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Investigating the Effects of Land-Cover Change on the Hydrologic Conditions of a Restored Agricultural Area in Everglades National Park

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INVESTIGATING THE EFFECTS OF LAND-COVER CHANGE ON THE HYDROLOGIC CONDITIONS OF A RESTORED AGRICULTURAL AREA IN EVERGLADES NATIONAL PARK

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Dillon Nicholas Reio

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To: Dean Michael R. Heithaus
College of Arts, Sciences, and Education

This thesis, written by Dillon Nicholas Reio, and entitled Investigating the Effects of Land-Cover Change on the Hydrologic Conditions of a Restored Agricultural Area in Everglades National Park, having been approved in respect to style and intellectual content, is referred to you for judgement.

We have read this thesis and recommend that it be approved.

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ABSTRACT OF THE THESIS

INVESTIGATING THE EFFECTS OF LAND-COVER CHANGE ON THE HYDROLOGIC CONDITIONS OF A RESTORED AGRICULTURAL AREA IN EVERGLADES NATIONAL PARK

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In the Florida Everglades, remodeling of natural wetlands to promote agriculture and human settlement, have profoundly altered its hydrologic regime. As a result of anthropogenic changes, many restoration programs have been initiated to restore hydrologically controlled wetland ecosystems. One such restoration project that has been ongoing for the past 27 years is the Hole-in-the-Donut restoration program in Everglades National Park. The restoration program is unique in that it utilized an unorthodox technique to restore the landscape. The viability of the restoration technique was assessed by coupling long-term hydrologic and evapotranspiration data with water chemistry analyses. Key results indicated that the restoration method did not change groundwater levels within and down gradient of the restored sites. Evapotranspiration rates were significantly reduced as a function of restoration. Concentrations of ions and nutrients were significantly different in groundwater and surface water within the restored areas compared to outside the restored areas.

TABLE OF CONTENTS

LIST OF TABLES

TABLE PAGE

LIST OF FIGURES

FIGURE PAGE

ABBREVIATIONS AND ACRONYMS

A	Cross-Sectional Area
AM	Arbuscular Mycorrhizae
ANOVA	One-way Analysis of Variance
CERP	Comprehensive Everglades Restoration Plan
CSR	Complete Soil Removal
DBHYDRO	South Florida Water Management District Environmental Data
EAA	Everglades Agricultural Area
ENP	Everglades National Park
ET	Evapotranspiration
FIU	Florida International University
FPAR	Fraction of Photosynthetically Active Radiation
GIS	Geographic Information System
HID	Hole-in-the-Donut
HSD	Honest Significance Difference
K	Hydraulic Conductivity
LAI	Leaf Area Index
MODIS	Moderate Resolution Imaging Spectroradiometer
N	Nitrogen
NAVD-88	North American Vertical Datum of 1988
NGVD-29	National Geodetic Vertical Data of 1929
NH_4^+	Ammonium

NO_3^-	Nitrate
NRC	National Resource Council
NTSG	Numerical Terradynamic Simulation Group
P	Phosphorus
P_r	Precipitation
Q	Groundwater Discharge
Q_{in}	Groundwater Inflow
Q_{out}	Groundwater Outflow
RPL	Royal Palm Ranger Station
S	Storage
SAS	Surficial Aquifer System
SERC	Southeastern Environmental Research Center
SFWMD	South Florida Water Management District
SRP	Soluble Reactive Phosphorus
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
WCA	Water Conservation Areas

I. INTRODUCTION

Wetland ecosystems bridge the terrestrial biosphere and the hydrologic cycle. They support biodiversity for native flora and habitat for native fauna, as well as provide invaluable ecosystem services such as protection of water quality by absorbing and filtering out pollutants and sediments, altering and storing damaging floodwaters, nutrient processing, and recharging/discharging groundwater (Abtew & Melesse, 2013; Maltby & Dugan, 1994). Since the turn of the 19th century, these valuable and productive ecosystems have experienced a precipitous decline in total area, with the conservative estimate that 50% of world-wide wetland area has been lost as a result of anthropogenic forces (Zedler & Kercher, 2005). In the Florida Everglades, one of the most important and diverse wetland ecosystems in the world, anthropogenic changes, specifically remodeling of natural wetlands to promote agriculture and human settlement, have profoundly altered the hydrology and thus services of the ecosystem (Light & Dineen, 1994).

These anthropogenically induced changes to the region have reduced the pre-drainage functions of the vast Florida Everglades wetland ecosystem by half (Graf, 2013). Alterations to the South Florida landscape, namely changes from natural vegetation to agriculture, water storage, and urban and suburban land use, have on a peninsula-wide scale, increased summertime maximum temperatures, decreased convective rainfall patterns, and on a regional scale, have changed surface hydrologic features, such as sheet flow (Marshall et al., 2004). The Everglades is currently undergoing a massive hydrologic restoration in an effort to rehabilitate the landscape to function as a more natural wetland, to increase historic water flow, and to decrease eutrophication associated with agricultural runoff (Fling et al., 2004). The Comprehensive Everglades Restoration Plan (CERP) was passed by Congress in 2000 with the goal of restoring as much of the historic freshwater flow as possible, while continuing to protect urban establishments from wet season floods and ensure a robust water supply (Chimney & Goforth, 2001).

The remaining Everglades is made up of the Everglades agricultural area (EAA) and water conservation areas (WCAs) in the north and Everglades National Park (ENP) in the south (Figure 1). The ENP is an oligotrophic wetland (Noe et al., 2001) at the southernmost reaches of the Florida Peninsula and embodies 1/5 of the historical Everglades (Light & Dineen, 1994; Childers et al., 2006). During the 20^{th} century, humans contained the remaining portions of the northern Everglades by building the WCAs. The WCAs, along with the network of canals, levees, and spillways that bisect part of the landscape, have obstructed much of the southward water flow into ENP. Obstruction of historic water flow has deleterious impacts on wading bird populations, indicators of ecosystem health, spurs intrusion of cattail into native sawgrass and slough habitat, and facilitates invasion of exotic plant species (Light & Dineen, 1994; Rader & Richardson, 1992; Davis & Ogden, 1994; Thayer et al., 2000). The flora and fauna of the Everglades are adapted to the hydrologic and physio-chemical conditions characteristic of the region (Gunderson & Loftus, 1993). Changes in the quality, quantity, timing, and overall distribution of water to ENP are longstanding issues that have arisen because of the drainage and manipulation of the ecosystem (Chimney & Goforth, 2001).

Although ENP is currently a 600,000 ha protected area, it includes former agricultural land that underwent and still to this day is undergoing restoration, and may have experienced different hydrologic conditions as its usage changed. The Hole-in-the-Donut (HID) (Figure 1) is a 2670-ha parcel of abandoned farmland located within ENP

(Doren et al., 1990). The HID is located between the two major waterways of ENP, with larger Shark Slough bounding the western portion and smaller Taylor Slough bounding the eastern portion. Separating the two major waterways is a topographic high in ENP, a remnant of an oolitic limestone ridge, called the Miami Rock Ridge (Ewe & Sternberg, 2002).

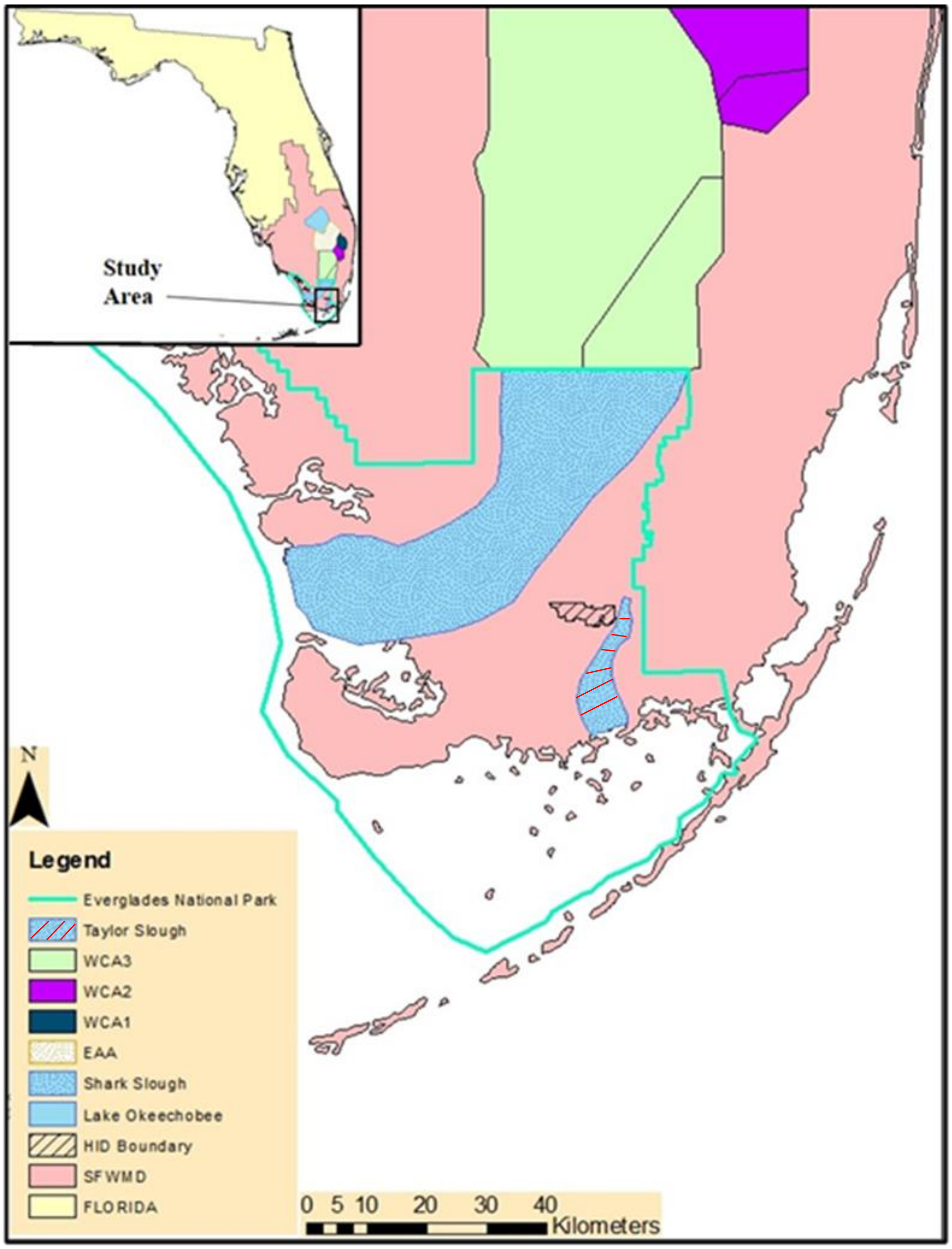

Figure 1. Map showing the HID's relative location to major hydrologic features in south Florida.

The Florida Department of Environmental Protection (FDEP) officially classifies the HID restoration program as a wetland mitigation bank. In 2001, The National Research Council (NRC) created wetland mitigation banks in order to reduce inefficiencies in permit performances, long-term monitoring, and high rates of noncompliance among previous compensatory wetland mitigation programs (NRC, 2001). Thus, the HID has been designated for restoration with the intent of restoring the chemical, physical, and biological integrity of wetland resources prior to deterioration (Reiss et al., 2009). Of 29 permitted Florida wetland mitigation banks presented in the Reiss et. al (2009) case study, the HID ranked first in the number of potential credits (i.e., banking credits) issued, a testament to the magnitude of degradation experienced by this wetland ecosystem as a result of an extensive agricultural history spanning 50 plus years (O'Hare, 2008).

Approximately 1700-ha of the 2800-ha HID was subjected to rock-plowing — crushing of the limestone bedrock into fine grains to allow it to mix with marl or organic soil above—throughout its agricultural history to make the normally inundated land more suitable for farming (Loope & Dunevitz, 1981; Smith et al., 2011). Rock-plowing altered the physical characteristics of the natural soil in the HID (Smith et al., 2011). The HID was teeming with sawgrass and pines before farming began, but an exotic species of plant, Brazilian Pepper (*Schinus terebinthifolius)*, came to dominate the HID where farming had been most intense (Dalrymple et al., 2003). The invasion by exotic species into the native biological mosaic poses a threat to natural biodiversity and can have deleterious effects on ecosystem functioning, specifically, geomorphological processes, biogeochemical processes, and hydrological processes, including water table depth and surface-flow patterns (Macdonald et al., 1989; Gordon, 1998). Rock plowing of the substrate, decades of fertilizing, and high rates of vegetable production changed the soil substrate making it more hospitable to Brazilian Pepper (Li & Norland, 2001).

In ENP, Brazilian Pepper is a major invader of disturbed areas (e.g., fallow farmlands) as well as natural communities like pinelands, hardwood hammocks, and mangrove forests (Ewel et al., 1982). As recently as 2014, Brazilian Pepper occupied approximately 30,000-ha of land, making it the most widely distributed and abundant invasive species within ENP (Rodgers et al., 2014). Brazilian Pepper growth in the HID was originally thought to be stimulated by increased calcium carbonate concentrations—a product of rock plowing— reacting with phosphorus (P) fertilizers, leaving high levels of P available in a naturally oligotrophic environment (Orth & Conover, 1975). However, subsequent studies conducted by Meador (1977), Ewel (1986), and Aziz et al. (1995) found that the presence of arbuscular mycorrhizae (AM) fungi coupled with bird dispersal facilitated the establishment of Brazilian Pepper and had an essential role in fostering its foothold in the HID. To stop the proliferation of the invasive species, land managers explored different means of eradication, including mowing, burning, and substrate removal. Of all the methods examined the most effective in eradication of the Brazilian Pepper was complete soil removal (CSR) (Doren et al., 1990). Restoration of the HID has been ongoing since 1989, when the first plot of land had its entire soil substrate scraped down to the bedrock (Doren et al., 1990).

Several studies of top soil removal as a restoration method in wetlands world-wide have described positive effects on nutrient availability, groundwater levels, and recolonization of native species after restoration. For example, in Dutch fen-meadows, removal of approximately 20 cm or more of top soil increased the influence of groundwater seepage and decreased nutrient availability, thereby allowing less competitive native fen-meadow species to reestablish themselves (Klimkowska et al., 2007; Klimkowska et al., 2015). In German fen-meadows, removal of degraded peat top soils reduced the potential for P release after rewetting and promoted reestablishment of low nutrient conditions following prolonged rewetting (Zak et al., 2015). Furthermore, top-soil removal on former agricultural land in northeastern Ohio demonstrated increased water levels and removed invasive species seed banks, promoting obligate wetland species reestablishment (Hausman et al., 2007). Following those studies, the removal of the entire soil layer in the HID could a) increase groundwater seepage and b) decrease the nutrient concentrations found in groundwater underneath the restored area.

There is a dearth of literature relating CSR as a restoration method to changes in local hydrologic conditions, as even the notion of top soil removal described above is considered a, “radical restoration method” (Klimkowska et al., 2015). Previous studies conducted by researchers in the HID region of ENP have primarily focused on understanding Brazilian Pepper ecophysiology and the mechanisms by which it colonized the landscape. For instance, Ewel et al. (1982), Loope & Dunevitz (1981), and Krauss (1987) reported on the relationships between native successional plant assemblages and invasive species on abandoned fallow farmland. Dalrymple et al. (2003) and O’Hare et al. (2008) examined hydroperiods to assess restoration success using stage recorders installed in wells on previously restored sites. O’Hare (2008) and Serra (2009) went further and used the same data to create Geographic Information System (GIS) maps of hydroperiod. More recent studies in the HID examining primary succession have found biogeochemical mechanisms that cause wetlands restored by CSR to switch from Nitrogen (N)-limitation immediately after restoration to a co-limitation of P and N approximately 16 years post restoration (Inglett & Inglett, 2013). Conspicuously missing from these prior investigations are identification of long-term groundwater flow patterns, quantification of evapotranspiration, or assessment of groundwater chemistry. The previous studies are good starting points for a hydrologic analysis, but the other aspects outlined above must be adequately studied to provide restoration managers a more complete picture of the potential impacts of CSR to the surrounding wetland ecosystem.

