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RESEARCH ARTICLE

Evaluating water table response to rainfall events in a shallow aquifer and canal system

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Abstract

Shallow aquifers typically have greater hydrologic connectivity and response to recharge and changes in surface water management practices than deeper aquifers and are therefore often managed to reduce the risk of flooding. Quantification of the water table elevation response under different management scenarios provides valuable information in shallow aquifer systems to assess indirect influences of such modifications. The episodic master recession method was applied to the 15-min water table elevation and NEXRAD rainfall data for 6 wells to identify water table response and individual rainfall events. The objectives of this study were to evaluate the effects of rainfall, water table elevation, canal stage, site-specific characteristics, and canal structure modification/water management practice on the fluctuations in water table elevations using multiple/stepwise multiple linear regression techniques. With the modification of canal structure and operation adjustment, significant difference existed in water table response in the southern wells due to its relative downstream position regarding the general groundwater flow direction and the structural modification locations. On average, water table response height and flood risk were lower after than before the structure modification to canals. The effect of rainfall event size on the height of water table response was greater than the effect of antecedent water table elevation and canal stage on the height of water table response. Other factors including leakance of the canal bed sediment, specific yield, and rainfall on $i-1$ day had significant effects on the height of water table response as well. Antecedent water table elevation and canal stage had greater and more linear effects on the height of water table response after the management changes to canals. Variation in water table response height/rainfall event size ratio was attributed to difference in S_y, antecedent soil water content, hydraulic gradient, rainfall size, and run-off ratio. After the structure modification, water table response height/rainfall event size ratio demonstrated more linear and proportional relationship with antecedent water table elevation and canal stage.

KEYWORDS
canal, rainfall analysis, shallow aquifer, water table response

1 | INTRODUCTION

Shallow aquifers, characteristic of coastal areas, are typically characterized by greater response to rainfall events and surface water dynamics compared to deeper aquifer systems. Likewise, evaporation is a significant process in shallow aquifers due to their close proximity to surface weather conditions (Werner & Simmons, 2009). The sensitivity of shallow aquifer systems to hydrologic processes requires adaptive management practices to prevent flooding or other saturated soil conditions that lead to loss of land function. For example, shallow aquifer depths have been shown to significantly impact crop growth and vegetation development (Nayak, Rao, & Sudheer, 2006; Rahman, 2008; Reilly, Plummer, Phillips, & Busenberg, 1994; Zencich, Froend, Turner, & Gailitis, 2002). Hence, accurate predictions of water table elevation response and potential risk in shallow aquifer systems must consider these hydrologic processes and the required conditions for maintaining land use function.

Rainfall has been identified as a primary factor affecting shallow water table elevations (Chin, 2008; Crosbie, Binning, & Kalma, 2005; Tan, Shuy, Chua, & Mzila, 2006; Van Gaalen, Kruse, Lafrenz, &

Burroughs, 2013; Viswanathan, 1984; Wu, Zhang, & Yang, 1996). Linear models have been developed to accurately estimate water table elevations in unconfined coastal aquifers using rainfall and effective rainfall as dependent variables (Chin, 2008; Viswanathan, 1984). Nonlinear behaviour has also been explored in rainfall–recharge evaluations. In a study conducted in central Florida, Van Gaalen et al. (2013) assessed the nonlinear behaviour of water table elevation at rainfall extremes using data from 11 wells located in uplands and wetlands. Results revealed that by incorporating stage and rainfall event size, forecasting of water table rise was improved by more than 30%. Tan et al. (2006) developed two sets of nonlinear regression equations, which adequately estimated gross recharge percentage using daily rainfall intensity, vadose zone thickness, and daily potential evaporation as input variables. Depending on the system, rainfall/recharge relationships have been defined using linear or nonlinear relationships.

Aquifer recharge can also be influenced by site characteristics such as depth to water table, soil characteristics, distance from canals, ground surface elevation, hydraulic conductivity, evapotranspiration, ocean tide, barometric pressure changes, pumping, and earth tide (Allocca, De Vita, Manna, & Nimmo, 2015; Chin, 2008; Crosbie et al., 2005; Edmunds & Gaye, 1994; Healy & Cook, 2002; Jan, Chen, & Lo, 2007; Nolan, Baehr, & Kauffman, 2003; Palumbo, 1998; Townley, 1995; Wu et al., 1996). For example, Van Gaalen et al. (2013) investigated the variation in water table response/rainfall ratio as a function of antecedent water table elevation and rainfall event depth. Their study showed that the response/rainfall ratio was higher in wetlands as compared to uplands. This was attributed to the lower specific yields and the greater lateral influx in the wetland sites. Allocca et al. (2015) investigated the dependence of recharge to the precipitation ratio on soil water content and rainfall intensity and established a multiple linear relation among them. Crosbie et al. (2005) presented a method to infer water table recharge from rainfall and fluctuation of water table by removing water rises caused by trapped air, evapotranspiration, and atmospheric tides. Thus, researchers have reported a variety of site characteristics, which were found to influence aquifer recharge.

Land surfaces in shallow aquifer systems often include constructed canals or surface waters to reduce the risk of flooding (Light & Dineen, 1994; Tol & Langen, 2000). Shallow aquifers may in fact intersect with surface waters or canals. Due to the strong interaction between canal water and shallow aquifer systems, even small structural modification or management adjustment to the canal system may influence local hydraulic conditions. For example, high-capacity pumps used to move water through canals were observed to increase vertical hydraulic gradients in water table elevations, thus locally influencing water exchange between canals and underlying aquifers (Harvey & McCormick, 2009; Krupa, Hill, & Diaz, 2002; Miller, 1988).

As far as we know, there is no published methodology on how to statistically evaluate structural modification or management adjustment to a canal and shallow aquifer system in terms of rainfall recharge response. Therefore, the study goal was to evaluate the influence of rainfall, site-specific characteristics, and canal structure modification/water management practice on shallow aquifer response. Our objectives were to (a) develop master recession curves (MRCs) for each well using time series of water table elevations; (b) identify individual rainfall events and their associated water table response; (c) evaluate whether significant difference exist in water table response, shallow aquifer water table elevation, and canal stage for time periods before and after canal structure modification/operational adjustment; (d) investigate trends among water table response height, rainfall event size, antecedent water table elevation, and canal stage; (e) identify other site-specific characteristics that influence water table response; and (f) develop multiple regression/stepwise multiple regression equations to predict water table response using rainfall event size, antecedent water table elevation, canal stage, and other significant site characteristics.

2 | MATERIALS AND METHODOLOGY

2.1 | Experimental site

The study was conducted in an agricultural area approximately 17 km^2 located in southern Miami-Dade County, Homestead, Florida (Figure 1). The area is east of Everglades National Park (ENP) between canals C111 and C111E managed by the South Florida Water Management District (SFWMD). Water levels in both canals are regulated by remotely operated spillway S177 and S178, respectively. The two canals join to become a single canal at the southern end. The primary function of the C-111 canal system is to provide flood protection and drainage for agricultural areas along the eastern boundary of ENP.

