Simulating water table response to proposed changes in surface water management in the C-111 agricultural basin of south Florida

I. Kisekka, K. W. Migliaccio, R. Muñoz-Carpena, B. Schaffer, T. H. Boyer, and Y. Li

Published Version Information

Citation: Kisekka, I., Migliaccio, K. W., Muñoz-Carpena, R., Schaffer, B., Boyer, T. H., & Li, Y. (2014). Simulating water table response to proposed changes in surface water management in the C-111 agricultural basin of south Florida. Agricultural Water Management, 146, 185-200.

Digital Object Identifier (DOI): doi:10.1016/j.agwat.2014.08.005

Publisher's Link:
http://www.sciencedirect.com/science/article/pii/S0378377414002443#

Simulating water table response to proposed changes in surface water management in the C-111 agricultural basin of south Florida

I. Kisekka[ab], K.W. Migliaccio[b], R. Muñoz-Carpena[c], B. Schaffer[b], T. H. Boyer [d], and Y. Li[b]

Kansas State University, Southwest Research-Extension Center, 4500 E. Mary St., Garden City, KS 67846, E-mail: ikisekka@ksu.edu [a]

University of Florida, IFAS Tropical Research and Education Center 18905 SW 280th St Homestead, FL 33031, klwhite@ufl.edu, bas56@ufl.edu, yunli@ufl.edu [b]

University of Florida, Agricultural and Biological Engineering Department, P. O. Box 110570, Gainesville, FL 32611, carpena@ufl.edu [c]

University of Florida, Environmental Engineering Sciences Department, P.O. Box 116450, Gainesville, FL 32611, thboyer@ufl.edu [d]

[b]Corresponding author: Kati W. Migliaccio; Tel.: +1 305-246-7001 x288; fax: +1 305-246-7003.

E-mail address: klwhite@ufl.edu.

Abstract

As part of an effort to restore the hydrology of Everglades National Park (ENP), incremental raises in canal stage are proposed along a major canal draining south Florida called C-111, which separates ENP from agricultural lands. The study purpose was to use monitoring and modeling to investigate the effect of the proposed incremental raises in canal stage on water table elevation in agricultural lands. The objectives were to: (1) develop a MODFLOW based model for simulating groundwater flow within the study area, (2) apply the developed model to determine if the proposed changes in canal stage result in significant changes in water table elevation, root zone saturation or groundwater flooding and (3) assess aquifer response to large rainfall events. Results indicate the developed model was able to reproduce measured water table elevation with an average Nash-Sutcliffe > 0.9 and Root Mean Square Error < 0.05 m. The model predicted that incremental raises in canal stage resulted in significant differences ($p < 0.05$) in water table elevation. Increases in canal stage of 9 and 12 cm resulted in occasional root zone saturation of low elevation sites. The model was able to mimic the rise and fall of the water table pre and post Tropical Storm Isaac of August 2012. The model also predicted that lowering canal stage at least 48 hours prior to large storm (>2 year return period storm), reduced water table intrusion into the root zone. We conclude that the impact of operational changes in canal stage management on root zone saturation and groundwater flooding depended on micro-topography within the field and depth of storm events. The findings of this study can be used in fine tuning canal stage operations to minimize root zone saturation and groundwater flooding of agricultural fields while maximizing environmental benefits through increased water flow in the natural wetland areas. This study also highlights the benefit of detailed field scale simulations.

Key words: Water table, Root zone, Groundwater flooding, MODFLOW, Canal-aquifer interactions

1. Introduction

The C-111 canal constructed in 1966 is the southernmost canal of the central and south Florida canal system and serves a 259 square-kilometer basin. The primary function of the C-111 canal system is to provide flood protection and drainage for agricultural areas along the eastern boundary of Everglades National Park (ENP). Taylor Slough is a natural drainage feature of the Everglades that empties its fresh water into Florida Bay (Fig. 1). Past dredging of the C-111 canal redirected water flow, causing water to flow east from ENP into C-111 (Fig. 1). This resulted in reduced flows in Taylor Slough which impacted water quality, fisheries and ecology of Florida Bay (U.S. Army Corps of Engineers [USACP] and South Florida Water Management District [SFWMD], 2011). The re-direction of water flows to the east results in approximately 6.4 million cubic meters of water a day to be removed from the Taylor Slough system (US Army Corps of Engineers, 2009).

To address some of the unintended consequences of the canal system, hydrological modifications are occurring in south Florida as part of the Comprehensive Everglades Restoration Plan (CERP), which has the overall goal of restoring the natural ecosystem that was negatively impacted by an extensive canal network originally constructed to allow for development and provide flood protection (United States Geological Survey [USGS], 1999). One of the 68 components of the CERP is the C-111 spreader canal project (U.S. Army Corps of Engineers [USACP] and South Florida Water Management District [SFWMD], 2011). Through operational adjustments and structural modifications, the goal of the C-111 spreader canal project is to restore the quantity, timing and distribution of water delivered to Florida Bay via Taylor Slough to levels as near as possible to pre-drainage conditions, while maintaining flood protection for nearby agricultural lands. In addition, there is a goal to restore hydroperiods that support pre-drainage vegetation patterns in ENP. To achieve the objectives, operational adjustments are proposed that include incrementally raising the canal stage by 3.0 cm per year up to a maximum of 12.0 cm at structure S-18C which is a gated spillway (Fig. 1).

It is anticipated that raising the C-111 canal stage will affect water table levels in the adjacent agricultural fields (Fig. 1). Earlier research has indicated substantial interaction between the highly permeable Biscayne aquifer and surface water in south Florida canals (Graham et al., 1997; Genereux and Slater, 1999; Lal, 2001; Ritter and Muñoz-Carpena, 2006). The hydraulic connection between the Biscayne aquifer and the C-111 canal causes the shallow water table system to fluctuate with respect to changes in canal stage. An increase in water table elevation, due to a rise in canal stage could result in prolonged root zone saturation or temporary groundwater flooding (groundwater flooding occurs in low-lying areas when the water table rises above the land surface [USGS, 2000]) which could affect agricultural production in agricultural areas adjacent to ENP. Prolonged saturation of the root zone or short-term groundwater flooding could impact yield potential through impaired root growth caused by anoxia, reduced stomatal conductance and net CO_2 assimilation (Schaffer, 1998). It is not known how the proposed operational adjustments (involving incremental raises in canal stage) along the C-111 canal would impact water table elevation which would in turn impact optimum crop growth in adjacent farmlands.

MODFLOW, a widely used numerical groundwater flow computer code from the United States Geological Survey (USGS), has previously been used in investigations of canal-aquifer interactions in south Florida (Wilsnack et al., 2000; Bolster et al., 2001; Saier et al., 2004; Hughes et al., 2012). In MODFLOW modeling, various approaches exist for representing a surface water body either as a head dependent boundary using the river package (McDonald and Harbaugh, 1988) or by using more complex approaches that implicitly couple a numerical open channel flow model to MODFLOW such as MODBRANCH developed by Swain (1996). Although MODFLOW based groundwater flow models have been used to simulate Biscayne aquifer in south Florida (Hughes et al., 2012), most of these models are regional and lack the spatial resolution to address water resources issues at a field scale, particularly groundwater flooding issues in agricultural fields that are influenced by small scale micro-topography. For example Brion et al. (2001) used the South Florida Regional Simulation Model in the south Florida Everglades with a grid size of 3.2 km x 3.2 km.

The purpose of the present study was to investigate through monitoring and modeling the effect of the proposed incremental raises in the C-111 canal stage on water table elevation levels in agricultural fields adjacent to ENP. The objectives were to: (1) develop a MODFLOW based model for simulating groundwater flow within the study area, (2) apply the developed model to determine if the proposed changes in canal stage result in significant changes in water table elevation, root zone saturation or groundwater flooding and (3) assess aquifer response to large rainfall events and explore the effect of pre-storm canal stage drawdown in the mitigation of root zone saturation and groundwater flooding of agricultural lands.

2. Materials and methods

2.1 Study Area

The study was conducted in southern Miami-Dade County, close to Homestead, Florida, United States in a small agricultural area approximately 17 km^2 (Fig. 1). The area is located east of ENP between SFWMD canals C-111 and C-111E which are planned to experience increases in canal stage under the C-111 spreader canal project. The topography at this site is close to flat with elevation ranging approximately between 1.2 to 2.0 m National Geodetic Vertical Datum (NGVD) 29. The climate is subtropical with warm wet summers and mild and dry winters. Annual mean temperature is 25°C, mean annual rainfall is 1460 mm. Typically evapotranspiration is 60 to 70% of rainfall (Duever et al., 1994). Canal stage upstream in the two canals is controlled by a remotely operated spillway at S177 and a culvert at S178, respectively. C-111 is the larger of the two canals and the two join to become a single canal at the southern end of the study area which is managed using a gated spillway at S18C. It is proposed that stage will be increased by modifying operation of S18C and thus affect canal stage in the reach of C-111 between S177 and S18C. A groundwater flow model was applied to predict the impact of proposed canal stages on water table elevation in the adjacent agriculture areas.

Data from six groundwater observations wells were used (Table 1). Data were collected from August 2010 to March 2013. Observation wells 4 and 6 were maintained by the SFWMD while the other wells

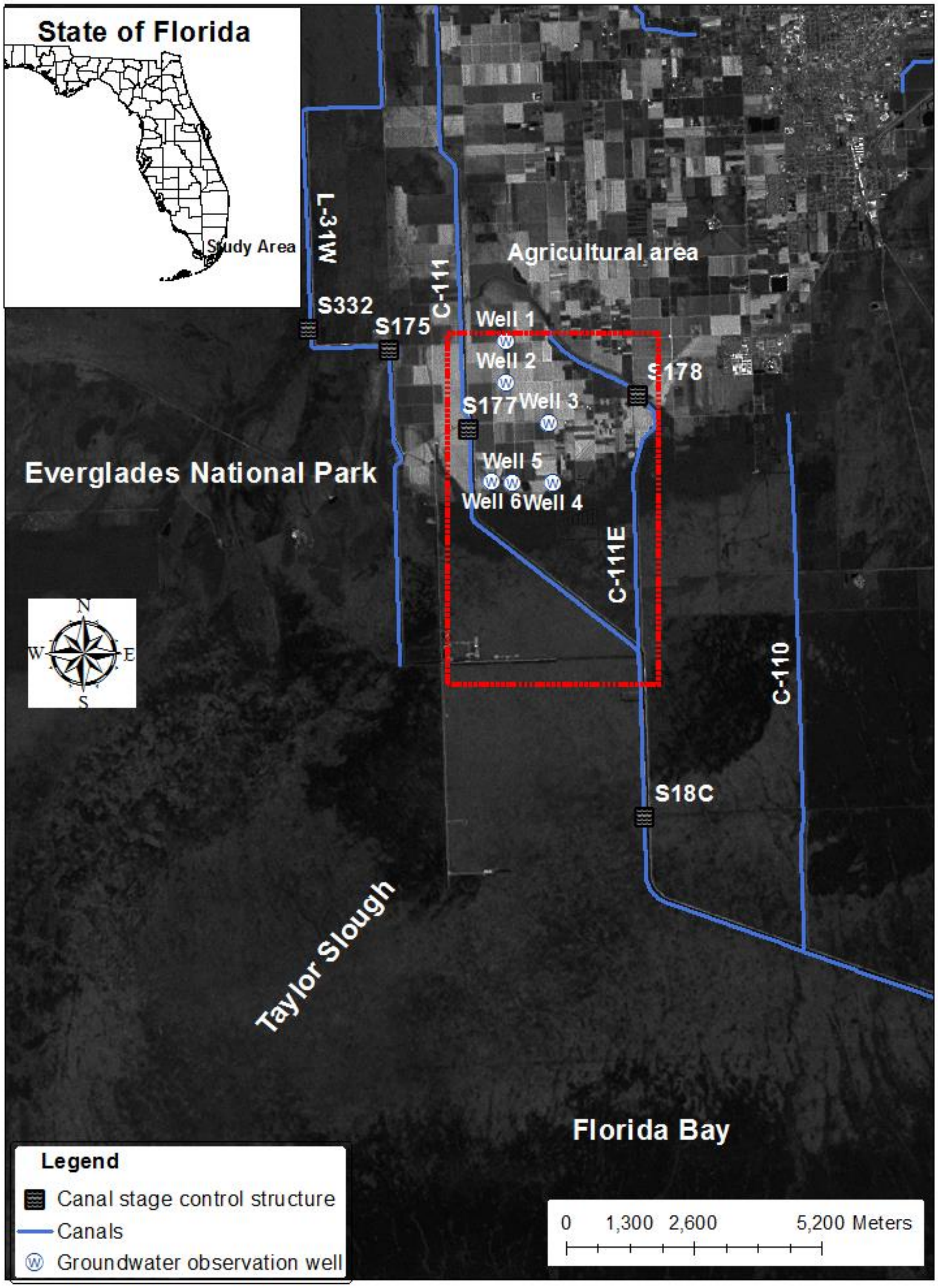
(1, 2, 3, and 5) were maintained by University of Florida (UF), IFAS (Kisekka et al., 2013a). UF wells were equipped with level loggers (Levelogger, Gold Solinst Canada Ltd., 35 Todd Rd, Georgetown, Ontario, Canada) to record water table elevation every 15 minutes although daily averages were used in modeling. UF observation wells were drilled to a depth of 6m. Atmospheric corrections were accounted for using a STS Barologger (Solinst Canada Ltd) in well 5 (Fig. 1). Data were downloaded weekly and as a quality control procedure, water table elevations were also measured manually with a Model 102 laser water level well meter (Solinst, Canada Ltd). Elevations at the top of the well manholes were measured using a laser level with reference to a SFWMD bench mark with elevation 1.19 m NGVD29 near well 4. Water table elevation data for wells 4 (C-111AE) and 6 (C-111AW) drilled to a depth of 4 m were processed by SFWMD and published on DBHydro (http://www.sfwmd.gov/dbhydroplsql/show_dbkey_info.main_menu).

