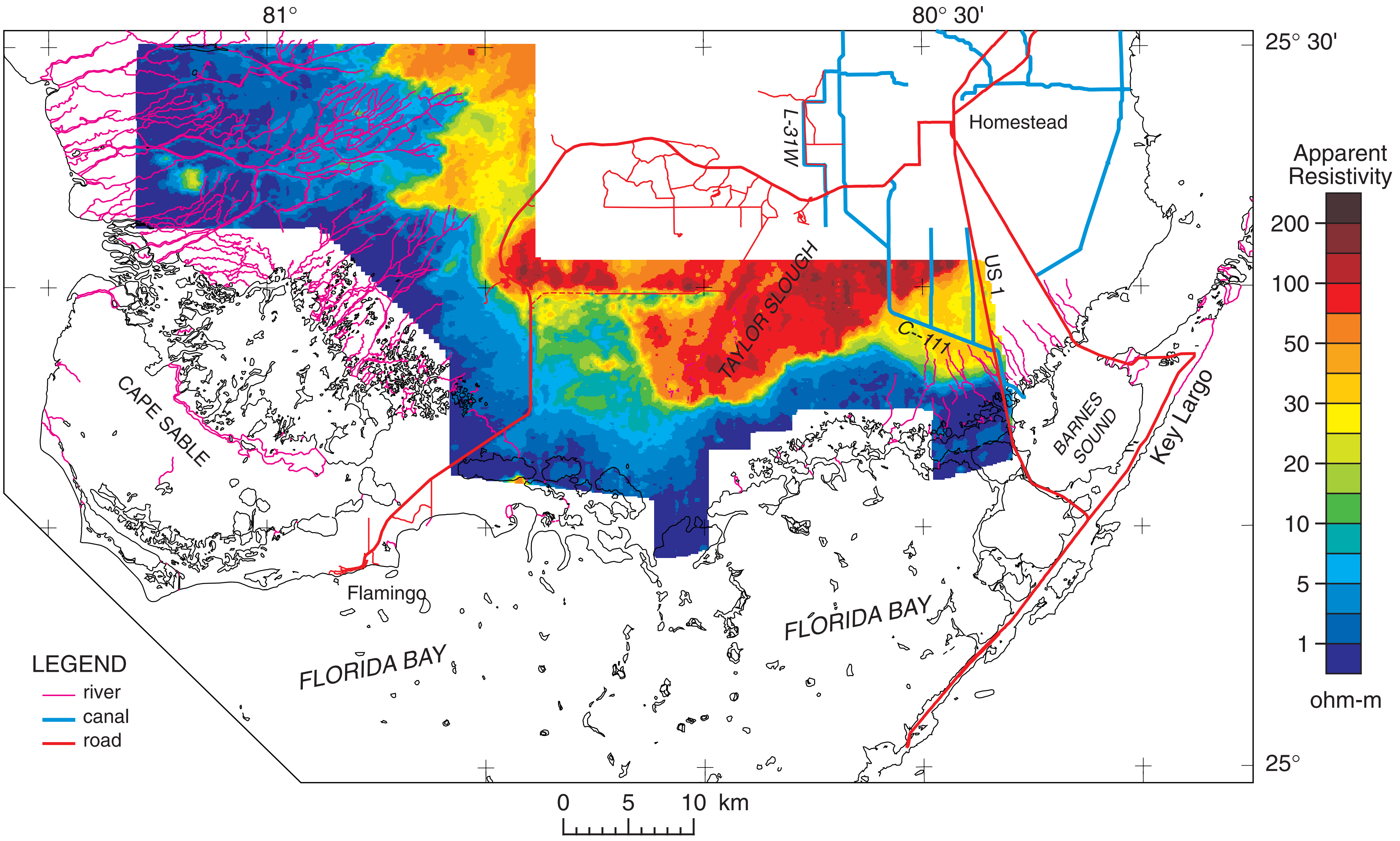

Figure 4 HEM 56-kHz apparent resistivity map from Everglades National Park.