The soil at the study site is shallow (10–20 cm) with underlying Biscayne aquifer, which consists of porous limestone rock with hydraulic conductivities reported to exceed 10,000 m/day (Kisekka, Migliaccio, Muñoz-Carpena, Khare, & Boyer, 2013; Merritt, 1996). The topography at this site is essentially flat with elevation ranging approximately between 0.2 and 3.7 m above sea level NGVD 29 and shallow coastal unconfined aquifer water table elevations generally occurring between 0.2 and 1.7 m.

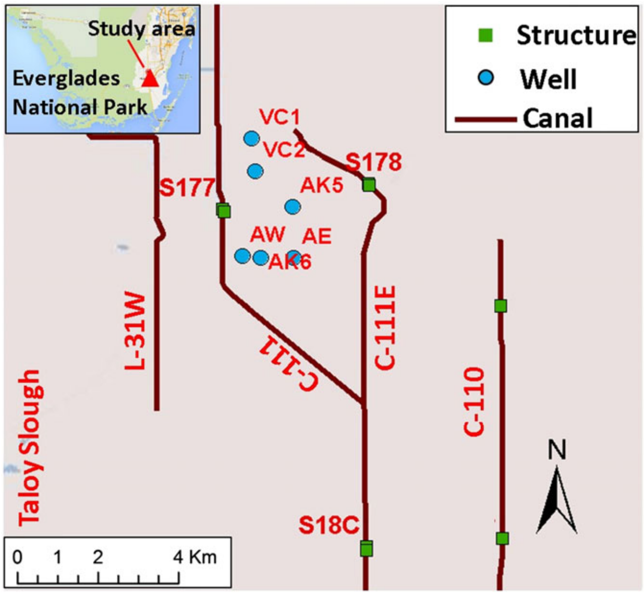

FIGURE 1 Satellite map of wells of VC1, VC2, AK5, AK6, AE, and AW

The climate is maritime subtropical with distinct annual pattern of wet and dry seasons (Duever, Meeder, Meeder, & McCollom, 1994). The mean annual precipitation is 1.48 m with approximately 59.1% of rainfall received during the wet season from June to September. October is the transitional month between wet and dry seasons. The wet season usually extends until October for the study area. Tropical storms and hurricanes in wet season create intense periods of rainfall, and flood control is a concern in South Florida (Perry, 2004). An urban and agricultural canal system provides flood protection for the area, which also has large effects on system hydrology (Choi & Harvey, 2000; Miles & Pfeuffer, 1997; Miller, 1988; Muñoz-Carpena, Ritter, & Li, 2005). The hydraulic connection between the Biscayne aquifer and canals causes the shallow water table system to fluctuate with respect to changes in canal stage (Chin, 2008; Kisekka et al., 2013). To restore the natural ecosystems near ENP and to balance different spatial and temporal water distributions among the ENP, Taylor Slough, Southern Glades, and the nearby agricultural areas, in January 2012, the SFWMD completed construction on several project components near canals C111 and C111E that were fully operational by June 2012 (Doviak & Zrnic, 1993). The structural modifications and operational adjustments included the following:

1. A pump station (S200) upstream of the existing S177 structure was added routing excess water to an above ground detention area, which would otherwise be discharged down the lower C111 canal via the S177 spillway. Pumping begins in the wet season (mid-June/July) and ceases in the middle of dry season (mid-January to March).
2. A second pump station (S199; with maximum discharge capacity of 5.50 × 10^5 m^3/day) was constructed immediately upstream of the existing S177 structure and downstream of State Road 9336. Same pumping constraints apply to the S199 structure as they do to the S200. The pump station routes water to the Aerojet canal via a northerly extension of the canal. Aerojet canal is located to the west of canal C111.
3. Ten earthen plugs were constructed at within the C110 canal to promote sheet flow within the Southern Glades and return water flow back into historic wetlands (Corps, U.S.A., District, S.F.W.M, 2014; Figure 1).

2.2 | Data summary

Data used in the study included time series for shallow aquifer water table elevations and rainfall. Site-specific data such as ground surface elevation of the wells, specific yield, aquifer thickness, hydraulic conductivity, and distance of the well from the C111 canal were also used.

2.2.1 | Water table elevation data

Water table elevation data were obtained from six wells. Four observation wells (VC1, VC2, AK5, and AK6) screened at the well bottom (6 m below the ground surface) were constructed and maintained by the University of Florida Institute of Food and Agricultural Sciences (Figure 1).Water table elevation data were recorded every 15 min at these four observation wells using level loggers (Solinst Canada Ltd., Georgetown, Ontario, Canada). To compensate for fluctuations in atmospheric pressure, data from a barologger were used, which was installed in the observation well AK6. Water table elevation data were downloaded from each well on a weekly basis and compared with the manual measurements taken using a water level meter (Solinist Canada Ltd., Georgetown, Ontario, Canada). Two additional observation wells, AE and AW, screened at the well bottom (4 m below the ground surface), were maintained by SFWMD. Fifteen-minute interval water table elevation data were available for these two wells from DBHYDRO (District, 2007; Figure 2).

Ground surface elevation data for the wells were obtained from the survey conducted by SFWMD in 2015. Site-specific characteristics for each well (Table 1) were obtained from a previous study conducted in the same area by Kisekka, Migliaccio, Munoz-Carpena, Schaffer, and Li (2013), among which, canal bed leakance *a* is defined as (Barlow & Moench, 1998; Kisekka et al., 2013):

$$a = \frac{K_x}{K_s} D, \tag{1}$$

where K_x is the horizontal conductivity of the aquiter (m/d), K_s is the hydraulic conductivity of the canal bed sediment (m/d), and D is the thickness of the canal bed sediment (m). Noted that the amount of water exchanged between the canal and the aquifer is proportional to K_s and inversely proportional to D; thus, a higher canal bed leakance value represents a smaller capability of the leakance between canal and the surrounding aquifer. To simplify the analysis, we used the term "leakance of the canal bed sediment (1/d)," which is defined as K_s/D, in the remaining sections of this paper. The amount of water exchanged between the canal and the aquifer is proportional to leakance of the canal bed sediment.

