CONSOLIDATION AND HYDROLOGY OF RECLAIMED PHOSPHATIC CLAY SETTLING AREAS[1]

by

Walter R. Reigner, P.E., CPESC; Cornelis Winkler III, P.G.; Mark A. Schwartz, P.E.[2]

Abstract. Presently operating phosphate mines in central Florida comprise about 57,000 acres of clay settling areas (CSAs), with an additional 20,000 acres designated for future CSAs. The Florida Institute of Phosphate Research sponsored a three-year project to further evaluate the unique characteristics of CSAs. This research included monitoring hydrologic and meteorological conditions, mapping soils and vegetation, and developing topographic maps using photogrammetry. Field and laboratory data were used in models to estimate the effects of clay consolidation on post-reclamation topography and to calibrate hydrologic simulation programs. This paper presents the research objectives, work plan, and study results of a three-year research project designed to monitor and evaluate the hydrology and clay consolidation behavior of phosphate CSAs. Results from this investigation indicate that CSAs discharge less surface water than previously expected, with hydrologic characteristics that change over time. Based on results from the investigation, guidelines for CSA reclamation were developed including - monitoring, testing, model reevaluations and possible modification of discharge control structures at CSAs.

Introduction

Current estimates indicate that 102,000 acres of the Peace and Alafia River watersheds are comprised of CSAs. This accounts for 10 to 15 percent of the combined Peace River watershed above Zolfo Springs, the North Prong of the Alafia River above Keysville, and the South Prong of the Alafia River above Lithia. Since hydrologic monitoring indicates that CSAs function much differently than natural or urban areas, restoring the hydrologic function of reclaimed settling areas is critical to establishing a viable hydrologic regime in central Florida.

Approximately one-third of central Florida's phosphate matrix consists of fine-grained clay-sized materials that are able to pass through a minus 150-mesh screen. During the phosphate ore beneficiation process, the fine-grained material is separated from the coarse-grained sand and phosphatic material. The fine-grained material (clay) is pumped to above-grade impoundments as a diluted slurry. Upon completion of clay filling, quiescent consolidation, and mechanical dewatering, the CSAs are typically reclaimed by flattening the outside slopes of the embankments, minor interior grading and shaping, and revegetation. Typical post-reclamation land uses include pasture, silviculture, habitat areas, and wetlands. Final reclamation also includes breaching the embankment and constructing an outfall to enable controlled surface water discharge. Figure 1 provides an illustration of a typical post-reclaimed CSA, showing the overburden mounds, retention pond, outfall control structure, and underlying hydrogeology.

This paper presents the research objectives, work plan, and study results of a three-year research project designed to monitor and evaluate the hydrology and clay consolidation behavior of phosphate CSAs. A more detailed description of this investigation can be found in BCI (1999). The primary objective of the study was to develop a procedure for predicting the hydrology of above-ground CSAs that directly considers the short- and long-term effect of clay consolidation. Challenges associated with predicting the post-reclamation hydrologic behavior of CSAs include:

- Difficulties in predicting hydrologic functionality.
- Lack of confidence regarding the selection of model parameters.
- Inability to accurately predict long-term topographic changes.
- Difficulty in quantifying small-scale topographic variations and depression storage.
- Uncertainty with regard to ground water interaction.
- Concern regarding regulatory objectives.
- Time necessary to achieve CSA equilibrium.

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[2] Walter R. Reigner is Vice President of BCI Engineers & Scientists, Inc., 2000 E. Edgewood Drive, Ste. 215, Lakeland, FL 33803; Cornelis Winkler III is Mining Services Manager of BCI Engineers & Scientists, Inc., 2000 E. Edgewood Drive, Ste. 215, Lakeland, FL 33803; Mark A. Schwartz is Senior Water Resources Engineer of BCI Engineers & Scientists, Inc., 2000 E. Edgewood Drive, Ste. 215, Lakeland, FL 33803.

