A Preliminary Seepage Evaluation of Proposed Discharges from Pump Stations S-332B and S-332C

By

M. M. Wilsnack

TECHNICAL NOTE
HHB Report # 2018-XXX
November 2018

Hydrology & Hydraulics Bureau
South Florida Water Management District

Table of Contents

Executive Summary 2
Introduction and Purpose 3
Hydrogeologic Setting 4
  Background and Previous Studies 4
  Characterization of Ground Water Flow Zones within the Biscayne Aquifer 5
Hydrogeologic Conceptualization within the Study Area 5
Seepage Model Development 9
  Conceptual Model and Modeling Approach 9
  Model Code 10
  Model Setup and Input 10
    Boundary Conditions 10
    Model Input 11
  History Matching 11
    Calibration Targets 11
    Boundary Stages 12
    Calibration Results 13
Seepage Model Applications to Selected Operational Scenarios 13
Summary and Conclusions 14
References 15

Executive Summary

A cross sectional ground water flow model of the Biscayne aquifer was constructed for the South Detention Area (SDA) along with surrounding areas to the east and within the ENP. The hydrostratigraphic model forming its basis was constructed using available geologic data along with the conceptualization of the various stratigraphic zones of the Biscayne aquifer established previously by the USGS for the Lake Belt mining area located further north. The ground water flow model was developed using the analytic element method in order to limit the discretization of the ground water flow domain to the model boundaries. The model was calibrated to an average estimated SDA seepage rate over the period of record spanning July 21 – August 3, 2016.

The model was used to simulate several seepage scenarios involving an estimated range of stages for the SDA, ENP and L-31N borrow canal. These stages included 8.0 and 8.5 feet NGVD for the ENP and SDA, respectively, under the CEPP-PACR operating plan. For the base ERTP (i.e. pre-CEPP) operational conditions, the aforementioned stages were 7.5 and 8.1 feet, respectively. The L-31N borrow canal stage ranged from 4.2 – 4.8 feet NGVD, consistent with the ERTP Increment 2.0 operational scenario. Under these conditions, the model results suggest that about half of the pumpage from S-332B and S-332C will return to the L-31N borrow canal as seepage. This percentage may be less than historical observations due to the head difference between the SDA and ENP being set at high, limiting values. Return seepage rates into the L-31N borrow canal were in the range of 142 - 186 cfs per mile. SDA seepage rates differed by only 3 – 4% between the two operational plans.

The results also indicate that seepage may increase by about 18 cfs per mile after SDA operations evolve from pre-CEPP to CEPP conditions. For the L-31N reach located along the length of the SDA (approximately 4.7 miles), this translates to about 85 cfs of additional seepage under the conditions examined or roughly 43 cfs per pump station. A safety factor of 2 applied to the computed seepage rates would then suggest that each pump station should have its capacity increased by slightly more than 80 cfs to accommodate increases in seepage rates to the L-31N borrow canal.

Seepage rates computed by the model are highly uncertain due to uncertainties inherent to both the conceptual hydrostratigraphic model and the model parameters. The model is currently only suitable for providing the order-of-magnitude estimates of seepage needed for cost estimating purposes. Before performing any seepage analyses needed for future phases of design, it is highly recommended that the surficial aquifer within the study area be better characterized using the techniques previously employed by the USGS in the Lake Belt mining area of Miami-Dade County.

Introduction and Purpose

Pump stations S-332B and S-332C discharge through long conduits and into the South Detention Area (SDA) located within the eastern Everglades National Park (ENP) (Figure 1). This outlet configuration was originally designed to lessen the amount of pumped flows that return to the L-31N borrow canal through seepage. Additionally, this detention area helps to distribute the pumped flows spatially.

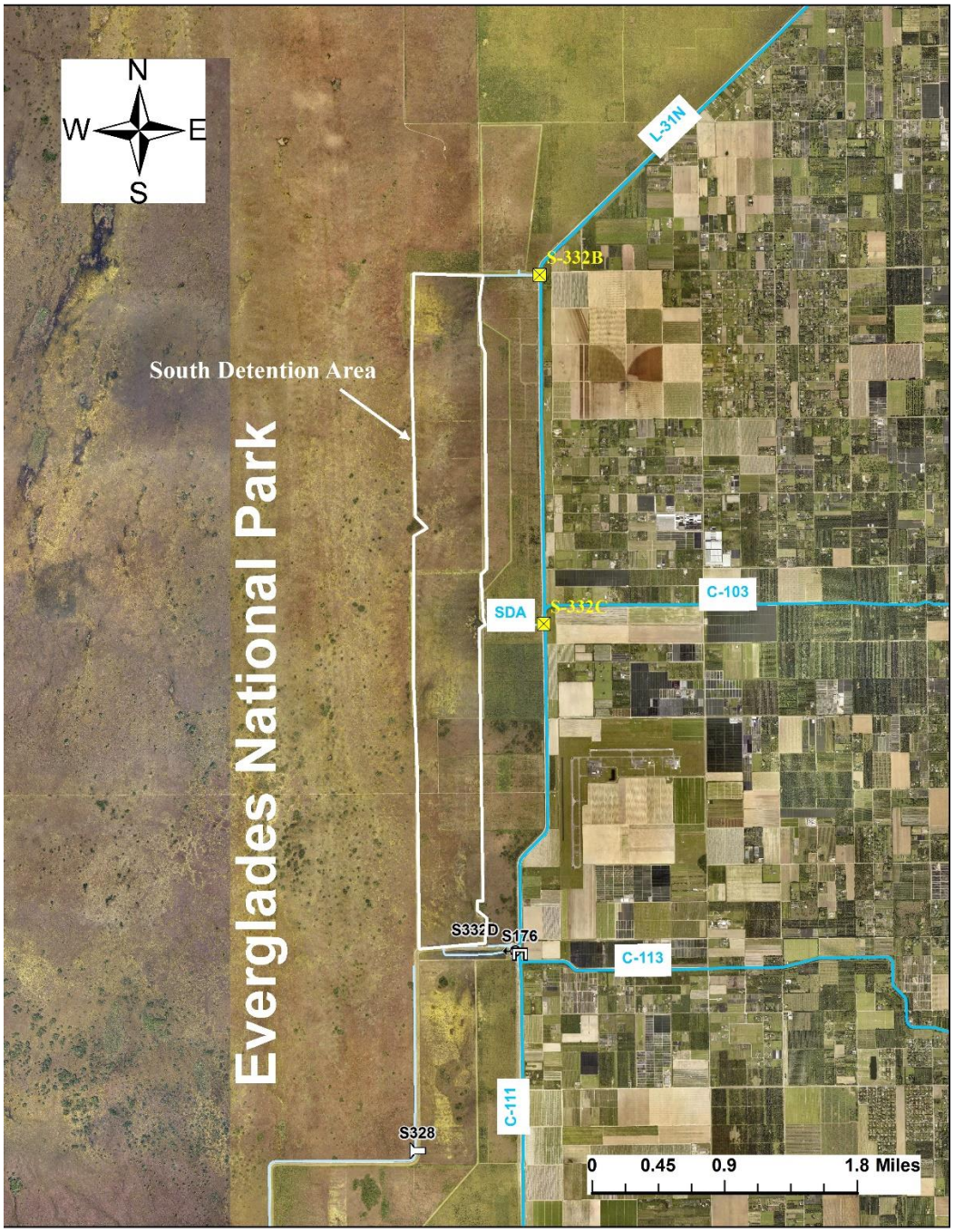


Figure 1. Locations of S-332B, S-332C and the South Detention Area (SDA).