2.2.2 | Rainfall data

To minimize the error associated with the spatial variability of rainfall in South Florida, the use of gauge-adjusted next generation radar (NEXRAD) has been preferred in previous studies (Kisekka et al., 2013; Skinner, Bloetscher, & Pathak, 2009). SFWMD has estimated

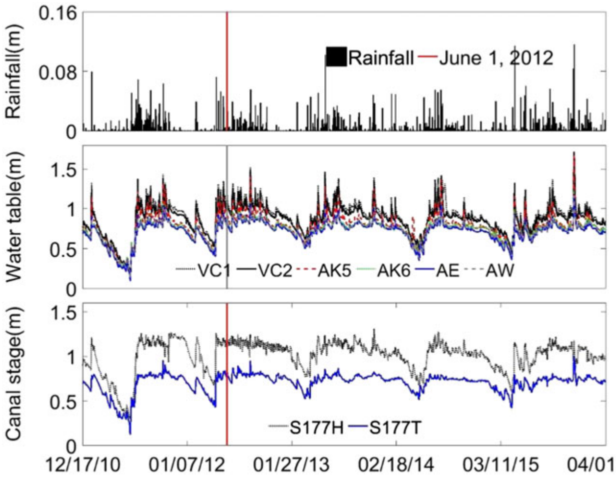

FIGURE 2 Rainfall, water table elevation, and canal stage data used for developing multiple regression equations

TABLE 1 Site-specific data for wells VC1, VC2, AK5, AK6, AE, and AW in South Florida (obtained from Kisekka et al., 2013except for ground surface elevation)

Wells	Ground surface elevation (NGVD29 m)	Hydraulic conductivity K_x (m/s)	Aquifer thickness D (m)	Canal bed leakance a (m)	Distance from canal (m)
VC1	1.89	0.1478	15.92	187.45	1,000
VC2	1.60	0.1478	15.92	187.24	1,000
AK5	1.94	0.1479	15.96	203.36	1,999
AK6	2.19	0.1477	15.90	187.45	1,000
AE	1.19	0.1480	15.97	203.06	1,999
AW	1.21	0.1475	15.83	165.57	500

gauge-adjusted NEXRAD rainfall data for the study site since July 2002 (Skinner et al., 2009). Rainfall was measured every 5 to 10 min, with the spatial resolution of 2 km × 2 km (Skinner, 2006; Skinner et al., 2009). The gauge-adjusted NEXRAD rainfall data with the precision of 0.003 m, same as the typically reported precision for the rain gauge, were used for analysing rainfall and its corresponding water table response (Figure 2).

2.3 | Water table recession evaluation

Height and width of the water table peak and associated rainfall event size were identified and quantified using episodic master recession (EMR) method developed by Nimmo, Horowitz, and Mitchell (2015). This method applies a water table fluctuation (WTF) method (Crosbie et al., 2005; Heppner & Nimmo, 2005; Meinzer, 1923) for estimating recharge using hydrographs of water table data. The recharge, R (m), during a particular event is calculated using WTF method (Nimmo et al., 2015) as

$$R = S_y \times H, \tag{2}$$

where S_y is specific yield and ΔH (m) is the rise in the water table corresponding to the event. We focused on the component ΔH, representing the rise in the water table due to rainfall.

To implement EMR method, MRCs were developed. The MRCs were fit using time series of water table data (H) and rate of change of water table data (dH/dt), where H refers to the part of water table hydrograph that represents the behaviour of the falling limb (Heppner & Nimmo, 2005). The prior to June 2012 time series include August 13, 2010, to May 31, 2012; the after June 2012 time series include June 1, 2012, to December 31, 2015. We refer to the period prior to June 1, 2012, as prealteration period and the period after June 1, 2012, as postalteration period. MRC can be used to compensate for the recessional process such as evaporation and lateral saturated-zone transport that occurs while the water table is rising due to recharge, thus can be used to predict the elevation of water table when it is declining due to no recharge (or when the infiltration ceases). Details of the MRC method are presented in Heppner and Nimmo (2005). We used data from the falling limb of the water table hydrograph after storm events to develop the equation for each well. Data from all the storms were combined, and a bin-average method was used (Heppner & Nimmo, 2005). By using bin-average method, an average value of dH/dt was obtained for different bin H. Linear relationships were developed between dH/dt (m/hr) and bin H (m) for each well.

The primary criteria we used in the analysis are described in this paragraph. For the detailed description of the algorithm, please refer to Nimmo et al. (2015).The observed rate of change of water table $(dH/dt)_o$ (subscript "o" represents observed rate of change) should be equal to the rate predicted by using the MRC $(dH/dt)_p$ (subscript "p" represents rate of change predicted using the MRC). There could be small deviations in the observed rate due to noise. Maximum range of noise that does not produce significant fluctuation in the water table is considered fluctuation tolerance (δt). The period of recharge is defined as when $(dH/dt)_o$ exceeds $(dH/dt)_p + \delta t$ (Nimmo et al., 2015). We used a fluctuation tolerance of 0.009 m for all wells. The value of fluctuation tolerance was determined manually by trial and error method (Nimmo et al., 2015). Any events that produced a peak greater than 0.009 m were identified by the EMR programme. Lag time is the time difference between the start of a rainfall event and the start of rise in the water table (t_{lag}). We identified that the minimum time for the water table to start rising after a rainfall was around 45 min for our wells. Average lag time for the wells was 5 hr for VC1 and VC2, 3 hr for AK5, AE, and AW, and 2.5 hr for AK6. Width of the peak refers to the duration for which the rise in the water table lasted. The recharge event starts when the observed curve $(dH/dt)_o$ intersects the curve predicted by MRC $(dH/dt)_p + \delta t$ before passing it, and the recharge event ends when the observed curve $(dH/dt)_o$ again intersects the MRC curve after having entered the tolerance band. The rainfall and water table elevation data for each well were input to the EMR programme developed by Nimmo et al. (2015). The EMR programme locates the water table peaks and identifies the corresponding rainfall event that caused the fluctuation in the water table. Note that to compare the mean, standard deviation, and distribution of water table response, only events occurring between June 1, 2011, and May 31, 2012, and between June 1, 2012, and May 31, 2015, were selected for analysis.

2.4 | Regression methods for predicting water table response

Both multiple regression and stepwise multiple regression (Aiken, West, & Reno, 1991; Draper & Smith, 2014) were performed to investigate the linear relationship between identified water table response height and independent variables including rainfall event size, antecedent shallow aquifer water table elevation, canal stage, specific yield, leakance of the canal bed sediment, distance from canal, rainfall on (i − 1) day, and water stage at ENP. The term "antecedent water table elevation (GW)" is used to describe the groundwater level at the onset of a rainfall event. F statistic test of the null hypothesis that the coefficient of the corresponding term is equal to zero (no effect) was conducted for each regression equation. To compare the effect of explanatory variables on response variables in multiple regressions, variables were standardized by subtracting the means and the differences were then divided by the standard deviations, so the coefficients are comparable. A stepwise regression technique was adopted to discard variables that did not significantly contribute to the index prediction using a critical p value of .05. Multicollinearity was detected using variance inflation factors (O'brien, 2007) and was eliminated by averaging or removing independent variables (Kisekka et al., 2013). A variance inflation factor threshold of 2 was chosen for this study.

2.5 | Statistical methods evaluating differences

A statistical test developed by Fisher (1921) was performed to compare the slopes of MRC lines and the slopes of water table response height versus rainfall event size for the periods prealteration and postalteration. The null hypothesis for the test is that the slopes for the two lines being considered are the same. In order to compare the slopes, the t values were calculated using

$$t=\frac{s1-s2}{SE_{s1-s2}}, \tag{3}$$

where $s1$ and $s2$ are the slopes of the MRC lines for the periods prealteration and postalteration and SE_{s1-s2} is the standard error of the difference between the two slopes

$$SE_{s1-s2}=\sqrt{SE1^2+SE2^2}, \tag{4}$$

where $SE1$ and $SE2$ are the standard error of the slopes. p values that are calculated based on t values and degree of freedom were used to test whether linear regression slopes are significantly different at a significance level of .05.