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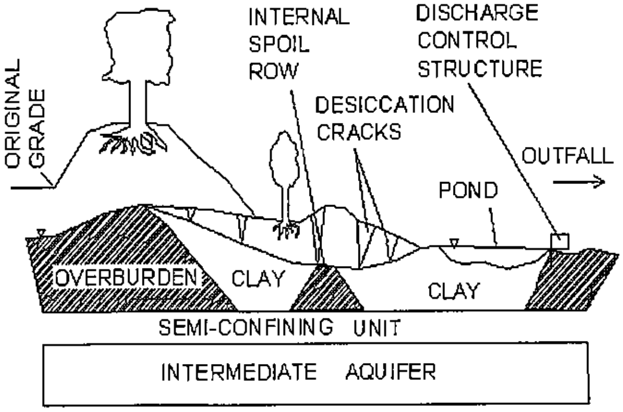

Figure 1. Cross Section of a Reclaimed Clay Settling Area

Clay Settling Area Site Selection

Site selection was a joint effort among the Hydrologic Advisory Committee (HAC) of FIPR, the United States Geological Survey (USGS), and BCI Engineers and Scientists, Inc. (BCI). The USGS and BCI evaluated more than 15 sites and provided a list of four recommended sites and monitoring plans for approval by the HAC. The four CSAs selected were:

- IMC-Agrico's Achan 10 (IMC),
- Estech General Chemical Company's SA-10 (Estech),
- Williams Acquisition Holding Company's AC-OP-06 (Williams), and
- PCS Phosphate White Springs' 10 SR (PCS Phosphate).

Figures 2 shows the general location of the four study sites.

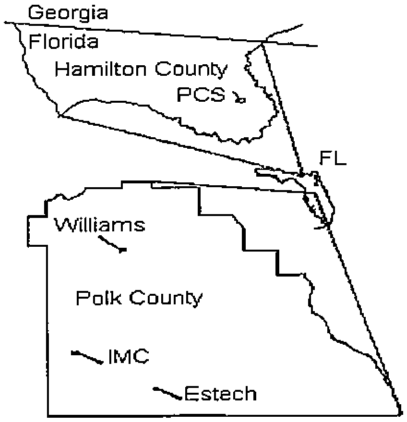

Figure 2. Location of Clay Settling Areas Used in Study

Clay Consolidation

Accurately predicting the filling of a CSA has many benefits. By defining the tonnage capacity and fill-date accurately, the construction and utilization of subsequent CSAs can be optimized. The benefits of accurate clay consolidation modeling extend to the dewatering and reclamation phases of CSA management. Accurately predicting long-term consolidation will help quantify target perimeter-ditch invert elevations and provide the data necessary to develop reasonable estimates of post reclamation topography.

Highly plastic phosphatic clays (typical plasticity index values range from 100 to 180) consolidate at a very slow rate. Two physical parameters - compressibility and permeability - control the magnitude and rate of consolidation. These parameters were determined in the laboratory from soil samples taken from each site. Compressibility and permeability are non-linear and independently variable, requiring computer modeling to accurately simulate consolidation during clay deposition and subsequent dewatering and reclamation activities.

Computer models were used to estimate the tonnage of clay (in dry tons) deposited in each CSA, to predict quiescent submerged consolidation, and to determine the ultimate clay height (including the effect of the lowered post-reclamation water table in the clay). Topographic elevations based on aerial photogrammetric techniques were measured for all sites at the beginning and end of the three-year monitoring period. The average change in measured topographic elevations at each CSA were compared to the simulated change in the average elevation of the clay surface based on the history of the CSAs. Simulated elevations were obtained using the proprietary consolidation programs QSNS1 and ULTSIMP based on equations originally described in Carrier et al., 1983.

The best prediction of the clay elevation and rate of elevation change was made for the PCS Phosphate site. Measured elevations were 0.8 feet. higher than predicted elevations using the ULTSIMP consolidation model (Figure 3). These excellent results are due to the accurate modeling input data for the site. For PCS Phosphate, the CSA geometry and filling history are more accurately known than for the other CSAs, and the model representation of clay characteristics have been calibrated during periodic clay sampling and testing over the past 15 years.