Both pump stations were constructed in 2000 as part of the C-111 Interim Operating Plan (IOP). Furthermore, they were constructed as temporary facilities with the intent to replace them with permanent structures at some future date. The initial phase of this effort is currently underway, where increases in the discharge capacities are under consideration.

The purpose of this seepage evaluation is to provide an initial assessment of any changes in return flows through ground water to the L-31N borrow canal resulting from changes in water levels due to increased pumping along with proposed modifications to water management plans. The results of the seepage analyses will be used to develop preliminary cost estimates of the proposed pump stations that will replace S-332B and S-332C.

Hydrogeologic Setting

Background and Previous Studies

The Biscayne aquifer, the upper-most aquifer unit of the Surficial Aquifer System (SAS), is the primary water-bearing geologic unit beneath the study area. According to Fish and Stewart (1991), it generally includes the shallow and highly transmissive oolitic limestone of the Miami Limestone formation along with limestone, sandstone and other sediments with varying degrees of permeability that are within the underlying Fort Thompson formation. Beneath the Fort Thompson formation lies the Tamiami formation which contains water bearing units that are generally of lower transmissivity than those of the Fort Thompson formation. An aquitard consisting of sands, silts, clays and other low permeability sediments separates the Fort Thompson formation from any transmissive units of the Tamiami formation.

The Biscayne aquifer has been studied by numerous investigators over the years, including Parker, et al. (1955), Perkins (1977), Halley and Evans (1983) and Cressler (1993). In order to better characterize the Biscayne aquifer for water supply development and ground water management purposes, Causarus (1987) developed lithologic logs of numerous boreholes drilled within the SAS and distributed throughout Miami-Dade County. These logs, along with the results of ground water pump tests and other hydrogeologic data, were used by Fish and Stewart (1991) to develop estimates of aquifer transmissivity and hydraulic conductivity throughout Miami-Dade County. Genereux and Guardiario (1998) and Lal (2006) obtained more local estimates of the Biscayne aquifer transmissivity in the Frog Pond area, located about 4 miles south of structure S176 (Figure 1). In their studies, estimates of the aquifer's hydraulic properties were derived from an analysis of canal-aquifer interactions.

The results of the hydrogeologic characterization of the Biscayne aquifer carried out by Fish and Stewart (1991) have been utilized by various ground water flow modeling efforts carried out within the vicinity of the L-30, L-31N and C-111 corridors. These include Wilsnack et al. (1997), Sonnenshein (2001), Nemeth et al., (2000) and Wilsnack et al. (2005). A far more rigorous, detailed and advanced hydrogeologic characterization of the Biscayne aquifer within the Lake Belt area and northern L-31N corridor (approximately 12 miles northeast of the study area) was carried out by Cunningham et al. (2004). This study focused on the identification and characterization of ground water flow zones within the upper portions of the Biscayne aquifer. The investigators used ground-penetrating radar (GPR), geophysical logs, heat-pulse flowmeter data, borehole imaging and drilled cores to identify and, to a limited extent, characterize potential ground water flow zones within the study area. They essentially found that the

hydraulic properties of the Biscayne aquifer are highly heterogeneous and anisotropic, and that ground water flow occurs primarily within localized flow zones created by "solution-enlarged carbonate grains, depositional textures, bedding planes, cracks, root molds and paleokarst surfaces". The investigators concluded that preferential flow occurs through zones of inter-vug connections that form sheet-like geometry. Cunningham et al. (2004) found that these zones can be aerially extensive in their study area and can occur at various depths. Additionally, other less permeable but aerially extensive zones were identified, where the porosity is of an interparticle and intraparticle nature with vugs that are mostly separate and connected through a soil matrix.

Of particular interest to seepage investigations along the L-30 and L-31N corridors is a semiconfining unit identified by Cunningham et al. (2004) that spans the base of the Miami Limestone and the top of the Fort Thompson formation. This unit can be very leaky due to what the investigators describe as preferred vertical dissolution that occurred during paleo-vadose events. This unit affects the vertical movement of surface water into the Fort Thompson formation.

Characterization of Ground Water Flow Zones within the Biscayne Aquifer

In order to provide a conceptual framework for ground water flow modeling, Cunningham et al. (2004) defined a new high-resolution hydrogeologic framework that divides the upper part of the Biscayne aquifer into various zones that are each defined by one of four ground water flow classes. These ground water flow classes include: (1) a peat, muck and marl ground water flow class with low permeability; (2) a horizontal conduit ground water flow class; (3) a leaky, low-permeability ground water flow class; and (4) a diffuse-carbonate ground water flow class. In the horizontal conduit class, ground water flow is conceptualized as inter-vug flow within a pore system characterized by connected vugs. In contrast, the porosity of the diffuse ground water flow class is a combination of both intergrain porosity and separate vug porosity. Ground water flow characterized by this class was conceptualized by the investigators as ground water movement from matrix to vug to matrix. The leaky, low-permeability ground water flow class was considered to have a matrix of relatively low horizontal permeability while its vertical permeability was found to be substantially higher than the horizontal permeability due to the presence of root molds that are semivertical in direction and enlarged through solutioning.

Hydrogeologic Conceptualization within the Study Area

Given the preceding discussions, the objective was to conceptualize the hydrostratigraphy of the study area according to the aforementioned ground water flow classes. Strictly speaking, this would require the implementation of same technologies used by Cunningham et al. (2004). These required technologies are summarized by Cunningham and Sukop (2011) and include ichnology, cyclostratigraphy and computational methods. Unfortunately, the necessary data acquired through these technologies cannot be obtained within the time frame for the current study. Consequently, all geologic and geotechnical data that are currently available and acquired in the proximity of the study area were reviewed and correlated to one of the ground water flow classes discussed previously. In doing so, lithologic descriptions and logs were examined in detail for key words such as "porous", "vuggy", "cavity" and "highly permeable" in addition to lithologic classifications. While such clues are sketchy at best and the propensity for erroneous ground water flow classification may be high when based on this type of information alone, it should be recalled that the purpose of the resultant hydrostratigraphic conceptualization is to

serve as the required framework for a seepage analysis that is needed for planning and cost estimating purposes only. Since numerous realizations of the hydrostratigraphy could be developed from the available information, interpretations that enhance ground water flow will be favored where considerable uncertainty exists. This will lead to more conservative results, as appropriate.