Restoring the hydrology and vegetation of a wetland back to its original state is the main goal of any wetland restoration project (Abtew & Melesse, 2013). Accordingly, one of the cornerstones in the hydrologic restoration of ENP is increased freshwater flow that mimics pre-drainage conditions. Therefore, providing detailed measurements on changes in groundwater levels, and thus groundwater flow patterns, is integral for assessing wetland restoration. However, identifying changes in groundwater levels is only part of the restoration equation. To fully understand how restoration has progressed, accurate quantification of evapotranspiration (ET) within the spatiotemporal domain must be addressed (Abtew & Melesse, 2013). Because ET represents the fraction of water lost from the system to the atmosphere, assessing its magnitude at different stages in the restoration is critical for understanding how well the system is recovering (Abtew & Melesse, 2013). Estimates of ET rates for Brazilian Pepper within the HID vary seasonally; during the wet season (October) ET reached a maximum of 5.48 mm day^{-1} and during the dry season (May) had a minimum of 2.86 mm day^{-1} (Villalobos-Vega, 2010). The removal of Brazilian Pepper is expected to decrease the amount of evapotranspiration locally, because after its removal it can no longer transpire large quantities of water back to the atmosphere, thereby providing a mechanism for groundwater levels to increase (Mahmood et al., 2014; Villalobos-Vega, 2010).

Additionally, identifying potential sources of water and constituents for ENP are a concern of restoration efforts. The Everglades is an oligotrophic environment and the inputs of additional nutrients and constituents can result in cascading ecological effects such as shifts in macrophyte and periphyton species compositions (Harvey & McCormick, 2009). Analysis of major ions (cations and anions) have been utilized as tracers to determine groundwater-surface water interactions in ENP (Price & Swart, 2006). Although the restoration of the HID has been ongoing for the past 25 years, water chemistry analyses have not been conducted on surface water or groundwater samples, leaving the quality of the water flowing through this system unknown.

Characterization of the HID's hydrologic response to the CSR restoration technique is necessary for assessing the overall health of the wetland and for evaluating the progression of restoration. The goal of the present investigation is to understand how the CSR restoration method impacts major hydrologic parameters of a wetland and its associated hydrogeochemical constituents. Three main hypotheses were tested: (1) complete soil removal down to the bedrock increases groundwater levels after restoration, (2) ET rates decrease as a result of CSR, and (3) concentrations of dissolved ions and nutrients are higher outside of the HID where no restoration has taken place and where no Brazilian Pepper is found. To accomplish these objectives and to test the hypotheses, long-term water levels were integrated with GIS to produce groundwater flow maps. Furthermore, evapotranspiration was quantified, and geochemistry was analyzed to discern if hydrologic functioning has changed as a result of restoration and whether dissolved chemical constituents in the groundwater have changed over time, respectively. The CSR restoration was expected to decrease ET, increase groundwater levels, partly due to a greater tendency for groundwater seepage and partly due to the decrease in ET, and finally, decrease the concentrations of major ions and nutrients in the restored area's groundwater.

II. METHODS

Site Description

The present research was conducted in the southeastern region of ENP, near Taylor Slough, in the HID (Figure 2). The HID is an approximately 2,800-ha parcel of land that prior to farming was a mixture of pine rockland to the north and marl prairie to the south (Krauss, 1987; Serra, 2009). According to historic aerial photography of land cover interpreted from 1940, agriculture occupied 21.6 %, marl prairie occupied 63.3 %, pine rockland occupied 14.7 % and hardwood hammock occupied 0.4%. (Serra, 2009). Classification of soils in the HID are dependent upon the depth to the bedrock. If the depth to the limestone bedrock was less than or equal to 51 cm then the soil was classified as a Biscayne marl, and if the depth to the bedrock was between 51-102 cm then it was classified as a Perrine marl (USDA, 1996). The average soil depth was found to be 56.3 cm in the unfarmed native vegetation, while the average soil depth in restored sites ranged from 5.8 cm to 9.5 cm (O'Hare, 2008).

The south Florida climate is similar to other tropical regions and is dominated by annual wet and dry seasons. Approximately 70% of the rain falls in the wet season (May-October) and 30% falls during the dry season (November-April) (Duever et al., 1994; Kotun & Renshaw, 2014). Rainfall measured at the Royal Palm Ranger Station (RPL), which resides in close proximity to the HID, averages approximately 140 cm annually (Kotun & Renshaw, 2014). Evapotranspiration rates exhibit seasonal variability, paralleling solar irradiance as well as water availability. ET is highest in the summer wet months when solar irradiance is highest and surface water is available for evaporation, and are the lowest during the winter months (Duever et al., 1994). Evapotranspiration of undisturbed wetlands in south Florida have been estimated to return 70-90% of the precipitation in these systems back into the atmosphere (Duever et al., 1994).

The characteristic karstic geology of south Florida exerts significant influence on the hydrology of the region. Much of south Florida is underlain by extremely porous and permeable limestone and calcareous sandstone units called the Miami Limestone and Fort Thompson Formations, respectively. These two units make up the majority of the unconfined Biscayne Aquifer, which forms the top of the surficial aquifer system (SAS) (Fish & Stewart, 1991). The SAS varies in lateral extent reaching depths of approximately 30 meters underneath ENP, while increasing in depth as it moves eastward towards the Atlantic Ocean to approximately 240 meters (Fish & Stewart, 1991). The Biscayne aquifer is the primary source of potable water for south Florida (Fish & Stewart, 1991). The astoundingly high transmissivity (3.4×10^7 m^2 yr^{-1}) and hydraulic conductivity (between 1.64×10^6 and 4.45×10^6 m yr^{-1}) make it one of the most productive aquifers in the world.

On the basis of empirical measurements, the low elevation and flat topography of south Florida produces a gentle hydraulic gradient of 0.00005 for the Everglades region (Price & Swart, 2006). The near horizontal slope causes surface water to move slowly in the sloughs before it drains into Florida Bay and the Gulf of Mexico (Sandoval, 2016). The entirety of the HID is underlain by the Biscayne Aquifer, and overlain by mixtures of marl and peat soils. Peat and marl have much lower hydraulic conductivities than limestone (Fish & Stewart, 1991), and may act as an aquitard, restricting the interaction between groundwater and surface water. In the event of topsoil removal, in a case like the HID with CSR, interactions between groundwater and surface water could increase because of the hydraulic connection in the SAS (Fish & Stewart, 1991; Price & Swart, 2006).

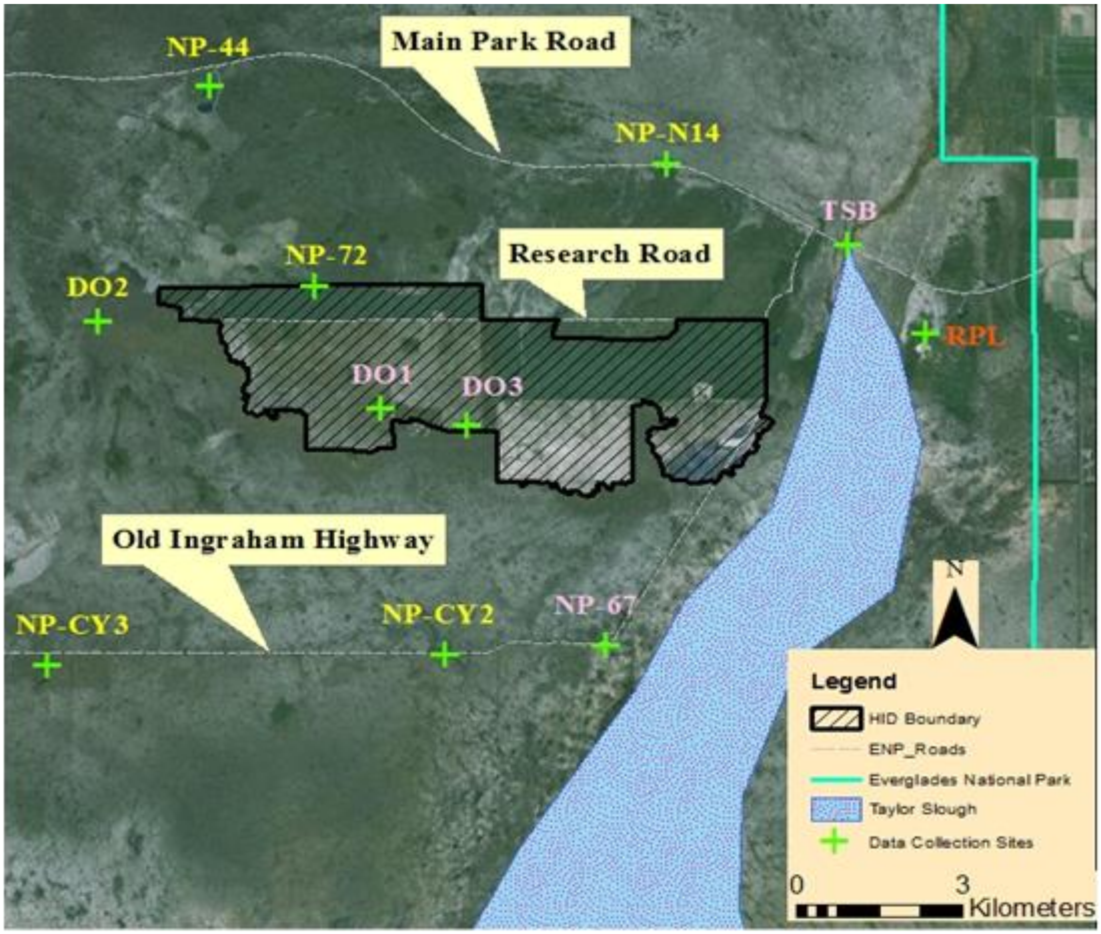

Figure 2. The Hole-in-the-Donut as visible from satellite imagery. Groundwater wells used in this investigation are indicated. The four wells labeled in pink will be sampled for water chemistry. Royal Palm Ranger Station is highlighted in orange. Image courtesy of ESRI, 2016.

Hydrologic Data Collection

Currently there are only two groundwater monitoring stations inside the HID (DO1 & DO3). In order to asses if local groundwater levels changed significantly over the periods of restoration, eight additional stations were strategically selected to create a boundary around the HID. The 10 well sites used in this project were: DO1, DO3, NP-67, TSB, NP-N14, NP-44, DO2, NP-72, NP-CY2, NP-CY3 (Figure 2). Mean daily stage data for all 10 wells were obtained through the SFWMD DBHYDRO database (http://www.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu). As stage data from DBHYDRO were reported in feet referenced to National Geodetic Vertical Datum of 1929 (NGVD-29), the data were converted to meters referenced to the more updated North American Vertical Datum of 1988 (NAVD-88) using the National Geodetic Survey's orthometric height conversion software, VERTCON (http://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html#).

Time-Series Analysis

The first hypothesis that complete soil removal down to the bedrock increases groundwater levels after restoration was addressed by investigating long-term water levels to ascertain if cyclical patterns, disturbance trends, and/or stresses could be detected in the 10 wells. Hydrographs of monthly averaged water levels were created for the 10 wells to observe changes in water level with respect to time. To smooth the cyclicity of the time series that results from the pattern of rainfall observed in south Florida, a six month moving average was computed for the monthly averaged time series to allow for the overall trends of the data to be observed. A 25-year time frame, from

1991 through 2015 was selected to encompass the entire duration of the HID restoration (to date). Data from 5 groundwater wells were available through those 25 years (Table 1). Other wells had available data spanning 16-22 years (Figure 3). In addition to filtering the time series data, linear regression was used at five year intervals to detect changes in water levels with respect to periods of interventions in the HID. Regression analysis was applied in five year intervals as follows: 1991-1995; 1996-2000; 2001-2005; 2006-2010; 2011-2015. Pertinent values collected from the regression analysis include: R^2, p-value, slope, standard error, and number of observations.

Linear Modeling

Two simple linear regression models were used to determine relative contributions of parameters that may have influenced groundwater levels in the HID. The parameters were computed from 1989-2014 and include: average annual water levels from DO1, total annual rainfall from RPL, and total annual acres scraped. The first model used total annual rainfall as the predictor variable and average annual water level as the response variable. The second model used the residuals from the first model as the response variable and total annual acres scraped across the HID as the predictor variable. Scatterplots were created for both models and include their respective regression lines. Pertinent values evaluated include the R^2 value, the coefficients of both predictor and response variables, and the p-value.

Table 1. Period of record table for 10 data collection sites.

Well Name	Data Record Begins	Years Active	Data Record Ends	Interval Measured
NP-44	1960	56	Current	Daily
TSB	1960	56	Current	Daily
NP-67	1962	54	Current	Daily
NP-72	1966	50	Current	Daily
DO1	1989	27	Current	Daily
NP-N14	1994	22	Current	Daily
DO2	1996	20	Current	Daily
NP-CY3	1996	20	Current	Daily
NP-CY2	1996	20	Current	Daily
DO3	2000	16	Current	Daily

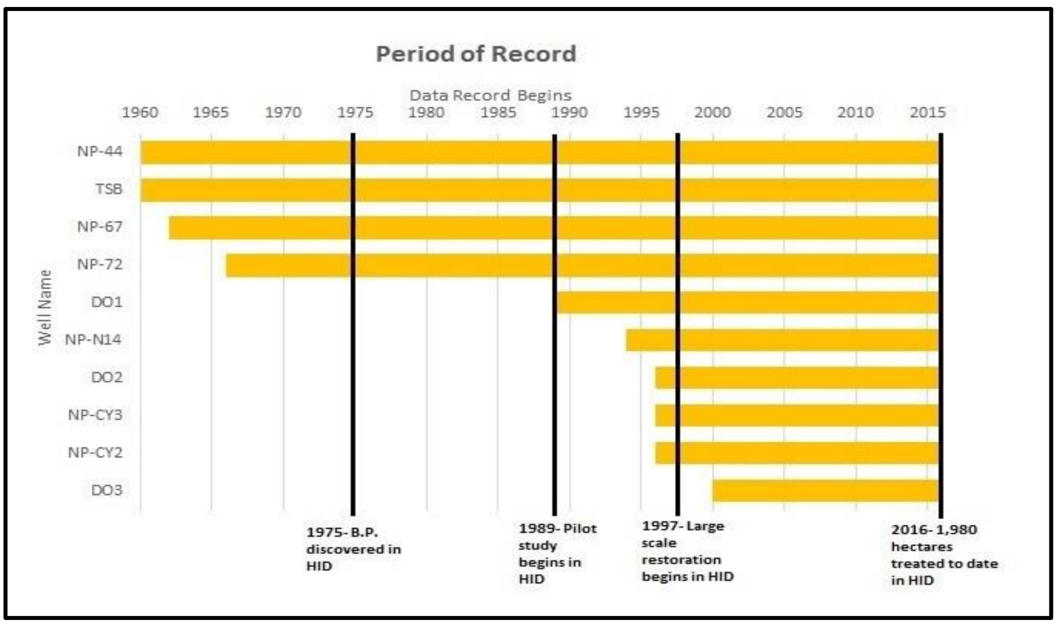

Figure 3. Period of record graph for the ten data collection sites.

GIS Groundwater-flow Modeling

Newly converted stage data were input into the GIS platform ArcMap in order to perform a linear interpolation using the Spatial Analyst Kriging tool. Interpolation was necessary for this analysis as a result of the low density of wells where stage data was measured in the HID. Interpolation of the point well data provided estimates of stage values using a weighted sum of data values at surrounding locations. Kriging works on the primary assumption that there is spatial continuity between data points. In other words, two wells that are closer together should have more similar stage values than two wells that are far apart (Isaaks & Srivastava, 1989).

The kriging surfaces generated model the expected stage contours for the HID and surrounding area. As a consequence of the lack of continuous data before 2000 in all ten of the wells, kriging maps were created for years: 2000, 2001, 2003, 2004, 2005, 2009, 2010, 2011, 2013, 2014 on a monthly time step and then averaged in yearly intervals. Using these interpolated stage maps, historical groundwater flow directions were estimated, and then compared with the 2014 map to assess how hydrologic conditions vary with time in the HID.