Kolmogorov–Smirnov test was used to test if the distribution of aquifer water table elevation, canal stage, rainfall, and identified water table response for prealteration period and postalteration period was significantly different (Massey, 1951; Miller, 1956; Simard & L'Ecuyer, 2011). Nash–Sutcliffe model efficiency coefficient (NS; Nash & Sutcliffe, 1970) and coefficient of determination (R^2; Steel & James, 1960) were used to measure the goodness of fit.

3 | RESULTS AND DISCUSSION

3.1 | Comparison of MRCs for the periods prealteration and postalteration

Two separate MRCs were developed for each well for datasets prealteration and postalteration (Table 2). The value of dH/dt is negative during the recession period. For the same value of H, a lower dH/dt value represents a faster recession rate. Thus, in Table 2, a recession equation with lower coefficient of H indicates a faster recession rate. Generally for the same antecedent water table elevation, recession rate was slower for the period prealteration than it was for postalteration. Statistical tests suggest that only the slopes for MRCs developed for well AE were significantly different at a significance level of .05 (Table 2). The lack of significant difference in the rate of recession at most locations implies that drainage characteristics of the system after rainfall events were not significantly modified by the management changes implemented.

3.2 | Water table response and associated rainfall amount

The means and standard deviations of the height of water table responses obtained from EMR results are summarized in Table 3. Results suggested that the height of water table response distributions was significantly different during prealteration period and postalteration period for southern wells AK6, AE, and AW at a significance level of .05. On average, water table response height was lower after the structure modification than previously (Table 3), indicating that flood risk was lower during postalteration period than in prealteration period for similar rainfall events. As expected, the distribution of identified rainfall event size was not significantly different for prealteration period and postalteration period. The influences of the canal modification to the water table response were more obvious in the southern part of the study area (wells AK6, AE, and AW), because after the structural modification, pumping at stations S199 and S200 had routed excess water from upstream of C111 canal, which would not be discharged down the lower C111 canal via the S177 structure, and wells AK6, AE, and AW are closer to the lower C111 canals. Another reason is that the general direction of the groundwater flow for this area is from the northwest to the southeast, so the downstream wells are more influenced than the upstream wells in the northern part. Actually, as all wells are not close to canal C110 and canal C110 is located at the southeast end of the study area, the

TABLE 2 Master recession curves (MRC) for wells VC1, VC2, AK5, AK6, AE, and AW where H is the water table elevation in wells, dH/dt is the change in elevation with time, R^2 is the regression statistic describing the fit of the data (p value marked with * represents the linear regression slope is significantly different at a significance level of alpha equal to .05)

Well	MRC (prealteration)	MRC (postalteration)	p value
VC1	$dH/dt = -0.0077\,H + 0.011$, $R^2 = 0.826$	$dH/dt = -0.0161\,H + 0.041$, $R^2 = 0.839$	.065
VC2	$dH/dt = -0.0093\,H + 0.012$, $R^2 = 0.730$	$dH/dt = -0.0170\,H + 0.042$, $R^2 = 0.767$	.182
AK5	$dH/dt = -0.0233\,H + 0.055$, $R^2 = 0.815$	$dH/dt = -0.0237\,H + 0.054$, $R^2 = 0.898$	.944
AK6	$dH/dt = -0.0136\,H + 0.0151$, $R^2 = 0.711$	$dH/dt = -0.0325\,H + 0.0747$, $R^2 = 0.846$	.077
AE	$dH/dt = -0.0095\,H + 0.0064$, $R^2 = 0.716$	$dH/dt = -0.0260\,H + 0.0569$, $R^2 = 0.942$	.023*
AW	$dH/dt = -0.0096\,H + 0.0008$, $R^2 = 0.889$	$dH/dt = -0.0374\,H + 0.0775$, $R^2 = 0.832$	.069

TABLE 3 Means and standard deviations (*SD*) of the height of water table responses for six wells during the prealteration period and postalteration period

	Prealteration				Postalteration			
			Height (m)				Height (m)	
Well	*n*1	*n*2	Mean	*SD*	*n*1	*n*2	Mean	*SD*
VC1	62	44	0.239	0.173	124	93	0.225	0.167
VC2	64	42	0.272	0.188	113	86	0.239	0.183
AK5	55	38	0.221	0.157	108	86	0.198	0.175
AK6	69	44	0.195	0.114	145	111	0.118	0.091
AE	53	45	0.175	0.112	160	125	0.113	0.089
AW	49	41	0.223	0.138	152	116	0.155	0.104

Note. The number of events is also presented in the table (*n*2). During the prealteration period, the number of rainfall events identified with the episodic master recession method between August 13, 2010, and May 31, 2012, for wells VC1, VC2, AK5, and AK6 and between December 16, 2010, and May 31, 2012, for wells AE and AW is listed as *n*1. During the postalteration period, the number of rainfall events identified with the episodic master recession method between June 1, 2012, and December 31, 2015, for all six wells is listed as *n*1.

influence of the canal C110 to the study area was limited, and this had been verified in our previous research (Migliaccio & Zhang, 2016).

3.3 | The influence of structure modification on water table elevation and canal stage

Figure 3 shows the distribution of daily water table elevation and canal stage before and after the structure modification and management adjustments implemented in June 2012. As the six wells showed essentially the same trend, only water table elevations for wells VC1 and AK6 were plotted in Figure 3. Daily water table elevation and canal stage were calculated by averaging 15-min interval data not only during rainfall period but from the entire time period. The tails of both water table and canal stage distribution in the negative direction extend further before than after structural modification, which indicated that the minimum water table elevation and canal stage increased after June 1, 2012. The minimum value corresponded to the tail of water table and canal stage distributions in the negative direction in Figure 3. The modes of water table elevation and canal stage distribution for the postalteration period are on the left side of the modes for the prealteration period, meaning that most often water table elevation and canal stage were lower after than before structure modification. This was because after June 1, 2012, for 7–8 months per year, excess water from upstream of C111 canal was routed by pumping at stations S199 and S200, which would otherwise be discharged down the lower C111 canal via the S177 structure. The decreased water table elevation in wells and canal stage at S177H and S177T led to the left-shifted modes after June 1, 2012 (Figure 3). Kolmogorov–Smirnov test indicated that water table elevation in all wells and canal stage at S177H and S177T were significantly different in prealteration period and postalteration period, indicating that canal structure modification and operation adjustment had changed hydraulic gradient and surface water–groundwater interaction. However, there was no significant difference in daily rainfall event size during prealteration period and postalteration period.

3.4 | Trends between height of water table response and associated rainfall amount

The relationship between rainfall and water table elevation change is significantly influenced by canopy interception, the amount of storage available above and below ground, and specific yield. The initial rainfall in an event is used to fill available field capacity and canopy interception (Chin, 2008; Van Gaalen et al., 2013). Excess rainfall contributes to water table rise in the aquifer, and the maximum no-recharge rainfall is taken as the threshold rainfall (Chin, 2008; Van Gaalen et al., 2013). The values of threshold rainfall for the six study wells ranged from 0.0051 to 0.0064 m (intercept on *x* axis; Table 5), which is close to the range of 0.0056 to 0.0122 m estimated by Chin (2008) for another study site located in Miami-Dade County, Florida.

