The Effect of Hurricane Irma Storm Surge on the Freshwater Lens in Big Pine Key, Florida using Electrical Resistivity Tomography

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Introduction

Oceanic islands often contain a freshwater lens which floats on top of the higher density seawater (Figure 1). Because of their proximity to the ocean, these freshwater aquifers are vulnerable to sea level rise, saltwater intrusion and storm surge. The impact of the storm surge on the freshwater lens is shown schematically in Figure 1.

On September 10, 2017, Hurricane Irma made landfall in the Florida Keys as a category 3 storm. In the Florida Keys, the landfall wind speed was estimated at 213 km/hr and a minimum pressure of 931 mb. Storm surge heights in the lower Keys were in excess of 2 m. The islands in the lower Keys, generally have a maximum elevation of 3 meters, making the freshwater lens on these islands especially vulnerable to salinization from storm surge events.

In this study, we investigate the effect of the Hurricane Irma storm surge on the freshwater lens of Big Pine Key, FL using Electrical Resistivity Tomography (ERT). We compare ERT imaging results and well data collected six years before Irma (November 2011) with data collected three to four months (November, 2017/January, 2018) and eight months (May 2018) after the storm.

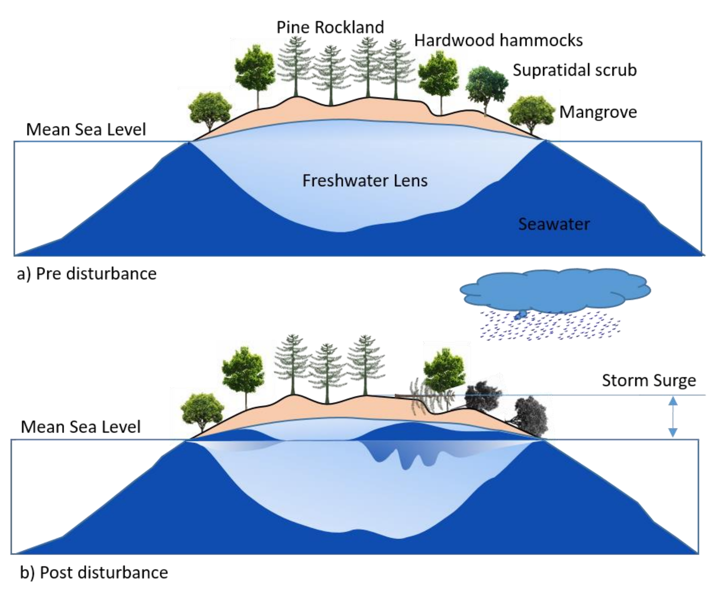

Fig. 1. Illustration of the effect of storm surge inundation on oceanic islands. (a) Pre disturbance condition. (b) Post disturbance condition showing the impact of the storm surge on the freshwater lens, where a saline water is deposited on the top of the freshwater lens and forest communities are impacted.

Study Site

Big Pine Key (BPK) is the largest island in the lower Keys, Florida with an average length of about 10 km and width of 3 km (Figure 2). The northern half is occupied by the Key Deer National Wildlife Refuge and the southern part is suburban residential. The lower Florida Keys have diverse species communities such as pine rocklands, hardwood hammocks and supratidal scrub. Pine rocklands are found at interior of the islands at higher elevation followed by the hardwood hammocks. Near the shore line, the supratidal scrub and mangrove forest are the dominant species communities (Ross et al., 1992). The lower Keys have a humid subtropical climate with a wet season from June to October and dry season from November to May.

The geology of the BPK consists of Miami formation and Key Largo Limestone. The Key Largo Limestone underlies the Miami Oolite in BPK and there is sharp contact between the two layers on the southeastern part of BPK.