2.2 Hydrologic system

The highly permeable Biscayne aquifer system comprises of rocks (primarily limestone) and sediments. The hydrogeology of Biscayne aquifer consists of two limestone formations: Miami limestone formation (3-9 m) overlying the Fort Thompson limestone formation (10-14 m). The top of the aquifer is the land surface (with a thin scarified soil layer) while the bottom of the aquifer is a semi confining layer that separates the surficial Biscayne aquifer from the less permeable Tamiami and Hawthorn formations. Detailed lithological logs and descriptions of the geology of Biscayne aquifer can be found in Causaras (1987). Fisher and Stewart (1991) reported that hydraulic conductivity of Biscayne aquifer limestone formations could exceed 10,000 m/day. The high hydraulic conductivities could be attributed to secondary-solution cavities in the limestone formation. The cavities are typically less than 2" in diameter but they are very abundant making the aquifer behavior like a sponge (Fisher and Stewart, 1991). This could also explain the high connectivity between the canals and the aquifer. Fisher and Stewart (1991) also noted that there were significant local variations in hydraulic conductivity within the aquifer.

Field determination of hydrogeologic parameters using pumping tests is very challenging for highly conductive geologic formation such as those found in the Biscayne aquifer. Genereux and Guardiario (1998) attributed it to the following reasons: 1) very large pumps and conveyance systems that usually required for producing a drawdown large enough to be measured, 2) large amounts of water generated that have to be deposed of and 3) violation of assumptions made in the analysis of well pumping data. Through a large scale canal drawdown experiment Genereux and Guardiario (1998) also reported a thickness of 13.6 m for our current study site with roughly one third (~4.5 m) accounted for by the Miami limestone formation. Kisekka et al. (2013b) applied inverse modeling using a quasi-canal-aquifer interaction model and estimated Biscayne aquifer thickness at our study site to range between 13.5 and 18.2 m). Specific yield at our study site was estimated as 0.102 (ranging between 0.07 and 0.13) by Kisekka et al. (2013b) which is within range of 0.15 estimated using a large scale canal drawdown by Bolster et al. (2001). Canal-aquifer interaction hydraulic parameters will be determined using inversing modeling in the present study.

Canal C-111 was constructed in 1966 as the principle flood control canal for south Miami-Dade County and partially penetrates the Biscayne aquifer to a depth of approximately 5 m (i.e., 4 m through the Miami Limestone formation and 1 m into the Fort Thompson Limestone formation). Flow in C-111 is south towards Florida Bay and topography is essentially flat ranging between 1.0 to 2.2 m National Geodetic Vertical Datum (NGVD) 29. The width of the canal increases towards the south with an average of approximately 29 m at the S177 gated spillway (Fig. 1). Currently little is known about hydraulic properties of canal bed sediment in the lower C-111; however, presence of a low permeability canal bed sediment layer which is a mixture of carbonate mud and natural organic matter in several canals within the C-111 basin has been documented (Chin, 1991; Genereux and Guardiario, 1998; Merkel, 2000). Using inverse modeling and a quasi-canal-aquifer interaction model, Kisekka et al. (2013b) estimated the ratio of canal bed thickness to bed sediment hydraulic conductivity as 0.015 (ranging between 0.009 and 0.020) days which is close to the 0.029 days estimated by Bolster et al. (2001) for nearby canal L-31W (Fig. 1).


State of Florida
Study Area
L-31W
C-111
S332
S175
Agricultural area
Well 1
Well 2
S178
S177
Well 3
Everglades National Park
Well 5
Well 6
Well 4
C-111E
N
W
E
S
C-110
S18C
Taylor Slough
Florida Bay
Legend
Canal stage control structure
Canals
Groundwater observation well
0 1,300 2,600 5,200 Meters

164

Figure 1. Study area showing groundwater monitoring sites, agricultural lands adjacent to Everglades National Park (ENP), and canal network within the C-111 basin of south Miami-Dade County, Florida and the modeled area is enclosed in the red box.

Table 1. Water table elevation monitoring sites with descriptors.

[1]Site name	Distance from canal C-111 (m)	Ground surface elevation (m) NGVD29	Latitude	Longitude
Well 1	1000	2.07	25.41883	-80.550041
Well 2	1000	1.86	25.41110	-80.550375
Well 3	2000	2.07	25.40347	-80.541933
Well 4	2000	1.19	25.39261	-80.541605
Well 5	1000	2.23	25.39317	-80.553724
Well 6	500	1.21	25.39283	-80.549543

2.2 Numerical model

A 2D (two dimensional) conceptual model in (Fig. 2) shows the location of the canals, Biscayne aquifer limestone layers, observation wells and surface topography. The hydrogeologic system was modeled as a one layer unconfined aquifer with 2D horizontal flow similar to the approach used by Bolster et al. (1998). The assumption of predominately horizontal flow was based on earlier investigations by Genereux and Guardiario (1998) that showed generally zero difference between piezometers installed at various depths into the Biscayne aquifer. Recently Brakefield (2012) has also demonstrated using stochastic MODFLOW simulations that conceptualizing Biscayne aquifer as 2D one layer flow system was adequate for describing subsurface flow within the aquifer.

MODFLOW was used to simulate groundwater flow in the agricultural lands adjacent to C-111 canal. The governing equation for saturated flow in porous media implemented in MODFLOW is (McDonald and Harbaugh, 1988; Harbaugh et al. 2000):

$$S_s \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + W \qquad (1)$$

where h [L] is the hydraulic head or water table elevation, S_s [L^{-1}] is the specific storage of the porous media, K_{xx}, K_{yy}, and K_{zz} [L T^{-1}] are hydraulic conductivity along the x, y, and z directions, t is time [T], W [T^{-1}] is a source/sink term, with $W > 0$ for flow into the aquifer and $W < 0$ for flows out of the aquifer. Due to its computational efficiency and the improved ability to control the conversion between wet and dry cells, the Preconditioned Conjugate-Gradient (PCG) package was used to solve the finite difference equations at each time step of the MODFLOW stress period. For unconfined flow, MODFLOW modifies Eq. 1 by substituting the specific storage with the specific yield and allows transmissivity to vary based on the changes in aquifer saturated thickness.

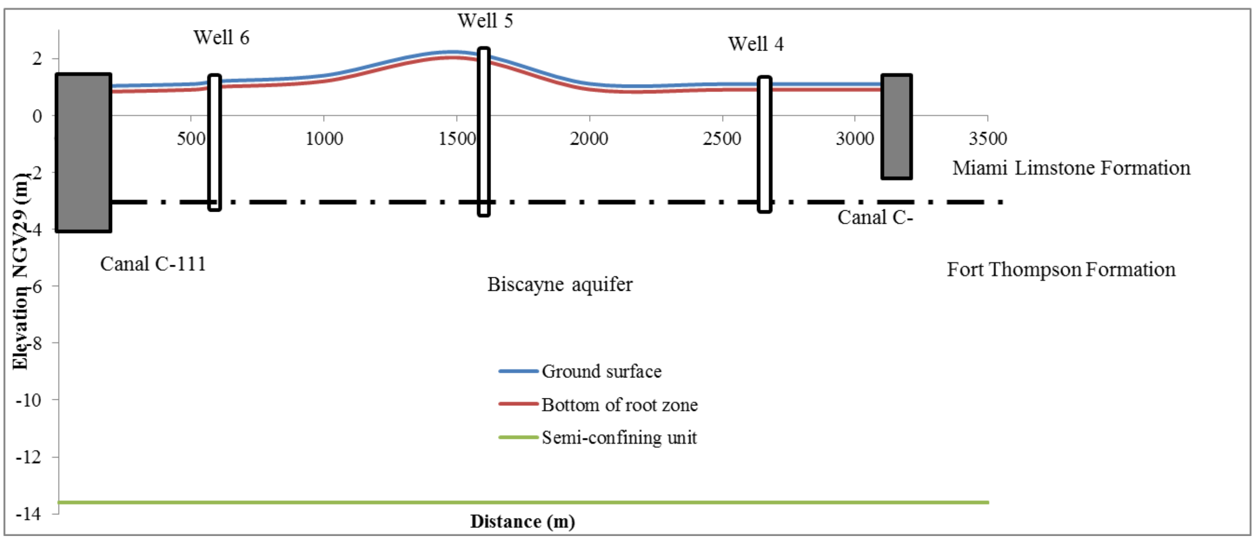


Figure 2. Conceptual model of the study area showing topography, location of observation wells, canals and Biscayne aquifer limestone layers.

2.2.1 Boundary conditions

The following boundary conditions were used in the simulation: canals stage, evapotranspiration, and recharge. Fig. 3 shows time series of the boundary, observed water table levels and rainfall during the study period. The bottom boundary was described as a no-flow boundary consistent with observed 2D horizontal flow in the study area. Canals C-111 and C-111E formed the west, east, and south boundaries of the flow domain. C-111 is the larger of the two canals with an average width of 29 m near the gated spillway at structure S177. Both canals partially penetrate the Biscayne aquifer with C-111 having an average depth of approximately 5 m. Water levels in C-111E are controlled using a gated culvert at structure S178 (Fig. 1). C-111E joins C-111 at the southern tip of the flow domain to become one canal.

Surface water-groundwater interactions were simulated using the RIVER (RIV) package. The RIV package was selected as a simple and adequate representation of the interaction between the C-111 canals and Biscayne Aquifer. Canal stage data for reaches of C-111 and C-111E surrounding the study area were obtained from DBHydro. In the RIV package both canal stage and canal conductance (Eq. 2) control the extent of water exchange between the aquifer and the canals.

$$C = \frac{K_s * L * W}{d} \qquad (2)$$

where C is canal conductance [L^2T^{-1}], K_s is the hydraulic conductivity of the low permeability bed sediment [LT^{-1}], W is the width of the canal [L], L is the length of the canal reach [L], and d is the thickness of the sediment layer [L]. The canal conductance multiplier in MODFLOW was set to range between 702 and 1560 m^2/day for headwater and tail water reaches of C-111 based on estimates of the K_s/d ratio by Kisekka et al. (2013b). Given the substantially smaller size of C-111E compared to C-111, canal conductance multiplier for C-111E was set to values ranging from 200 to 500 m^2/d with lower values assigned to the headwater side of the S178 gated culvert. Given the relatively flat topography, the average of tailwater canal stage at S177T and the headwater stage at S18C were used to represent the west and south boundary conditions for all cells downstream of S177 while head water canal stage at S177H was used to represent canal stage for all cells north of S177. Similarly, canal stage at S178 (tail waters) and S18C (headwaters) represented the east boundary condition for all cells. Canal stage data were measured by the SFWMD and are publically available on DBHydro. The northern boundary was described as a general head boundary using groundwater levels from a well installed by University of Florida IFAS (i.e., well 1).

Evapotranspiration was simulated using the EVT package in MODFLOW (McDonald and Harbaugh, 1988) in which the elevation of the evapotranspiration surface was set to 1.0 m and the evapotranspiration extinction depth to 0.9 m based on ranges reported in Chin (2008) and water table elevation recorded during the study period. We assumed that for water table depths less than 1 m from the land surface, evapotranspiration occurred at the potential rate which was computed from micro-meteorological data obtained from a Florida Automated Weather Network (FAWN; http://fawn.ifas.ufl.edu/) station located 15 km northeast of the study site. The American Society of Civil Engineers (ASCE) standardized Penman–Monteith equation and the REF-ET tool by Allen (2011) were used to estimate ET_o values.