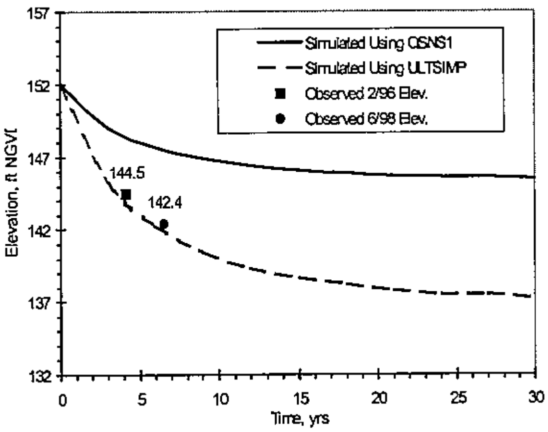

Figure 3. PCS Phosphate Clay Settling Area Ultimate Height Comparison

Measured rates of average elevation change varied from 0.1 foot per year at Estech to 0.9 foot per year at PCS Phosphate. The largest rate of elevation change was measured at the PCS Phosphate site, where clay filling ended only three years prior to commencement of our study. Our method of estimating elevation change after reclamation may be more suited to relatively new sites and not ones that remained in an unreclaimed state for more than a decade.

Figure 4 contrasts the difference between the post reclamation topography of the conceptual design and actual post reclamation topography. The typical conceptual design portrays a simplified topographic surface having a single, well-defined storage component. On the other hand, actual topography typically consists of a complex network of isolated and connected depressions and a large microtopographic storage component.

The timing and magnitude of consolidation and ultimate consolidation have a significant impact on the accuracy of post-reclamation hydrologic predictions. The estimated storage volume below the invert of the discharge control structure increases most rapidly following initial dewatering, and the rate of increase slows with time.

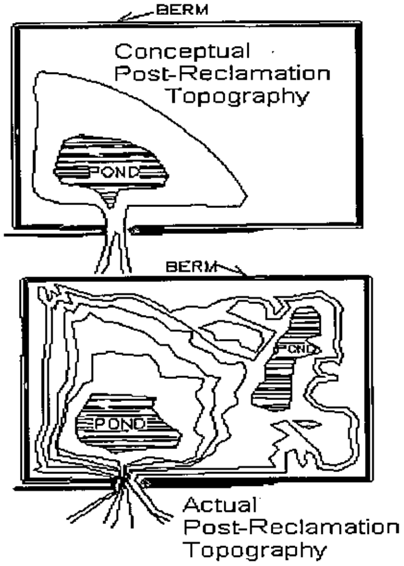

Figure 4. Conceptual and Actual Post-Reclamation Topographic Map (Typical Clay Settling Area)

USGS Collected Data

As part of this cooperative investigation, the USGS collected hydrologic and climatic data for a two-year period at each CSA. The data collection network at each site included: stream flow, pond stage, periodic and continuously recording water levels in wells, rainfall, wind speed and direction, water temperature, relative humidity, air temperature, and pan evaporation.

At each of the four CSAs, streamflow and pond-stage data were collected by electronic data-loggers that recorded water-level elevations in a stilling well from the rising and falling of a float. Discharge at each basin was monitored by a streamflow gage at the outfall of each CSA. One to three water level stage gages were installed in each basin to monitor pond fluctuations. The relationship between stage and discharge at the outfall(s) of each CSA was determined via field measurement. Monitoring data collected by the USGS were used to estimate the water balance (Table 1) at each CSA and to calibrate and verify the hydrologic models used in this investigation.

Table 1. Estimated Water Balances for the CSAs.