Water Balance

The kriging maps were also used to compute a water balance for the HID. According to Darcy's Law:

$$\mathrm{Q} = -\mathrm{KA}\frac{dh}{dl} \qquad \text{(Eq. 1)}$$

Where Q is discharge (m^3 yr^{-1}), K is hydraulic conductivity (m yr^{-1}), A is the cross-sectional area (m^2) at the inflow and outflow boundaries and $\frac{dh}{dl}$ is the dimensionless hydraulic gradient. The K used was 3,048 m day^{-1} and was obtained from literature on the hydrogeology of the Biscayne aquifer and the Everglades and converted to m yr^{-1} (Zapata-Rios & Price, 2012; Fish & Stewart, 1991). The length of the inflow and outflow boundaries were 12,229.73 m and 12,560.19 m, respectively, and were measured using ArcMap (Figure 4). The thickness of the Biscayne aquifer for the model domain was 9.6 m as obtained from contour lines published by the USGS (Fish & Stewart, 1991). Multiplying the length of the inflow and outflow boundaries by the thickness of the aquifer results in A. The kriging maps were used to obtain the gradient from three transects at the inflow and three transects at the outflow (Figure 4). The inflow and outflow gradients computed for all transects were averaged to obtain one average inflow and outflow gradient for each year. From Darcy's Law it is possible to obtain the inflow (Q_{in}) and outflow (Q_{out}) from the HID. A water balance equation was used to obtain the change in storage:

$$(\mathrm{P_r} + Q_{in}) - (\mathrm{ET} + Q_{out}) = \Delta \mathrm{S} \quad \text{(Eq. 2)}$$

where P_r was average annual precipitation from RPL, Q_{in} was groundwater inflow, ET was average annual evapotranspiration in the HID as determined by remote sensing data described in the next section, Q_{out} was groundwater outflow, and S was change in storage. Before adding P_r and ET to the left and right sides of the water balance equation, respectively, the area of model domain (41,023,784.19 m^2) was divided by Q_{in} and Q_{out} to convert from volume (m^3 yr^{-1}) to length units (m yr^{-1}).

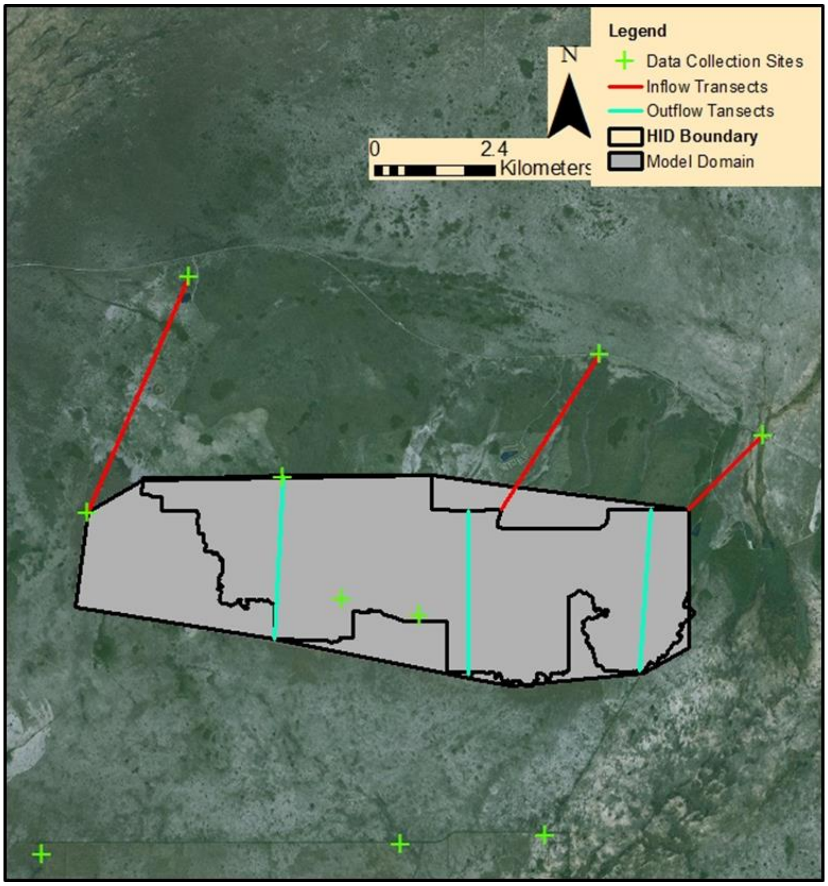

Figure 4. Map showing the inflow (red) transects and outflow (blue) transects used to compute the average inflow and outflow gradients used in the water balance.

Evapotranspiration Modeling

The second hypothesis that ET rates decrease as a result of CSR was tested by collecting and analyzing remotely sensed data of ET in the HID. Remote sensing provides the most efficient means to monitor regional and global ET information that is spatially distributed over Earth's surface (Mu et al., 2011). NASA's Terra and Aqua satellites have the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard, allowing them to provide groundbreaking information on vegetation dynamics and surface energy variations (Justice et al., 2002), which can then be utilized for estimations of regional and global scale ET (Mu et al., 2011). MODIS sensors record data to provide high radiometric sensitivity in 36 spectral bands ranging in wavelength from 0.4 to 14.4 μm (https://modis.gsfc.nasa.gov/about/design.php). Wavelength of 29 spectral bands are collected at a resolution of 1 km, which was the resolution used for this project. A detailed list of all 29 spectral bands and their associated wavelengths are provided on the NASA MODIS website (https://modis.gsfc.nasa.gov/about/specifications.php). Remotely sensed parameters, including albedo, land cover, leaf area index (LAI), fraction of photosynthetically active radiation (FPAR), are combined with surface meteorological observations including air temperature, humidity, solar radiation, and wind speed (Mu et al., 2011). These parameters are input into an algorithm that uses the logic of the Penman-Monteith equation, which results in an estimate of land surface ET (Figure 5). The ET data has been calibrated and validated with ET measured at Eddy Flux towers from 232 watersheds around the world (Mu et al., 2011). One limitation of the method is that the algorithm doesn't account for the vegetation age, disturbance history, or species composition, resulting in differences between tower ET measurements and ET estimates by the algorithm (Mu et al., 2011).

Evapotranspiration data were obtained from the Numerical Terradyanmic Simulation Group (NTSG) at the University of Montana. These data are available online through the NTSG data portal and can be accessed by following the link below (http://files.ntsg.umt.edu/data/NTSG_Products/MOD16/MOD16A3.105_MERRAGMAO/). The data are provided in a 1 km x 1 km grid. Data were downloaded for 2000, 2001, 2003, 2004, 2005, 2009, 2010, 2011, 2013, and 2014. These years were selected to correspond with active restoration in the HID. After the data were obtained from NTSG, it was transferred and stored in a geodatabase in ArcGIS for further analysis. Once in ArcGIS, the data were first converted to the "UTM_17_N" coordinate system using the Project Raster tool in the ArcToolbox. The coordinate system has units of meters, and preserves the original pixel size of the data. All maps created in the present study use this coordinate projection. After the data are projected to the new coordinate system, the image is clipped to only include the HID using the Extract by Mask tool in the ArcToolbox. Since the HID is a relatively small component of Everglades National Park and the cell size of the MODIS image is coarse, a resampling of the cell size was performed. The Resample tool in ArcToolbox allows for the pixel size to be changed to a smaller size. The cubic resampling method was selected to reduce the pixel size of the MODIS images to 46 m x 46 m. This pixel size corresponds with the pixel sizes of the kriging maps produced for water levels.

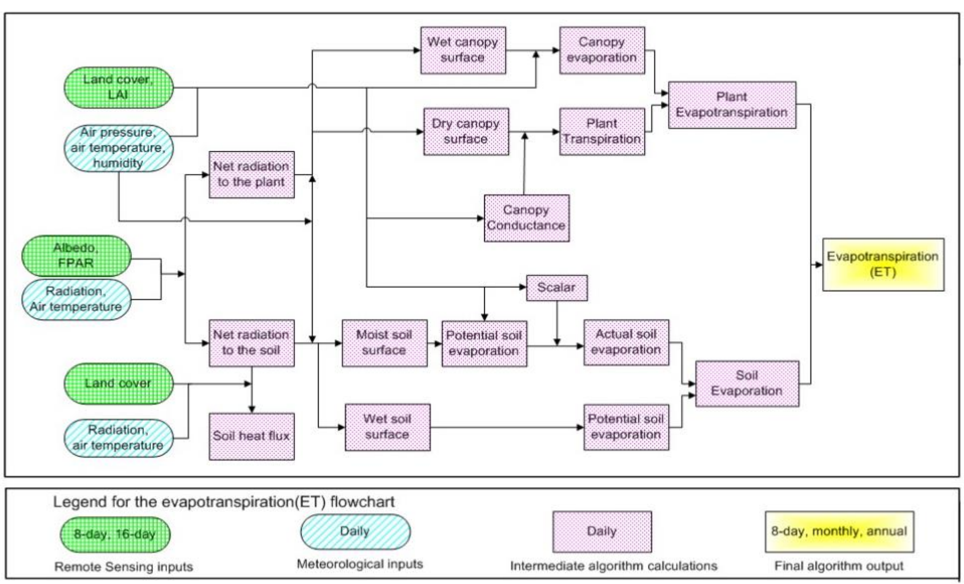

Figure 5. Flowchart of the MOD16 ET algorithm. Adapted from Mu et al., 2011.

Groundwater and Surface-Water Chemistry

The third hypothesis that concentrations of dissolved ions and nutrients are higher outside of the HID where no restoration has taken place and where no Brazilian Pepper is found was addressed by collecting groundwater and surface water samples in and outside the HID. A total of four groundwater and four surface-water sites were sampled four times a year in December, May, and September at the HID in 2015 and 2016. The four sites include: DO1, DO3, NP-67, and TSB. Wells DO1 and DO3 are located within two restored parcels of the HID wetland. Well NP-67 is located along Old Ingraham Highway amongst thickets of vegetation. Well TSB is adjacent to the Main Park Road, approximately 20 meters from Taylor Slough Bridge. Wells DO1, DO3, and NP-67 are cased in PVC pipe and are circumscribed into wooden platforms that are fitted with metal covers. Well TSB is flush mount with the ground surface and protected at the surface by a metal cover. The installation and depths of the three wells vary as such: DO1 is 7.5 meters deep and installed in 1989; DO3 is 3 meters deep and installed in 2000; NP-67 is 5.6 meters deep and installed in 1960; TSB is 4.1 meters deep and installed in 1997.

To collect groundwater and surface-water samples in the field, a gas powered pump was used to purge three well volumes before sampling and then a peristaltic pump was used to collect the samples. Surface water samples were collected adjacent to each well if present. At each sampling location, two samples were filtered through a 0.45 μm membrane filter, and two unfiltered samples were collected and stored on ice at 4°C and transported back to Florida International University (FIU) for final storage. Samples for total phosphorus and cations were preserved with 10% hydrochloric acid. Measurements taken in the field included: pH, conductivity, and temperature, all of which were measured with a Thermo Scientific Orion™ 3-star pH meter and an YSI 85™ meter, respectively.

The Southeastern Environmental Research Center (SERC) Nutrient Analysis Laboratory analyzed the groundwater and surface-water samples for total nitrogen (TN), total phosphorus (TP), and total organic carbon (TOC) using an Alpkem 300 Series 4 Channel Rapid Flow Analyzer, an Alpkem Rapid Flow Analyzer with 2-Channel ER Detector, and a Shimadzu TOC-V, respectively. The FIU Soil/Sediment Biogeochemistry Laboratory analyzed the groundwater and surface-water samples for soluble reactive phosphorus (SRP), nitrate (NO_3), and ammonium (NH_4). The FIU Hydrogeology Laboratory analyzed the groundwater and surface-water samples for total alkalinity, major anions (chloride [Cl^-] and sulfate [SO_4^{2-}]) and cations (Calcium [Ca^{2+}], Magnesium [Mg^{2+}], Sodium [Na^+], and Potassium [K^+]) using a Brinkman Titrino™ 751 Titrator and a Dionex-120™ Ion Chromatograph, respectively.

Statistical Analysis

Box-and-whisker plots were created to graphically depict the statistical distribution of Ca^{2+}, Mg^{2+}, K^+, Na^+, SO_4^{2-}, Cl^-, HCO_3^-, TN, TP, TOC, NO_3^-, and NH_4^+ concentrations as a function of sampling location. A one-way analysis of variance (ANOVA) was used to determine the statistical difference between chemical constituents at the different sampling locations. A Tukey honest significance difference (HSD) test was run after the ANOVA to asses if the means of the chemical constituents were statistically different.

III. RESULTS

Time-Series Analysis

Regression analysis of the time series data from the 10 wells showed two distinct periods where significant changes in water levels were observed with respect to time (Table 2). During 1991-1995, there were statistically significant ($p < 0.01$) changes in mean water levels at wells NP-44, NP-67, NP-72, DO1, and TSB. The seasonally detrended hydrographs have a 12-point moving average superimposed that picked up the increasing water level signal during the 1991-1995 interval (Figure 6A, 6B, 6C, 6D, 6E). The hydrographs depict water levels that were generally lower than the mean at all stations rising slowly until 1995, where they reach a relative peak in the time series. The slopes of the regression lines for all wells during this period were positive indicating a general increase in water levels (Table 2). The other five wells, NP-CY2, NP-CY3, DO2, DO3, and NP-N14 did not have enough data for regression analysis to be applied in the 1991-1995 interval.

The second interval where significant water level changes were observed with respect to time was 2006-2010. In this period, all 10 wells had statistically significant changes in mean water levels ($p < 0.1$). The moving average for all hydrographs show that at the beginning of 2006 water levels were slightly above each well's respective long term mean (Figures 7A, 7B, 7C, 7D, 7E). Water levels reach another relative peak in all hydrographs at the end of 2010. The overall observed trend for 2006-2010 is positive, as indicated by the positive slope of the regression coefficients (Table 2).

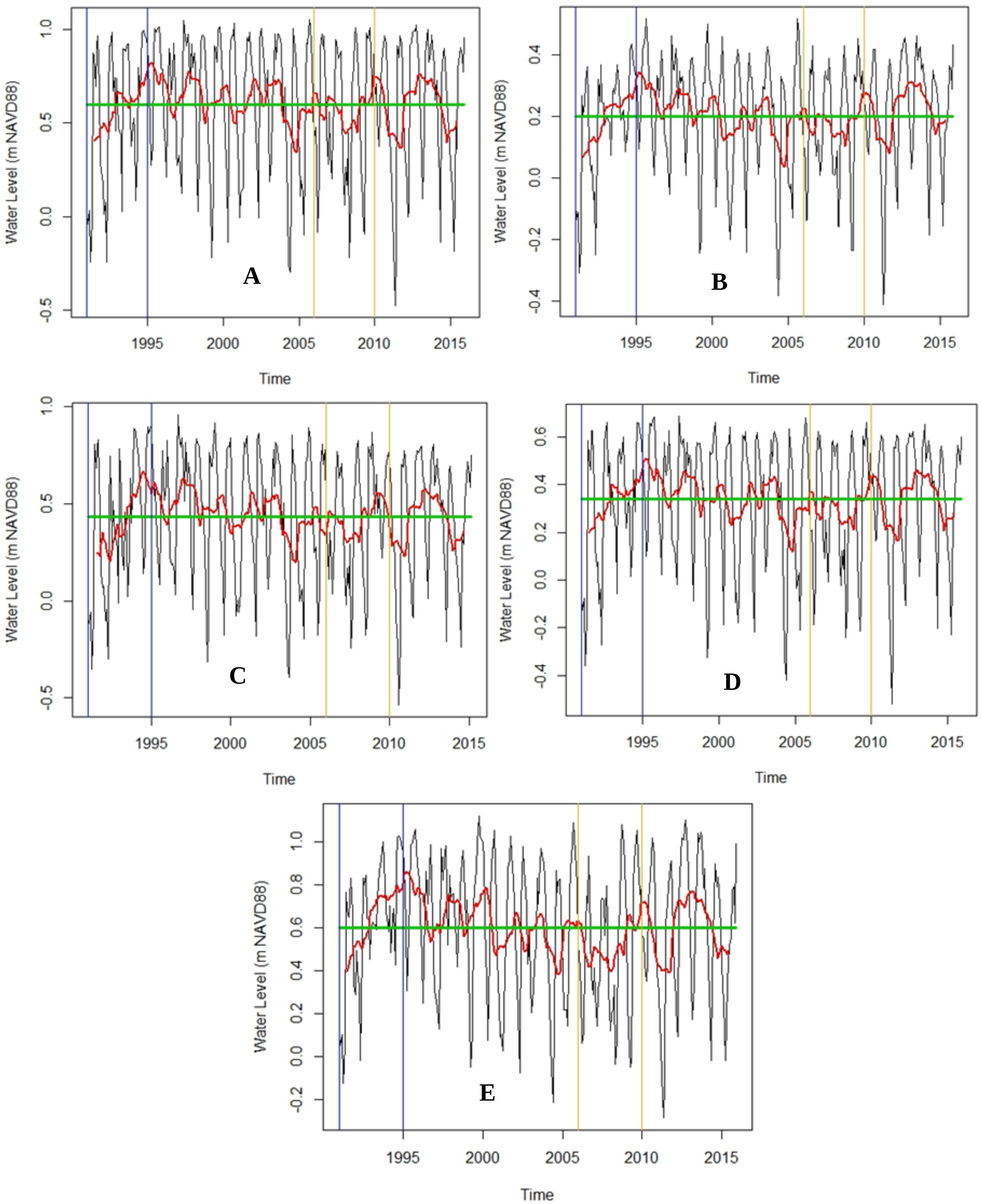

Figure 6. Hydrographs of monthly-averaged water levels as a function of time: A) NP-44; B) NP-67; C) NP-72; D) DO1; E) TSB. The black line is the original signal, the red line is the six month moving average, and the green line is the 25-year mean water level. Blue and orange vertical lines demarcate 1991-1995 and 2006-2010, respectively. Elevation is given in meters relative to NAVD-88.