The most recent subsurface investigation within the project area is presented in the geotechnical data report for the C-111 Project, Phase II (USACE, 2005). This geotechnical investigation included six deep borings over 50 feet deep, eight shallow borings ranging from 15 to about 20 feet in depth, and 17 test pits that were 3 – 5 feet deep. The test pit and boring locations are shown in Figure 2. Two of the deep borings and two of the shallow borings were obtained in 1995 near pump station S-332D (Figure 1); four deep borings were taken near pump station S-332C; six shallow borings were taken about 1800 feet west of L-31N between S-332B and S-332C; and the test pits were excavated at various locations ranging from about 2300 – 4900 feet west of L-31N. Additionally, geologic boring G-3314 from Causarus (1987) is located in the southeastern part of the study area.

The investigation by USACE (2005) revealed that the Biscayne aquifer in this area is generally overlain by a thin layer (on the order of 1 foot or so) of surficial sediments and extends to about 50 feet below ground surface. The aquifer was found to be comprised primarily of fossiliferous limestone with varying degrees of porosity, permeability and weathering. Intermittent layers of sand, silty sand and clay were found in several of the borings located near S-332C, although they were thought to be of limited extent. Of particular interest is the fact that this investigation found no oolitic limestone in the project area. This suggests that the Miami Limestone formation does not exist in the investigated area and that the Fort Thompson formation extends to the veneer of surficial sediments. In was noted that none of the lithologic descriptions provided by Causarus (1987) for the shallower layers of boring G-3314 specifically identify oolitic limestone, although some of the fossils within these layers were described as “oolite-bearing”.

Using the information mentioned above, the lithologic log of each boring was converted to the ground water flow classes discussed previously. In the converted boring log descriptions, each ground water flow class was designated by the number assigned to it by Cunningham et al. (2004). For convenience, these designations are provided in Table 1. The lithologic logs converted to the ground water flow classes are provided in Appendix A.

Table 1. Ground water flow class designations and descriptions (from Cunningham et al., 2004)

Ground Water Flow Class Number	Description
1	peat, muck and marl with low permeability
2	horizontal conduit type flow
3	leaky, low-permeability matrix
4	diffuse-carbonate, matrix to vug to matrix flow

After considerable review of the reclassified borings along with the new hydrostratigraphic scheme established by Cunningham et al. (2004) for the upper Biscayne aquifer along the L-31N corridor further north, the simplified hydrostratigraphic conceptualization of the Biscayne aquifer shown in Figure 3 and Table 2 is proposed for the project area.

Figure 2. Locations of core borings and test pits in the project area (from USACE, 2005)

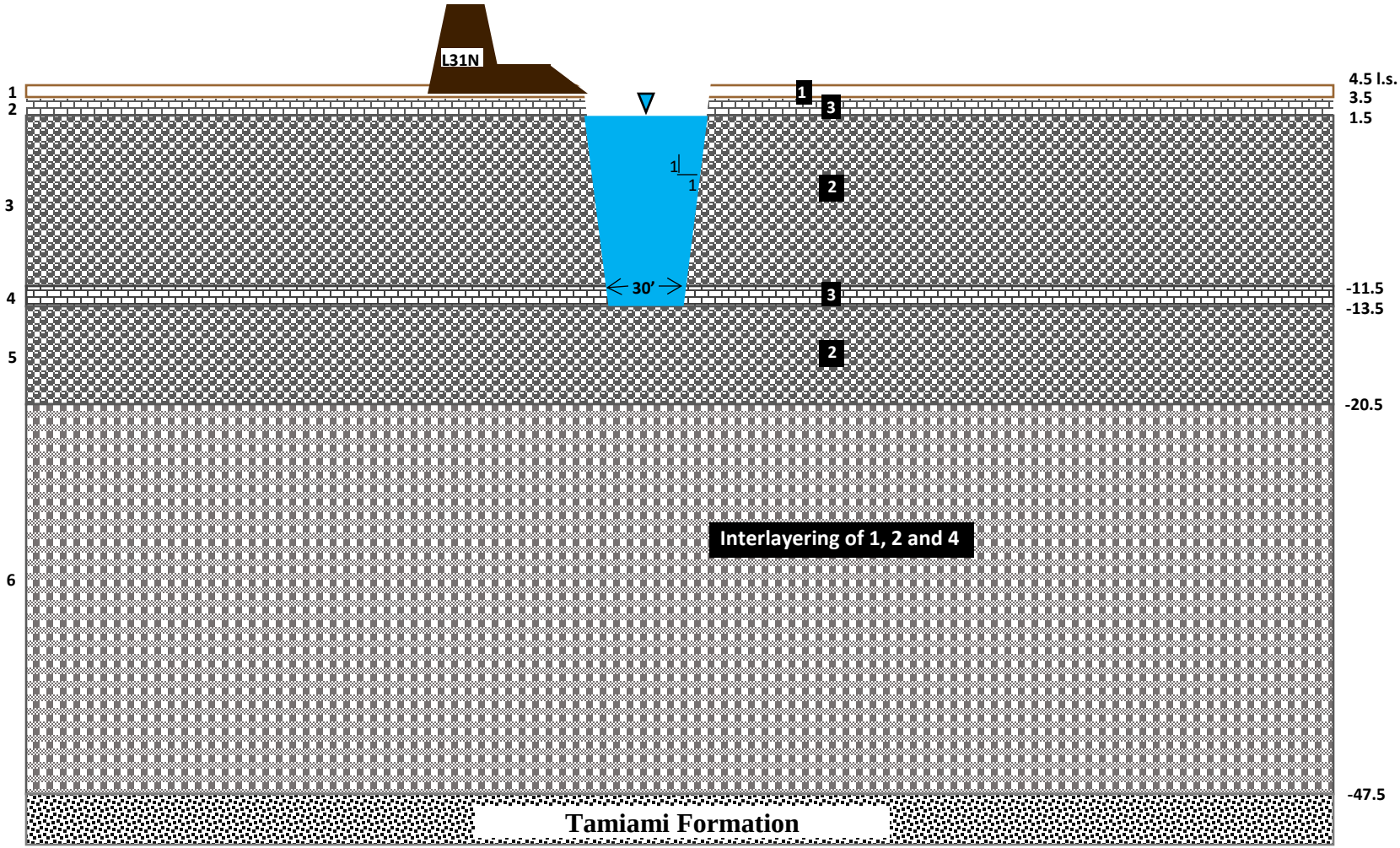


Figure 3. Conceptual layering of the Biscayne aquifer within the study area according to ground water flow class (looking north, N.T.S.). Layer numbers are displayed to the left while layer bottom elevations (NAVD) are shown to the right. Ground water flow class numbers are as displayed in the black boxes.