Recharge to the aquifer was simulated using the RCH package. The recharge amount entering groundwater was calculated as the difference between rainfall and evapotranspiration. A recharge value was assigned to each stress period which was one day. To minimize the uncertainty associated with spatial variability of rainfall in south Florida, gauge adjusted NEXRAD (Next Generation Radar) rainfall data were used (Skinner et al., 2008).

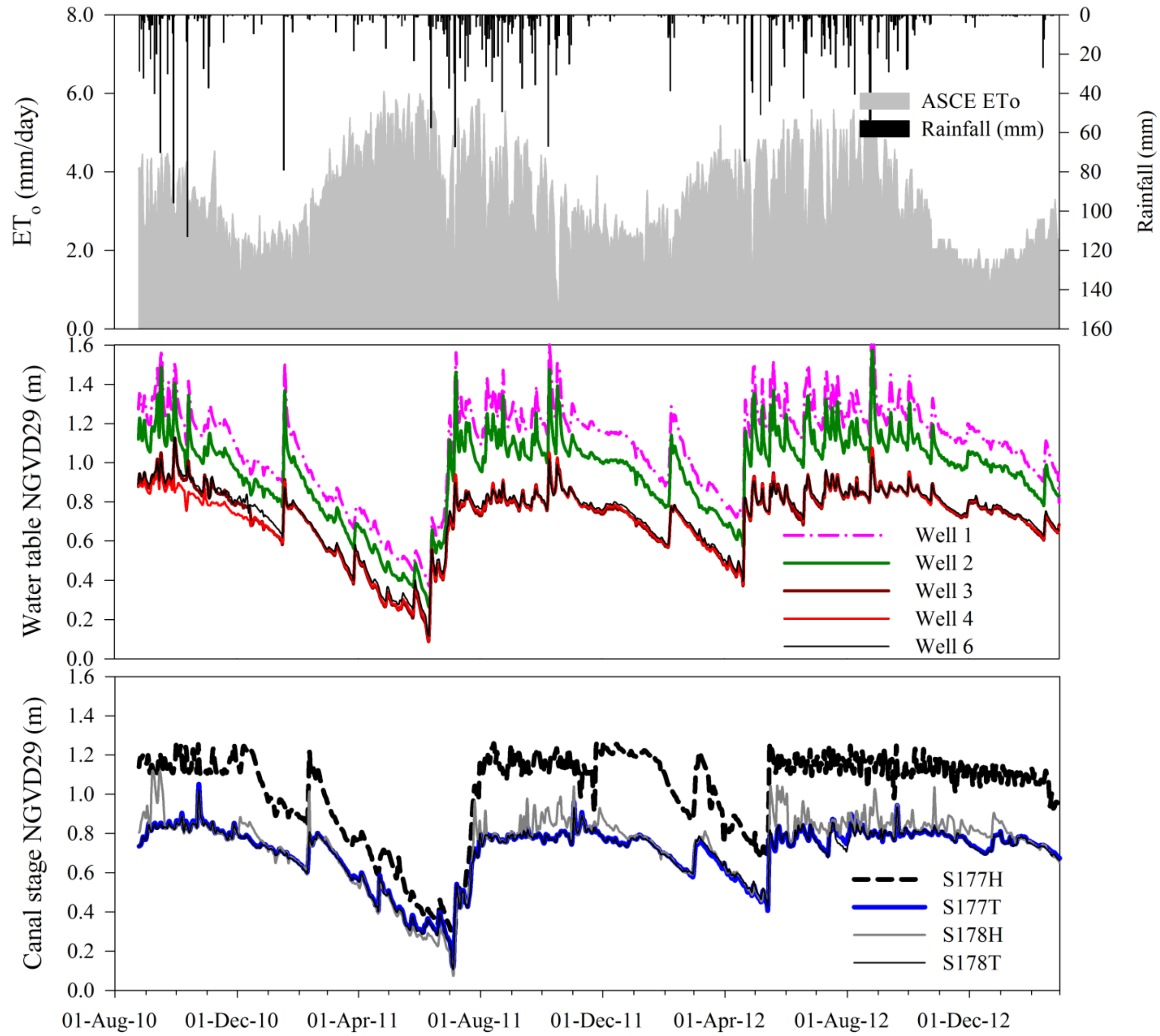


Figure 3.Time series of boundary conditions (canal stage, rainfall and evapotranspiration) and observed water table elevations.

2.2.2 Space and time discretization

The finite difference grid consisted of a single layer covering approximately 17 km^2. The model layer was discretized into 69 rows (running east to west) and 46 columns (fig. 4). Nodal spacing for the columns ranged from 53.5 m to 105.6 m from west to east with the smallest spacing closest to the canal since this is where greater changes in hydraulic head would be expected. Nodal spacing for the rows was constant over the model domain and set to 100.6 m. Further reductions in discretization did not appear to improve simulation results. All the spatial discretization was implemented using a pre and post processor for MODFLOW called MODFLOW Graphical User Interface Plug-In Extension (GUI-PIE) version 4.34.00, an Argus One Plug-In Extension (PIE) (Winston, 2000).

The model simulated conditions from 25 August 2010 to 28 February 2013. The time step and stress period sizes were set to one day; the multiplier was also set to one day. The period from 25 August 2010 to December 2011 was used to calibrate the model, while the data from 01 January 2012 to 28 February 2013 was used to validate the model. It was assumed that canal stage did not change during each stress period which was reasonable because 24-hour variations in canal stage were small unless a large rain event occurred or an operational change in canal stage management was implemented. Initial conditions over the model domain were obtained from observation well data at the start of the simulation and interpolated over the model domain using Argus ONE interpolation utilities.

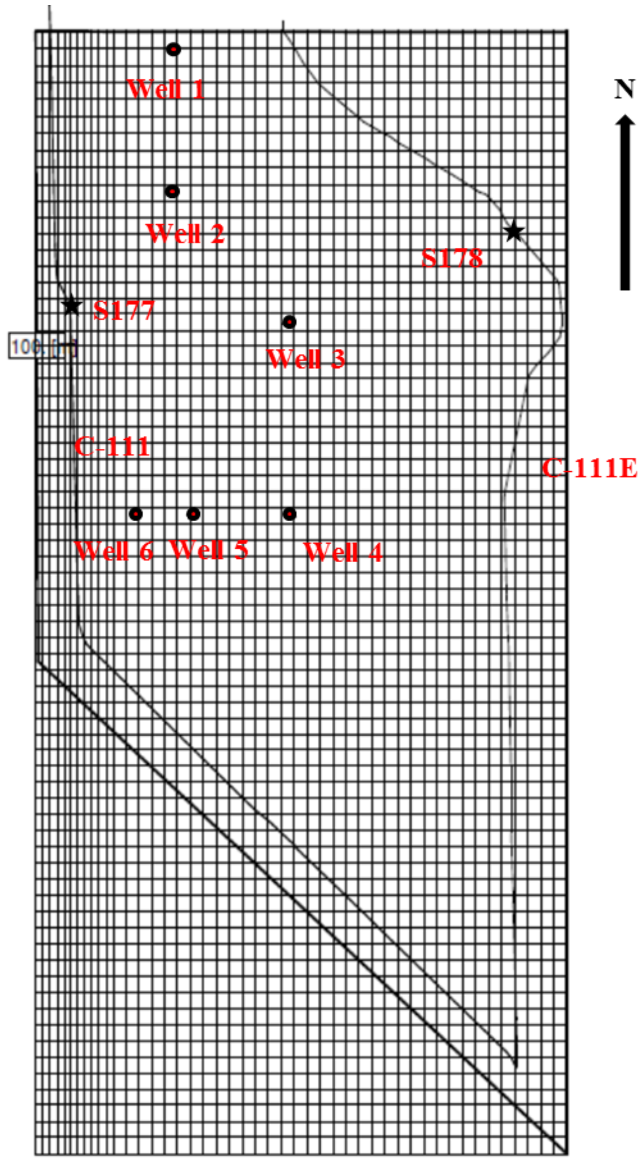


Figure 4. Showing model discretization grid for the modeled area, canal C-111 and C-111E and groundwater observation wells.

2.2.3 Sensitivity analysis and parameter estimation

Sensitivity analysis and parameter estimation were performed using the sensitivity and parameter estimation (PES) processes in MODFLOW 2000 (Hill et al. 1998; Hill et al., 2000). PES calculated parameter values that minimized a weighted least squares objective function using nonlinear regression. The objective function was minimized using the modified Gauss-Newton (also known as the Levenberg-Marquardt method) as well as prior information on the parameter estimates (Hill et al., 1998). To reduce problems associated with inverse modeling such as insensitivity, instability and non-uniqueness, only parameters identified through sensitivity analysis to have greatest influence on model output were estimated. The sensitivity equation method was used in the sensitivity analysis package.

Output from MODFLOW 2000 also includes inferential statistics such as dimensionless scaled sensitivities (DSS) and composite scaled sensitivities (CSS). These inferential statistics measure the amount of information provided by the observations and the uncertainty with which the parameters values are estimated (Hill, 1998). DSS are typically used to compare the importance of different observations for estimation of a single parameter. CSS are calculated for each parameter using DSS for all the observations and indicate the amount of information provided by the observations for the estimation of a single parameter.

2.3 Model validation

Model validation was implemented using a statistical model evaluation tool called FITEVAL (Ritter and Muñoz-Carpena, 2012). FITEVAL computes a non-dimensional goodness-of-fit indicator Ceff (Nash-Sutcliffe coefficient of efficiency), a dimensional goodness-of-fit indicator RMSE (Root Mean Square Error) as well as model prediction uncertainty ranges. FITEVAL computes a 95% confidence interval based on a goodness-of-fit probability density function estimated using bootstrap technique. FITEVAL also provides some reference values as guides for judging model performance. The model is judged to be very good if the probability that Ceff > 0.9, good if Ceff is between 0.8 and 0.9, acceptable for Ceff between 0.65 and 0.8 and unacceptable for Ceff < 0.65 (Ritter and Muñoz-Carpena, 2012).

2.4 Model application: Canal stage operational adjustment scenarios

Before application of the model, graphical exploration of the temporal variation in water table elevation in reference to the root zone was completed to determine if under present canal stage operational criteria water table elevation extended into the root zone during the study period. The developed model was then applied to evaluate the effect of the proposed incremental raises in canal stage on water table elevation. Incremental raises in canal stage were proposed in the project implementation report to be operationalized at S18C by increasing current "open and close" triggers in increments of 3.0

cm up a maximum of 12 cm (U.S. Army Corps of Engineers and SFWMD, 2011). For numerical simulation purposes, incremental raises in canal stage were mimicked by adding the proposed increments of 0.06, 0.09 and 0.12 m to canal stage. Only tail water canal stage at S177 and S178 were modified. Canal stage of the head waters at S177 and S178, rainfall, and evapotranspiration from the period of record were used. The initial condition was taken as the interpolated surface for water table elevation at the start of the simulation. Graphical analysis was used to determine if the proposed increments in canal stage would result in root zone saturation and groundwater flooding at any of the sites analyzed. The Two-sample equal variance t-Test was used to determine if the water table elevation before and after the incremental rises in canal stage were significant.

2.4.1 Assessing aquifer response to large storms

When a large storm is forecasted, the SFWMD uses data products from the National Hurricane Center (NHC) to make pre-and post-storm operational plans. These include making forecasts of quantitative precipitation that are accurate within 2-4 days prior to the storm and corresponding regional canal level lowering to ensure continued flood protection. During the storm event, the SFWMD continues to monitor flood control structures as well as storm position and intensity. During Tropical Storm Isaac, the SFWMD requested the USACE to put C-111 in pre-storm mode in order to minimize potential impacts. USACE approved pre-storm drawdown request and gate openings and pumping were initiated August 23, 2012 (Strowd, 2012).

The period August 21 to August 30, 2012 was chosen for the analysis of Biscayne Aquifer response to large storms as this period corresponded to Tropical Storm Isaac (> 60 mm total rainfall in one day). To simulate aquifer response to large storm events, MODFLOW was used with a small time step of 15 minutes. A stress period size of one day was also used to match available tail water canal stage and precipitation data at S177 and S178 (Fig. 1). Model simulations of aquifer response to recharge were checked using the water table fluctuation method described in Healy and Cook, 2002 (eq. 3):

$$S_y = \frac{\mathrm{Re}\,charge}{Head\,difference} \qquad (3)$$

where S_y is the aquifer specific yield, recharge refers to net input from rainfall and evapotranspiration and head difference refers to the change in water table elevation resulting from the recharge.