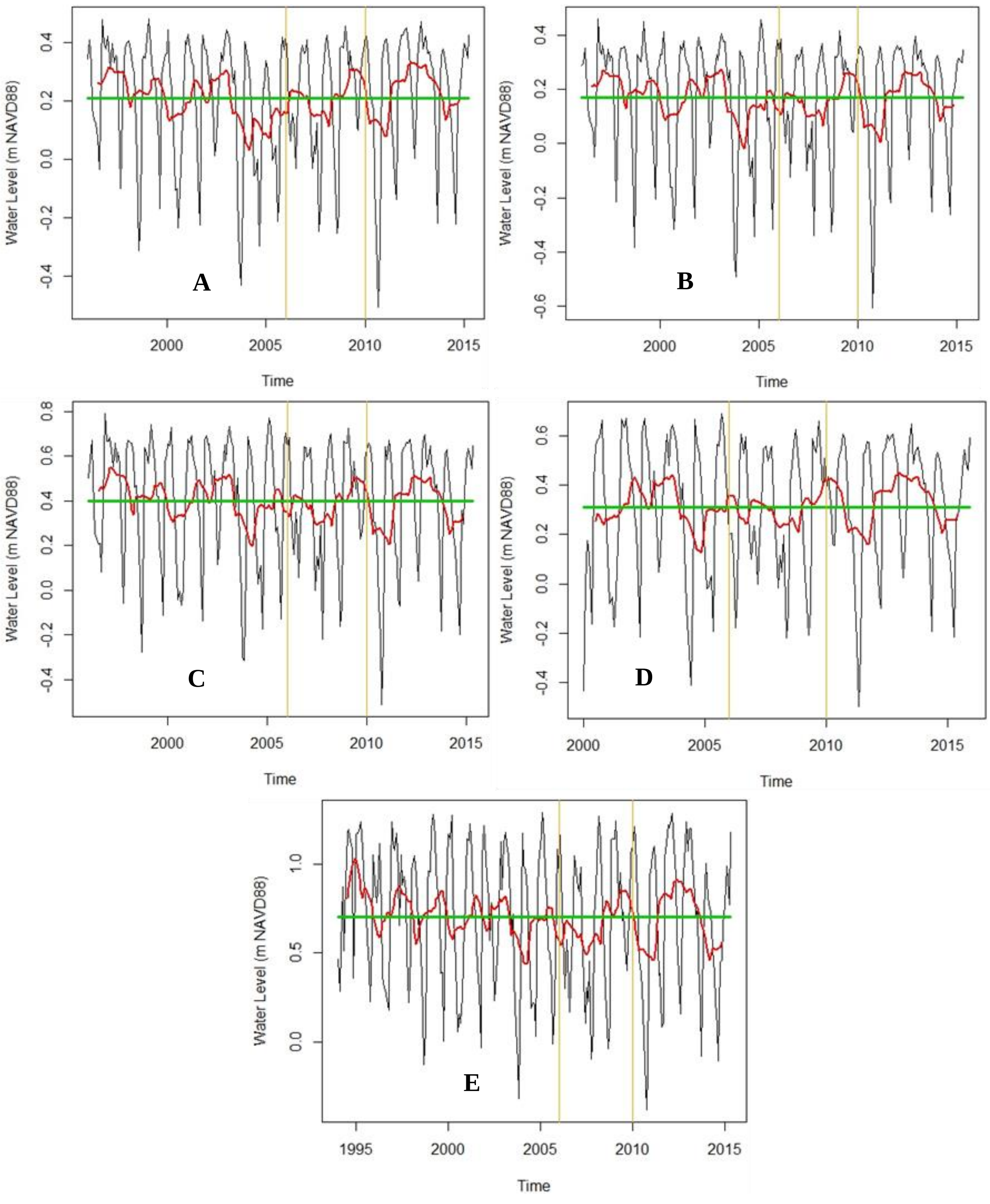

Figure 7. Hydrographs of monthly-averaged water levels as a function of time: A) NP-CY2; B) NP-CY3; C) DO2; D) DO3; E) NP-N14. The black line is the original signal, the red line is the six month moving average, and the green line is the 25-year mean water level. Orange vertical lines demarcate 2006-2010. Elevation is given in meters relative to NAVD-88.

Table 2. Major statistical parameters obtained from regression analysis. Only significant values are reported.

Well	Interval	R-square	Slope	p-value	Standard Error	Observations
NP-44	1991-1995	2.20E-01	3.22E-04	<0.001	0.32	60
NP-67	1991-1995	3.82E-01	2.11E-04	<0.001	0.14	59
NP-72	1991-1995	2.73E-01	3.28E-04	<0.001	0.31	51
DO1	1991-1995	2.11E-01	2.35E-04	<0.001	0.24	60
TSB	1991-1995	3.94E-01	3.44E-04	<0.001	0.23	60
NP-44	2006-2010	4.56E-02	1.34E-04	0.1	0.33	60
NP-67	2006-2010	6.15E-02	8.27E-05	<0.1	0.17	60
NP-72	2006-2010	5.12E-02	1.27E-04	<0.1	0.29	60
DO2	2006-2010	4.40E-02	1.00E-04	0.1	0.25	60
NP-CY3	2006-2010	5.73E-02	8.96E-05	<0.1	0.19	60
NP-N14	2006-2010	7.43E-02	1.93E-04	<0.1	0.37	60
DO1	2006-2010	5.32E-02	1.08E-04	<0.1	0.24	60
DO3	2006-2010	5.75E-02	1.09E-04	<0.1	0.24	60
NP-CY2	2006-2010	7.77E-02	1.03E-04	<0.1	0.19	60
TSB	2006-2010	1.06E-01	1.90E-04	<0.1	0.30	60

Linear Modeling

The results of the first model fit between water levels and rainfall showed a positive linear relationship (Figure 8A). The R^2 value was 0.19, the intercept of the regression line was 0.0545, and the slope of the rainfall coefficient was 0.0002. Analysis of variance (ANOVA) of the model revealed that rainfall contributed significantly to the variance ($p < 0.05$). A comparison of the residuals from the model fit between water levels and rainfall and the total acres scraped on a yearly basis (Figure 8B) produced a negative linear relationship with a low R^2 value of 0.001, and a non-significant result.

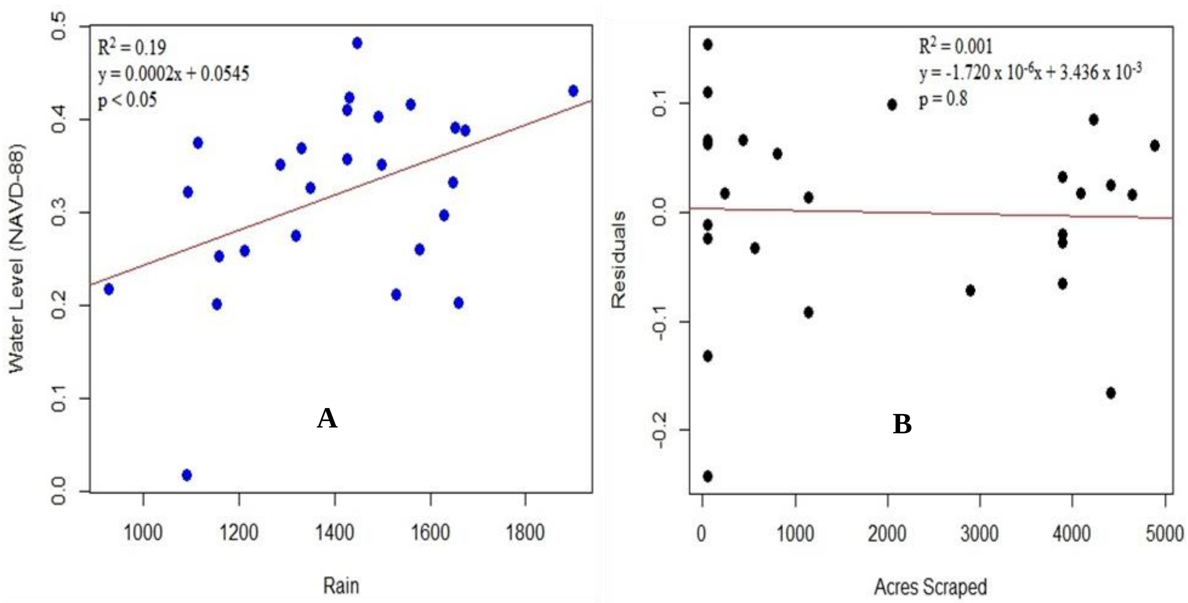

Figure 8. Regression models for: A) water level and rain; B) residuals of A) and acres scraped.

GIS Groundwater-flow Modeling

The predominant direction of groundwater-flow for years 2000, 2001, 2003, 2004, 2005, 2009, 2010, 2011, 2013, and 2014 were similar occurring from a NE to SW direction (Figure 9 & Figure 10). The mean water level observed inside the HID from the 10 annual maps was 0.39 m relative to NAVD-88. Water levels ranged from a minimum of 0.17 m (2004 and 2011) to a maximum of 0.66 m in 2013. The total drop in water level from NE to SW across the map domain was 0.60 m. Higher water levels, as indicated by blue on the maps, generally persisted in 2000, 2003, 2010, and 2013 (Figures 9A, 9C, 10B, 10D). Lower water levels have a greater proportion of red in the maps and were observed in 2004 and 2011. While there were fluctuations in water levels observed for the ten annual kriging maps, regression analysis of the mean water levels with respect to time did not result in a statistically significant difference ($p = 0.8$).

While the annually averaged groundwater-flow patterns didn’t differ, there were differences in flow patterns observed between the wet season (Figure 11A) and dry season (Figure 11B). The wet season map illustrates higher water levels and a higher hydraulic gradient, approximately 0.00004, as depicted by more groundwater contours occurring throughout the map domain (Figure 11A). Alternatively during the dry season, lower water levels prevailed along with a lower hydraulic gradient, approximately 0.00002, as illustrated by fewer groundwater contours occurring across the map domain (Figure 11B).

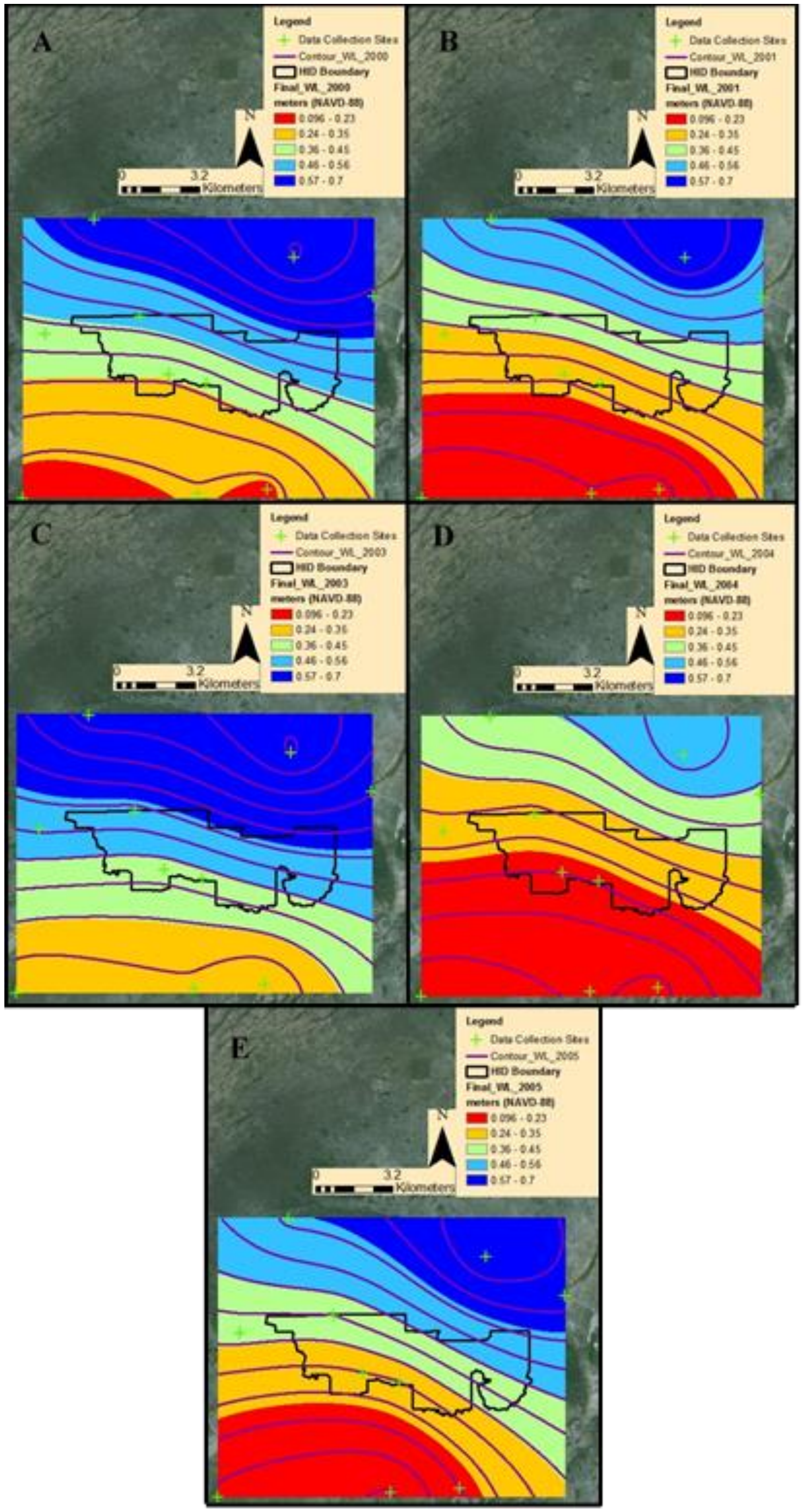

Figure 9. Results of ordinary kriging interpolations: A) 2000; B) 2001; C) 2003; D) 2004; E) 2005. Contour lines are indicated in purple. The contour interval is 0.05 m. Elevation is given in meters relative to NAVD-88.