Table 2. Proposed hydrostratigraphic layering scheme for seepage analysis

Layer Number	Top Elevation (NAVD)	Thickness (ft)	Ground Water Flow Class	Comments
1	4.5	1	1	Thicknesses vary throughout the study area; a 1-foot average depth was reported by USACE (2005)
2	3.5	2	3	
3	1.5	13	2	
4	-11.5	2	3	
5	-13.5	7	2	
6	-20.5	27	see comments	Data suggest that this zone contains an interlayering of ground water flow classes 1, 2 and 4. They are lumped into a single layer for seepage modeling purposes. The effective hydraulic conductivities of this layer will be reduced accordingly.

Seepage Model Development

Conceptual Model and Modeling Approach

Given the spatial extents shown in Figure 1, it is evident from Figure 3 that the vertical dimensions of the geologic layers controlling ground water flow are much smaller than the horizontal dimensions of project area. Haitjema (2005) indicates that ground water flow within very elongated domains can be difficult to model with grid-based numerical techniques due to potential grid resolution problems. Additionally, the large number of cells or nodes needed to cover the entire domain with adequate resolution could also be problematic. Moreover, using analytic element techniques to simulate ground water flow within elongated, narrow layers can also be difficult due to the proximity of collocation points of within the various line sinks and line doublets (Haitjema et al., 2010).

To circumvent these difficulties and maintain realistic model aspect ratios, Haitjema et al. (2010) demonstrated that Cauchy type vertical boundary conditions can be assigned to the two ends of the model so as to account for the truncated portions of the contributing aquifer and wetlands. This approach to establishing the terminal boundary conditions can lead to a model that maintains a practical aspect ratio while also accounting for, at least in an approximate sense, the portions of the aquifer and wetlands that contribute to ground water flow and seepage but are not directly included in the model. In fact, numerous cross-sectional ground water flow models for south Florida levees have successfully been constructed using this approach (Wilsnack et al., 2008). Examples of such efforts include Wilsnack and Kelson (2007), and Haitjema et al. (2010).

The analytic element method (Strack, 1989; Haitjema, 1995) can be advantageous in modeling this type of ground water flow system, conceptualized as described above, since it only requires discretization of the model boundaries. This yields a ground water flow domain that is continuous. Furthermore, the boundary conditions can be conveniently represented through line sinks while line doublets can be used to demark the various hydrostratigraphic zones. Haitjema (1995)

provides detailed discussions on the use of analytic elements to model both external and internal boundary conditions.

Model Code

A ground water flow model representing the hydrogeologic conceptualization given in Table 2 and Figure 3 was constructed using the software AnAqSim release 2018-2 (Fitts Geosolutions, 2018). AnAqSim was selected since it employs a novel approach to the analytic element modeling of ground water flow. More specifically, it enables the ground water flow system depicted in Figure 3 to be divided into separate subdomains, each with its own analytic flow model and local aquifer parameters (Fitts, 2010). This can be computationally advantageous when modeling ground water flow within the extensive and layered system under consideration here. Furthermore, AnAqSim conveniently affords the use of higher-order line sink elements. Jankovic and Barnes (1999) demonstrate that this can improve accuracy in model results.

Model Setup and Input

Boundary Conditions

The western limit of the cross-section model was set in the ENP at approximately 500 feet west of the SDA. The vertical boundary condition within each layer at this location was specified as a Cauchy boundary with a resistance set equal to the ratio of the layer's characteristic seepage length (see, for example, Verruijt, 1970) to its hydraulic conductivity (Haitjema et al., 2010). The specific calculations performed by Haitjema et al. (2010) in determining the boundary resistances for a cross-sectional ground water flow model located along the L-67A levee were performed for the current model as well. While establishing the western boundary condition in this manner will approximately account for the truncated portion of the aquifer west of the study area, Haitjema et al. (2010) nonetheless recommend that the boundary be placed far enough from the area of interest so that it contributes a negligible amount to the overall water budget. Haitjema et al. (2010) indicate that this can be accomplished by placing the boundary at least three characteristic seepage lengths away from the levee (i.e. in this case the west SDA levee). During model calibration, it was found that the maximum characteristic seepage length for any of the model layers was about 65 feet. Hence, this implies that the west vertical boundary should be at least 200 feet away from the levee, much less that the 500 feet that was actually used. Additional verification of this boundary condition is provided in Appendix B.

The eastern limit of the model was set at approximately 1000 feet east of the L-31N borrow canal. Like the boundary condition at the west end, the boundary condition at the east end is a Cauchy boundary condition with a specified resistance value that represents the resistance to flow between the boundary location and the remote location of a hydraulic boundary in the field. Such a remote boundary is not well defined. For modeling purposes, this remote boundary was taken to be at the tail water location of structure S-196.

The side walls of the L-31N borrow canal were modeled using line sinks with a specified head and no resistance since they are assumed to be open to the aquifer. Additionally, the channel bottom was assumed to contain a fine sediment layer that is two feet thick. The canal bottom along with the portions of the channel sides below the top of this sediment layer were therefore included as head-dependent line sinks with a resistance that is indicative of the sediment layer.

Layer 1 identified in Table 2 was not explicitly modeled and only its vertical resistance to leakage was incorporated into the model. The bottoms of the SDA and the portion of ENP located west of the SDA were represented by head-dependent line sinks with resistances that are based on an average muck thickness and hydraulic conductivity. The bottom muck layer within the portion of the ENP located between the SDA and L-31N was modeled as a leaky barrier that separates the top aquifer layer and surface water flow within the wetland. A flow domain with very high hydraulic conductivity was included above this leaky barrier to account for surface water flow within these wetlands.

Impermeable flow barriers were placed along the land surface under the levees. These include L-31N along with the east and west levees of the SDA. The flow barriers were modeled as normal flux-specified line sinks with a normal flux rate set to zero. Similarly, the same type of line sink was specified along the bottom of the aquifer.

Model Input

Table 3 lists the initial values for hydraulic conductivity and anisotropy. The initial hydraulic conductivity values were assumed, based on information provided by Fish and Stewart (1991). The values for anisotropy in ground water flow classes 2 and 3 were based on the findings of Cunningham et al. (2004).