The MODFLOW model was also applied to assess aquifer response to two, five, ten and 25 year return period storms. Maximum daily rainfall depth for the return periods where obtained from isohyetal maps for central and south Florida developed by Pathak (2001). Pathak (2001) obtained maximum daily depth of 114, 168, 203, and 254 mm for two-, five-, ten-, and 25-year return period storms, respectively for our study area. Based on analysis of over 113 years of rainfall data, large storms (i.e., 2- to 25-year return storms) in south Florida occur between August and October. With October being a transitional month between the wet and dry seasons and also corresponds to the time when growers begin to prepare the land and plant winter vegetables. For this reason, the period from October 25 to November 5, 2012 was selected to explore canal-aquifer system responses to large storms. Various canal drawdown scenarios that would minimize root zone saturation and groundwater flooding in the agricultural lands were also explored. Drawdowns were implemented by incrementally reducing canal stage 48 hours prior to a forecasted large storm in the reaches of C-111 and C-111E surrounding the study area. The desired scenario was when the water table elevation did not exceed the elevation of the bottom of the root zone.

3.0 Results and Discussion

3.1 Sensitivity analysis and parameter estimation results

The CSS for our study summarized in (Fig. 5) indicated that water table elevation measurements provided more information in the estimation of specific yield and hydraulic conductivity compared to estimation of canal conductance. The CSS also indicate that water table elevation data alone did not provide sufficient information for accurate estimation of canal bed conductance in the reaches of C-111 and C-111E surrounding our study site. The need to have different types of data during parameterization of groundwater flow models was noted by earlier investigators (Saier et al., 2004; Zechner and Frielingsdorf, 2004). Zechner and Frielingsdorf (2004) observed that to accurately parameterize a canal-aquifer interaction model with many parameters, in addition to groundwater head observations, other observations such as canal seepage and pore-water solute concentration provided more information for parameter estimation and improved model prediction. However, Saier et al. (2004) using different combinations of observed data including groundwater head, aquifer discharge to the canal and groundwater chloride concentration noted that inverse-solution uniqueness was not required for accurate prediction of groundwater head but was required for prediction of seepage. Implying that water table head observations are sufficient for calibrating models aimed at prediction of groundwater head, but models for predicting other state variables such as seepage should been calibrated with more than one type of observation.

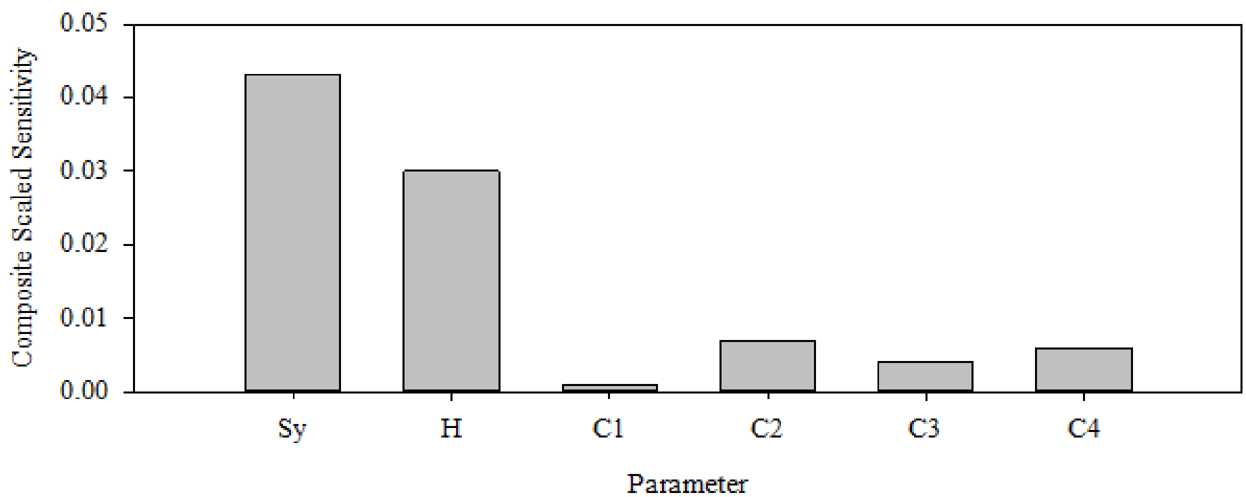


Figure 5. Composite scaled sensitivities for the parameters selected for estimation in the model were Sy is specific yield, H is hydraulic conductivity, C1 is canal bed conductance multiplier for the reach of C-111 on the head water side at S177, C2 is canal bed conductance multiplier for the C-111 reach between S177 and the point where C-111 joins C-111E to become a single canal, C3 is canal bed conductance multiplier for reach of C-111E on the tail water side of S178 and C4 is canal bed conductance multiplier for the reach of C-111E on the headwater side of S178.

During parameter estimation, the least squares objective function was minimized after five iterations. Based on data from 5 observation wells a hydraulic conductivity value of 12,115 m/day was estimated. This value was within the range of 7,590 to 14,900 m/day observed by Genereux et al. (1998) based on a large scale canal draw down experiment and close to 12,768 m/day estimated by Kisekka et al. (2013b). Specific yield was estimated as 0.184 which is close to an estimate of 0.15 determined by Bolster et al. (2001) using data from a large scale canal draw down experiment and to mean of 0.102 estimated by Kisekka et al. (2013b). Information from observations was not sufficient to accurately estimate canal conductance along the reach of C-111 on the headwater side of S177. A canal bed conductance multiplier for the longest and largest reach i.e., the reach between S177 and the point where C-111 joins C-111E to become a single canal was estimated as 1,965H m^2/day, where H represents the length of the reach in meters. The canal bed conductance multiplier for C-111E was less than that of C-111 (i.e., 27H m^2/day tail water side of S178 and 10H m^2/day head water side of S178). There are no readily available values for canal bed conductance for the reaches of C-111 and C-111E considered in this investigation, however, for purposes of comparison, Genereux et al. (1998) estimated a canal bed conductance of 720H for the nearby L-31W canal which is located near C-111 along the eastern boundary of ENP.

3.2 Model Calibration and validation

Calibration (August 25, 2010 to December 31, 2011) results reproduced observed water table elevations (WTEs) at five observation wells (2 to 6) with an average Ceff greater than 0.9 (Table 2). Temporal variations in WTE showed seasonal increases and decreases in WTE. The dry season was characterized by decrease in WTE due to low rainfall while increased WTE in the wet season was due to increase in rainfall and changes in canal stage management. The RMSE ranged from 1.0 cm to 7.0 cm with the lowest value observed at well 6 and the highest value at well 4. Study site topography is essentially flat implying that small variations in hydraulic head govern which direction water flows, therefore it was desired to achieve the lowest RMSE possible (e.g., < 6 cm). However, it was not possible to obtain RMSE < 6 cm at all wells due to limitations e.g., uncertainties in model parameters, model structure, and model input, all of which introduce uncertainties in model simulations. There could also be errors in the observed data used for model calibration. This type of error was minimized by comparing level logger data with manual measurements during each download. Under the C-111 spreader canal project the smallest proposed incremental raise in canal stage at S18C is 3 cm. However, the RMSE of our model predictions are larger than 3 cm at four out of the five observation wells within the study area domain, for this reason only the 6, 9 and 12 cm incremental raises in canal stage were further analyzed for their effect on water table elevation.

Figs. 6 to 10 show FITEVAL summary of the goodness-of-fit statistics for validation of model predictions at all the observation wells. Overall the agreement between simulated and observed water table elevations was very good (Ceff > 0.9 and 1 cm < RMSE < 5 cm) with the exception of site well 4, at which model performance was determined to be acceptable ($0.68 <$ Ceff < 0.78). The over prediction at observation well 4 could be attributed to several factors e.g., heterogeneity in hydrogeological conditions and uncertainty in model input parameters and observed data. The very good performance of the model at all the other sites indicates boundary conditions definition was sufficient to describe groundwater flow. The results also indicate that describing canal-aquifer interactions using the simple RIV package (Harbaugh et al., 2000) in MODFLOW was adequate. The good performance of the RIV package could be attributed to the underlying assumptions in the RIV package being valid for our study site e.g., there was negligible change in canal stage during each stress period which was set as one day. Our results are also within range of model coefficient of efficiency (a measure of agreement between measured and predicted values) obtained by prior investigators. Bolster et al. (2001) applied MODFLOW to Biscayne Aquifer and obtained a model coefficient efficiency of 0.99. Saiers et al. (2004) using their numerical model of groundwater flow and solute transport in the Biscayne Aquifer obtained goodness-of-fit model coefficient efficiency of 0.95. The results also indicated that general groundwater flow was in the south-east direction, which implies that a large increase in hydraulic head west of C-111 could increase rate of groundwater flows to the eastern side of the canal. Based on the period evaluated, model validation results indicated that with the exception of well 4, the model developed for the study area was accurate and not biased implying it could be used to further investigate the impact of proposed incremental raises in canal stage on water table elevation.

Table 2.

Table 2. Goodness-of-fit statistics for model calibration for water table elevation predictions using MODFLOW

Well	Ceff[1] Calibration	RMSE[2] Calibration (cm)
Well 2	0.97-0.98	4.0-5.0
Well 3	0.94-0.96	4.7-5.7
Well 4	0.80-0.90	6.0-7.0
Well 5	0.93-0.95	4.6-5.3
Well 6	0.99-1.00	1.0-1.2

[1]Nash-Sutcliffe coefficient of efficiency

[2]Root mean square error

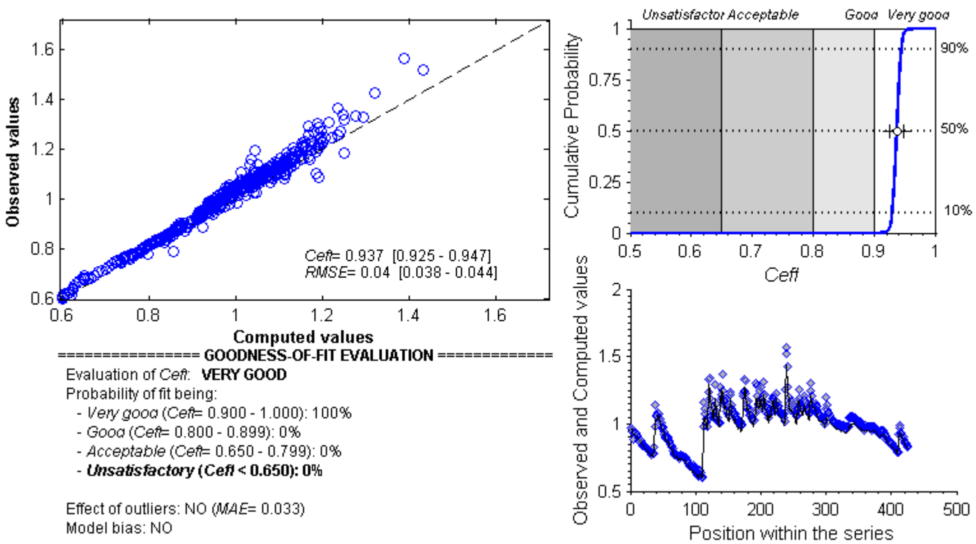


Figure 6. Validation goodness-of-fit indicators from FITEVAL for MODFLOW simulations at well 2 for the period January 01, 2012 to February 28, 2013.

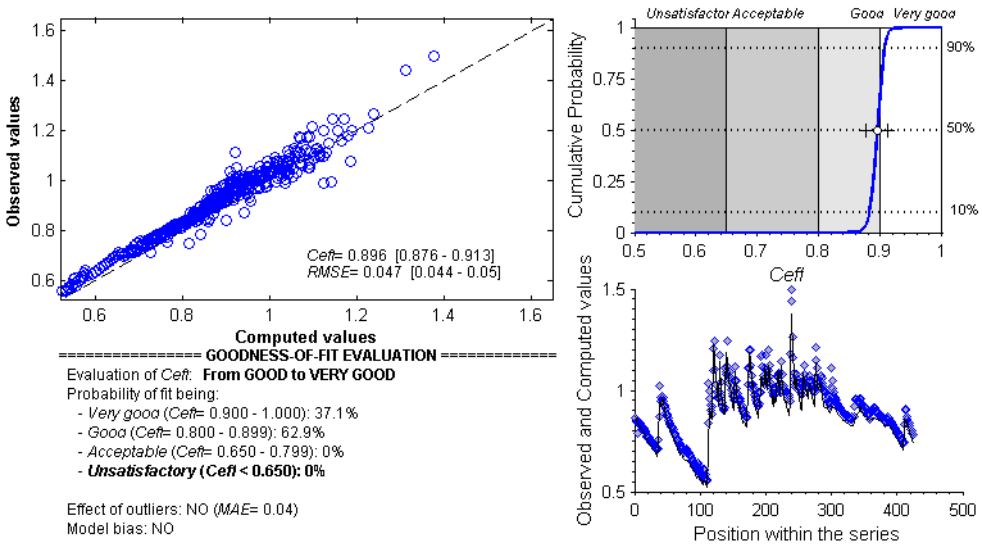


Figure 7. Validation goodness-of-fit indicators from FITEVAL for MODFLOW simulations at well 3 for the period January 01, 2012 to February 28, 2013.