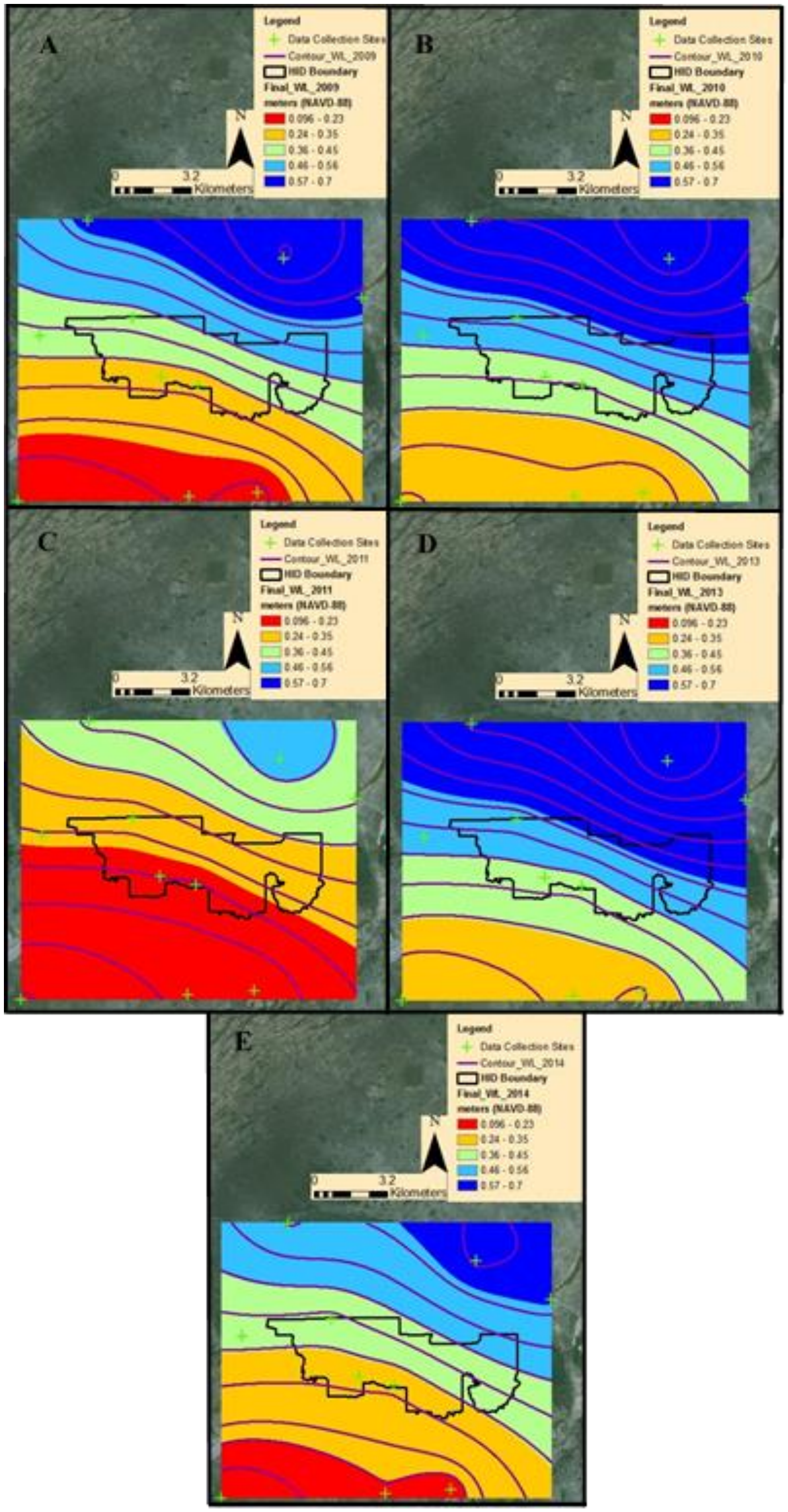

Figure 10. Results of ordinary kriging interpolations: A) 2009; B) 2010; C) 2011; D) 2013; E) 2014. Contour lines are indicated in purple. The contour interval is 0.05 m. Elevation is given in meters relative to NAVD-88.

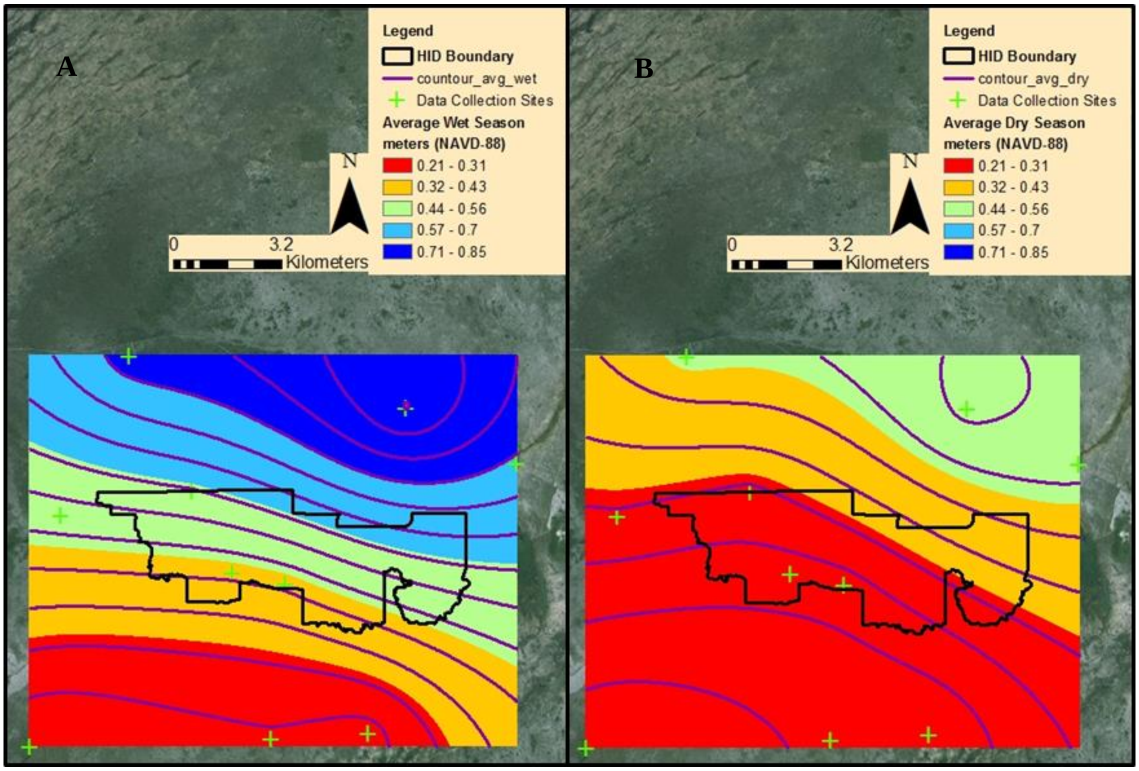

Figure 11. Seasonal maps computed from averaging all wet season rasters and dry season rasters using Spatial Analyst Raster Calculator tool: A) average wet season and B) average dry season.

Water Balance

The results of the water balance for 2000, 2001, 2003, 2004, 2005, 2009, 2010, 2011, 2013, and 2014 revealed that a positive change in storage (when inflow exceeds outflow) was a function of the average annual rainfall in the HID (Figure 12). The 25-year average of rainfall (1991-2015) at RPL was 1210.33 mm (Figure 13). For the 10 years the water balance was calculated, there were four years (2001, 2005, 2011, and 2013) where rainfall was above the 25-year average. Conversely, there were four years (2000, 2004, 2009, and 2014) were rainfall was below the 25-year average. For all years except 2000, the mean annual rainfall exceeded the mean annual ET. Additionally, for all 10 years, the inflow exceeded the outflow into the HID, leading to positive changes in storage. The magnitude of the change in storage was positively and linearly correlated with the amount of annual rainfall ($R^2 = 0.8683$; $p < 0.001$; Figure 12). No significant relationship was observed between change in storage and mean ET ($p = 0.3$) or change in storage and acres restored ($p = 0.2$).

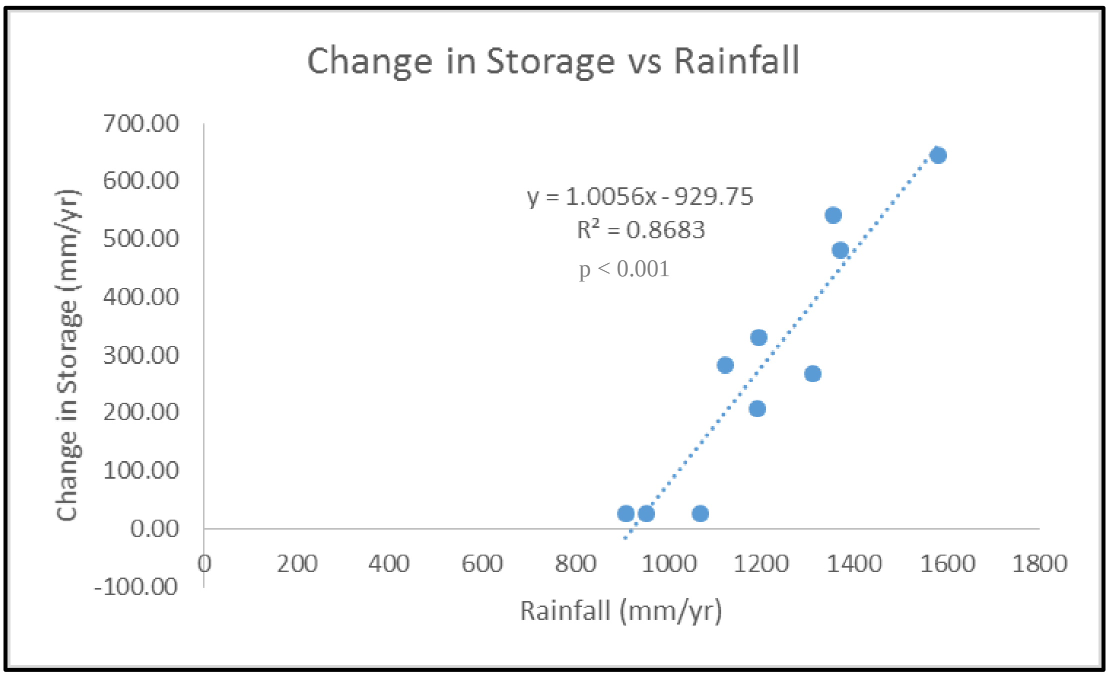

Figure 12. Scatterplot showing the strong linear relationship between change in storage values and rainfall in the HID.

Table 3. Water balance results. The top row in red boldface text is representative of the parameter values outlined in Eq.1.

Area of Model Domain (m^2)	4.10E+07	**K (m/yr)**	1,131,500	**Inflow Xsectional Area (m)**	12,229.73	**Outflow Xsectional Area (m)**	12,560.19	**Thickness (m)**	9.60
Year	**Mean Rainfall (mm/yr)**	**Mean ET (mm/yr)**	**Avg. Inflow dh/dl**	**Avg. Outflow dh/dl**	**Q_{in} (m^3/yr)**	**Q_{out} (m^3/yr)**	**Inflow (m/yr)**	**Outflow (m/yr)**	**Storage (m/yr)**
2000	1071.27	1083.40	4.14E-05	5.20E-05	-5.50E+06	-7.09E+06	0.94	0.91	0.03
2001	1311.33	1079.62	4.14E-05	5.14E-05	-5.50E+06	-7.01E+06	1.18	0.91	0.27
2003	1192.38	1025.99	4.11E-05	5.20E-05	-5.46E+06	-7.09E+06	1.06	0.85	0.21
2004	954.22	950.48	3.57E-05	4.15E-05	-4.74E+06	-5.66E+06	0.84	0.81	0.03
2005	1356.81	848.69	4.29E-05	5.22E-05	-5.70E+06	-7.12E+06	1.22	0.68	0.54
2009	1122.64	872.57	4.11E-05	4.99E-05	-5.46E+06	-6.80E+06	0.99	0.71	0.28
2010	1194.37	893.36	4.31E-05	5.10E-05	-5.73E+06	-6.95E+06	1.05	0.72	0.33
2011	1372.35	909.90	3.22E-05	3.72E-05	-4.27E+06	-5.07E+06	1.27	0.79	0.48
2013	1583.49	963.43	4.62E-05	5.24E-05	-6.13E+06	-7.15E+06	1.43	0.79	0.64
2014	909.31	891.62	3.65E-05	3.84E-05	-4.85E+06	-5.24E+06	0.79	0.76	0.03

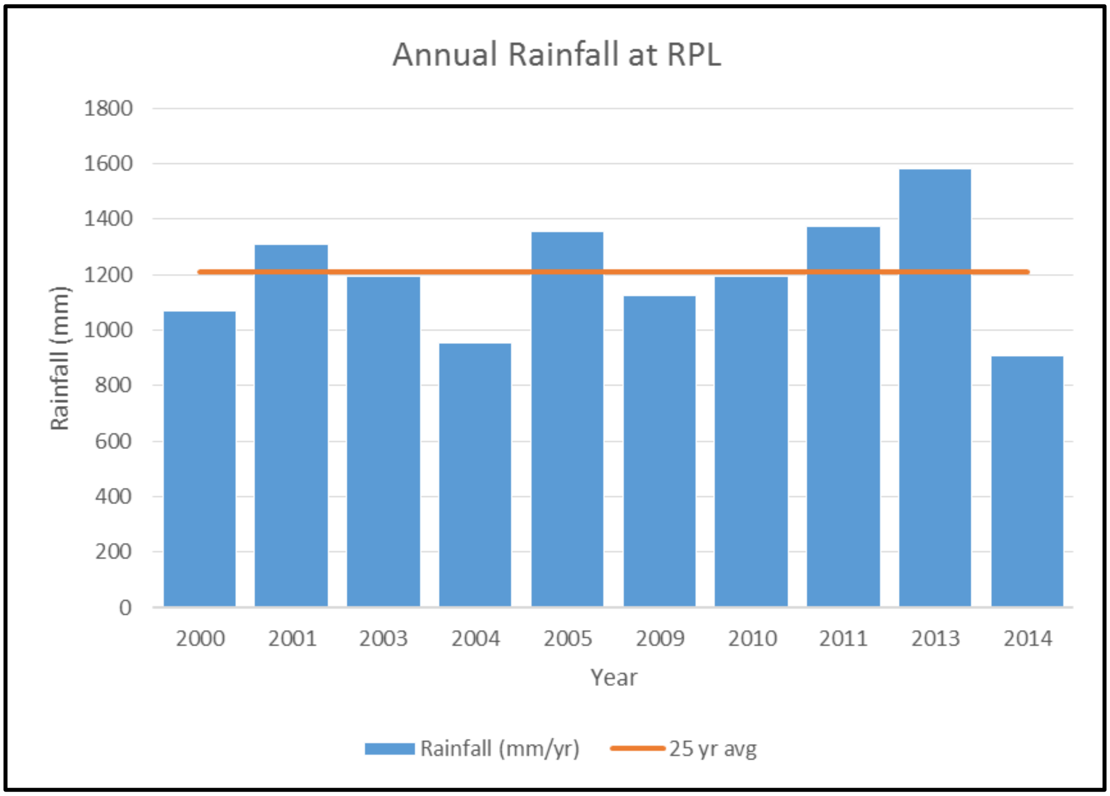

Figure 13. Bar graph of average annual rainfall at RPL for the 10-year water balance. 25-year average computed from 1991-2015.

Evapotranspiration Modeling

Annual ET maps from 2000-2014 resulted in a reduction in ET rates in each portion of the HID remediated by CSR (Figures 14 & 15). After CSR was employed to remove the invasive Brazilian Pepper, the ET rate was reduced approximately by a factor of two in each restored plot. For example, the restoration plot area restored in 2004 had a maximum ET of 1326.2 mm year^{-1} in 2003 the year prior to restoration, indicative of the high rates of ET associated with the Brazilian Pepper. After completion of restoration in 2004, the maximum ET observed in Res2004 was 773.7 mm year^{-1}. A similar trend in reduction of ET following restoration was observed in every plot restored in the HID, although the magnitude differed slightly. The highest mean ET obtained for the HID was 1083.4 mm $year^{-1}$ in 2000, when only 808 acres was restored. The lowest mean ET value observed was 848.7 mm $year^{-1}$, after 3890 acres had been restored (Table 4). The downward trend in ET following restoration continued through the end of 2005. There was no restoration from 2006 through the end of 2008, thereby allowing natural vegetation to regrow. As a result of the break in restoration, increases in mean ET were observed from 2009 through 2013, although they were still lower than observed at the start of 2000. There was another observed downturn in ET following restoration in 2014. A linear regression between acres restored as the predictor variable and mean ET rate as the response variable (Figure 16), resulted in a significant negative relationship ($R^2 = 0.77$; $p < 0.001$).