Table 3. Initial aquifer parameters

Ground Water Flow Class	K_h (ft/day)	K_v / K_h
1	0.1	10
2	1000	10
3	100	10

History Matching

Calibration Targets

In order to help ensure that the model can provide realistic estimates of SDA seepage, a limited calibration effort was carried out. Due to a lack of observed flow data for the reach of the L-31N borrow canal located along the SDA, the only history matching exercise that could be performed over a designated period of record included (i) assigning average historical water levels to the western ENP, the SDA, the L-31N borrow canal and the terminal boundaries, (ii) comparing SDA seepage to average pumped SDA inflow rates, (iii) comparing the percentage of the pumped inflows that returns as seepage to the L-31N borrow canal to field observations by operations staff, and (iv) comparing the percentage of return seepage intercepted by the L-31N borrow canal to the percentage predicted by the linear functions in the calibrated Regional Simulation Model (RSM) that serve as water movers between ENP, the L-31N borrow canal and the aquifer to the east. According to P. F. Linton (personal communication dated 7/20/18), sustained maximum pumping with S-332C has historically resulted in about 2/3 of the pumpage returning to the L-31N borrow canal as seepage. In the calibrated RSM, seepage from the ENP in this area is given by (Kelson, et al., 2006)

$$Q_m = K_{mc} (H_m - H_c) + K_{md} (H_m - H_d) \quad \text{(1a)}$$

where Q_m is the seepage from ENP; H_m, H_c, and H_d are the stages in the ENP, L-31N borrow canal and the developed lands to the east, respectively; and the coefficients are RSM calibration parameters. Similarly, the ground water inflow to the L-31N borrow canal (Q_c) can be stated as:

$$Q_c = K_{mc} (H_m - H_c) + K_{dc} (H_d - H_c) \quad \text{(1b)}$$

For given water levels in the ENP, borrow canal and the aquifer to the east, dividing Equation 1b by 1a yields the fraction of the total ENP seepage that flows into the L-31N borrow canal.

The aforementioned information allows results from the seepage model to be compared to historical information indicated by items (ii), (iii) and (iv) listed above. This should be carried out for a period of record with sustained pumping from S-332B and S-332C into the SDA. The selected period of record for history matching was July 21 – August 3, 2016. This was a period of sustained pumping from both S-332B and S-332C, where S-332B discharge rates varied from about 270cfs to about 350 cfs while S-332C outflows ranged from about 530 cfs to about 630 cfs. While this latter discharge rate is higher than the nominal design capacity of 575 cfs, the flow rating analysis for this pump station indicates that the pumps may be capable of producing somewhat higher flow rates. However, there are insufficient measured flow data to verify this rating. *Consequently, it is recommended that the flow rating for S-332C be verified or updated with additional field flow measurements, if possible, prior to the next phase of design.* The reported flow rates for this period of record were nonetheless used in this analysis for conservative design purposes.

Outflows from both pump stations were added to give the total pumped inflow and this was added to the net aerial inflow rate (rainfall – ET_p) to the SDA derived from the SDA area along with daily rainfall and ET_p records from station S331W. This resulted in a total inflow rate hydrograph for the SDA. For the aforementioned period of record, the average total inflow rate to the SDA was about 970 cfs. Given a total SDA length of about 24,250 feet in the north-south direction, this results in a unit inflow rate of about 0.04 cfs/ft or 3456 ft^2/day. This value was used as a history matching target for total SDA seepage.

Boundary Stages

An average SDA stage for the history matching period of record was estimated from surface water gauges with data available for this time window. This included sites RG4, S332CS_T, DS3 and NTS18. The temporal and spatial average stage for all these sites over the period of record is 7.39 feet NGVD = 5.84 feet NAVD.

The average ENP stage between the western model boundary and then western SDA boundary was estimated from water level data obtained from the RUTZKE well. Its average water level for the period of record is 7.06 feet NGVD = 5.51 feet NAVD. This stage was applied to the western boundary as well. The average tail water stage for S-196 during the period of record was assigned to the eastern terminal boundary (2.39 feet NAVD).

The average stage in L-31N along the length of the SDA was estimated using head water stage data at S-176, S-332C and S-332B. The average head water stage at these sites within the history matching period of record was approximately 2.7 feet NAVD.

Calibration Results

The vertical hydraulic conductivities of the SDA and ENP surficial sediments along with the horizontal hydraulic conductivities of the model layers were adjusted during the history matching process until the model results came close to the calibration targets discussed above. The resultant model parameters are provided in Table 4.

Table 4. Calibrated model parameters

GW Flow Class	Parameter Adjusted	Final Value (ft/day)
1 (Muck)	K_v^*	200
2	K_h	34,800
3	K_h	2,400

*This value is for the SDA which was assumed to be four times as high as K_v for the ENP due to the scraping of the SDA bottom during construction

Seepage Model Applications to Selected Operational Scenarios

The calibrated model was used to obtain estimates of seepage from the SDA for two operation plans that bracket the range of hydrologic and hydraulic conditions that could prevail in and around the SDA when late wet season discharges from both pump stations occur. The first operational plan depicts a base condition resulting from Increment 2.0 of the Everglades Restoration Transition Plan (ERTP). The second operational scenario pertains to the Central Everglades Planning Project (CEPP) and is expected to result in higher water levels in the project area.

Based on the results of RSM simulations of both operational plans along with historical wet season observations by water managers, the water levels given in Table 5 were used as boundary conditions in model simulations. The SDA stages shown represent an average water level for the detention area while each of the ENP stages are an average stage for the area immediately west of the SDA. Also shown in Table 5 are the seepage rates computed for each set of boundary conditions. Model simulations were performed using a L-31N stage of 4.2 feet NGVD and then repeated with the L-31N stage set at 4.8 feet NGVD. These two canal stages capture the operating range of the ERTP Increment 2.0 plan.

Table 5. Seepage return rates for limiting SDA, ENP and L-31N stages

Operational Plan	**Water Level (ft NGVD)**			**Seepage Rate (CFS/Mi)**		**% Return Seepage**
	ENP	***SDA***	***L-31N***	***From SDA***	***To L-31N***	
CEPP	8.0	8.5	4.2	307	186	60
Pre-CEPP	7.5	8.1		315	168	53
CEPP	8.0	8.5	4.8	281	160	57
Pre-CEPP	7.5	8.1		289	142	49

It is evident that over the ranges of ENP, SDA and L-31N water levels examined, roughly half of the seepage out of the bottom of the SDA returns to the L-31N borrow canal. SDA seepage rates for CEPP conditions are 2 – 3 % lower than the seepage rates under pre-CEPP conditions due to the higher stage difference inherent to the latter operational scenario. Additionally, increasing the L-31N stage from the lower limit of the ERTP Increment 2.0 range (4.2 feet NGVD) to the upper limit (4.8 feet NGVD) reduces the return seepage rate to the L-31N borrow canal about 14% under CEPP operational conditions and about 15% under pre-CEPP conditions.

Summary and Conclusions

A cross sectional ground water flow model of the Biscayne aquifer was constructed for the SDA along with surrounding areas to the east and within the ENP. The hydrostratigraphic model forming its basis was constructed using available geologic data along with the conceptualization of the various stratigraphic zones of the Biscayne aquifer established previously by the USGS for the Lake Belt mining area located further north. The ground water flow model was developed using the analytic element method in order to limit the discretization of the ground water flow domain to the model boundaries. The model was calibrated to an average estimated SDA seepage rate over the period of record spanning July 21 – August 3, 2016.