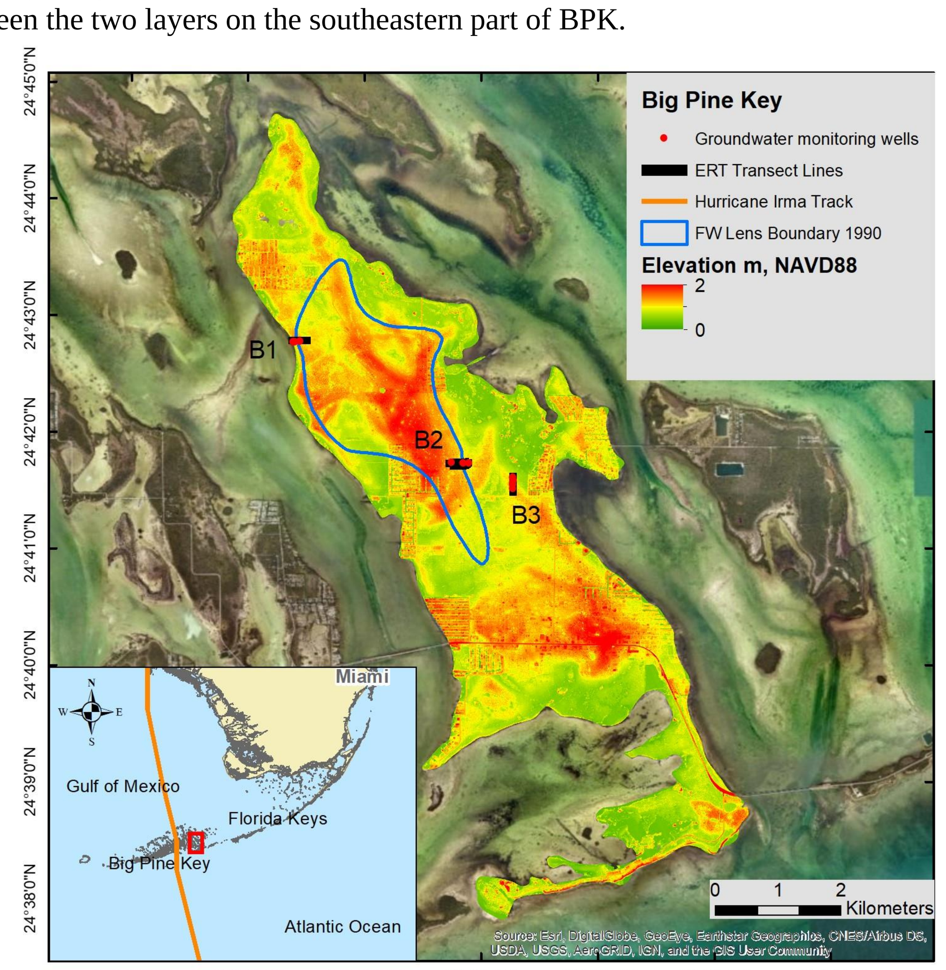

Fig. 2. Topographic map of Big Pine Key showing location of ERT lines and boundary of the freshwater lens (Wightman, 1990). Inset shows track of Irma

Data and Method of Analysis

ERT surveys were conducted on three profiles ranging in length from 194 m to 278 m. Profiles B1 and B2 cross the freshwater lens boundary defined by (Wightman, 1990), whereas B3 is outside the freshwater lens (Figure 2). ERT data were collected using a 28 electrode, 2 m spacing roll-along Wenner array configuration using an AGI Super Sting R1 IP resistivity imaging system. A series of ~1 m deep monitoring wells were installed along the ERT profiles in 2010 (Ogurcak, 2015; Figure 2). During each ERT data collection, temperature, specific conductivity (the reciprocal of resistivity), and salinity were measured with a YSI conductivity meter.

The ERT data were inverted with the, R2 inversion program (Binley and Kemna, 2005). The Inverse solution in R2 is obtained by minimizing an objective function combined with a weighted least square and uses Occam-type, regularized optimization. The 2011 data were inverted using a uniform starting model of 100 Ω-m but for the Nov2017/Jan 2018 data and the May 2018 data, the ERT data were inverted using a difference inversion algorithm which utilizes the previous inversion results as a starting model (LaBrecque and Yang, 2001, Tucker, 2013). The resistivity models were then converted to pore fluid resistivity by applying an electrical formation factor 9.5 for BPK (Tucker, 2013). Finally, the pore water resistivity was converted to salinity using the empirical equations given by (Wagner et al, 2006).