Linear regression equations between height of water table response (*Rsp*) and rainfall event sizes (*P*) were developed for each well for dataset during prealteration period and postalteration period (Table 4). Compared with the slopes of the regression equation for period prealteration, the slopes for the postalteration period decreased for all wells except for wells AK5 and AK6. This indicated that for the same rainfall amount and antecedent water table elevation, height of water table response and flooding risk were lower after than before the structure modification and management adjustment for all the wells except for wells AK5 and AK6. Slopes for wells AK5 (7.67 vs. 8.00) and AK6 (6.13 vs. 6.18) were almost the same for prealteration and postalteration periods (Table 4). Statistical tests suggested that the slopes for all wells except for well AK6 were significantly different (Table 4).

Given that the research area is characterized by karstic Biscayne aquifer with high conductivity, flat landscape, quite thin soil layer

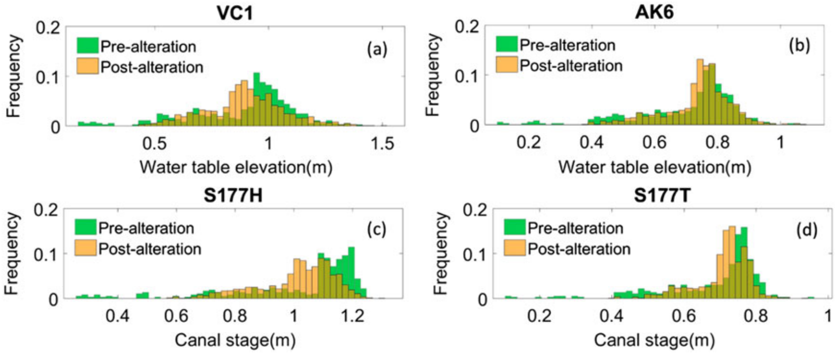

FIGURE 3 Comparison of water table elevation distribution for wells (a) VC1 and (b) AK6 and canal stage distribution for sites (c) S177H and (d) S177T during prealteration and postalteration periods

TABLE 4 Linear regression equations developed between height of water table response (*Rsp*; m) and corresponding rainfall event sizes (*P*; m) for the six wells prealteration and postalteration, where S_y is approximately estimated as the inverse of the slope after unit transformation

Well	Prealteration	R^2	S_y	Postalteration	R^2	S_y	*p* value
VC1	$Rsp = 8.52P - 0.04$	0.79	0.12	$Rsp = 7.38P - 0.04$	0.77	0.14	<.001*
VC2	$Rsp = 8.72P - 0.04$	0.80	0.11	$Rsp = 7.77P - 0.04$	0.82	0.13	<.001*
AK5	$Rsp = 7.67P - 0.04$	0.77	0.13	$Rsp = 8.00P - 0.04$	0.80	0.13	<.001*
AK6	$Rsp = 6.13P - 0.04$	0.68	0.16	$Rsp = 6.18P - 0.04$	0.81	0.16	.19
AE	$Rsp = 6.84P - 0.04$	0.87	0.15	$Rsp = 5.24P - 0.03$	0.83	0.19	<.001*
AW	$Rsp = 7.64P - 0.05$	0.73	0.13	$Rsp = 5.14P - 0.03$	0.64	0.19	<.001*

Note. R^2 is the regression statistic describing the fit of the data. *p* value marked with * represents the linear regression slop is significantly different at a significance level of alpha equal to .05.

thickness (10–20 cm), and shallow water tables, we assumed that except for the initial rainfall that is used to fill the canopy interception and available field capacity, the remaining rainfall infiltrates during major storm events (Chin, 2008; Merritt, 1996; Parker, Ferguson, & Love, 1955). By assuming that evaporation from the saturated zone is generally negligible over rainfall event time scale, the slope of the height of the water level response versus rainfall event size could approximately be thought of as the inverse of the average specific yield (S_y; Chin, 2008; Merritt, 1996; Parker et al., 1955; Van Gaalen et al., 2013). Note that S_y is not a constant value and depends on existing soil moisture and depth to water table. The estimated S_y values for this study represent the mean S_y values corresponding to different water table depth. Average S_y was estimated as 0.11–0.19, which is close to an estimate of 0.15 determined by Bolster, Genereux, and Saiers (2001) using data from a large-scale canal drawdown experiment and to mean of 0.102 estimated by Kisekka et al. (2013; Bolster et al., 2001). By dividing rainfall event size by corresponding water table response in South Florida, estimated S_y values of 0.20, 0.20, and 0.26 were obtained by Parker et al. (1955), Merritt (1996), and Chin (2008), respectively. The estimated S_y values for wells VC1, VC2, and AK5 were lower than for other wells (Figure 1 and Table 5). Estimated average S_y values for wells VC1, VC2, AE, and AW were greater for postalteration period, which suggests that different water table elevations correspond to different S_y values. The maximum water table response height/rainfall event size (*Rsp/P*) ratio occurred during events with rainfall size being smaller than 0.08 m (Figure 4). As all six wells show essentially the same trend in *Rsp/P* versus *P*, only plot for well AW was included in Figure 4. Variability exists in *Rsp/P* ratio due to difference in S_y, antecedent soil water content, crop, and plant cover type. However, results suggested that in general, large rainfall events produced the lowest *Rsp/P* ratio, indicating that large rainfall events contributed some water to overland/run-off flow (Figure 4). By using Equation 2 and S_y estimations in Table 4, we estimated that the average ratio between groundwater recharge and rainfall event size (*R*/*P*) was approximately equal to 0.8 when rainfall event size was larger than 0.08 m. We did not observe relatively lower *Rsp/P* ratio during small rainfall events in this study; however, Van Gaalen et al. (2013) in their research conducted in Central Florida found that the peak *Rsp/P* ratio

TABLE 5 Multiple linear regression equations developed using height of water table response (*Rsp*; m) as the dependent variable and corresponding rainfall event sizes (*P*; m) and antecedent water table elevations (*GW*; m) as the independent variables for the six wells during prealteration period and postalteration period

Well	Prealteration	R^2	Postalteration	R^2
VC1	$\boldsymbol{Rsp^* = 1.09P^*} + 0.01GW^* + 0.07$	0.87	$\boldsymbol{Rsp^* = 1.18P^* + 0.27GW^*} + 0.04$	0.92
VC2	$\boldsymbol{Rsp^* = 1.13P^*} + 0.08GW^* + 0.08$	0.91	$\boldsymbol{Rsp^* = 1.08P^* + 0.26GW^*} + 0.01$	0.92
AK5	$\boldsymbol{Rsp^* = 0.93P^* + 0.22GW^*} - 0.04$	0.78	$\boldsymbol{Rsp^* = 1.04P^* + 0.32GW^*} + 0.03$	0.93
AK6	$\boldsymbol{Rsp^* = 1.02P^*} + 0.06GW^* + 0.07$	0.82	$\boldsymbol{Rsp^* = 0.80P^* + 0.18GW^*} - 0.03$	0.87
AE	$\boldsymbol{Rsp^* = 0.95P^*} - 0.07GW^* + 0.02$	0.90	$\boldsymbol{Rsp^* = 0.84P^* + 0.16GW^*} - \mathbf{0.06}$	0.89
AW	$\boldsymbol{Rsp^* = 0.61P^*} - 0.02GW^* - \mathbf{0.16}$	0.71	$\boldsymbol{Rsp^* = 0.69P^* + 0.22GW^*} - \mathbf{0.10}$	0.74

Note. Independent variable in bold represents that the coefficient of the corresponding term is significant in the linear model at the 5% significance level. Variables were standardized and expressed with * followed. Equations are only valid when original *Rsp* (before being standardized) is positive.