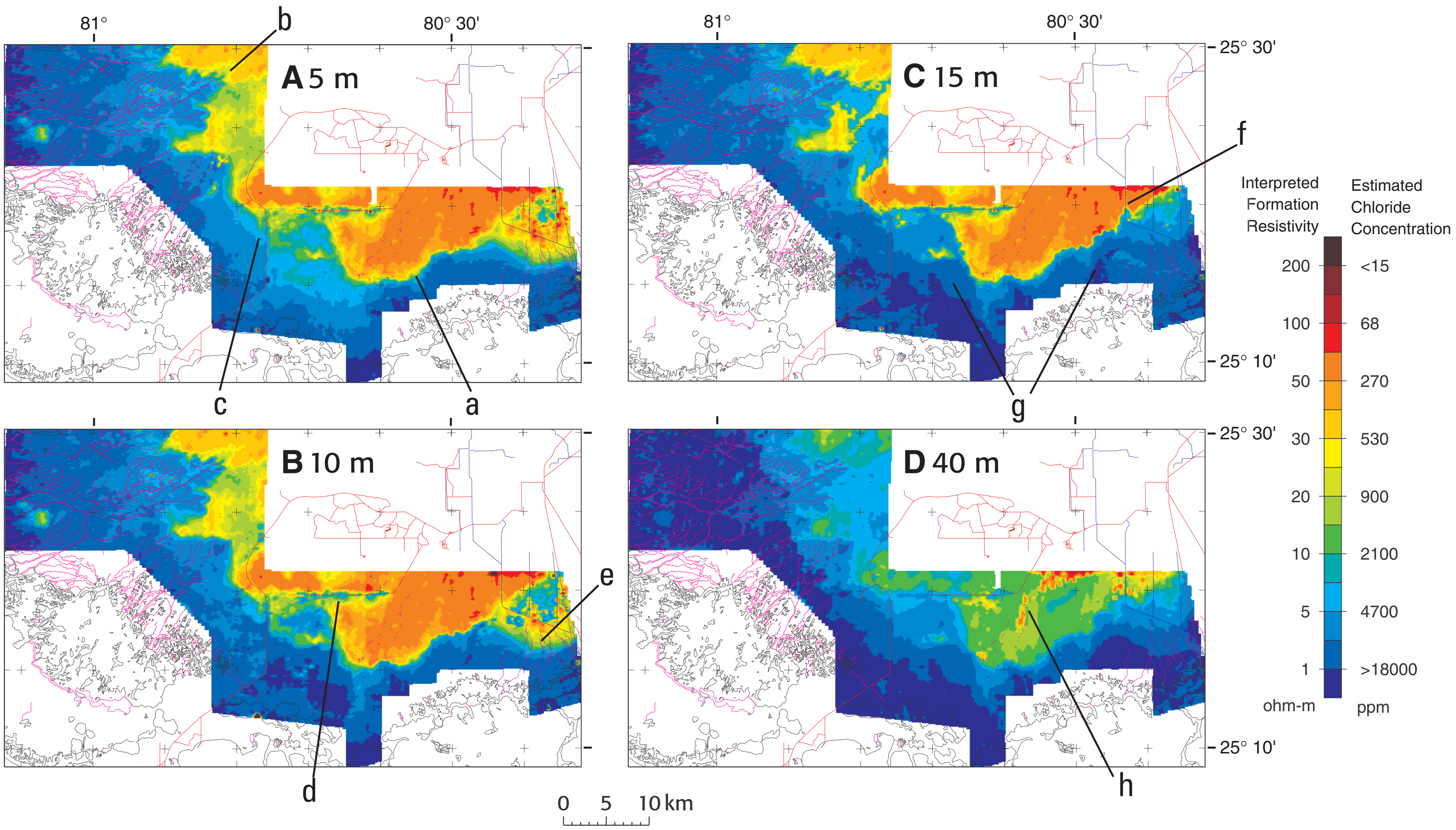

Figure 5 Interpreted HEM resistivity-depth-slice map from Everglades National Park for depths of 5 m (A), 10 m (B), 15 m (C), and 40 m (D). Annotated features are discussed in the text.