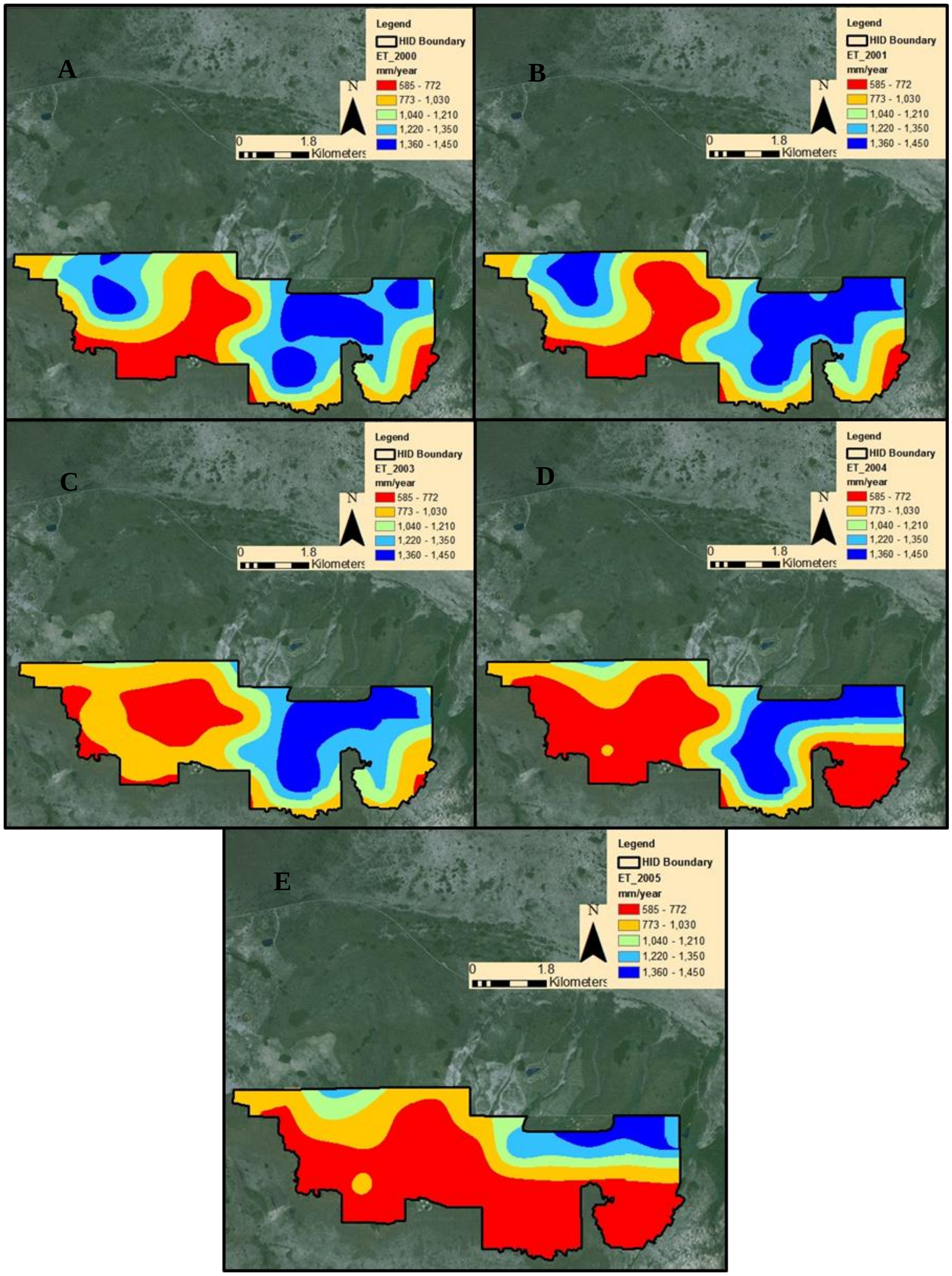

Figure 14. Maps quantifying the effect that CSR has on ET in the HID: A) 2000; B) 2001; C) 2003; D) 2004; E) 2005. Notice how after each restoration the blue area, representative of Brazilian Pepper, decreases.

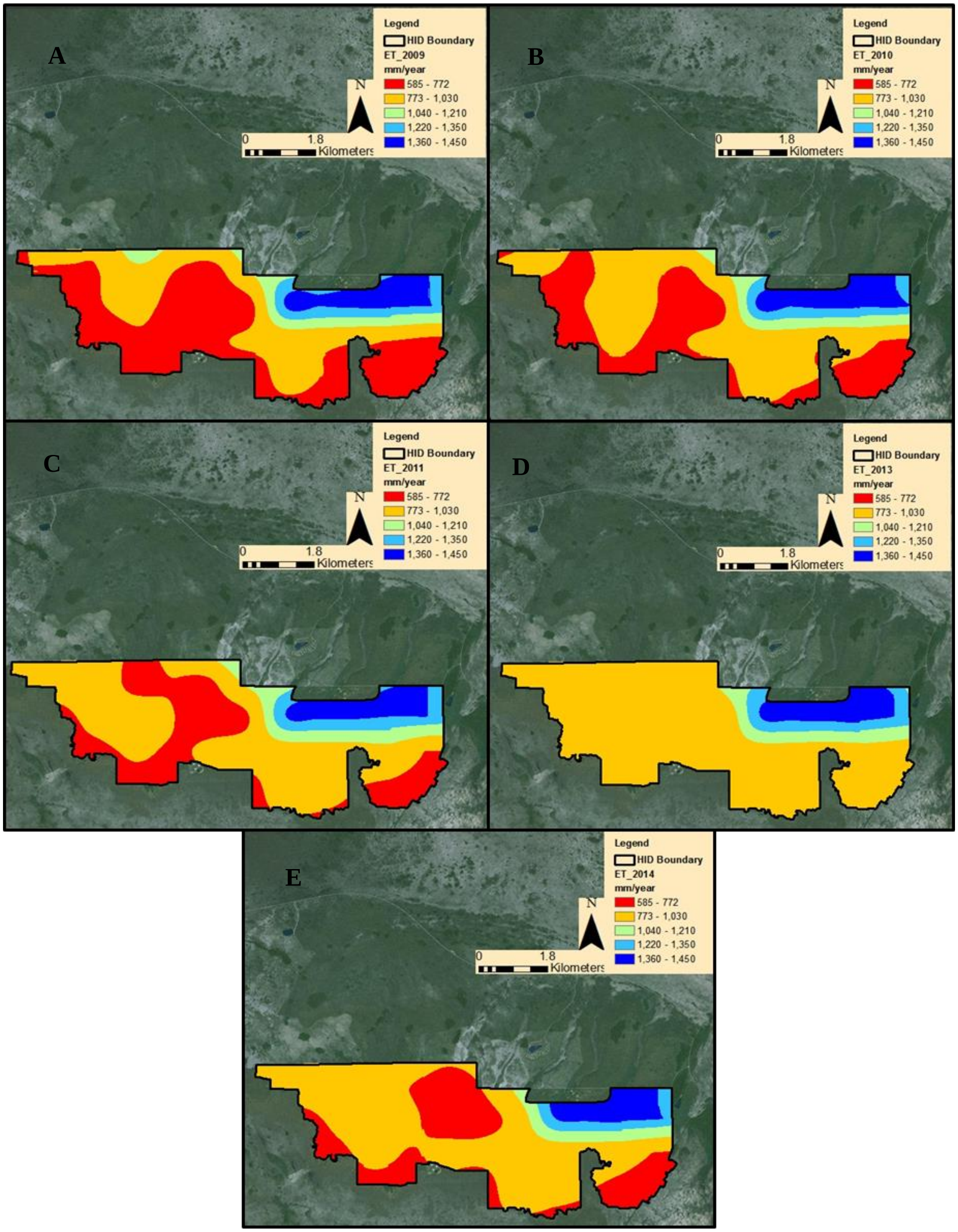

Figure 15. Maps quantifying the effect that CSR has on ET rates in the HID: A) 2009; B) 2010; C) 2011; D) 2013; E) 2014. Notice how after each restoration the green and blue colors, representative of Brazilian Pepper, decreases.

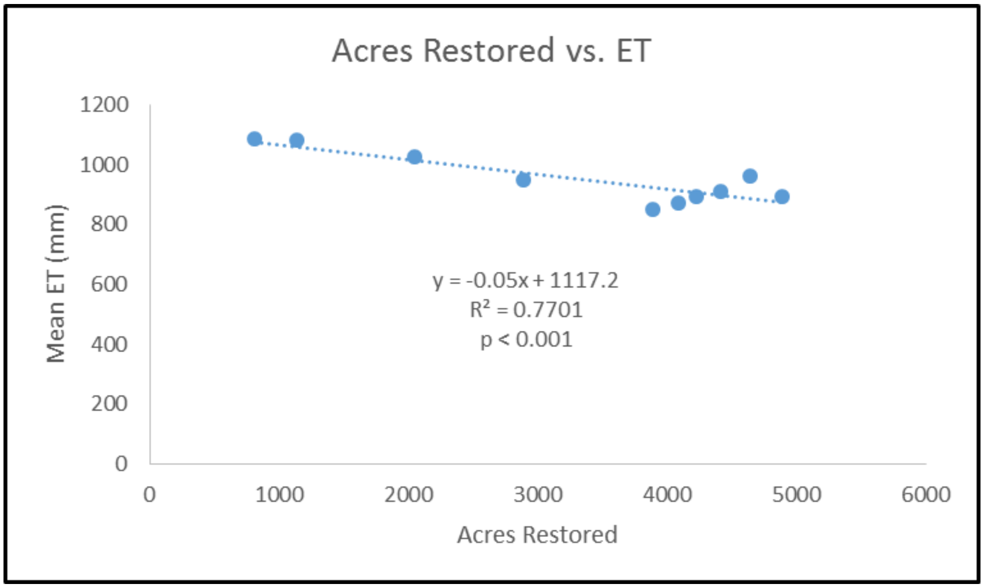

Figure 16. Linear regression of acres restored and mean ET, showing a strong negative relationship.

Table 4. Summary statistics of ET rasters. Values reported in mm yr^{-1}.

Year	Minimum	Maximum	Range	Acres Restored	Mean	Standard Deviation
2000	584.8	1450.7	865.9	808	1083.4	256.7
2001	590.0	1442	852.0	1141	1079.6	263.1
2003	698.6	1429.4	730.8	2051	1025.9	246.0
2004	603.9	1490.8	886.9	2890	950.5	281.4
2005	594.7	1437	842.3	3890	848.7	225.3
2009	627.3	1442.6	815.3	4091	872.6	223.1
2010	667.3	1434.6	767.3	4225	893.4	212.9
2011	675.1	1419.9	744.8	4414	909.9	203.8
2013	775.0	1425.2	650.2	4639	963.4	174.8
2014	677.5	1447	769.5	4893	891.6	195.3

Groundwater and Surface-Water Chemistry

Box-and-Whisker Plots

Graphical analysis of nutrient concentrations in the water samples displayed a tendency to cluster based on sampling locality and type, whether groundwater or surface-water (Figures 17A, 17B, 17C, 17D, & 17E). For instance, the surface-water TN concentrations inside the HID were higher than the groundwater TN concentrations inside the HID. However, outside the HID the TN concentrations were higher in the groundwater as opposed to the surface water. Overall, water samples collected outside the HID had consistently higher TN concentrations apart from NP-67 surface-water. Conversely, TP concentrations were low (less than 0.5 μmol L^{-1}) and similar at all sampling localities. Water collected at NP-67 had the highest TP concentrations in both groundwater and surface-water, while TSB had the lowest TP concentrations in both surface-water and groundwater, making it difficult to tell which area (inside or outside the HID) had the overall higher TP concentrations.

TOC concentrations were higher outside the HID in both the surface-water and groundwater. Surface-water TOC was always higher than groundwater TOC both inside and outside the HID. In general, NO_3^- concentrations were higher outside the HID in both the surface-water and groundwater, with the only exception being TSB groundwater which was lower than DO3 groundwater. Conversely, NH_4^+ concentrations were lower in the surface water outside the HID. In the groundwater outside the HID, NH_4^+ on average had higher concentrations than the groundwater inside the HID.

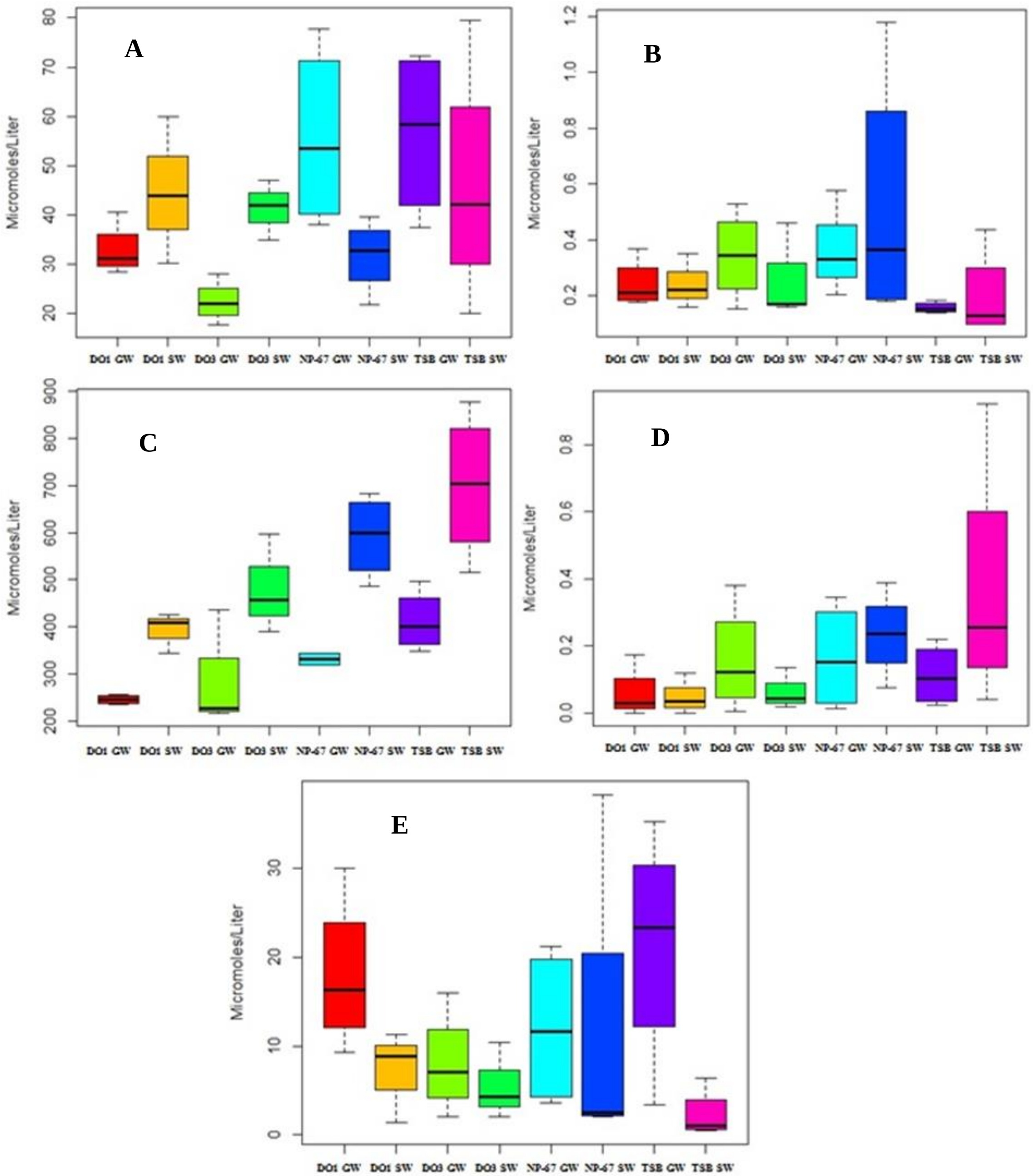

Figure 17. Box-and-whisker plots of total nutrients from inside and outside the HID: A) TN; B) TP; C) TOC; D) NO_3^-; E) NH_4^+. All values are reported in micromoles per liter.