The model was used to simulate several seepage scenarios involving an estimated range of stages for the SDA, ENP and L-31N borrow canal. These stages included 8.0 and 8.5 feet NGVD for the ENP and SDA, respectively, under the CEPP-PACR operating plan. For the base ERTP (i.e. pre-CEPP) operational conditions, the aforementioned stages were 7.5 and 8.1 feet, respectively. The L-31N borrow canal stage ranged from 4.2 – 4.8 feet NGVD, consistent with the ERTP Increment 2.0 operational scenario. Under these conditions, the model results suggest that about half of the pumpage from S-332B and S-332C will return to the L-31N borrow canal as seepage. This percentage may be less than historical observations due to the head difference between the SDA and ENP being set at high, limiting values. Return seepage rates into the L-31N borrow canal were in the range of 142 - 186 cfs per mile. SDA seepage rates differed by only 3 – 4% between the two operational plans.

Table 5 also indicates that seepage may increase by about 18 cfs per mile after SDA operations evolve from pre-CEPP to CEPP conditions. For the L-31N reach located along the length of the SDA (approximately 4.7 miles), this translates to about 85 cfs of additional seepage under the conditions examined or approximately 43 cfs per pump station. A safety factor of 2 applied to the computed seepage rates would then suggest that each pump station should have its capacity increased by slightly more than 80 cfs to accommodate increases in seepage rates to the L-31N borrow canal.

Seepage rates computed by the model are highly uncertain due to uncertainties inherent to both the conceptual hydrostratigraphic model and the model parameters. The model is currently only suitable for providing the order-of-magnitude estimates of seepage needed for cost estimating purposes. Before performing any seepage analyses needed for future phases of design, it is highly recommended that the surficial aquifer within the study area be better characterized using the techniques previously employed by the USGS in the Lake Belt mining area of Miami-Dade

County. Also needed are additional survey data for the L-31N canal along with improved surface water monitoring within the ENP.

References

Causarus, C. R. 1987. Geology of the Surficial Aquifer System, Dade County, Florida. U. S. Geological Survey Water Resources Investigations Report 86-4126, 240 pp., 3 sheets.

Cressler, Alan. 1993. The Caves of Dade County, Florida. Georgia Underground: Dogwood City Grotto, Inc., of the National Speleological Society, Inc., v. 30, No. 3, pp. 9-16.

Cunningham, Kevin J., Janine L. Carlson, G. Lynn Wingard, Edward Robinson and Michael A. Wacker. 2004. Characterization of Aquifer Heterogeneity Using Cyclostratigraphy and Geophysical Methods in the Upper Part of the Karstic Biscayne Aquifer, Southeastern Florida. U. S. Geological Survey Water Resources Investigations Report 03-4208, 66 pp., 5 plates.

Cunningham, Kevin J. and Michael C. Sukop. 2011. Multiple Technologies Applied to Characterization of the Porosity and Permeability of the Biscayne Aquifer, Florida. U. S. Geological Survey Open-File Report 2011-1037, 8 pp.

Fish, J. E. and Mark Stewart. 1991. Hydrogeology of the Surficial Aquifer System, Dade County, Florida. U. S. Geological Survey Water Resources Investigations Report 90-4108, 50 pp., 11 plates.

Fitts, C. R. 2010. Modeling aquifer systems with analytic elements and subdomains. *Water Resources Research*, 46, W07521, doi:10.1029/2009WR008331.

Genereux, David and Jose Guardiario. 1998. A Canal Drawdown Experiment for Determination of Aquifer Parameters. *Journal of Hydrologic Engineering*, Vol. 3, No. 4, pp. 294-302.

Haitjema, H. M. 1995. *Analytic Element Modeling of Ground Water Flow*, Academic Press, San Diego, CA.

Haitjema, H. M. 2005. Modeling flow in the vertical plane with GFLOW. http://www.haitjema.com/documents/ModelingflowintheverticalplanewithGFLOW.pdf dated July 7, 2005.

Haitjema, H., M. Gusyev and M. Wilsnack. 2010. Truncating Cross-Sectional Groundwater Models under Wetlands. *Journal of Hydrologic Engineering*, Vol. 15, No. 7, pp. 537-543.

Halley, R. B. and C. C. Evans. 1983. The Miami Limestone: A Guide to Selected Outcrops and Their Interpretation. Miami Geological Society, 67 pp.

Jankovic, I. and R. Barnes. 1999. High-order line elements in modeling two-dimensional groundwater flow. *Journal of Hydrology*, 226, 211-223.

Kelson, V. A., M. M. Wilsnack and D. J. Dahlstrom. 2006. Using an Analytic Element Cross-Sectional Model and PEST to Develop Seepage Coefficients for the South Florida Regional Simulation Model. *Proceedings of MODFLOW 2006*, Golden, Colorado, pp. 310-314.

Lal, A. M. W. 2006. Determination of multiple aquifer parameters using generated water level disturbances. *Water Resources Research, 42*, W03429, doi:10.1029/2005WR004218.

Nemeth, M. S., W. M. Wilcox and H. M. Solo-Gabriele. 2000. Evaluation of the Use of Reach Transmissivity to Quantify Leakage Beneath Levee 31N, Miami-Dade County, Florida. U. S. Geological Survey Water Resources Investigations Report 00-4066, 80 pp.

Sonenshein, R. S. 2001. Methods to Quantify Seepage Beneath Levee 30, Miami-Dade County, Florida. U. S. Geological Survey Water Resources Investigations Report 01-4074, 36 pp.

Strack, O. D. L. 1989. *Groundwater Mechanics*, Prentice Hall, Englewood Cliffs, NJ.

USACE. 2005. Draft Geotechnical Data Report for C-111, Phase II, Central and Southern Project for Flood Control, and Other Purposes, Dade County, Florida. Geotechnical Branch, Jacksonville District Corps of Engineers, 103 pp.

Verruijt, A. 1970. *Theory of Groundwater Flow*. Macmillan, London.

Wilsnack, M. M. and V. A. Kelson. 2007. An Application of the Analytic Element Method to the Cross Sectional Modeling of Levee Seepage from the Everglades National Park. Florida. Proceedings of the 2007 ASCE World Water and Environmental Resources Congress: Restoring Our Natural Habitat, May 15-19, 2007, Tampa, Florida, pp. 1-12.

Wilsnack, M. M., V. A. Kelson, D. J. Dahlstrom, H. M. Haitjema, R. Arteaga, L. Brownell and J. Doherty. 2008. Ground Water Flow Modeling Under Selected Levee Reaches. Department of Hydrologic and Environmental Systems Modeling, South Florida Water Management District, West Palm Beach, Florida, 263 pp.

Wilsnack, M. M., V. P. Kelson and J. F. Wittman. 2005. An Application of the Analytic Element Method in Modeling Florida Everglades Hydrology. *Journal of the American Water Resources Association* 41(1): 67-76.

Wilsnack, M. M., S. K. Nair and J. Obeysekera. 1997. Hydrologic Modeling of Initial Lake Belt Alternative Configurations: Ground Water Modeling. Hydrologic Systems Modeling Division, South Florida Water Management District, West Palm Beach, Florida, 66 pp.