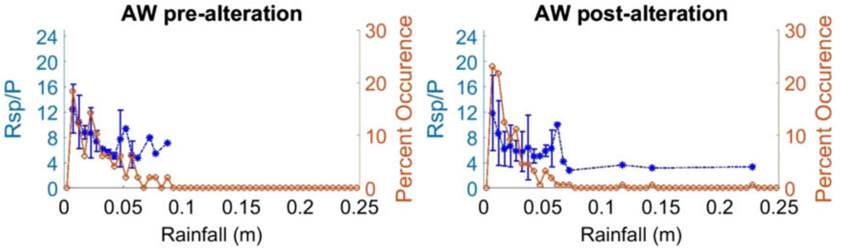

FIGURE 4 Water table response height/rainfall event size ratio (m/m) binned as a function of rainfall size with bin interval of 0.05 m. Left *y* axes and blue start show mean and standard deviation of ratio; right *y* axes and orange open circle represent percent of time that the rainfall event size was recorded at each 0.05-m bin for well AW during prealteration and postalteration periods

occurred at events with intermediate-sized rainfall size smaller than 0.10 m, whereas low *Rsp/P* ratio corresponded to small or large rainfall volumes due to interception by plants and unsaturated zone or generation of overland flow. Previously, we assumed that initial rainfall was used to fill the available field capacity and excess rainfall contributed to water table rise in the aquifer during major storm events. However, Figure 4 shows that lower *Rsp/P* ratios corresponded to the largest rainfall events with very low occurrence frequency. Whereas for the more common rainfall events occurring at intermediate levels, *Rsp/P* ratios changed only slightly. So the assumption that the initial rainfall in an event is used to fill available field capacity and canopy interception and excess rainfall contributes to water table rise in aquifer during major storm events still can be used to estimate the S_y values for this study, just as previous researcher did in their studies (Chin, 2008; Merritt, 1996; Parker et al., 1955).

3.5 | Trends among height of water table response, associated rainfall event size, and antecedent water table elevation/canal stage

Multiple linear regression between heights of water table response (*Rsp*) and corresponding rainfall event sizes (*P*) and antecedent water table elevations (*GW*) was developed for each well for dataset of prealteration and postalteration periods. R^2 values were improved for all the regression equations compared with those where antecedent water table elevations were not included in the multiple linear equation (Tables 4 and 5). By comparing the coefficients of each variable, the effect of *P* on *Rsp* is much greater than the effect of *GW* on *Rsp* (Table 5), suggesting that *P* was the primary factor that influence the *Rsp*. This can be attributed to the fast rainfall infiltration rate and the large amount of rainfall entered into the aquifer systems. The dominant role of *P* in controlling *Rsp* can also be attributed to the extremely high hydraulic conductivity and very shallow water table elevations of the study area. All models were significant at the 5% significance level based on the *F* test.

Rainfall event size had significant effect on the height of the water table response for all wells before and after structural modification (Table 5). Antecedent water table elevation had significant effect on the height of the water level response for well AK5 during prealteration period at significance level of .05, whereas antecedent water table elevations were significant in the linear model for all the wells during postalteration period, which can be attributed to the impact of the structural modification implemented in June 2012. Other researchers also identified the significance of antecedent water table elevations to water table response. For example, Wu et al. (1996) showed that the relationship between rainfall and water table recharge was dependent on the depth to water table. Different antecedent water table elevations may correspond to different porosity, evaporation rate, and specific yield (Chin, 2008; Duke, 1972; Schmoker & Halley, 1982; Sophocleous, 1985), which also may influence water table response to rainfall.

The effect of antecedent water table elevation can also be observed from *Rsp/P* ratio versus *GW* plots (Figure 5). For the prealteration period, Figure 5 shows complications in *Rsp/P* ratio versus *GW*. The lowest *Rsp/P* ratio for this period occurs in dry season with *GW* ranging between 0.2 and 0.4 m, on which condition, the soil moisture content is lower, so rainfall fills the storage in the unsaturated zone first. Allocca et al. (2015) also found that the groundwater recharge to the precipitation ratio is linearly proportional to antecedent soil water content. Two *Rsp/P* ratio peaks exist in plots for wells AK6, AE, and AW during prealteration period. One peak corresponds to GW ranging between 0.4 and 0.8 m when the soil is not so dry, and S_y for this depth may be small. The other peak corresponds to the highest GW in the wet season when rainfall recharges water tables in aquifer directly and the antecedent soil water content is high. For the more common shallow aquifer water table elevations occur at intermediate levels, *Rsp/P* ratios are not too high nor too low. Van Gaalen et al. (2013) found in a study conducted in Central Florida that at eight of the 11 sites, the most frequently occupied antecedent water table elevations correspond to the maximum *Rsp/P* ratio. And their results also showed compilations of *Rsp/P* ratio versus antecedent water table elevations. With the structure modification and management adjustment implemented in June, 2012, antecedent water table elevation had greater and more linear effect on height of water table response (Figure 5 and Table 5). Thus, WTF and flooding risk were more predictable based on rainfall event size and antecedent canal stage using the linear multiple regression equations. Quantitative prediction of flood risk and detailed representation of hydrologic interaction between surface water and shallow water table elevation will be achieved by incorporating a hydrologic model in future studies. Results obtained in this study such as specific yield trend, threshold rain, food risk trend, the role of soil water content, run-off and lateral flow, and the influence of the management changes to canals will provide guidelines for characterizing an integrated model in our future work. Canal stage effects were evaluated in the same way, and canal stage was found to have essentially the same influence as water table elevation on water table response.

3.6 | Predict height of water table response

Equations were developed to fit the observed water height of water table response using the combined data during the periods 2010 to 2011 and 2012 to 2014, respectively, for all the wells. The equations were validated by predicting the water table response of various wells due to rainfall events that occurred in 2012 (validation period) and 2015 (validation period), respectively. Independent variables including leakance of the canal bed sediment, specific yield, and distance from canal were held constant for a specific well. The effects of these factors cannot be evaluated with stepwise regression equations without using combined data from all wells.

Linear regression equations developed using only rainfall event size as the independent variables for periods 2010 to 2011 and 2012 to 2014 are shown in Table 6. The two models are significant at the 5% significance level based on the *F* test on the model. The equations were validated for the periods 2012 and 2015, respectively. The results are shown in Figure 6a,b. The NS and R^2 criteria indicate that the fit is very good between the predicted and observed height of water table response for the period January 1, 2012, to May 31, 2012, and for year 2015.