Source or Sink	Site and Period of Observation used in Estimates				
	IMC[1] **10/3/95 – 9/30/97**	**Estech[2]** **10/1/95 – 10/1/97**	PCS[3] 7/24/96 – 9/30/98	**Williams[4]** **4/26/96 – 10/1/98**	**Estimated Error (plus or minus)**
Water Released Through Consolidation (inches)	12	2	13	8	1 %
Discharge (inches)	-13	-3	-27	-42	5 %
Rainfall (inches)	95	80	104	95	10 %
Factored Pan Evap. (inches)	-83	-83	-97	-83	25 %
Change In Storage(inches)	-0	9	0	1	125 %
Remaining (inches)	11	5	-7	-21	
Negative values indicate a loss of water from the CSA.					

[1] IMC-Agrico's Achan 10 Clay Settling Area

[2] Estech General Chemical Company's SA-10, Clay Settling Area

[3] Williams Acquisition Holding Company's AC-OP-06, Clay Settling Area

[4] PC Phosphate White Springs' 10 SR, Clay Settling Area

Hydrologic Modeling

An objective of this investigation was to estimate hydrologic model parameters suitable for representing the hydrology of CSAs based on calibration and comparison with collected monitoring data. Frequently used public domain and proprietary computer programs (both lumped and distributed parameter models) selected for use in replicating the hydrology of the four reclaimed CSAs monitored during this investigation include: SWMM (Huber et al. 1987), HSPF (Imhoff et al. 1984), BRN (Boyd 1993), HEC-1 (U.S. Army Corps of Engineers 1985), ICPR (Singhofen and Eaglin 1995), and TR-20 (Soil Conservation Service 1983). SWMM and HSPF are appropriate for simulating one (event simulations) or more events (continuous simulations), since the moisture conditions at the start of a rain event are adjusted over time in these process oriented models. The user modeling with BRN, ICPR, and TR-20 sets antecedent moisture conditions and these models are appropriate for single rain event simulations only. Values compared in the calibration include:

- Total discharge (percent difference between simulated and observed).
- Peak discharge (percent difference between simulated and observed).
- Time to peak discharge (difference in hours).
- Mean error (differences between simulated and observed discharges and stages).
- Mean absolute error (absolute value of the differences between simulated and observed discharges and stages).

Comparisons of simulated and observed event and continuous hydrographs are provided in Figures 5 and 6.

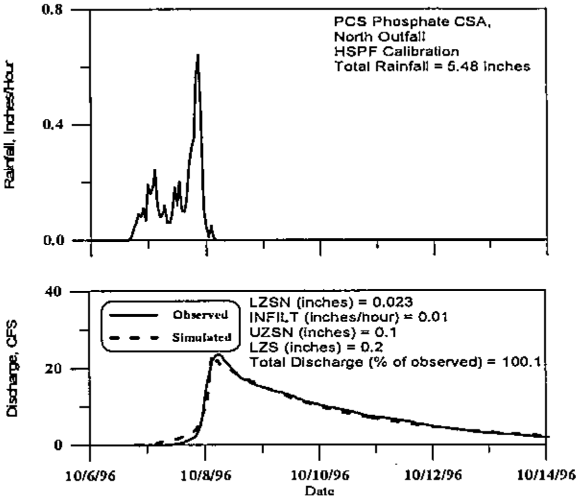

Figure 5. HSPF Event Storm Calibration Simulating Discharge at PCS Phosphate Clay Settling Area, North Outfall

The calibration process also included a sensitivity analysis. If parameters were selected such that the statistics listed above did not significantly improve with small changes in the parameter values, then the model was assumed to be calibrated. After the model calibration and sensitivity analyses were concluded, a second independent event was selected for use in verifying model parameters.

A program was also developed based on Soil Conservation Service (SCS) methods to estimate the curve number for a site using long-term observed rainfall, ground water stage, and discharge (i.e., volumetric calculations of curve number). Using this program, rainfall events were defined as having a minimum 12-hour inter-event period, and the maximum ground water storage potential was assumed to be a function of the observed water table depth below land surface. Adjusting the effective soil storage capacity above the water table minimized the difference between the cumulative simulated and observed discharges (Figure 7).