Appendix A

Lithologic Logs Converted to Ground Water Flow Class

Deep Borings at S-332C (USACE, 2005)

Table A1. Converted deep borings at S-332C (all borings begin at land surface)

CP02-S332CP-CB-0001			CP02-S332CP-CB-0002			CP02-S332CP-CB-0003			CP02-S332CP-CB-0004		
Layer	***Thickness (ft)***	***GW Flow Class***	***Layer***	***Thickness (ft)***	***GW Flow Class***	***Layer***	***Thickness (ft)***	***GW Flow Class***	***Layer***	***Thickness (ft)***	***GW Flow Class***
1	1.5	1	1	0.5	1	1	0.8	1	1	3	1
2	27.5	2	2	11	2	2	16.7	2	2	24.5	2
3	10	1	3	6.5	4	3	4	4	3	5	1
4	2	2	4	7	2	4	6	3	4	9.5	2
5	2.4	1	5	3	1	5	2.5	2	5	1.5	1
6	2.1	2	6	5	4	6	3.5	1	6	2.2	2
7	1.5	1	7	3	2	7	18.9	2	7	1.8	1
8	2.5	2	8	3	1	8	7.6	1	8	4	2
9	10.5	1	9	3	2				9	8.5	1
			10	1.5	1						
			11	1	2						
			12	3	4						
			13	1	1						
			14	5.5	2						
			15	6	1						

Borings at S-332D (USACE, 2005)

Table A2. Converted deep and shallow borings at S-332D (all borings begin at land surface)

CB-S332D-1			CB-S332D-2			CB-S332D-3			CB-S332D-4		
Layer	***Thickness (ft)***	***GW Flow Class***	***Layer***	***Thickness (ft)***	***GW Flow Class***	***Layer***	***Thickness (ft)***	***GW Flow Class***	***Layer***	***Thickness (ft)***	***GW Flow Class***
1	1.5	1	1	11.9	1	1	11.5	1	1	12.8	1
2	11.7	4	2	6	2	2	7.2	2	2	6.4	2
3	6.2	2	3	3.2	3	3	3	3	3	1	3
4	3.1	4	4	6.8	4						
5	27	2	5	5.9	3						
			6	16.2	3						

Shallow Borings West of S-332C (USACE, 2005)

Table A3. Converted shallow borings west of S-332C (all borings begin at land surface)

Layer	CP03-C111P-CB-0001		CP03-C111P-CB-0002		CP03-C111P-CB-0003		CP03-C111P-CB-0004		CP03-C111P-CB-0005		CP03-C111P-CB-0006	
	Thickness (ft)	*GW Flow Class*	*Thickness (ft)*	*GW Flow Class*	*Thickness (ft)*	*Thickness (ft)*	*Thickness (ft)*	*GW Flow Class*	*Thickness (ft)*	*GW Flow Class*	*Thickness (ft)*	*GW Flow Class*
1	1	1	0.5	1	1	1	0.3	1	12	3	3	1
2	14	2	2	3	5	3	14.7	2	3	3	12	2
3			12.5	2	9	2						

USGS Boring G-3314 (Causarus, 1987)

Table A4. Converted G-3314 boring

G-3314		
Layer	***Thickness (ft)***	***GW Flow Class***
1	12	2
2	2	2 or 3
3	16	2
4	6	4
5	1	2
6	4	4
7	2	2
8	10	4

Test Pits West of S-332C

Table A5-1. Converted test pit lithologies

Layer	LA-TP-0001		LA-TP-0002		LA-TP-0003		LA-TP-0004		LA-TP-0005		LA-TP-0006		LA-TP-0007		LA-TP-0008		LA-TP-0009	
	Thickness (ft)	GW Flow Class	Thickness (ft)	GW Flow Class	Thickness (ft)	GW Flow Class	Thickness (ft)	GW Flow Class	Thickness (ft)	GW Flow Class	Thickness (ft)	GW Flow Class	Thickness (ft)	GW Flow Class	Thickness (ft)	GW Flow Class	Thickness (ft)	GW Flow Class
1	0.5	1	1	1	0.7	1	0.3	1	0.6	1	0.6	1	0.2	1	0.4	1	0.3	1
2	1	3	4	2	3.3	3	4.2	2	2.9	2	0.6	3	2.8	3	0.8	2	2.7	3
3	3	2									2.3	2			2.6	3	1.5	2

Table A5-2. Converted test pit lithologies (cont.)

Layer	LB-TP-0001		LB-TP-0002		LB-TP-0003		LB-TP-0004		LB-TP-0005		LB-TP-0006		LB-TP-0007		LB-TP-0008	
	Thickness (ft)	GW Flow Class	Thickness (ft)	GW Flow Class	Thickness (ft)	GW Flow Class	Thickness (ft)	GW Flow Class	Thickness (ft)	GW Flow Class	Thickness (ft)	GW Flow Class	Thickness (ft)	GW Flow Class	Thickness (ft)	GW Flow Class
1	0.6	1	0.8	1	0.7	1	0.5	1	0.4	1	0.7	1	0.3	1	0.9	1
2	3.4	3	3.7	2	2.3	3	2.5	3	1.4	3	2.8	2	2.7	2	2.1	3
3					1	2	1	2	3.2	2					1.5	2

Appendix B

Verification of the West Model Boundary Location

Two independent analyses were carried out to verify that the west vertical model boundary was set far enough from the SDA so that errors in the amount of accumulated seepage from the SDA to the ENP can be considered negligible with respect to the objectives of the study. First, a relationship between the percent change in accumulated seepage and distance from the western-most SDA levee was constructed using the model results for CEPP-PACR operational conditions and a L-31N stage of 4.8 feet NGVD. This relationship is shown in Figure B.1 (orange line).

Secondly, an analytic solution by Bruggeman (1999) for a similar ground water flow system but negligible levee width and a homogeneous, isotropic aquifer was used to construct the same relationship. In this case, the average horizontal hydraulic conductivity derived from the model was used. Details of this analysis are provided in the pages that follow. This analytic solution was used to derive the same relationship between accumulated seepage and distance from the levee. It is also provided in Figure B.2. It is readily evident both analyses demonstrate that at about 400 feet from the levee, nearly all of the seepage from the SDA to ENP has accumulated. It should be recalled that the western vertical model boundary depicting the truncated portion of the aquifer within ENP was placed about 500 feet from the levee. This explains why this boundary plays a negligible role in the global water budget of the model.