Results

The ERT data collected on November 2011 is used baseline to compare the change of pre and post-Hurricane Irma conditions. Modeled salinity contours of 3 PSU and 10 PSU are used to illustrate the boundary of the freshwater, brackish and saline groundwater. The temporal and spatial ERT and salinity changes along the three transect lines B1, B2, and B3 are described in detail below.

- In Nov 2017 and Jan 2018 the ERT data showed the deposition of saline water on top of the freshwater lens defined by 3 PSU contour line in the lower elevation sections of all profiles. This low resistivity/ high salinity is clearly visible east of 140m of profile B1 (Figure 3.1.c), throughout profile B2 (Figure 3.2.c), and between 150 to 250m in B3 (Figure 3.3.c).
- In May 2018, the ERT image revealed some limited recovery of the freshwater lens and was most pronounced east of 140 m profile B1 (Figure 3.1.d), east of 180 m on profile B2 (Figure 3.2.d), and south of 190 m on Profile B3 (Figure 3.3.d).
- The salinity change between post and Pre Irma increased significantly between 4 and 10 PSU in the top 2 m and is pronounced more in the lower elevations of all profiles (Figure 3.1-3.e).
- The salinity change after Irma showed a decrease of salinity between 2 and 6 PSU in the top 2 m and is pronounced more in the lower elevations of all profiles (Figure 3.1-3.f).