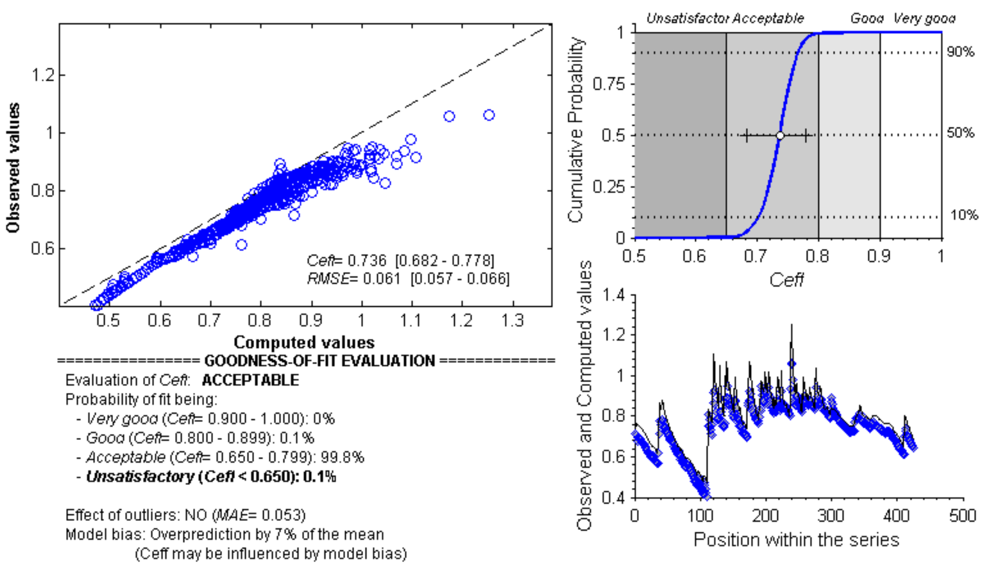


Figure 8. Validation goodness-of-fit indicators from FITEVAL for MODFLOW simulations at well 4 for the period January 01, 2012 to February 28, 2013.

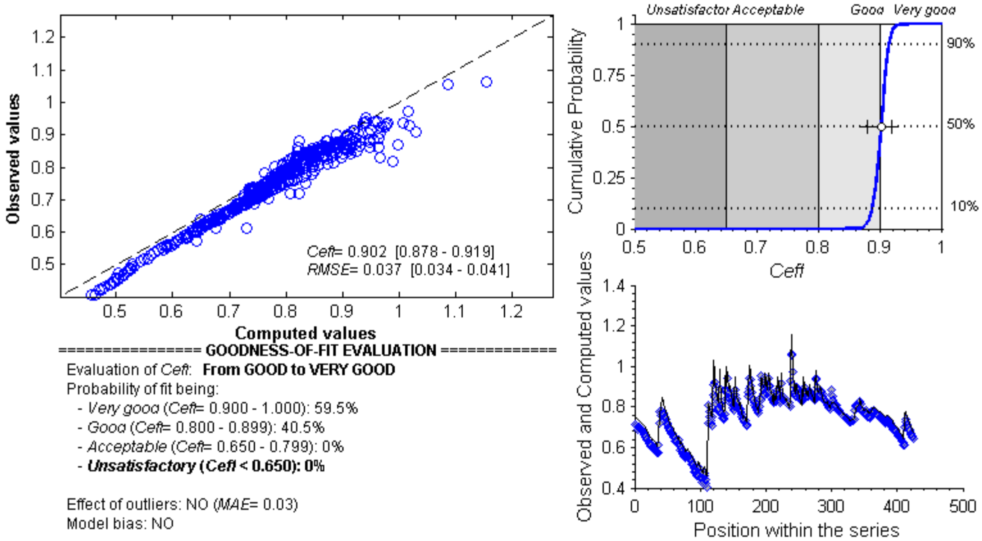


Figure 9. Validation goodness-of-fit indicators from FITEVAL for MODFLOW simulations at well 5 for the period January 01, 2012 to February 28, 2013.

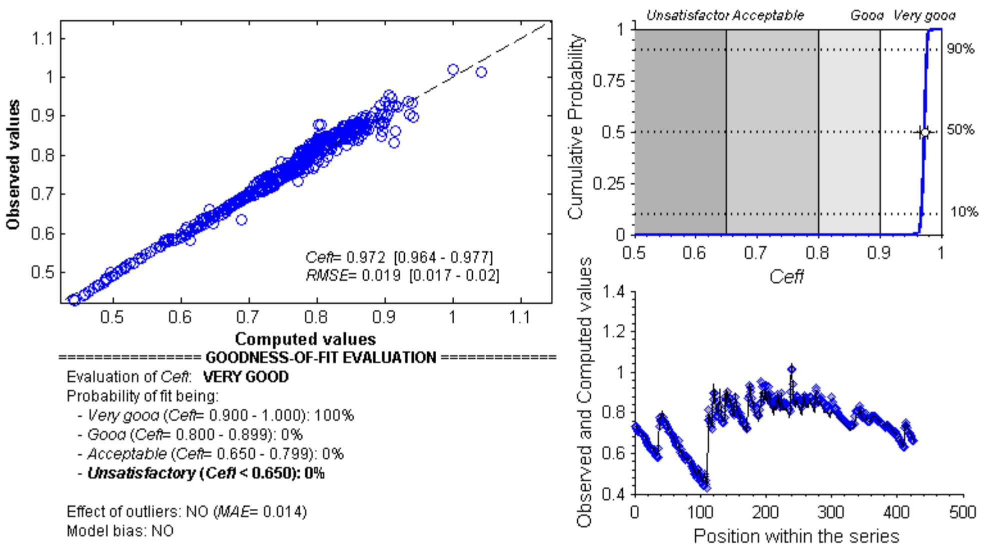


Figure 10. Validation goodness-of-fit indicators from FITEVAL for MODFLOW simulations at well 6 for the period January 01, 2012 to February 28, 2013.

3.3 Model application results

The root zone for all sites was approximately the first 20 cm from the ground surface as measured in the field. Visual exploration of temporal variation in water table elevation in reference to the root zone (Figs. 11 to 12) revealed that under current canal stage management criteria for the period August 25, 2010 to February 28, 2013, average daily water table elevation occasionally extended into the root zone at well 6 and well 4 study sites which also had the lowest ground surface elevation. At well 5 and well 3 sites, where land surface elevation exceeded 2 m, water table elevation was not observed to enter the root zone. Thus, surface topography might influence water table fluctuations into the root zone more than distance from the canal. Results from model applications (Figs. 13 to 15) revealed that average daily water table elevation before (grey shade) and after (blue shade) the incremental rises in canal stage was significantly different ($p < 0.001$) for monitoring well 4, well 6, and well 5 sites. For well 2 and well 3 sites, water table elevation before and after the proposed incremental raises in canal stage were not significantly different ($p > 0.05$) . The lack of significant difference in water table levels before and after the incremental raises in canal stage for wells 2 and 3 could be attributed to that fact canal stage was not changed north of S177 and S178 (Fig. 1).

The increase in water table elevation for wells 4, 6, and 5 corresponding to a 6 cm rise in canal stage ranged between 4.5 and 6.0 cm, while the increases corresponding to 9 and 12 cm were 7.0 to 9.0 cm and 11.0 to 12.0 cm, respectively. The almost equal increase in water table elevation predicted from the incremental rises in canal stage can be attributed to the high hydraulic connection between Biscayne Aquifer and the C-111 canal network. Visual analysis in Figs. 13 to 15 shows that low elevation lands (as found at well 4 and well 6 sites) were predicted to have a shorter growing season with canal stage increases of 9 cm and beyond resulting in longer periods of saturated conditions in the root zone. For example, at well 4 and well 6 sites after a 12 cm raise in canal stage, saturated conditions were predicted to persist until late October or early November. Typically land preparation for agriculture starts in late September and planting occurs in October. For high elevation sites such as well 5, the proposed increases in WTE were predicted not to cause root zone saturation or groundwater flooding (where groundwater flooding refers to a situation where water table elevation raises above the ground surface) under conditions similar to those experienced during the study period.

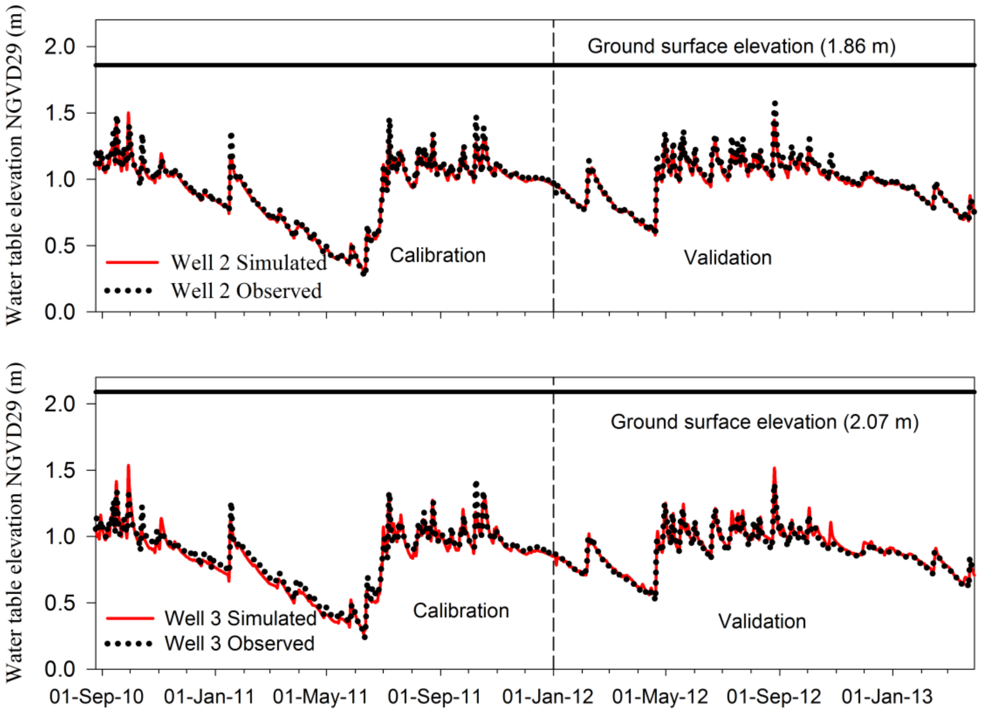


Figure 11. Temporal variation in water table elevation in reference to ground surface under current canal stage operation criteria at spillway S18C for observation of wells well 2 (ground surface elevation of 1.86 m NGVD29) and well 3 (ground surface elevation of 2.07 m NGVD29) on the headwater side of the spillway at S177 with calibration and validation separated by a vertical dash line.

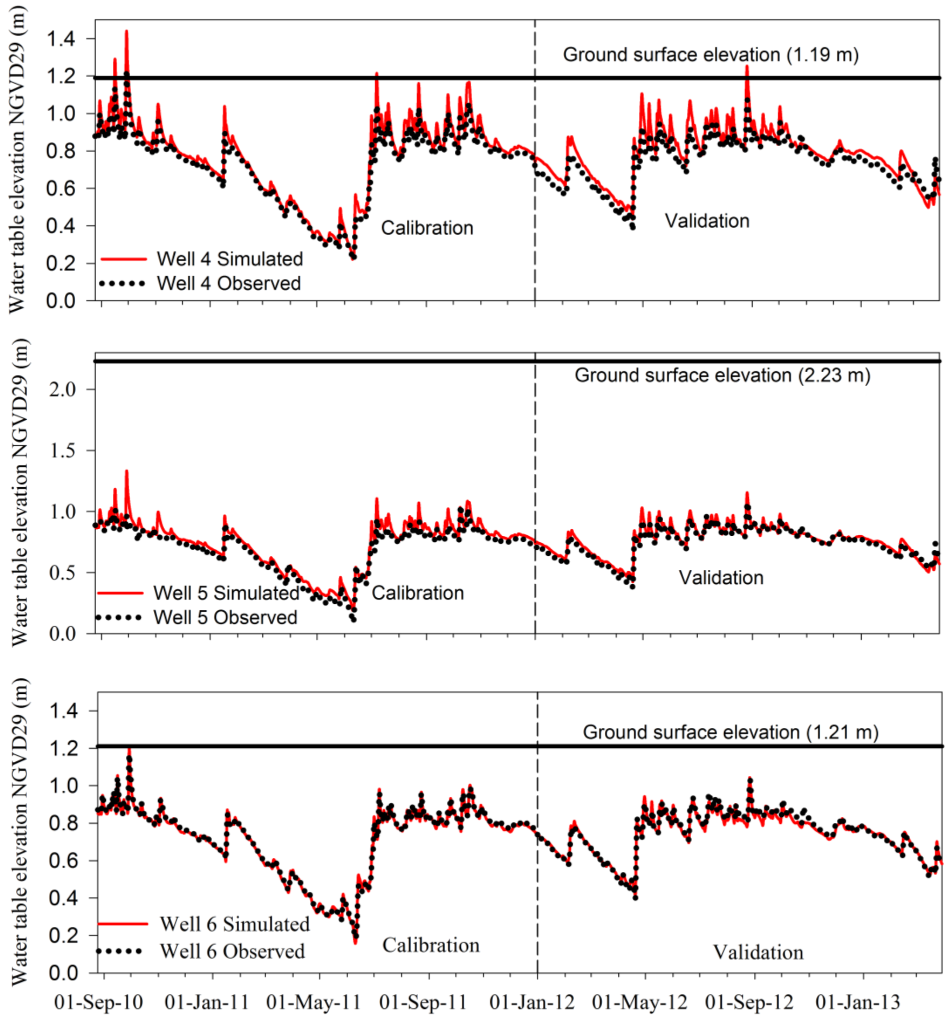


Figure 12. Temporal variation in water table elevation in reference to ground surface elevation under current canal stage operation criteria at S18C for observation wells well 4, well 5, and well 6 on the tail water side of the spillway at S177 with calibration and validation separated by a dash vertical line.