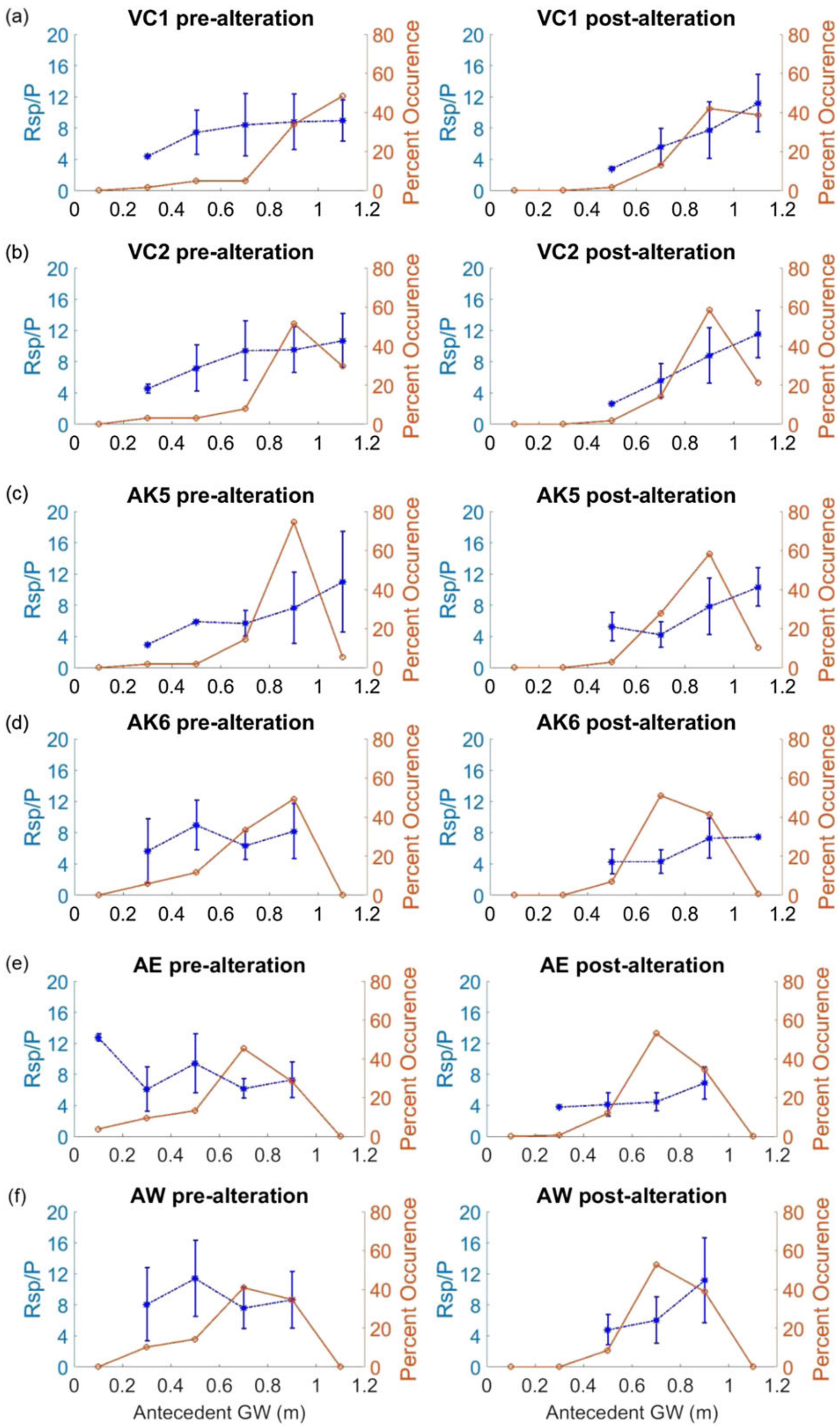

FIGURE 5 Water table response height/rainfall event size ratio (m/m) binned as a function of antecedent water table elevation with bin interval of 0.2 m. Left *y* axes and blue start show mean and standard deviation of ratio; right *y* axes and orange open circle represent percent of time that the antecedent water table elevation was recorded at each 0.1-m water level bin for wells (a) VC1, (b) VC2, (c) AK5, (d) AK6, (e) AE, and (f) AW during prealteration and postalteration periods

Another test was conducted by developing stepwise multiple regression equation using height of water table response as the dependent variable and using corresponding rainfall amount, canal stage at S177, antecedent water table elevation in well, specific yield, leakance of the canal bed sediment, distance of well from canal C111, rainfall amount on (i − 1) day, and water level stage at station ENPHC in Everglades National Park as independent variables. Variable canal stage at S177 was removed due to multicollinearity. For the period 2010–2011, independent variables of rainfall event size, antecedent water table elevation in the well, and specific yield were included in the final

TABLE 6 Overall linear regression equations developed using height of water table response (*Rsp*; m) as the dependent variable and corresponding rainfall event sizes (*P*; m) as the independent variables for all the wells during 2010–2011 and 2012–2014

Period	Equation	R^2	*p* value for model
2010–2011	**$Rsp = 6.56P - 0.04$**	0.75	<.001
June 1, 2012–2014	**$Rsp = 6.70P - 0.04$**	0.71	<.001

Note. Independent variable in bold represents that the coefficient of the corresponding term is significant in the linear model at the 5% significance level. Equations are valid only when *Rsp* is equal or larger than zero.

model. For the period after June 1, 2012, variables of rainfall event size, antecedent water table elevation in the well, leakance of the canal bed sediment, specific yield, and rainfall on *i* − 1 day were in the final model (Table 7). Variable water level stage at ENP was not in the final model for both of the periods. This can be explained by the 20-km distance between ENP and the study site. Other factors such as ocean tide and barometric pressure were not considered in the stepwise model, because the study area is several kilometres inland and unconfined aquifers are insensitive to change in barometric pressure (Crosbie et al., 2005; Freeze & Cherry, 1979). Both of the equations are significant at the 5% significance level. The two equations were validated for the periods 2012 and 2015, respectively (Figure 6c,d), which indicated that the equations were able to predict the water table response during 2012 and 2015 with greater accuracy than the equations developed in Table 6 based on NS and R^2 of the fit results.