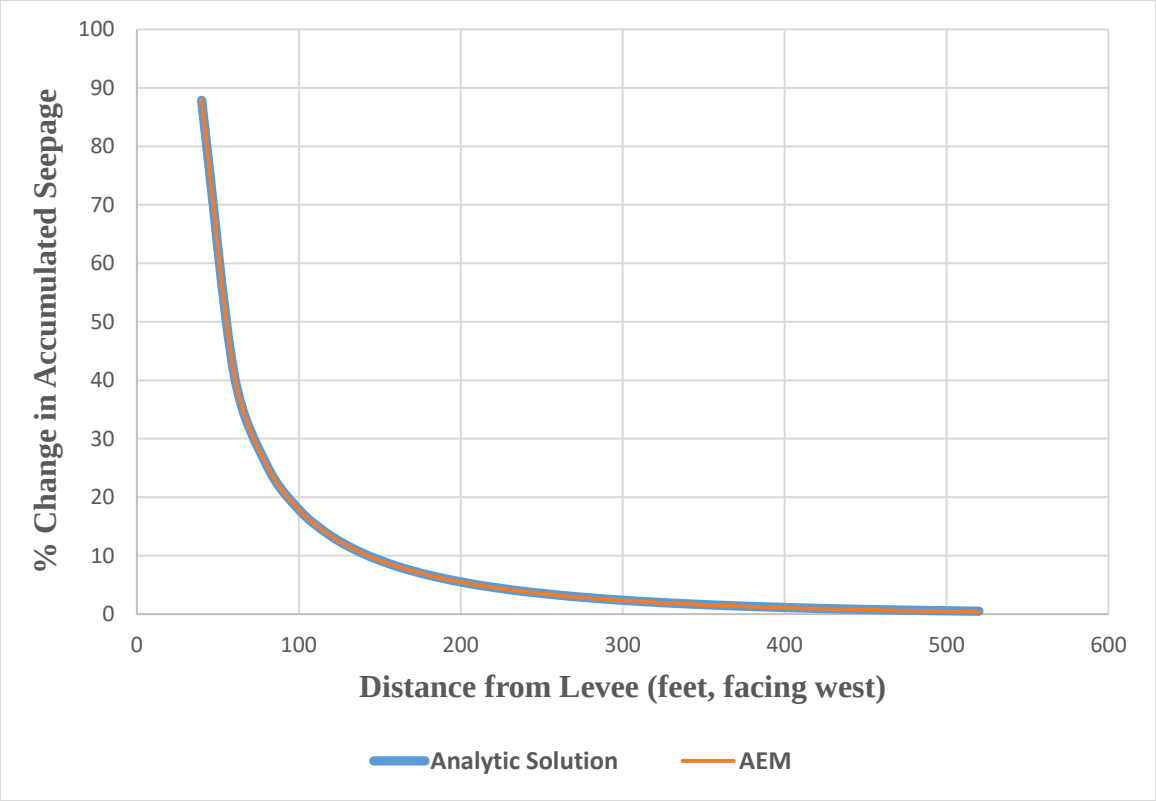


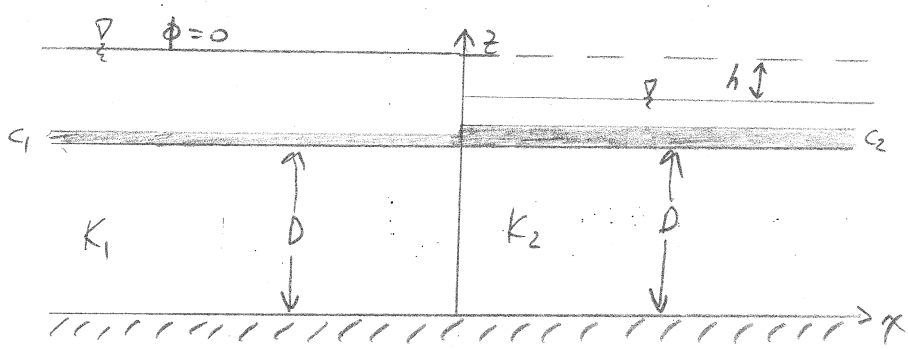
Figure 4. Accumulated westerly SDA seepage versus distance from the west SDA levee

South Florida Water Management District
HYDROLOGY AND HYDRAULICS BUREAU

Calculations

Form #0230
Rev.11/97

Project: S-332B,C RELOCATION — Sheet No. 1 of 2
Subject: SOA SEEPAGE TO ENP — Job No. / Program Code: 0397
Engineer: WILSNACK — Date: 9/25/13 Checked By: LZ



ACCORDING TO SOLUTION 370.07 OF "ANALYTICAL SOLUTIONS OF GEOHYDROLOGICAL SOLUTION" (BRUGGEMAN, 1999) FOR $K_1 = K_2 = K$ IT FOLLOWS THAT

$$\frac{\partial \phi}{\partial z}(x, D) \simeq \frac{2h}{KC_2} \sum_{n=0}^{\infty} \frac{\alpha_n \sin(\beta_n)\cos(\beta_n)}{\varepsilon \beta_n \beta_n (\alpha_n + \beta_n)} e^{\left(\frac{-\beta_n x}{D}\right)}$$

x = DISTANCE FROM A VERTICAL BARRIER AT $x = 0$
D = AQUIFER THICKNESS
K = " HYDRAULIC CONDUCTIVITY
C_1, C_2 = VERTICAL RESISTANCES OF THE SURFACE SEDIMENT LAYERS
h = STAGE DIFFERENCE BETWEEN THE TWO RESERVOIRS
ϕ = DRAWDOWN FROM $\phi = 0$

South Florida Water Management District
HYDROLOGY AND HYDRAULICS BUREAU

Calculations

Form #0230
Rev.11/97

Project: S-332B,C RELOCATION
Subject: SDA SEEPAGE TO ENP
Engineer: WILSNACK
Sheet No. 2 of 2
Job No. / Program Code: 0397
Date: 9/25/13 Checked By: LE

α_n = ROOTS OF $\alpha \tan\alpha = \frac{D}{KC_1}$

β_n = " " $\beta \tan\beta = \frac{D}{KC_2} = \delta$

$E_{\beta_n} = 1 + \frac{\delta}{\beta_n^2 + \delta^2}$

AT A DISTANCE $x = L$ FROM THE BARRIER, THE ACCUMULATED SEEPAGE FROM RESERVOIR 1 ENTERING THE SURFACE WATER OF RESERVOIR 2 IS

$$\int_0^L K \frac{\partial \phi}{\partial z}(x, 0)\, dx =$$

$$\frac{2Dh}{C_2} \sum_{n=0}^{\infty} \frac{\alpha_n \sin(\beta_n)\cos(\beta_n)}{E_{\beta_n} \beta_n^2 (\alpha_n + \beta_n)} \left[1 - e^{-\frac{\beta_n L}{D}}\right]$$

∴ FIND DISTANCE L BEYOND WHICH FURTHER ACCUMULATION OF SEEPAGE IS NEGLIGIBLE

FOR THE SDA – ENP SYSTEM,

$\bar{K}$ = 23,047 FT/DAY

C_1 = 0.005 DAYS D = 51 FT

C_2 = 0.02 DAYS $h \simeq 0.5$ FT