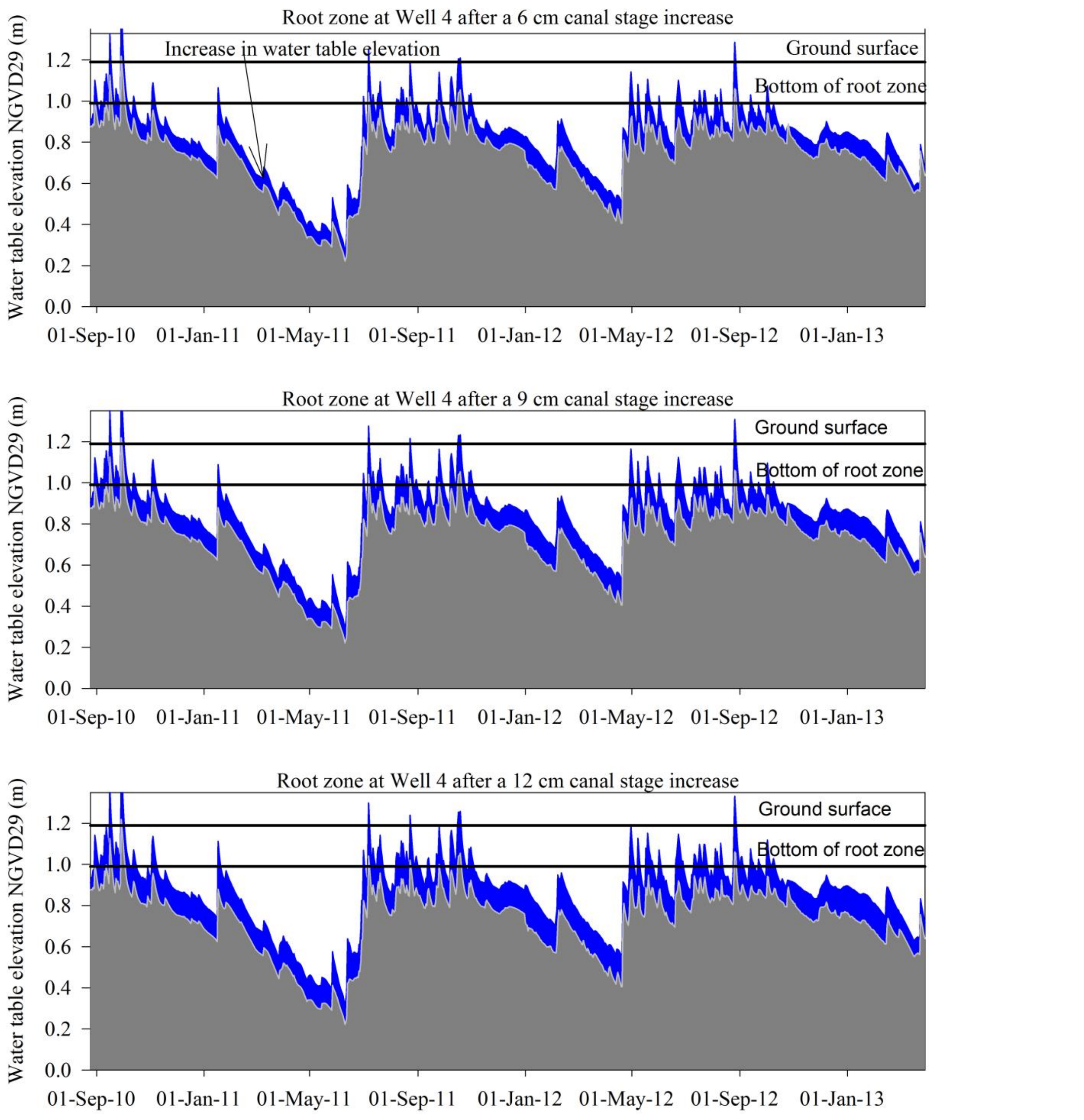


Figure 13. Temporal variation in water table elevation in reference to the root zone under proposed incremental raises in canal stage operation at S18C for observation well 4.

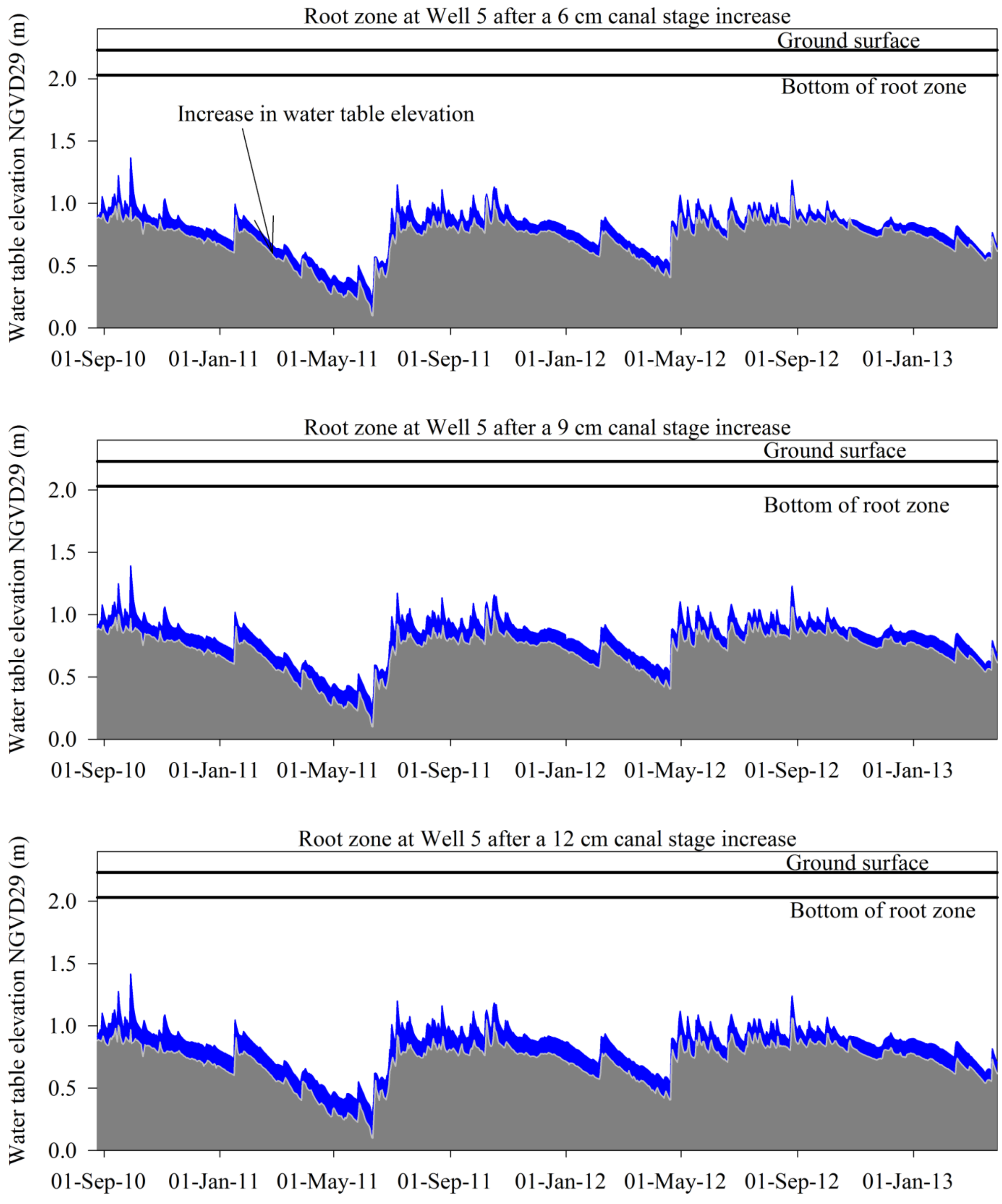


Figure 14. Temporal variation in water table elevation in reference to the root zone under proposed incremental raises in canal stage operation at S18C for observation well 5.

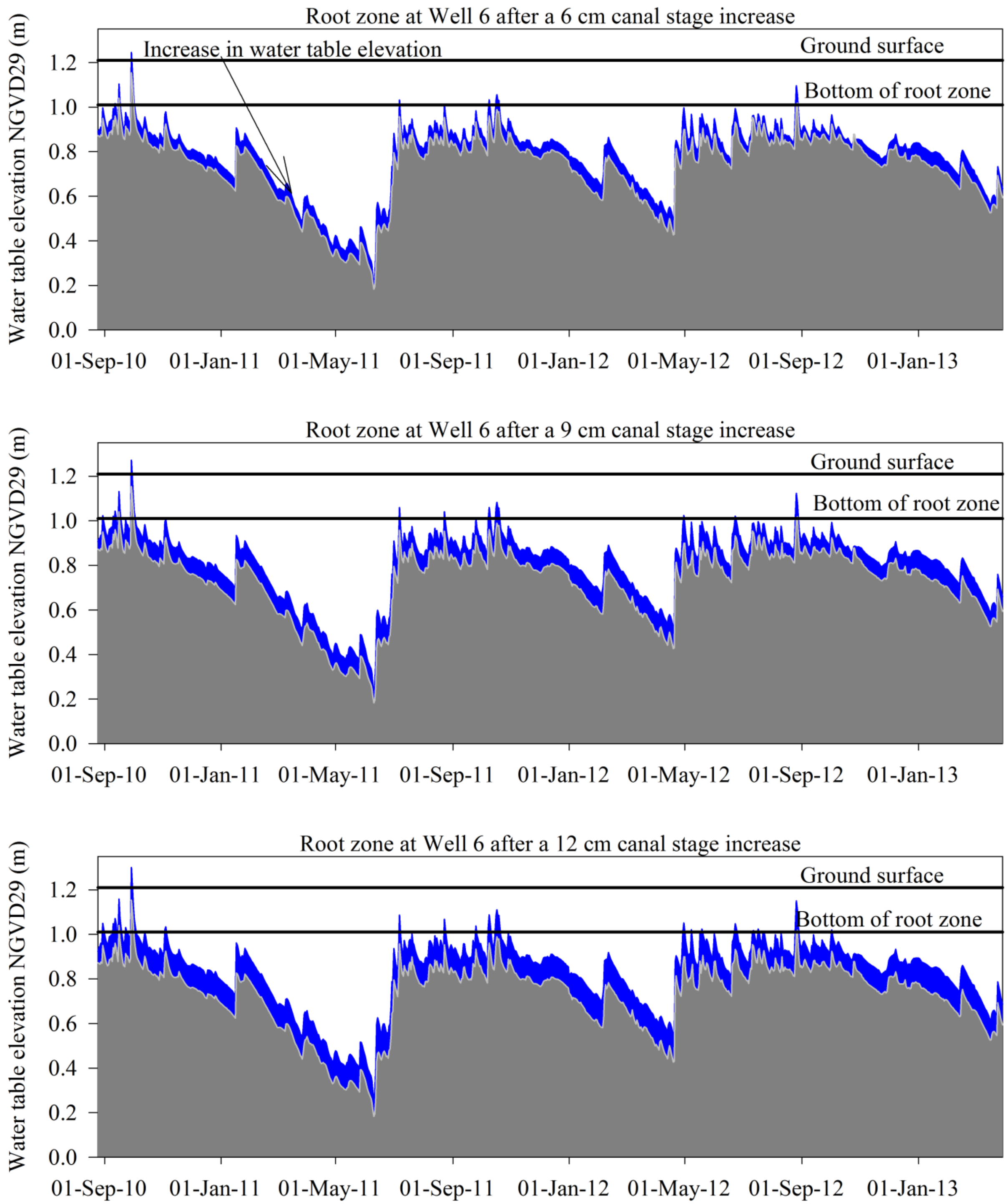


Figure 15. Temporal variation in water table elevation in reference to the root zone under proposed incremental raises in canal stage operation at S18C for observation well 6.