The single event calibrations and verifications conducted for the CSAs indicate that the models are generally not robust enough in their calculation methodology to consistently simulate the response of a system as dynamic and complex in nature as a CSA. In addition, the challenges associated with assigning physically based model parameters also adds to the difficulties in developing a model that simulates CSA hydrologic response under a wide range of conditions. During this investigation, parameters estimated through calibration did a relatively poor job of estimating discharges from the CSA for rainfall events selected for verification. From this observation we generally concluded:

- Field monitoring is needed to guide adjustments to model parameters and (or) interpretation of model results and ultimately allow for adjustment of the CSA outfall configuration.
- Improved estimates of clay consolidation are needed to more accurately estimate changes in storage within CSAs, both small and large scale.

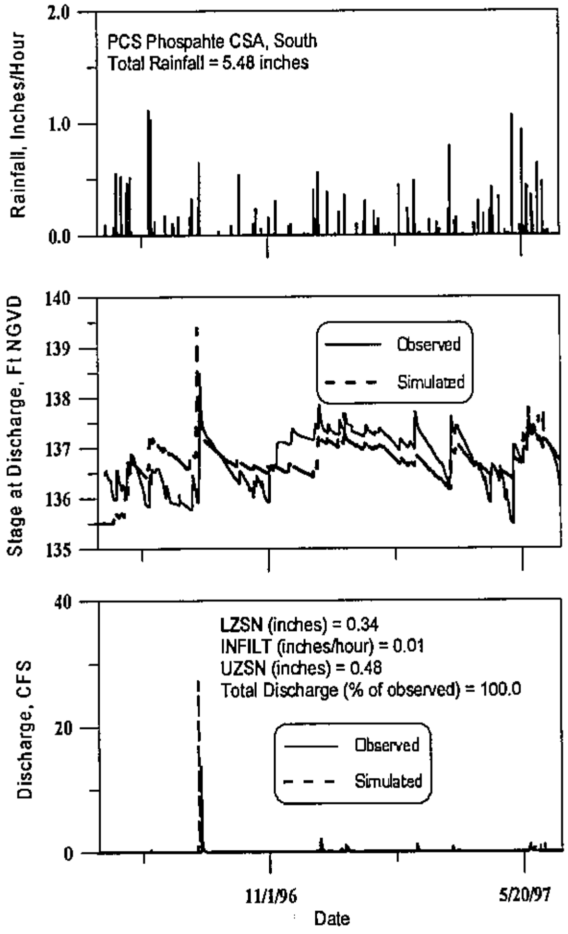

Figure 6. HSPF Continuous (long-term) Calibration, Simulated Discharge at PCS Phosphate Clay Settling Area, South Outfall