Statistical Analysis

ANOVA & Tukey HSD Post-Hoc Analysis

Results of the ANOVA with respect to ions and nutrients revealed significant differences among sampling localities and TN ($p < 0.05$), TOC ($p < 0.001$), bicarbonate ($p < 0.01$), sodium ($p < 0.001$), potassium ($p < 0.001$), calcium ($p < 0.001$), and chloride ($p < 0.01$). No significant differences were observed among sampling locations in TP ($p = 0.37$), NO_3^- ($p = 0.26$), and NH_4^+ ($p = 0.20$). To further ascertain the significant differences observed in the ions and nutrients at the sampling localities, a Tukey HSD post-hoc analysis was employed to tease out differences between sites (Appendix D). The main finding of the post-hoc test was that the mean groundwater concentrations of TN, TOC, Na^+, K^+ and Mg^{2+} were always significantly higher at TSB than at DO1 or DO3. Similarly, mean surface-water concentrations of TOC, Na^+, K^+, and Mg^{2+} were always significantly higher at TSB than at DO1 or DO3.

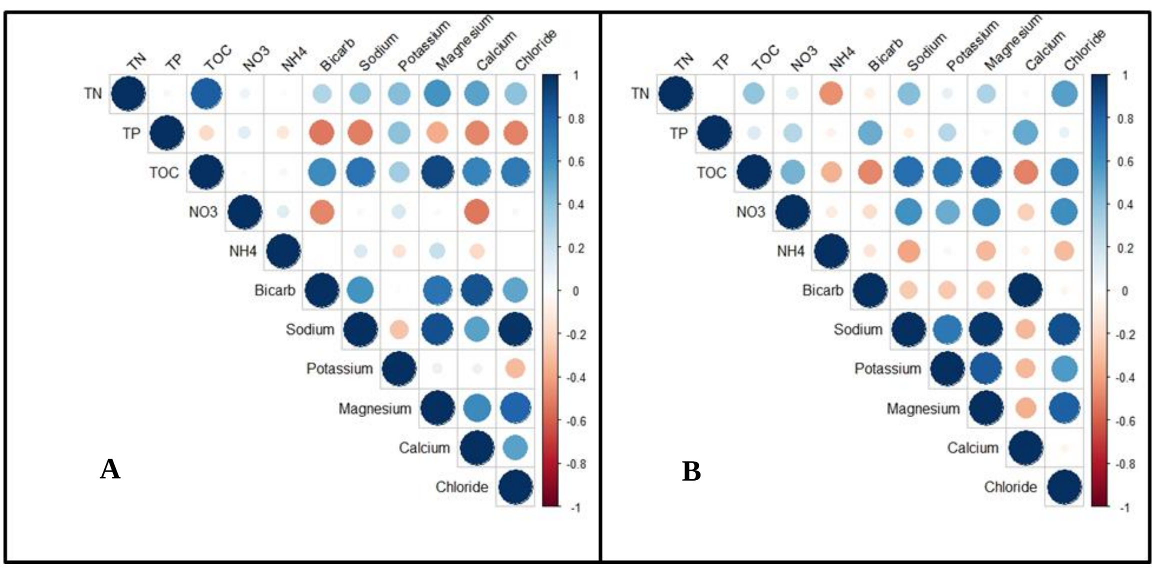

Figure 18. Correlation matrices for: A) groundwater; B) surface-water. Blue dots represent positive correlations and red dots represent negative correlations. The magnitude of the circle is proportional to the strength of the correlation.

IV. DISCUSSION

Changes in Groundwater Levels as a Function of Restoration

In general, changes in groundwater levels were not significantly related to the amount of acres restored ($p = 0.8$) in the HID. The main driver of water level change in the HID was rainfall, as indicated by the significant positive linear relationship obtained from the water balance between change in storage and rainfall (Figure 12). Furthermore, a significant positive relationship was observed between the long-term water level data obtained from DO1 and rainfall measured at RPL (Figure 8A). Conversely, there was no significant change in the direction of groundwater flow with respect to restoration.

The influence of rainfall as the primary driver of water levels presented in this study are consistent with previous research conducted in the southern Everglades. For example, time-series demodulation using Fourier analysis was conducted at a variety of well sites in the northern and southern Everglades and revealed that stage levels are directly impacted by rainfall, with large fluctuations in rainfall directly translating to large fluctuations in stage levels (Foti et al., 2015). Likewise, a water balance constructed by Zapata-Rios & Price (2012) indicated that precipitation was the greatest source of water into Taylor Slough. Interestingly, previous research conducted in the HID has demonstrated that CSR increased the duration of standing water (hydroperiod) in the restored sites (Smith et al., 2011 & Dalrymple et al., 2003). The increase in amount of flooded water observed throughout the year was a function of decreased elevation, as a result of completely removing the upper soil layer in the treated area, and seasonal rainfall. In fact, when the first pilot study was ongoing, the authors recognized that the

HID was far removed from canal structures and that the only source of water available for surface flooding was rainfall (Dalrymple et al., 2003).

The first hypothesis predicted that the CSR technique employed in the HID would result in an increase in observed water levels. This was predicted based on an intuitive sense that by completely removing the soil substrate, water would be allowed to percolate freely into the groundwater table, without any interception at the surface. This notion was supported by findings in the literature that top-soil removal in Dutch fen meadows had in fact increased the influence of groundwater seepage (Klimkowska et al., 2007; Klimkowska et al., 2015). However, these results did not hold true upon comparison to the southern Everglades. Firstly, the Dutch soil horizon was much more developed in the fen meadows (approximately 125 cm to water table), making the depth to the water-table significantly deeper than observed in the marl prairie portion of the southern Everglades. Secondly, the geologic substrates of the two study areas were not alike. The Netherlands aquifers are comprised of mostly sand and gravel units of Holocene to Pleistocene age, and have reported transmissivity values of approximately 10,000 m^2 day^{-1} (de Vries, 2007). In south Florida, one of the most productive aquifers in the world, the Biscayne Aquifer, is less than 50 cm from the soil surface in some areas and has reported transmissivity values of approximately 27,000 m^2 day^{-1} (Fish & Stewart, 1991).

Groundwater levels, relative to NAVD88, in the HID did not change after restoration, most likely due to the high infiltration rates and high hydraulic properties of the Biscayne Aquifer, allowing for a rapid assimilation of percolating rainwater to the groundwater table. Additionally, restoration was carried out over the course of many years, sometimes with several years in between treatments, so the influence of restoration on water levels could not be continuously monitored. The Dutch fen meadow case study may not have been the most appropriate analog to compare the HID restoration to, but it was one of the few studies available, since there is a dearth of literature on the subject of top-soil removal and the HID restoration is unique.

Changes in Evapotranspiration as a Function of Restoration

Overall, a negative trend in annual ET was observed throughout the study period and revealed that acres restored contributed significantly ($p < 0.001$) to the decrease in mean annual ET in the HID. The mechanism that produced the net loss in ET was most likely the decreased transpiration associated with the removal of the Brazilian Pepper. The MODIS maps (Figures 14 & 15) clearly depict that after each annual restoration there was an associated decrease in ET until 2005. After 2005 there was a three-year break until the next restoration in 2009. The increase in ET observed from 2009-2013 was probably a result of the previously restored areas regrowth of native plants, which could then contribute to the ET budget. Also, as restoration progressed, smaller plots were restored. For instance, the acres restored from 2000-2005 totaled 3082 acres. Conversely, from 2009-2014 only 802 total acres were restored. This would appear to explain why there was an observed increase up until 2013 followed by a decrease in 2014, as 31% of the total restoration between 2009-2014 occurred in 2014 (254 acres).

The range of ET values for Brazilian Pepper were between 1,040 and 1450 mm yr^{-1} before restoration and after restoration the range of values for the restored plots were between 585 and 1,030 mm yr^{-1}. The range of ET values reported in the present study (585-1450 mm yr^{-1}) were similar to values published for south Florida. For instance, Abtew (1996) used lysimeters to measure mixed marsh ET and open water/algae ET in south Florida over a one year period and found that mean ET rates for those ecosystems were 1277.5 mm $year^{-1}$ and 1350 mm $year^{-1}$, respectively. Furthermore, Douglas et al., (2009) measured ET rates from a variety of locations in south Florida, including two in the Everglades. The average ET for the two marsh sites, were 1410 mm $year^{-1}$ (Douglas et al., 2009). Likewise, Villalobos-Vega (2010) estimated ET for the Brazilian Pepper forest in the HID using White's method (1932) and found that the average ET was 1522 mm $year^{-1}$. While this estimate appears higher than predicted by the MOD16 algorithm, Villalobos-Vega (2010) cautioned that his ET measurements for the Brazilian Pepper forest may have been overestimated by the White method, as a result of the measurement taken in close proximity to a Hammock forest. We conclude that the MOD16 algorithm provides reasonable estimates of ET for the HID and for south Florida.

Land-cover change, especially deforestation, can decrease the amount of surface ET, and can even result in a decrease in the amount of precipitation over the deforested area (Mahmood et al., 2014). Furthermore, changes in vegetation type and density can cause changes in hydrologic fluxes and water storage (Bounoua et al., 2002). Likewise, land cover changes can alter the recycling of precipitation, with a reduction in evaporation leaving more water in the ground, thus altering the temporal distribution of precipitation, which may have an impact on climate (Bounoua et al., 2002). These examples illustrate that decreases in the mean annual ET can have profound impacts on climate in the area where the decrease in ET is observed. However, the findings from the present study cannot be extrapolated to suggest that reduction of ET in the HID promoted changes in climatic conditions, like the aforementioned research demonstrated. Firstly, the HID represents a small fraction (2800-ha) of the greater Everglades ecosystem (177, 965-ha), so it would not be reasonable to assume that such a localized change in ET could significantly impact the entire Everglades climate. Additionally, the amount of acres restored each year was small given the scope of the greater Everglades. The largest portion restored occurred in 2005 (404-ha), which represents 0.23% of the entire Everglades ecosystem. Finally, the HID restoration has been discontinuous, as large gaps between restoration episodes were observed throughout the years (e.g. 1990-1997; 2002; 2006-2008; 2012). The gaps between restorations provided the barren landscape with the opportunity to regrow and thus contribute to the total ET in the HID.

Changes in Groundwater Chemistry as a Function of Restoration

The water chemistry analyses indicate that groundwater and surface-water are significantly different inside the HID vs. outside the HID. The differences mainly occur between TSB and the HID wells, DO1 and DO3, with some differences occurring between NP-67 and the HID wells. In the groundwater, mean concentrations of TN, TOC, Na^+, K^+ and Mg^{2+} were always significantly higher outside the HID than inside the HID (Table 5). The surface-water followed a similar trend as mean concentrations of TOC, Na^+, K^+, and Mg^{2+} were always higher outside the HID than inside the HID. The only exception was between mean surface-water concentrations of HCO_3^- and Ca^{2+}, which were higher inside the HID vs outside HID. There were no significant differences observed in both the groundwater and surface-water between TP, NO_3^-, NH_4^+, or Cl^-. The chemical differences observed between TSB and the HID wells may indicate that groundwater does not exchange laterally between the wells even though they are adjacent. The HID may far enough into ENP to not be impacted by the release of canal water that is used to feed the headwaters of Taylor Slough. Additionally, removal of the Brazilian Pepper may facilitate lower concentrations of ions in the groundwater because of the absence of transpiration-driven ion accumulation (Sullivan et al., 2016). Furthermore, complete soil removal allows for rapid infiltration of rainwater to the karst aquifer with minimal contact time with geologic materials.

The third hypothesis was formulated around the idea that CSR would remove the elevated concentrations of nutrients previously found in the disturbed soils, thereby reducing concentrations in the groundwater and surface-water (Orth & Conover, 1975; Li and Norland, 2001). Research has been conducted domestically and around the world to evaluate the efficacy of top-soil removal as it pertains to reducing nutrient loads in soils. For example, Zak et al. (2015) showed that removal of highly decomposed peat soil layers on old agricultural lands supported wetland recovery to low nutrient conditions, especially with respect to P. Likewise, Klimkowska et al. (2015) and Verhagen et al. (2001) found that topsoil removal in Dutch fen meadows resulted in a decrease in nutrient availability, promoting reestablishment of less competitive fen-meadow species. Inside the HID, it has been established that removal of the altered, rock-plowed soil removes nutrients, thereby lowering nutrient availability (Smith et al., 2011). The chemistry data obtained from the present study supports the third hypothesis and also supports the literature that CSR reduces the nutrient availability in the restored wetland.

Table 5. Average concentrations of major ions and nutrients for groundwater and surface-water samples. Ion concentrations are reported in milligrams per liter and nutrient concentrations are reported in micromoles per liter.

Site	**HCO_3^- (mg/L)**	**Na^+ (mg/L)**	**K^+ (mg/L)**	**Mg^{2+} (mg/L)**	**Ca^{2+} (mg/L)**	**Cl^- (mg/L)**	**TN (µmol/L)**	**TP (µmol/L)**	**TOC (µmol/L)**	**NH_4 (µmol/L)**	**NO_3 (µmol/L)**
DO1 GW	256.52	9.3	0.42	1.99	81.89	18.43	32.84	0.24	246.75	18.01	0.06
DO3 GW	245.56	11.22	0.29	2.01	77.65	22.69	22.43	0.34	277.46	8	0.16
NP-67 GW	254.59	8.37	1.01	2.45	81.44	16.72	48.94	0.36	332.52	12.04	0.17
TSB GW	276.3	19.36	0.47	3.67	85.23	33.88	56.61	0.16	411.52	21.3	0.11
DO1 SW	264.07	10.29	0.41	2.18	81.35	21.45	44.69	0.24	393.26	7.17	0.05
DO3 SW	244.34	12.23	0.26	2.16	77.85	25.06	41.3	0.26	481.39	5.55	0.07
NP-67 SW	192.61	8.11	0.8	2.23	59.38	16.45	31.76	0.52	592.04	11.3	0.23
TSB SW	179.44	22.9	1.19	4.26	49.67	34.56	45.99	0.2	699.94	2.25	0.37

Unfortunately, this is the first study that has attempted to ascertain the concentrations of ions and nutrients in the HID's groundwater and surface-water and as a result must serve as a baseline for future temporal comparisons.

Inglett & Inglett (2013) evaluated the biogeochemistry of soils in the HID, specifically the ability of the soils to sequester macro-nutrients like N and P. They proposed that approximately 16 years post restoration, restored sites would undergo a shift from N-limitation to P-limitation (Figure 19) (Inglett & Inglett, 2013). The chemistry data from this study may support their claim. For instance, mean TN concentrations in groundwater and surface-water at DO1 were 32.8 μmol L^{-1} and 44.7 μmol L^{-1}, respectively, while mean TN concentrations in groundwater and surface-water at DO3 were 22.4 μmol L^{-1} and 41.3 μmol L^{-1}, respectively. The higher concentrations of TN in both groundwater and surface-water at DO1 suggests that DO1 is P-limited. Conversely, mean TP concentrations in groundwater and surface-water at DO3 were 0.34 μmol L^{-1} and 0.26 μmol L^{-1}, respectively, while mean TP concentrations in both groundwater and surface-water at DO1 were 0.24 μmol L^{-1}. The higher concentrations of TP in both groundwater and surface-water suggest that DO3 has yet to undergo the switch to P-limitation, or may be in the phase where it is co-limited with N. The land around DO1 was restored in 1989, 27 years before the time of this study. Conversely, the land around DO3 was restored in 2000, 16 years before this study. These results are consistent with Inglett and Inglett (2013) hypothesis and may be able to shed more light onto the topic of biogeochemical succession in subtropical calcareous freshwater wetlands like the HID. However, further groundwater and surface-water chemistry sampling is needed to assess when and if DO3 does switch to becoming fully P-limited, as hypothesized by Inglett & Inglett (2013).