3.4 Results of aquifer response to large storms

Event analysis was conducted for the period from August 21, 2012 to August 30, 2012 which corresponded to Tropical Storm Isaac. The aquifer responded to the storm by increasing water table elevation and took approximately two days for the water table elevation to recede back to pre-storm levels (Fig. 16). The three days of heavy rainfall during Tropical Storm Isaac would be expected to result in groundwater flooding causing the water table to rise to the ground surface; however this did occur as shown by observed water table elevations in Fig. 16. Simulated water table elevation were below ground surface with the exception of well 4 where ponding was simulated to occur for approximately one day. As indicated under model validation, performance was ranked as very good at well 6 and well 5 sites and acceptable at well 4 implying the model adequately represented the physical processes in the system. Attempts were made to estimate fluctuation in water table elevation resulting from tropical storm Isaac using equation (3), as a quick way to estimate aquifer response to predicted storms but the results seemed unrealistic (predicted an increase in water elevation of 0.6 m), i.e., very high compared to observed fluctuations in water table elevation after tropical storm Isaac therefore the approach was abandoned. There are three limitations of the water table fluctuation method expressed as equation (3): 1) although simple to use, it overly simplifies the complex process of water flow into and out of the aquifer, 2) the method assumes all the fluctuation in water table are due to recharge and ignores effects of other factors such as pumping, changes in atmospheric pressure, and entrapped air, 3) the method is also not suitable for aquifers that are in close proximity with streams or canals that directly influence water table fluctuations.

The absence of flooding at low elevation sites such as at well 4 and 6 could be attributed to the pre and post tropical storm Isaac canal drawdown that was undertaken by the SFWMD and USACE. This included regional lowering of canal stage particularly by operating canals C-111 under pre-storm mode and opening the flood control structures (Strowd, 2012). Tropical Storm Isaac occurred when the fields at well 5, well 4, and well 6 were fallow, so no risk to crop damage occurred. If a similar event were to occur when vegetable crops were present and with no pre-storm canal drawdown, sites with lower elevations (e.g., well 4 and well 6) would likely experience yield loss due to root zone saturation. The event would also delay entry into the field by any machinery for agricultural activity. Higher elevation sites (e.g., well 5) were expected to be less impacted by such a storm as the water table was still below the root zone. This further illustrates the need for detailed topographic data and field scale simulation of canal-aquifer system to better relate locations with potential risk of groundwater flooding. This model could be used to further explore drawdown scenarios for this area prior to major storm events.

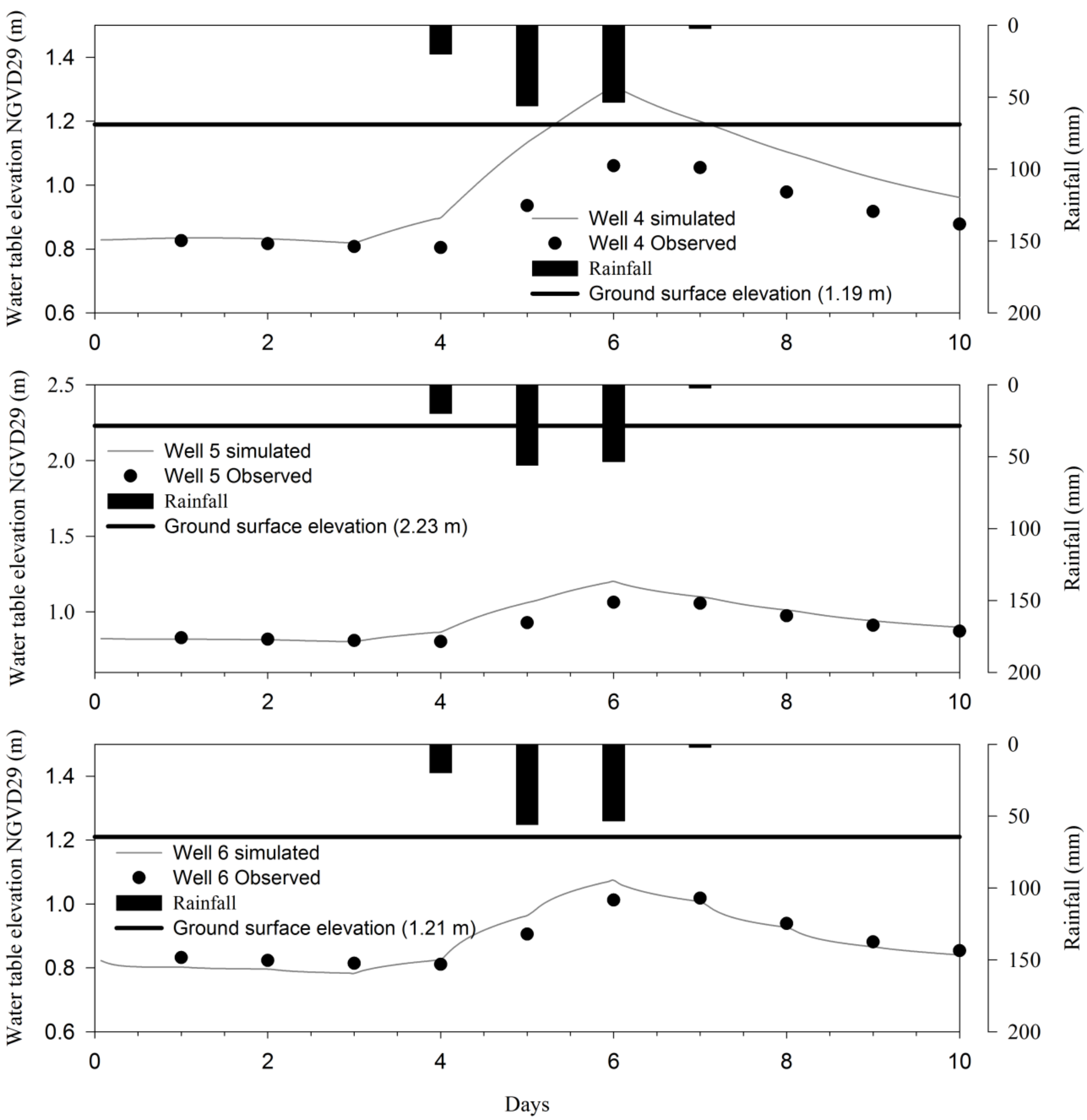


Figure 16. Aquifer response to Tropical Storm Isaac at observation wells south of the spillway at S177.

Analysis of canal-aquifer system response and exploration of various canal drawdowns scenarios that would minimize the impact of root zone saturation and groundwater flooding in agricultural lands due to large storms revealed that micro-topography within the fields was a major factor. Figs. 17 and 18 show that 3 out of the 4 sites analyzed for their response to two, five-, ten- and 25-year return period storms experienced groundwater flooding if canal drawdown was not implemented before the storm. With the exception of well 5 site with high surface elevation (2.2 m NGVD29), all the other sites experienced various degrees of groundwater flooding (Figs. 17 & 18). A ten and 25 return period storm caused groundwater flooding at well 2, well 3 and well 6 sites. Sites with ground surface elevation less than 1.2 m NGVD29 experienced groundwater flooding from all storm sizes analyzed. For agricultural purposes, it is desired that the water table elevation does not extend into the root zone since this condition could create anoxic conditions that result in root and / or plant death. Exploration of canal drawdown scenarios revealed that a 20 cm drawdown in canal stage 48 hours prior to a forecasted storm of 114 mm in 24 hours (2 year return period storm) would eliminate the risk of groundwater flooding at all the sites (Figs. 17 and 18). A 25 cm drawdown was effective in mitigating the impacting of root zone saturation and groundwater flooding from a 5 year return period storm at all sites, while drawdowns of 30 and 40 cm were effective for 10- and 25-year return period storms, respectively. It is worth noting that the influence of the 48 hour canal stage drawdown prior to a forecasted storm was dependent on the distance from the canal. As shown by the depressions in the drawdown graphs (Figs. 17 and 18) for well 6, well 5 and well 3 sites which are 500, 1000, and 1000 m from C-111 canal, respectively. Overall these results predict that canal drawdown is effective as a pre storm water management technique for ensuring continued flood protection of agricultural lands within the C-111 basin. However, it is critical to remember that management decisions should be made in view of the uncertainty associated with model predictions as shown in Figs. 6 to 10. Also, the size of the drawdown should match forecasted storm depth and post storm activities should ensure the canal drainage continues to provide other services such as control of salt water intrusion.

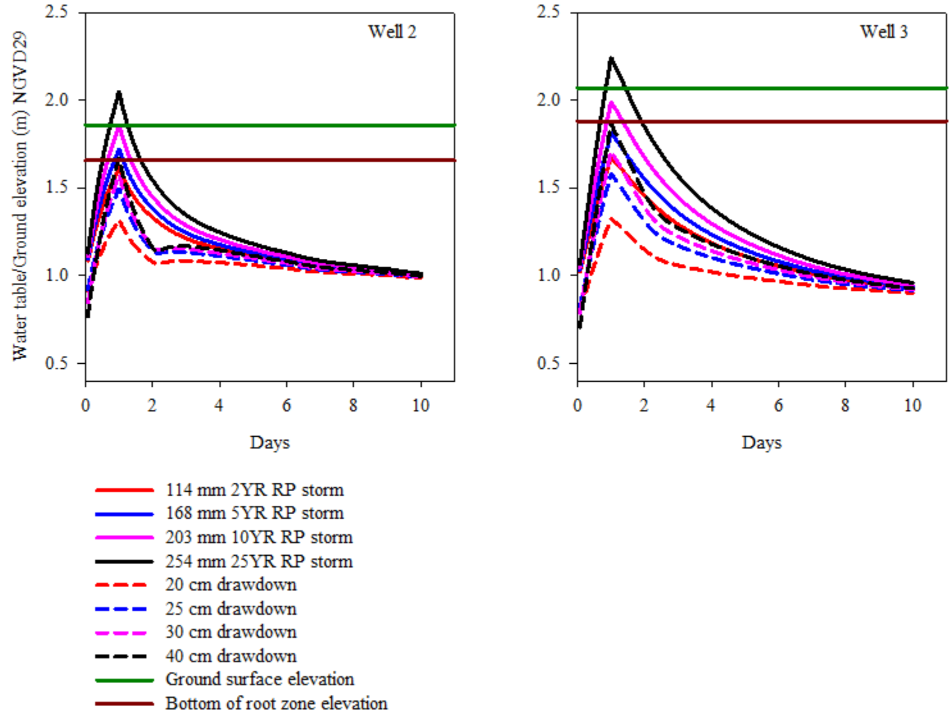


Figure 17. Canal-aquifer system response to large storms of various sizes for wells north of the spillway at S177, were YR refers to year and RP refers to return period, graphs also shows that canal stage drawdown prior to the forecasted storm reduces the risk of root zone saturation and groundwater flooding

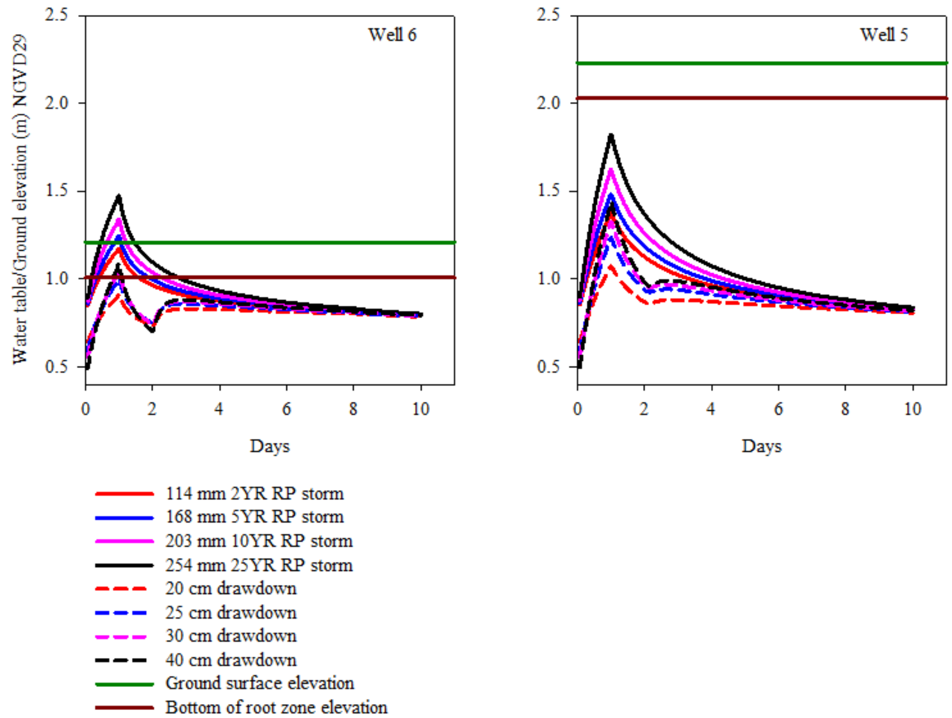


Figure 18. Canal-aquifer system response to large storms of various sizes for wells south of the spillway at S177, were YR refers to year and RP refers to return period, graphs also shows that canal stage drawdown prior to the forecasted storm reduces the risk of root zone saturation and groundwater flooding.