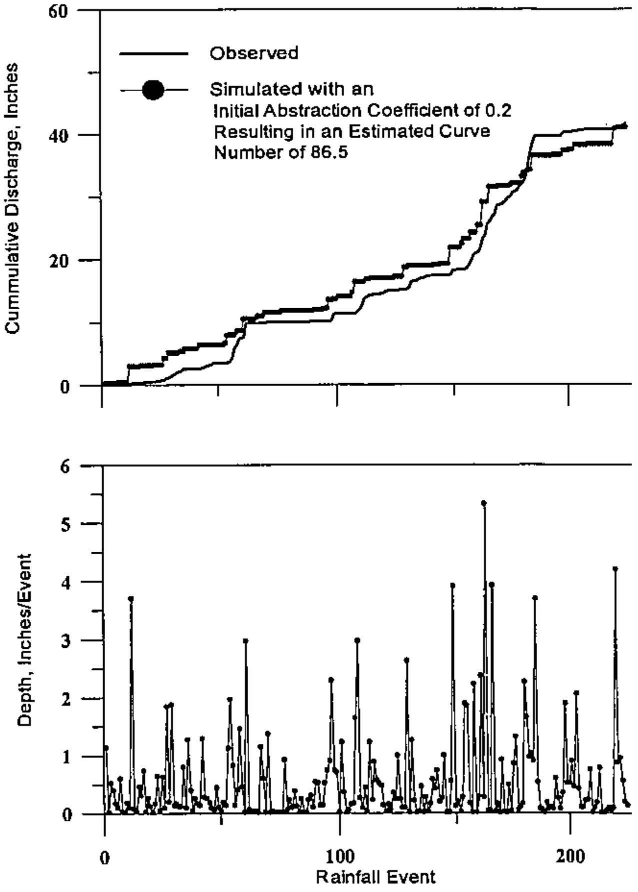

Figure 7. Rainfall Event Storms and Cumulative Discharge for Volumetric Calculations of Curve Number at Williams Clay Settling Area

If the model objectives are to prevent downstream flooding, then the event simulation models are useful given the proper selection of model parameters. Event based model results are generally utilized in comparative model (pre-mining versus post-reclamation) simulations such that the absolute prediction of event-based performance is not necessarily required. Rather, the goal is to design a post-reclamation landform that exhibits predicted hydrologic performance that is similar to predicted pre-mining conditions, primarily for large-scale rainfall events. The problem with this strategy is that the long-term post-reclamation discharge volumes, based on event-model design criteria and the known dynamic nature of CSA landforms, will most likely not match pre-mining discharge characteristics.

The curve numbers estimated during calibration were lower than expected for the relatively impermeable clays having greater than average (as compared to the pre-mining landscape) hydrologic slopes. The curve number varies with antecedent moisture conditions, and the low curve numbers may indicate dry antecedent moisture conditions. During these conditions, available storage capacity within the cracks in the clay may be quite large. This storage component is not directly included in the lump parameter models that utilize curve number methods. However, in the distributed parameter models (SWMM and HSPF), the depressional storage component can be adjusted to account for this storage. A summary listing of suggested parameter values for these models is provided as Table 2.

For the CSAs, the physical-based system parameters, which for other systems might be considered immutable, change drastically with time. These include such parameters as depressional storage, slope, pond storage, overland flow characteristics, and evapotranspiration (ET). These changes are caused by clay consolidation and subsequent clay cracking, surface subsidence, and significant vegetation changes that occur over several years. The model simulations indicate significant alteration in the hydrologic system response are caused by these changes. In addition, the wide range of parameters needed to describe the observed hydrology indicates an undetermined level of uncertainty in accurately predicting the hydrologic response of a CSA, particularly during the design phase of reclamation when little data exists to validate assumptions.

Several factors that generally limit the ability of hydrologic models to accurately and consistently predict the hydrology of CSAs include:

- Inaccuracies in predicting the topography of a CSA during the reclamation design phase. Even in the unlikely event that detailed aerial topographic maps are available at select intervals, the inaccuracies involved can still be very significant.
- Continued changes in topography caused by clay consolidation and variations in these changes between and within CSAs.
- Relatively short-tem changes in depressional storage and frictional characteristics caused by consolidation, clay cracking, and revegetation.
- Inaccuracies in determining if cracks in the clay contact underlying overburden spoil rows and how these might change through time with regard to their hydrologic significance.

In general, the factors listed above result in an underestimation of detention and retention, and overestimation of peak discharge and total discharge volumes. That is, by reducing peak discharges the designed systems do not often maintain the volume and character of long-term discharge that occurred prior to mining. There is need for model(s) that accurately predict changes in the topography within the CSA (i.e., cell-by-cell) to provide a more accurate estimate of storage changes within the CSA.

Comparison to Previous Reclamation Analyses

When comparing existing reclamation landforms with the landforms that were envisioned during design, the interiors of the CSAs consistently contain a larger area of wetland and water than was anticipated in the design. In addition, there seems to be less discharge from the CSAs than anticipated. This observation could indicate greater storage within ponds, and/or more depressions and cracks of the clay than assumed in the design. This observation also validates the impact associated with long-term consolidation of clays and the related gain in available water storage. Figure 8 shows the change in event-based hydrologic response as a result of topographic changes over a three-year period.