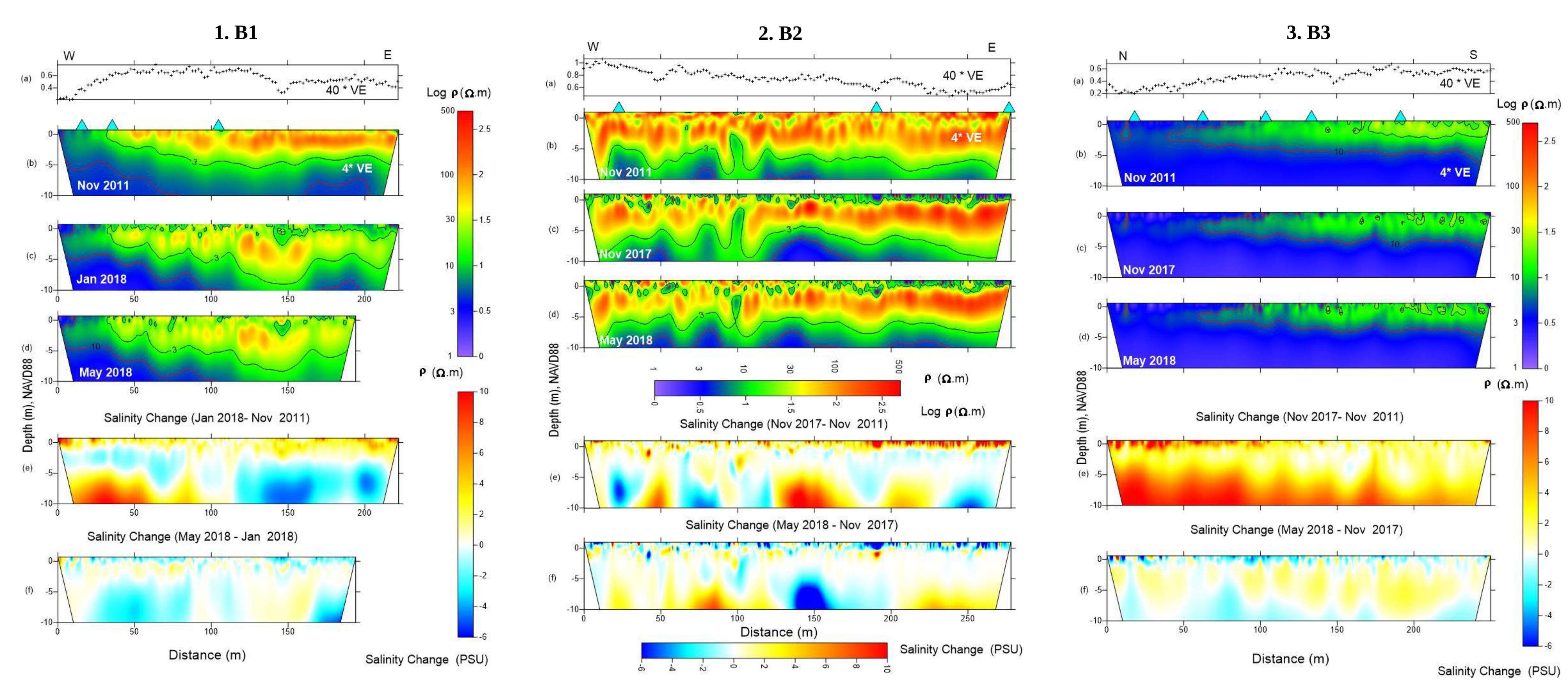

Figure 3: ERT results along profile B1, B2 and B3. a. Topography; b. November 2011; c. January 2018; d. May 2018 e. salinity change between November 2011 and January 2018 and f. salinity change between January 2018 and May 2018. The black and red contour line represents a salinity of 3 and 10 PSU. The triangles indicate the location of the wells. The location of the profiles is shown in Figure 2. Elevations are relative to NAVD88

- The well data collected on September 27, 2017 showed an abrupt increase in salinity at most wells along profile B2 and B3 (Figure 4b;4c) whereas little change was observed along profile B1 (Figure 4a). The well data along profiles B2 and B3 clearly showed the decrease of salinity by May 2018 (Figure 4b;4c).

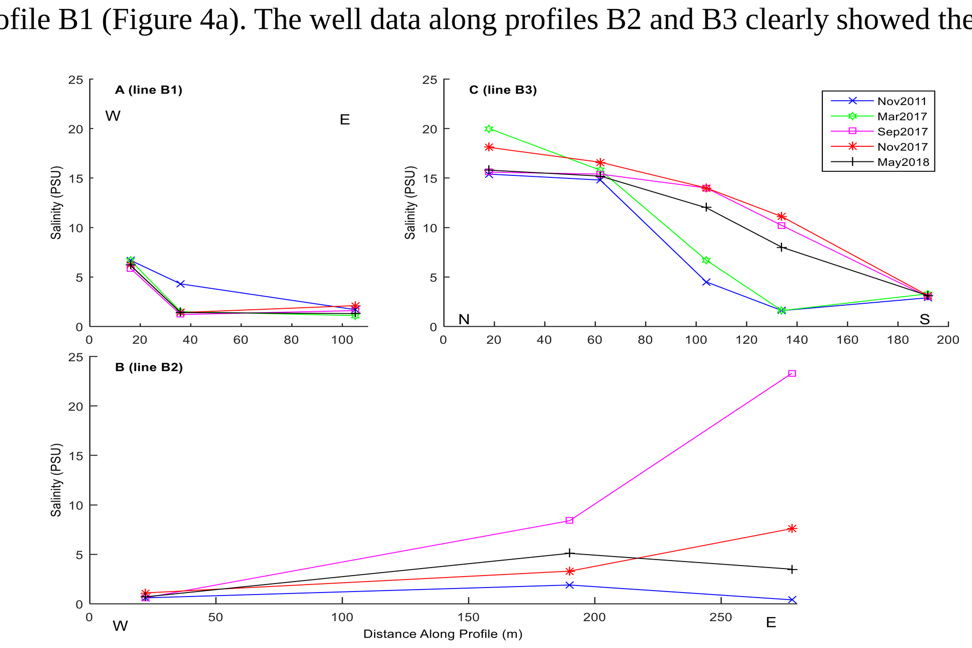

Fig. 4. Salinity recorded in the monitoring wells adjacent to the ERT profiles. A) Profile B1; B. Profile B2; C) Profile B3. Horizontal locations are relative to the start of each ERT profile (Figures 2).