More factors had significant effect on height of water table response after structure modification and management adjustment implemented in June 2012. The height of the water table response (*Rsp*) increased with the increasing rainfall amount and antecedent water table elevation for both the periods prealteration and postalteration. *Rsp* decreased with the specific yield for both the periods prealteration and postalteration. After the modification of the structure, *Rsp* increased as the leakance of the canal bed sediment (K_s/D) increasing. Although the influences of the leakance of the canal bed sediment to *Rsp* were not obvious for the period prealteration, which inferred that the interaction between canal and underling aquifer became stronger and canal leakance played a more significant role in adjusting water table elevations after structure modification. *Rsp* increased with the increasing rainfall on *i* − 1 day for the postalteration

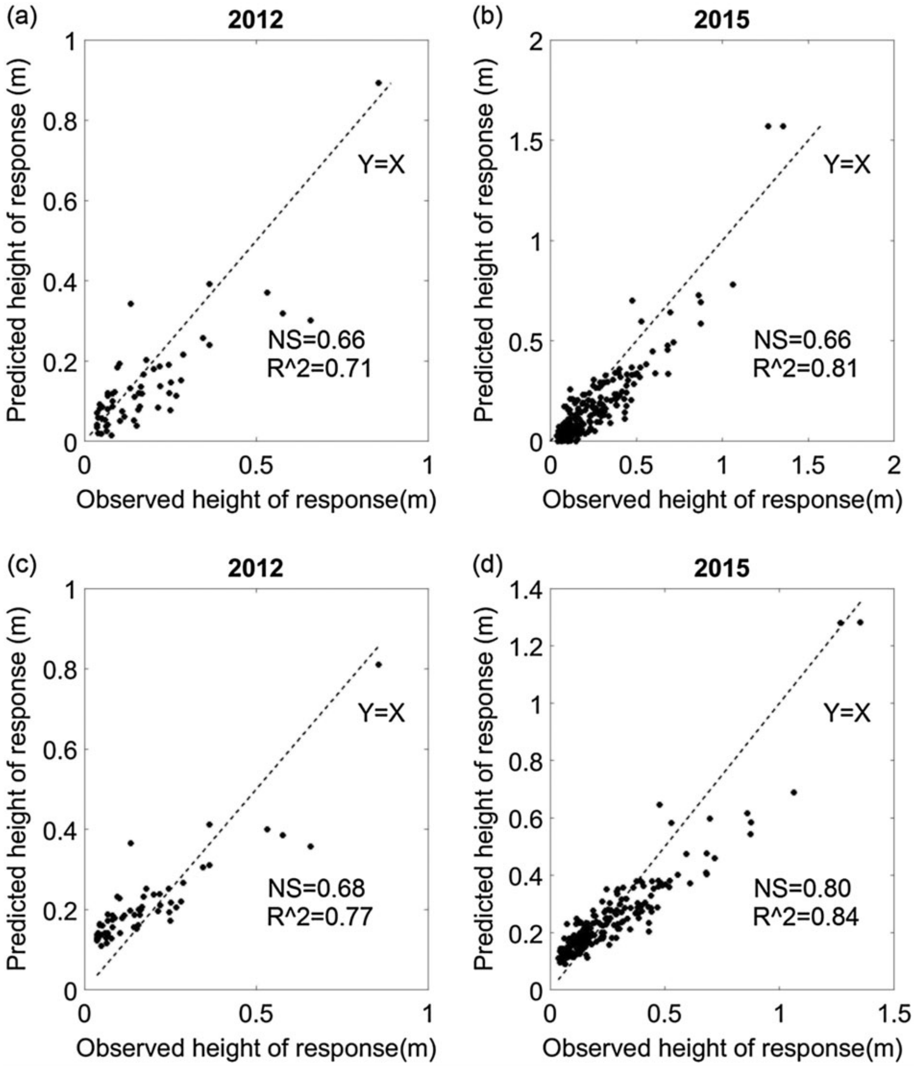

FIGURE 6 Comparison between observed and predicted water table response (a) using linear equation developed in Table 6 during validation period 2012, (b) using linear equation developed in Table 6 during validation period 2015, (c) using linear equation developed in Table 7 during validation period 2012, and (d) using linear equation developed in Table 7 during validation period 2015

TABLE 7 Stepwise regression results

Independent variable	2010–2011		June 1, 2012–2014	
	Coefficient	*p* value	Coefficient	*p* value
Intercept	0.12	**<.001***	−20.16	**<.001***
Rainfall (m)	5.25	**<.001***	4.97	**<.001***
Canal stage (m)	Removed due to multicollinearity			
Antecedent *GW* (m)	0.11	**<.001***	0.16	**<.001***
Leakance of the canal bed sediment (1/d)	−0.01	.98	0.01	**<.001***
Specific yield	−1.08	**<.001***	−0.91	**<.001***
Distance from canal (m)	0.04	.092	0.00	.172
Rainfall on (i − 1) day (m)	0.31	.339	0.65	**.009***
ENP stage (m)	−0.01	.617	0.00	.861

Note. ENP = Everglades National Park. Only the variables with *p* value smaller than .05 are included in the final model (marked with *). If a variable is in the final model, then the coefficient estimate for that term is a result of the final model, which means stepwise does not consider the terms it excluded from the model while computing these values. If a variable is not in the final model, then the corresponding coefficient estimate in results from adding only that term to the predictors in the final model.

period, which can be explained by the rise of the antecedent soil water content. Viswanathan (1983) and Viswanathan (1984) also found that rainfall occurring within several days had significant influence on water table response.

The linear regression equations had been validated to be adequate enough for identifying factors that significantly influenced water table responses in this study. The method we provided can be used to evaluate the management adjustments to canal systems in other coastal shallow aquifers. However, users are encouraged to check whether linear relationship exists among water table response, rainfall event size, and other potential variables for a specific application.

4 | CONCLUSIONS

We have explored and evaluated the influence of rainfall, shallow aquifer water table elevation, canal stage, site-specific characteristics, and canal structure modification/water management practice on the fluctuations in water table elevations in South Florida. The key conclusions can be summarized as follows:

1. When considering the minimum values for water table elevations and canal stages observed in the data, the minimums observed were greater after June 1, 2012. However, water table elevations in wells and canal stages were statistically lower after structure modifications.
2. With the modification of canal structure and operation adjustment, hydraulic gradient and surface water groundwater interaction may have changed, which resulted in significant difference in water table response in the southern wells AK6, AE, and AW. The southern area was influenced by the adjustment more significantly due to its relative downstream position regarding the general groundwater flow direction and the structural modification locations. On average, water table response height decreased after the structure modification, indicating that flood risk was lower during postalteration period than during prealteration period.
3. In general, the rates of water table recession were not influenced by management changes in the study area except for well AE. This implies that drainage characteristics of the system after rainfall events were not significantly modified by the management changes implemented.
4. By analysing the linear relationship between rainfall and water table elevation, we found that for the same rainfall event and antecedent shallow aquifer water table elevation, height of water table response and flooding risk were lower after than before the structure modification and management adjustment for all wells except for wells AK5 and AK6. The north part of the research area (upgradient) showed generally lower specific yield values than the southern part (downgradient).
5. The effect of rainfall event size on height of water table response was greater than the effect of antecedent water table elevation in aquifer and canal stage on height of water table response. Rainfall event size had significant effect on the height of the water table response for all wells during prealteration and postalteration periods. Antecedent water table elevation and canal stage had greater and more linear effect on height of water table response during the postalteration period. WTF and flooding risks were more predictable based on multiple linear regression equations after June 2012.
6. For the study area, the maximum water table response height/rainfall event size ratio occurred during events were rainfall size was less than 0.07 m, and large-sized rainfall events produced the lowest response height/rainfall event size ratio. The lowest water table response height/rainfall event size ratio occurred in dry season when the soil moisture content was low, thus rainfall filled the storage in the unsaturated zone first.

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