Guidelines and Recommendations

A significant rate of topographic change continues even after reclamation activities have been completed. Average clay elevation changes (declines) were, at the high end, about one-foot per year during the 2.4 years between topographic mapping efforts at the PCS Phosphate site. Incorporating the following data into the modeling of CSAs will improve the model accuracy in predicting CSA elevation, and thereby modeled hydrologic performance.

- Quantify CSA geometry prior to clay deposition via photogrametry or survey data.
- Monitor the fill height and clay tonnage during the active life of a CSA.
- Develop mine-specific consolidation parameters and calibrate them periodically.
- Obtain clay elevation topographic information at the start of dewatering activities.
- Re-establish the clay elevation when the CSA is released by the Florida Department of Environmental Protection (FDEP).

Table 2. Suggested Model Parameters for CSA Analysis

Model & Parameter	**Event Simulations**		**Continuous Simulations**
	Peak Discharges[1]	**Volume& Duration**[2]	**Volume & Duration**[2]
Curve Number	94	70	N/A
Time of Concentration	Calculated	Calculated	N/A
Antecedent Moisture Condition	II	II	N/A
Peak Rate Factor	484	256	N/A
Hydraulic Length	Calculated	Calculated	N/A
Hydraulic Slope	Calculated	Calculated	N/A
Initial Abstraction Coefficient	0	0.2	N/A
Rational Runoff Coefficient	0.8	0.3	N/A
HEC-1 Parameters			
QRCSN	0.2	0.2	N/A
RTIOR	1.1	1.1	N/A
Snyder's Peaking Coefficient	0.8	0.8	N/A
HSPF Parameters			
LZSN	0.1	0.8	0.5
INFILT	0.01	0.01	0.01
KVARY	0.9	0.9	0.9
AGWRC	0.9	0.9	0.9
NFEXP	1.62	1.62	1.62
INFILD	2	2	2
DEEPFR	0	0	0
BASETP	0.8	0.8	0.8
AGWETP	0.7	0.7	0.9
CEPSC	0.01	0.01	0.01
UZSN	0.1	0.5	0.5
NSUR	0.2	0.5	0.5
INTFW	0	0	0
IRC	0.9	0.9	0.9
LZETP	0.8	0.8	0.8
LZS	0.95	0.50	0.50
SWMM Parameters			
Basin Width	Longest side	Shortest side	Shortest side
Percent Impervious	100*Average pond area /basin area	100*Average pond area /basin area	100*Average pond area /basin area
Roughness	0.2	0.2	0.2
Depressional Storage (inches)	2	2	2
Average Capillary Suction (inches)	0.1	0.1	0.1
Green Amp Conductivity (inches/hour)	0.002	0.002	0.002
Initial Moisture Deficit	0.01	0.01	0.01
Bottom of Water Table	Measured	Measured	Measured

Table 2. Suggested Model Parameters for CSA Analysis (Continued)

Model & Parameter	Event Simulations		Continuous Simulations
	Peak Discharges	Volume & Duration	Volume & Duration
Ground Surface Elevations	Channel Bottom Elevation + 2 ft	Channel Bottom Elevation + 2 ft	Channel Bottom Elevation + 2 ft
Initial Water Table Elevation	Channel Bottom Elevation	Channel Bottom Elevation - 2 ft	Channel Bottom Elevation - 2 ft
Channel Bottom Elevation	As Designed	As Designed	As Designed
A1	2.25E-05	2.25E-05	2.25E-05
B1	1	1	1
A2	0	0	0
B2	1	1	1
A3	0	0	0
Soil Porosity (fraction of soil Vol.)	0.26	0.26	0.26
Wilting Point (fraction of soil Vol.)	0.15	0.15	0.15
Field Capacity (fraction of soil Vol.)	0.2	0.2	0.2
Saturated Conductivity (inches/hour)	0.15	0.15	0.15
Initial Upper Zone Moisture (fraction of soil Volume)	0.19	0.19	0.19

[1] Suggested model parameters when the model objectives are to match peak discharges rates

[2] Suggested model parameters when the model objectives are to match long-term discharge volumes

- Base ultimate elevation estimates on the external water table using the most accurate data gathered during the life of the CSA.