4.0 Conclusion

The effect of the proposed incremental raises in canal stage on water table levels in agricultural fields along a section of a major canal draining south Florida (i.e., C-111) and aquifer response to large storms was investigated using MODFLOW and graphical analysis. The incremental raises in C-111 canal stage are part of a large scale ecosystem restoration project which has the goal of restoring the hydrology of Everglades National Park. The MODFLOW model predicted that the incremental raises in canal stage resulted in significant differences in water table elevation within the adjacent agricultural areas. For the 9 and 12 cm increases in canal stage, water table elevations were predicted to occasionally extend into the root zone for 3 out of the 5 well sites. Well 3 and well 5 sites (with ground surface elevation exceeding 2 m) were predicted to not be affected by any of the incremental raises in canal stage. The impact of operational changes in canal stage management on the root zone saturation and groundwater flooding depended on land surface topography and depth of rainfall events. Thus micro-topography within the field can have a bigger influence on soil water content than distance from the canal. Based on graphical analysis, low elevation lands (with surface elevation<2 m NGVD29) could have shorter growing seasons if canal stage is increased 9 cm and beyond due to potential saturation of the root zone.

The MODFLOW based model was able to mimic the rise and fall of the water table similar to that measured for Tropical Storm Isaac. Further exploration of canal-aquifer system response to 2-, 5-, 10- and 25-year return period storms and canal drawdowns suggested that if crops are present during storms greater than a 2-year return period storm, yield losses could occur if pre storm canal drawdown is not implemented at least 48 hour prior to the forecasted storm particularly in low elevation sites. Overall the study concludes that canal drawdown is effective as a pre storm water management technique for ensuring continued flood protection of agricultural lands within the C-111 basin.

Acknowledgements

The authors would like to thank the South Florida Water Management District for providing the funding for this study, the University of Florida, IFAS, Tropical Research and Education Center, and the University of Florida, Agricultural and Biological Engineering Department, Dr. Richard Winston of the U. S. Geological Survey for technical support, Mr. Vito Strano and Mr. Sam Accursio for allowing us to use their lands and Ms. Tina Dispenza for her contribution towards data collection and processing.

References

Allen, R., 2011. REF-ET: Reference Evapotranspiration Calculation Software. User Manual.

Brakefield, L.K. 2012. Branching Between Geological Understanding and Model Process Design of the Biscayne Aquifer to Examine Effects from Model Uncertainty on Well-Field Capture-Zone Estimates. Geological Society of America Abstracts with Programs. Vol. 44, No. 7, p.206.

Bolster, C., Genereux, D., Saiers, J., 2001. Determination of specific yield for a limestone aquifer from a canal drawdown test. Ground Water. 39:768-777.

Brion, L., S. U. S. Senarat, A. M. W. Lal, and M. Belnap. 2001. Application of the South Florida Regional Simulation Model in the Everglades. Proc., ASCE Specialty Symp.: Integrated Surface and Groundwater Management, Orlando, Fla.

Causaras, C.R. 1987. Geology of the surficial aquifer system, Dade County, Florida: U.S. Geological Survey Water-Resources Investigations Report 86-4 126, 240 p., 3 sheets.

Chin, D., 1991. Leakage of clogged channels that partially penetrate surficial aquifers. Hydr. Eng. ASCE 117(4):467-488.

Chin, D.A., 2008. Phenomenological Models of Hydrologic Processes in South Florida. Journal of Hydrology. 349:230-243.

Duever, M.J., Meeder, J.F., Meeder, L.C., McCollum, J.M., 1994. The climate of south Florida and its role in shaping the Everglades ecosystem. In: Davis, S.M., Ogden, J.C. (Eds.), Everglades: The Ecosystem and its Restoration. St. Lucie Press, Delray Beach, FL, pp. 225–248.

Fish, J. E., Stewart, M., 1991. Hydrogeology of the surficial aquifer system, Dade County, Florida. Water Resource. Investigations Rep. No. 190-4108, U.S. GeoI. Survey, Tallahassee, Fla.

Genereux, D., Slater, E.,1999. Water exchange between canals and surrounding aquifer and wetlands in the Southern Everglades, USA. Journal of Hydrology. 219:153–168.

Genereux, D.P., and Guardiario, J.D.,1998. A canal drawdown experiment for determination of aquifer parameters. J. Hydr. Eng. 3 (4): 294-302.

Graham, W.D., Campbell, K.L., Mossa, J., Motz, L.H.,Rao,P.S.C., Wise, W.R., Genereux, D.P.,1997. Water management issues affecting the C-111 Basin, Dade County, Florida. Report number CNR-1997-1002, Center for Natural Resources, University of Florida, Gainesville, 156 pp.

Harbaugh, A.W., Banta, E.R., Hill, M.C., McDonald, M.G., 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model -User guide to modularization concepts and the Ground-Water Flow Process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Hill, M.C., 1998. Methods and guidelines for effective model calibration: U.S.Geological Survey, Water-Resources Investigations Report 98-4005, 90 p.

Hill, M.C., Banta, E.R., Harbaugh, A.W., Anderman, E.R., 2000. MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model -- User's Guide to the Observation, Sensitivity, and Parameter-Estimation Processes and Three Post- Processing Programs: U.S. Geological Survey Open-File Report 00-184, 220 p.

Hughes, J.D., Langevin, C.D., Chartier, K.L., White, J.T., 2012. Documentation of the Surface-Water Routing (SWR1) Process for Modeling Surface-Water Flow with the U.S. Geological Survey Modular Groundwater Model (MODFLOW-2005), U.S. Geological Survey Techniques and Methods 6-A40.

Kisekka, I., K.W. Migliaccio, R. Muñoz-Carpena, B. Schaffer and Y. Li. 2013a. Dynamic Factor Analysis of Surface Water Management Impacts on Soil and Bedrock Water Contents in Southern Florida Lowlands. Journal of Hydrology 488:55–72. http://dx.doi.org/10.1016/j.jhydrol.2013.02.035.

Kisekka, I., K.W. Migliaccio, R. Muñoz-Carpena, Y. Khare, and T. H. Boyer. 2013b. Sensitivity analysis and parameter estimation for an approximate analytical model of canal-aquifer interaction applied in the C-111 Basin. Trans. ASABE SW-10037-2012, in-press.

Lal, A.M.W., 2001. Modification of canal flow due to stream-aquifer interaction, Journal of Hydraulic Engineering. 127(7): 567-576.

McDonald, M.G., and A.W Harbauch. 1988. A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. Techniques of Water-Res. Invests. of the U.S. Geol. Survey, Book 6, Ch. A1: 586 pp.

Merkel, R., 2000. Element and Sediment Accumulation Rates in the Florida Everglades. Water, Air, and Soil Pollution. 122 (3-4): 327–349.

Pathak., C.S. 2001. Frequency Analysis of Short Duration Rainfall for Central and South Florida. ASCE Environmental and Water Resources 2001, Bridging the Gap. doi: 10.1061/40569(2001)227

Ritter, A., Muñoz-Carpena, R., 2012. Predictive ability of hydrological models: objective assessment of goodness-of-fit with statistical significance. J. of Hydrology doi:10.1016/j.jhydrol.2012.12.004

Ritter, A., Muñoz-Carpena, R., 2006. Dynamic factor modeling of ground and surface water levels in an agricultural area adjacent to Everglades National Park. Journal of Hydrology 317: 340-354.

Saiers, E. J., Genereux, D. P., Bolster, C. H., 2004. Influence of Calibration Methodology on Ground Water Flow Predictions. Ground Water. 42(1): 32-44. 32-44

Schaffer, B.,1998. Flooding Responses and Water-use Efficiency of Subtropical and Tropical Fruit Trees in an Environmentally-sensitive Wetland. Annals of Botany 81: 475–481. Available online at: http://aob.oxfordjournals.org/cgi/reprint/81/4/475.pdf. Accessed 07-13-2010.

Skinner, C., Bloetscher, F., Pathak, C.S., 2008. Comparison of NEXRAD and Rain Gauge Precipitation Measurements in South Florida. J. Hydrologic Engineering. 14(3):248-260.

Strowd, T. B. 2012. Tropical Storm Isaac. Readiness, Response, Recovery. Water Conditions Summary and After Action Assessment September 13, 2012. SFWMD. West Palm, Beach Florida. Accessed on online 04-06-2013 at: http://www.sfwmd.gov/portal/page/portal/xrepository/sfwmd_repository_pdf/gb_pres_ts_isaac_2012_0913.pdf.

Swain, E.D., Wexler, E.J., 1996. A coupled surface-water and ground-water flow model (MODBRANCH) for simulation of stream-aquifer interaction: U.S. Geological Survey Techniques of Water-Resources Investigations Report 6-A6, 125 p.

Tommy, T.B., 2012. Tropical Storm Isaac. Water Conditions Summary and After Action Assessment. Operations, Maintenance & Construction Division. South Florida Water Management District 3301 Gun Club Road, West Palm Beach, Florida.

U.S. Army Corps of Engineers, and South Florida Water Management District, 2011. Comprehensive Everglades Restoration Plan: C-111 spreader canal western project: Final Integrated Project Implementation Report and Environmental Impact Statement. U.S. Army Corps of Engineers Jacksonville, District. Last accessed 02/20/2013. Available at: http://www.usace.army.mil /Portals/2/docs/civilworks/CWRB/c_111/c_111_Briefing_slides.pdf .

USGS. 2000. Ground-Water Flooding in Glacial Terrain of Southern Puget Sound, Washington. USGS Fact Sheet 111-00. September 2000. U.S. Geological Survey, WRD, 1201 Pacific Avenue, Suite 600, Tacoma, WA 98402.

U.S. Geological Survey.1999. Florida Everglades. Circular 1182. U.S. Geological Survey. Last accessed 02/20/2013. Available at: http://sofia.usgs.gov/publications/circular/1182/ .

Wilsnack, M.M., Welter, D.E., Nair, S.K., Montoya,A.M., Zamorano, L.M., Obeysekera, J., Restrepo J.I., 2000. North Miami-Dade County Groundwater Flow Model, Hydrologic Systems Modeling Division, South Florida Water Management District, West Palm Beach, FL.

Winston, R.B., 2000. Graphical User Interface for MODFLOW, Version 4: U.S. Geological Survey Open-File Report 00-315, 27 p.

Zechner, E., and Frielingsdorf, W., 2004. Evaluating the use of canal seepage and solute concentration observations for aquifer parameter estimation. Journal of Hydrology. 289(1-4): 62-77.

Table 1. Water table elevation monitoring sites with descriptors.

[1]Site name	**Distance from canal C-111 (m)**	**Ground surface elevation (m) NGVD29**	**Latitude**	**Longitude**
Well 1	1000	2.07	25.41883	-80.550041
Well 2	1000	1.86	25.41110	-80.550375
Well 3	2000	2.07	25.40347	-80.541933
Well 4	2000	1.19	25.39261	-80.541605
Well 5	1000	2.23	25.39317	-80.553724
Well 6	500	1.21	25.39283	-80.549543

Table 2. Goodness-of-fit statistics for model calibration for water table elevation predictions using MODFLOW

Well	Ceff[1] Calibration	RMSE[2] Calibration (cm)
Well 2	0.97-0.98	4.0-5.0
Well 3	0.94-0.96	4.7-5.7
Well 4	0.80-0.90	6.0-7.0
Well 5	0.93-0.95	4.6-5.3
Well 6	0.99-1.00	1.0-1.2

[1]Nash-Sutcliffe coefficient of efficiency

[2]Root mean square error