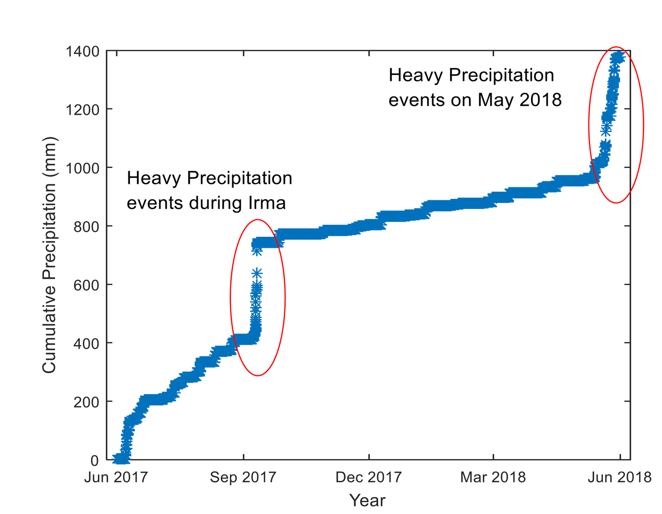

Figure 5: Cumulative Precipitation Data of National Key Deer, Big Pine Key, FL, US station (TS607) from Jun 1, 2017 to May 31 2018. The cumulative rainfall data is from https://mesowest.utah.edu (Horel et al., 2002).

Discussion

1.The Impact of the storm surge on the freshwater lens

- The well and ERT data collected three to four months (November, 2017/January, 2018) after the storm showed the deposition of saline water on top of the fresh water lens in the upper 2m of the section and demonstrate that, the impact on the freshwater lens is influenced by topography.
- Throughout Profile B1 (Figure 3.1.c) and in the lower elevation sections of Profile B2 (Figure 3.2.c), the base of the freshwater lens as indicated by the 3 PSU contour is depressed downward by the higher density saline water emplaced by the storm surge.
- The storm surge from Irma largely destroyed the relatively thin freshwater lens on Profile B3, leaving only minimal fresh water pockets (Figure 3.3.c). This suggests that thin freshwater lenses are susceptible to being completely destroyed by a storm surge.
- Hurricane Irma produced maximum storm surge heights of up to 2.4 m NAVD88 on the south and eastern shores of the island (USGS, 2017; Cangialosi et al., 2018). This pattern is reflected by both the ERT and well measurements and suggest that the highest storm surge flooded the island from the east.

2.The recovery history of the freshwater lens

- The cumulative precipitation recorded at BPK showed large precipitation events in September 2017 and May 2018 (Figure 5). As a result of this, the well and ERT data collected eight month after the storm revealed some limited recovery of the freshwater lens due to intense precipitation.
- The well data and salinity change after Irma, between May and January 2018 along profile B1 and between May 2018 and November 2017 along profile B2 and B3 showed a decrease of salinity in the top 2m. This decreases of salinity is pronounced more in the lower elevations. This suggests that the freshwater recovery due to precipitation is most pronounced in low elevation regions.
- Our results indicate that eight months after the storm, the salinity is on average 5 PSU higher than the pre-storm conditions and the lens has only recovered to 40% of the pre-storm conditions.

Conclusions

1. All profiles showed low resistivity/high salinity zones in the upper 2 m suggesting the deposition of the saline water on the top of the freshwater lens. This increase in salinity is most pronounced in the low elevation portions of the profiles.
2. At landfall, onshore winds from Hurricane Irma approached from a southerly. This is consistent with ERT results which indicate that the impact of the storm surge is more pronounced on the low-lying eastern side of the island.
3. The May 2018 data were collected at the end of the climatological dry season but were collected immediately after 2 weeks of intense precipitation. This freshwater recharge showed some limited recovery of the freshwater lens. This recovery is most pronounced in the lower elevation portions of the profiles.
4. The impact of storm surge and the freshwater recovery due to precipitation are most pronounced in low elevation regions where both saline and fresh water can collect at the surface.

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Acknowledgments

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