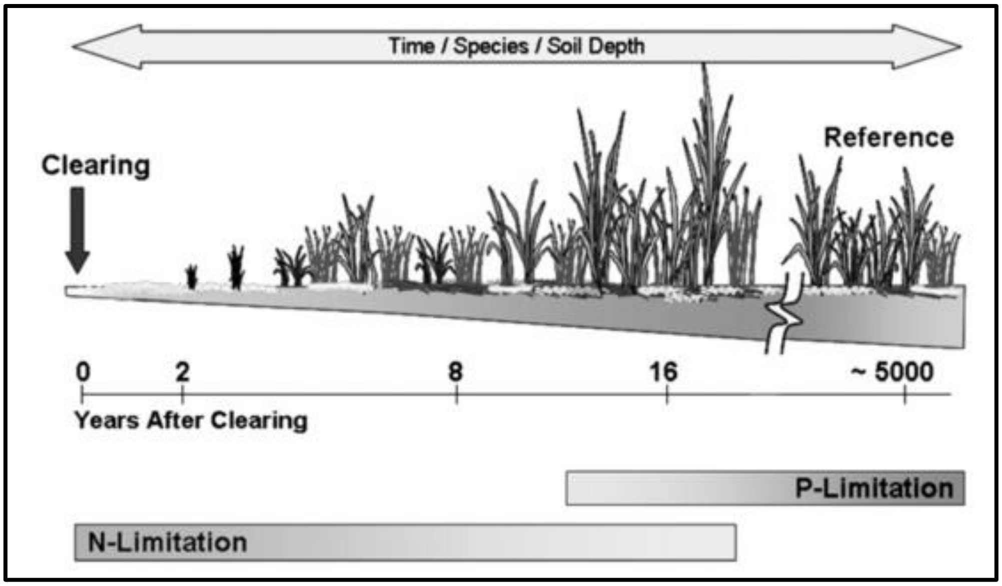

Figure 19. Conceptual model for biogeochemical succession in subtropical calcareous freshwater wetlands like the HID. Adapted from Inglett & Inglett (2013).

Recommendations for Restoration Managers and Future Research

The HID is a unique case study in the field of restoration ecology. The CSR technique, even to this day, is considered a costly and radical way to restore degraded wetlands (Hausman et al., 2007: Klimkowska et al., 2015). The estimated total cost of the HID restoration is $90-$120 million (ENP, 2009). While the cost must be considered for a project of this magnitude, the research is clear that CSR is an effective way to restore and revive native wetlands that have been overrun by noxious invasive species (Dalrymple et al., 2003; Doren et al., 1990; Smith et al., 2011). Furthermore, the restoration has been successful in its two main goals: eradicating the Brazilian Pepper and reducing elevation to increase hydroperiods (Smith et al., 2011 & Dalrymple et al., 2003). The present study has determined that the total number of acres scraped in the HID did not have a significant impact on groundwater levels, or groundwater flow direction. For restoration managers, this is an important result to consider. Before this study, it was unknown how the large-scale HID restoration impacted the surrounding wetland environment. The fact that restoration doesn't appear to change groundwater flow directions down gradient gives further credence to the viability of this restoration method.

The present study determined that ET was significantly reduced in areas restored. Now that there is a baseline for remotely sensed ET measurements in the HID, future studies can look at the progression of ET changes with respect to the actual vegetation on the ground. For instance, coupling remotely sensed ET data with ground-based empirical measurements of vegetation communities could provide useful information on how successional communities ET rates change along the restoration gradient. Additionally, it would be interesting to asses if the changes in mean ET in the HID have any sort of impact on microclimate variation, specifically with regards to rainfall. Future research in these areas would prove beneficial not only to restoration managers, but also to research scientists interested in how extreme restoration methods can impact fundamental components of the hydrologic cycle.

The water chemistry data presented in this study represent an important baseline for the HID restoration. The present study has demonstrated that chemical concentrations of nutrients and ions are significantly lower inside the HID vs. outside the HID. According to a technical report by O'Hare (2008), it was stipulated that for every 642 acres restored in the HID that one monitoring well should be installed. Currently, only two such monitoring wells exist (DO1 & DO3). Based upon the acreage restored through 2014 (~4893 acres), there should be 7 gauges on restored sites. If managers want more accurate measurements of water levels and wish to compare water chemistry between restored sites, these additional wells must be installed. The installation of these wells could allow future researchers the ability to interpolate water chemistry data to assess spatial variability solely inside the HID, with respect to major ions and nutrients. Besides the spatial component, these wells could provide temporal information that could be useful to see how the concentrations of major ions and nutrients change with respect to time. These data could provide valuable information pertaining to major ion and nutrient gradients that could expand the breadth of knowledge for restored subtropical calcareous wetlands.

V. CONCLUSIONS

Characterizing and quantifying the effects that the CSR restoration technique has on the hydrologic conditions of a restored wetland helped to support the long-term validity of the HID restoration program. A water balance model revealed that the controlling factor of groundwater level changes in the HID was rainfall and not acres restored. The total amount of acres restored did not significantly contribute to the changes in water levels observed. Additionally, the total amount of acres restored did not significantly alter the direction of groundwater flow to adjacent wetlands, suggesting that there are not harmful residual effects to the surrounding wetland environment as a result of restoration. The lack of an influence on groundwater levels and flow directions in the HID were most likely attributable to the small size of the HID compared to the extent of ENP, as well as to the high transmissivity of the Biscayne Aquifer. Caution should be given when applying the results obtained in this investigation with other CSR restoration sites having different geologic terrains.

Before the present study, it was not well understood how the effects of the CSR restoration technique impacted the mean annual ET rates in a restored wetland. In subtropical calcareous wetlands dominated by an invasive woody species, like in the HID with Brazilian Pepper, the CSR restoration technique reduced mean annual ET rates by approximately 18% from 2000 to 2014. The decrease in ET observed in the HID was likely too localized to have any significant impact on the amount of precipitation the central Everglades received annually, but this may be a topic for further research for other large wetlands undergoing long-term CSR restoration. Furthermore, analyzing how successional vegetation mean ET rates change along the restoration gradient could provide valuable data for restoration managers interested in community level ecosystem dynamics.

Groundwater and surface-water chemical analyses revealed significant differences between wells inside the HID (DO1 & DO3) and outside the HID (TSB & NP-67). The differences observed between the groundwater and surface-water suggest that restoration has been effective in reducing the concentrations of ions and nutrients in the soils of the HID. The subsequent reduction of soil nutrients has promoted lower concentrations in the groundwater and surface-water in the restored sites. The lowered concentrations of ions and nutrients are ideal for the reestablishment of natural oligotrophic conditions that existed prior to anthropogenic induced degradation of the landscape.

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APPENDIX A

Water Chemistry Data I: Cations and Anions

Sample Name	Collection Date	Na^{+} (mg/L)	K^{+} (mg/L)	Mg^{2+} (mg/L)	Ca^{2+} (mg/L)	HCO_3^{-} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)
DO1 SW	12/22/2015	10.25	0.66	2.17	77.43	255.86	19.66	0.10
DO1 GW	12/22/2015	9.37	0.54	2.03	78.59	250.78	17.59	0.01
DO3 SW	12/22/2015	12.29	0.49	2.16	78.82	250.98	24.26	BDL*
DO3 GW	12/22/2015	11.12	0.37	2.01	75.73	241.42	21.62	BDL
NP-67 SW	12/22/2015	5.92	0.79	1.89	49.63	156.81	10.28	BDL
NP-67 GW	12/22/2015	8.63	1.18	2.57	85.16	270.10	16.60	BDL
TSB SW	12/22/2015	12.72	0.73	2.82	50.58	195.25	1.10	0.25
TSB GW	12/22/2015	16.32	0.46	3.59	83.79	281.90	25.43	BDL
DO1 GW	5/17/2016	9.32	0.46	2.03	79.49	248.14	17.72	BDL
DO3 GW	5/17/2016	11.38	0.33	2.06	76.78	242.44	22.53	BDL
NP-67 GW	5/17/2016	8.40	1.10	2.39	78.45	247.32	16.38	0.01
NP-67 SW	5/17/2016	11.55	1.34	2.99	88.70	281.29	24.68	0.11
TSB GW	5/17/2016	16.76	0.34	3.50	83.64	280.68	28.72	BDL
TSB SW	5/17/2016	30.18	1.64	5.54	50.30	176.75	51.78	0.17
DO1 SW	9/16/2016	9.52	0.14	1.95	78.34	247.32	18.86	BDL
DO1 GW	9/16/2016	9.21	0.39	2.01	85.15	259.52	18.63	0.11
DO3 SW	9/16/2016	11.85	0.02	2.06	76.01	230.64	24.46	BDL
NP-67 SW	9/16/2016	6.85	0.26	1.81	39.80	139.73	14.39	BDL
NP-67 GW	9/16/2016	8.02	0.87	2.27	79.61	244.68	16.73	BDL
TSB SW	9/17/2016	23.19	1.23	3.99	37.22	132.00	39.13	BDL
TSB GW	9/17/2016	21.33	0.46	3.66	83.75	256.68	38.85	BDL
DO1 SW	12/16/2016	11.10	0.44	2.41	88.29	289.02	25.84	0.71
DO1 GW	12/16/2016	9.30	0.27	1.92	84.35	267.66	19.77	BDL
DO3 SW	12/16/2016	12.55	0.27	2.27	78.72	251.39	26.44	BDL
DO3 GW	12/16/2016	11.18	0.18	1.97	80.45	252.81	23.93	BDL
NP-67 GW	12/16/2016	8.44	0.89	2.56	82.56	256.27	17.17	BDL
TSB SW	12/16/2016	25.53	1.17	4.69	60.58	213.76	46.24	BDL
TSB GW	12/16/2016	23.01	0.62	3.94	89.73	285.97	42.51	BDL

* = Below Detection Limit

APPENDIX B

Water Chemistry Data II: Field Parameters

Sample Name	Collection Date	Time	Temp (°C)	Conductivity (µs/cm)	pH
DO1 SW	12/22/2015	9:14 AM	24.00	401	7.42
DO1 GW	12/22/2015	9:30 AM	24.80	421	7.29
DO3 SW	12/22/2015	10:54 AM	25.60	436	7.67
DO3 GW	12/22/2015	11:54 AM	25.20	426	7.28
NP-67 SW	12/22/2015	1:00 PM	24.70	284	7.3
NP-67 GW	12/22/2015	1:05 PM	25.80	452	7.12
TSB SW	12/22/2015	1:50 PM	25.80	325	7.91
TSB GW	12/22/2015	2:40 PM	25.50	507	7.17
DO1 GW	5/17/2016	9:40 AM	24.30	429	7.03
DO3 GW	5/17/2016	11:20 PM	24.80	476	7.09
NP-67 GW	5/17/2016	1:15 PM	25.40	487	7.06
NP-67 SW	5/17/2016	1:40 PM	27.10	528	7.18
TSB GW	5/17/2016	2:35 PM	26.20	505	7.01
TSB SW	5/17/2016	2:50 PM	34.80	576	7.73
DO1 SW	9/16/2016	8:57 AM	28.40	512	7.48
DO1 GW	9/16/2016	9:30 AM	26.70	473	7.57
DO3 SW	9/16/2016	10:40 AM	30.00	508	7.69
DO3 GW	9/16/2016	11:10 AM	29.10	406	7.51
NP-67 SW	9/16/2016	12:40 PM	30.70	298	7.49
NP-67 GW	9/16/2016	12:50 PM	25.70	468	7.38
TSB SW	9/17/2016	12:30 PM	33.60	419	7.99
TSB GW	9/17/2016	12:14 PM	27.80	601	7.18
DO1 SW	12/16/2016	9:00 AM	20.10	442	6.02
DO1 GW	12/16/2016	8:50 AM	24.50	442	6.00
DO3 SW	12/16/2016	11:15 AM	24.30	478	6.11
DO3 GW	12/16/2016	11:30 AM	23.10	451	6.03
NP-67 SW	12/16/2016	2:00 PM	22.10	406	6.02
NP-67 GW	12/16/2016	2:10 PM	25.60	480	6.10
TSB SW	12/16/2016	3:00 PM	25.40	594	6.24
TSB GW	12/16/2016	3:30 PM	26.00	477	6.18

APPENDIX C

Water Chemistry Data III: Nutrients

Sample Name	Collection Date	TN (µmol/L)	TP (µmol/L)	TOC (µmol/L)	NO_3 (µmol/L)	NH_4 (µmol/L)	SRP (µmol/L)
DO1 GW	12/22/2015	28.49	0.37	257.50	0.03	30.10	BDL*
DO1 SW	12/22/2015	30.18	0.16	344.46	0.03	11.33	BDL
DO3 GW	12/22/2015	17.72	0.40	217.42	0.08	15.95	BDL
DO3 SW	12/22/2015	34.97	0.17	389.42	0.02	4.28	BDL
NP-67 GW	12/22/2015	42.16	0.20	321.33	0.01	3.58	BDL
NP-67 SW	12/22/2015	21.81	0.19	486.50	0.08	38.33	0.28
TSB GW	12/22/2015	37.50	0.16	348.17	0.05	35.26	BDL
TSB SW	12/22/2015	20.06	0.10	514.92	0.04	1.47	BDL
DO1 GW	5/17/2016	30.81	0.23	235.33	0.17	14.86	0.14
DO3 GW	5/17/2016	21.60	0.29	230.83	0.38	7.85	BDL
NP-67 GW	5/17/2016	38.05	0.33	319.00	0.35	18.33	BDL
NP-67 SW	5/17/2016	39.66	1.18	682.67	0.25	2.31	BDL
TSB GW	5/17/2016	46.40	0.14	376.58	0.16	21.09	BDL
TSB SW	5/17/2016	44.31	0.10	876.67	0.23	0.47	BDL
DO1 GW	9/16/2016	40.65	0.19	242.17	0.00	17.80	0.04
DO1 SW	9/16/2016	59.91	0.22	426.33	0.00	1.37	0.10
DO3 GW	9/16/2016	28.12	0.53	437.33	0.16	2.01	BDL
DO3 SW	9/16/2016	47.06	0.16	597.17	0.04	1.99	0.03
NP-67 GW	9/16/2016	77.70	0.33	344.33	0.26	21.22	BDL
NP-67 SW	9/16/2016	31.68	0.18	552.83	0.22	2.57	BDL
TSB GW	9/16/2016	72.30	0.14	424.00	0.22	25.52	BDL
TSB SW	9/17/2016	79.53	0.16	762.67	0.28	0.66	BDL
DO1 GW	12/16/2016	31.41	0.18	252.00	0.03	9.29	0.06
DO1 SW	12/16/2016	43.98	0.35	409.00	0.12	8.82	0.01
DO3 GW	12/16/2016	22.29	0.15	224.08	0.01	6.21	0.04
DO3 SW	12/16/2016	41.87	0.46	457.58	0.14	10.37	BDL
NP-67 GW	12/16/2016	64.98	0.58	345.42	0.05	5.03	0.12
NP-67 SW	12/16/2016	33.91	0.54	646.17	0.39	2.00	0.02
TSB GW	12/16/2016	70.23	0.18	497.33	0.03	3.34	0.04
TSB SW	12/16/2016	40.06	0.44	645.50	0.92	6.40	0.01

* = Below Detection Limit

APPENDIX D

Tukey HSD Table

Comparison Between Location	**Constituent**	**p-value**
NP-67 SW-DO1 SW	HCO_3^-	0.10
TSB SW-DO1 SW	HCO_3^-	0.03
TSB GW-DO1 GW	Na^+	0.01
TSB SW-DO1 SW	Na^+	0.00
TSB GW-DO3 GW	Na^+	0.07
TSB SW-DO3 SW	Na^+	0.01
NP-67 GW-DO1 GW	K^+	0.08
TSB SW-DO1 SW	K^+	0.02
NP-67 GW-DO3 GW	K^+	0.04
TSB SW-DO3 SW	K^+	0.00
TSB GW-DO1 GW	Mg^{2+}	0.00
TSB SW-DO1 SW	Mg^{2+}	0.00
TSB GW-DO3 GW	Mg^{2+}	0.01
TSB SW-DO3 SW	Mg^{2+}	0.00
TSB SW-DO1 SW	Ca^{2+}	0.01
TSB SW-DO3 SW	Ca^{2+}	0.02
NP-67 GW-DO3 GW	TN	0.06
TSB GW-DO3 GW	TN	0.05
NP-67 SW-DO1 SW	TOC	0.10
TSB SW-DO1 SW	TOC	0.00
TSB SW-DO3 SW	TOC	0.06