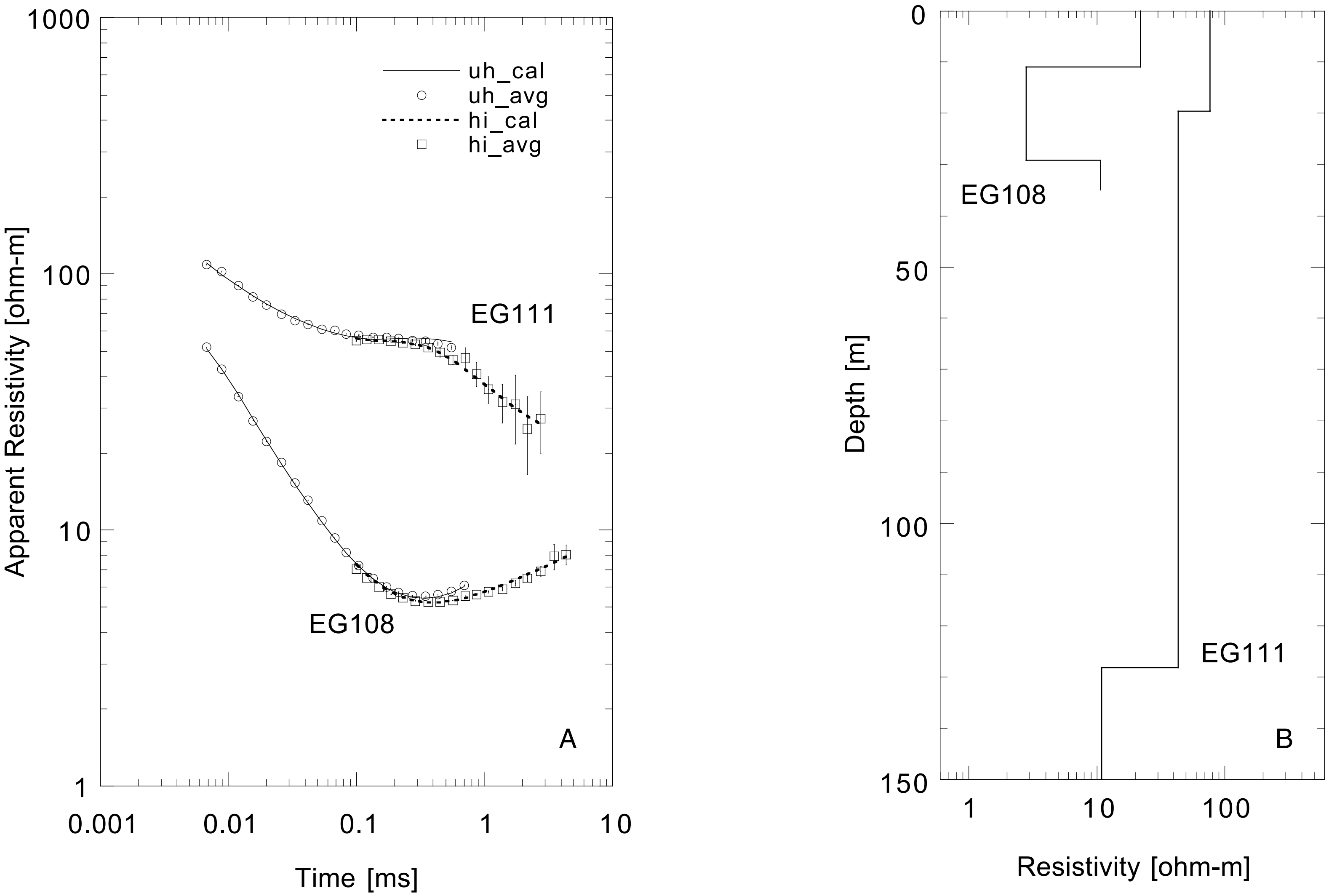

Figure 6 a) Apparent resistivity data and model interpretation for TEM sounding EG111 and EG108, which are located landward and seaward, respectively, of the FWSWI. Sounding locations are shown in Figure 1. a) Measured apparent resistivity data (avg) are plotted as symbols, while the calculated model results (cal) are plotted as lines. Vertical lines through the data points indicate the estimated uncertainty in the measurements. The data are collected using two transmitter repetition frequencies. The earlier data are denoted as ultra high (uh), and the later time data are denoted as high (hi).
b) Interpreted resistivity-depth models for the two soundings.