Utilizing accurate input data, backed up with confirmation during the filling and dewatering phases, will maximize the accuracy of predicted post-reclamation clay elevations. Accurate clay elevations will aid in proper sizing and invert elevation selection for outfall structures. Since the topographic and vegetative character of the CSA change with time – new structures (those that cannot be modified) or modification of existing structures may be required to preserve long-term hydrology.

To overcome the challenges associated with the dynamic nature of CSAs, a sequential methodology was developed for improving the post-reclamation hydrologic functionality of CSAs. In summary, the methodology is as follows:

- Document the pre-fill topography for a CSA.
- Collect and refine consolidation parameters, tonnage and filling history.
- Determine the clay surface topography prior to dewatering.
- Develop end-of-fill clay thickness map from pre- and post-fill topographic maps.

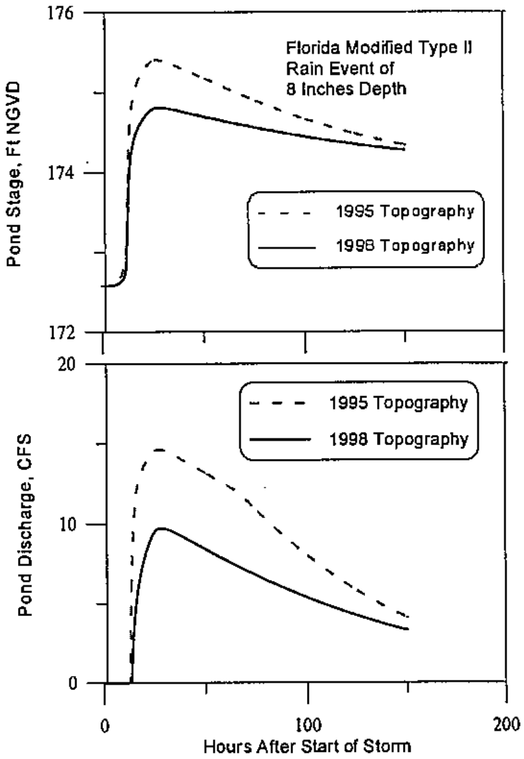

Figure 8. Achan Clay Settling Area - Effects of Additional Storage On Pond Stage and Discharge

- Conduct clay modeling and develop the relationship between clay thickness and consolidation.
- Apply this relationship to clay thickness map to generate a predicted post-reclamation clay surface topographic map.
- Utilize the post-reclamation topographic map as a guide in defining grading/earthmoving, revegetation, and drainage plans.
- Conduct coarse level modeling to establish preliminary outfall geometry and invert elevation.
- Complete earthmoving and revegetation activities.
- Develop as-built topographic map and compare to post-reclamation topographic map and refine as necessary.
- Review and refine as necessary the event-based hydrologic model.
- Install preliminary outfall and develop stage-discharge relationship.
- After several years, initiate coarse level hydrological/meteorological monitoring.
- Revisit hydrologic analyses and refine event-based (25-year return interval).
- Evaluate long-term functionality utilizing continuous or small magnitude event-based analyses.
- Adjust outfall configuration and invert elevation as necessary to optimize and balance flood protection and baseflow reestablishment.

In addition, the designer should thoroughly understand the impact that continued long-term clay consolidation has on the hydrologic behavior of CSAs. The goal for reclaiming CSAs is to restore the pre-mining hydrologic character and establish an internal hydrologic function that supports intended post-reclamation land uses. This requires close coordination and cooperation of an experienced team of professionals (mining, water resources, and environmental) that understand the complex dynamics of CSA reclamation.

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