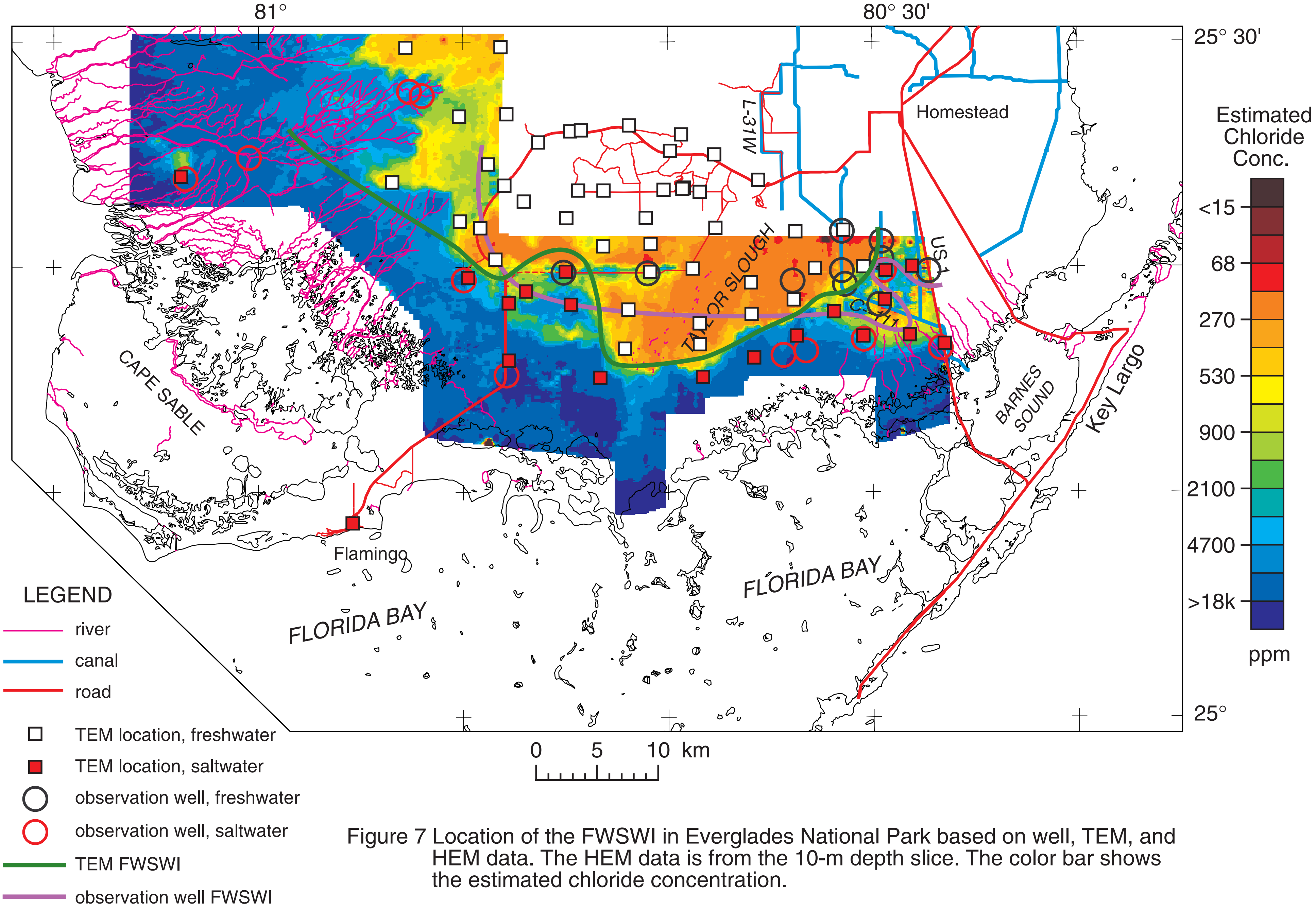

Figure 7 Location of the FWSWI in Everglades National Park based on well, TEM, and HEM data. The HEM data is from the 10-m depth slice. The color bar shows the estimated chloride concentration.