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TreeWell Technology as an AEM for Hammond AP-3

Date:	December 4, 2020
To:	Matt McGill, Georgia Power Company
	Lauren Petty, Georgia Power Company
From:	Joe Ivanowski and Jimmy Whitmer, Geosyntec Consultants, Inc.
Subject:	TreeWell® Technology as an AEM for AP-3, Plant Hammond, Floyd County, Georgia

INTRODUCTION

Geosyntec Consultants, Inc. (Geosyntec) has prepared this memorandum to summarize the technical approach and expected benefits of the installation of a TreeWell® system to supplement the closure of Ash Pond 3 (AP-3) at Plant Hammond, located in Floyd County, Georgia.

Georgia Power Company (Georgia Power) completed placement of the final cover system for the AP-3 closure-in-place in the second quarter of 2018 in accordance with State CCR Rule 391-3-4.10(7)(b), which incorporates the requirements of the Federal CCR Rule 40 C.F.R. § 257.102(d). Closure of AP-3 included grading the CCR within the unit to promote positive post-closure stormwater drainage and installing a geomembrane cover system. Additional details related to the closure method are provided in the Initial Written Closure Plan on the CCR Website, the Closure Plan included in the Permit Application, and the Closure Certification Report submitted to Georgia EPD on December 13, 2018.

In addition to the closure and capping of AP-3 with the final cover system, and the closure of nearby AP-1 by removal, Georgia Power has chosen to use *TreeWell* technology downgradient of the closed unit as an advanced engineering method (AEM). This is described in greater detail in the sections below.

SUMMARY OF TREEWELL TECHNOLOGY

The *TreeWell* system is a patented engineered phyto-system that uses the aggressive rooting ability of selected trees and other vegetation to capture, contain, and/or remediate groundwater. Using this technique, it is possible to capture groundwater from targeted zones at depths of up to 50 feet or more. Over the last three decades, phytotechnology has emerged as a feasible alternative compared to more active technologies, and the technology is gaining acceptance within regulatory agencies as well as the public (Linton 2018, Goldemund and Gestler, 2019).

The *TreeWell* system overcomes one of the major limitations of other phytotechnologies by targeting specific groundwater strata (even deeper aquifers), as opposed to just planting trees/vegetation into surface soil where most of the roots stay in fairly shallow soil. This is accomplished by casing off soil and groundwater from zones other than the stratum targeted for hydraulic control[1]. Large-diameter augers are used to advance a borehole that is lined with a plastic sleeve only open to the targeted stratum of interest. The lined borehole is backfilled with growing media to support the species selected, and trees are then planted into the refilled boreholes. The planted boreholes are then sealed off at the surface, which forces tree roots to exclusively use water from the targeted zone. The trees act as natural pumps to extract groundwater (i.e., provide hydraulic control) from within the cased borehole (or well), thus the name "*TreeWell*". For deeper applications, a small diameter well is installed within and through the bottom of the casing/plastic sleeve to act as a "straw" for target intervals. A conceptual schematic of a *TreeWell* is provided in **Attachment 1.**

The main advantages of a *TreeWell* system are (i) it is a proven technology to address site-specific conditions, (ii) once established (about three growing seasons), the system is essentially self-maintaining, sustainable, and requires no external energy input, and (iii) it requires minimal operation and maintenance costs. The proposed field of *TreeWell* units is located along the downgradient side (east) of AP-3 and would be intended to locally lower the water table and create an inward hydraulic gradient toward the *TreeWell* field. This would also reduce the volume of CCR below the potentiometric surface in the closed unit. This location is outside of the AP-3 footprint and therefore would not require disturbance of the AP-3 cover system or existing dike construction. Subsurface conditions (soil and groundwater geochemistry) at AP-3 are not expected to pose any significant issues for the trees to thrive.

The tree species selected for the *TreeWell* system will be based on site-specific conditions such as seasonal climate, proximity to surface water features, and agronomic properties of the soil. These factors will be evaluated during the design phase of the system. Initially, the trees will require three to four growing seasons for full canopy closure to achieve optimal groundwater extraction rates, but some positive effects on groundwater levels are expected to occur after about two

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[1] In the case of AP-3, the *TreeWells* are intended to serve as an AEM to provide a degree of hydraulic control and not as a corrective measure.

growing seasons. During the initial establishment period, site inspections (i.e., semi-annually) would be appropriate to monitor plant vigor and identify any potential issues (such as an insect infestation) that may require active intervention. Following the initial establishment period, only minor operation and maintenance activities such as pruning of the trees, occasional fertilization, and mowing of undergrowth may be needed.

Based on the conceptual site model, the uppermost portion of the highly fractured and weathered limestone is the predominant groundwater flow zone within the uppermost aquifer at AP-3. The terrace alluvium may act as a localized flow zone, but this unit is not laterally extensive across the AP-3 area. Thus, the highly fractured limestone unit, and potentially the coarse facies of the terrace alluvium (if present), are the target strata for the *TreeWells*. This/these unit(s) is/are expected to be encountered between 20 and 40 feet below the ground surface in the vicinity of the *TreeWell* field.

The location of the *TreeWell* field to the east of AP-3 is shown in **Attachment 2**. For purposes of use in a groundwater numerical model (discussed in the section below), the *TreeWell* units were modeled to be installed in the highly fractured limestone unit and are estimated to “pump” at approximately 40 gallons per day (gpd) per tree, or an approximate 4,300 gpd (or approximately 3 gallons per minute) for the entire field. This is based on commonly accepted estimates of evapotranspiration of approximately one million gallons per year per acre of full canopy forested land (McCutcheon and Schnoor, 2003). This water is drawn into the vascular system of the tree and then subject to evapotranspiration. Therefore, no effluent is generated, avoiding potential long-term discharge management.

ANTICIPATED BENEFITS OF THE TREEWELL SYSTEM

Georgia Power has closed AP-3 in-place, including the installation of a low permeability cover system, and is closing nearby AP-1 by removal. Based on predictive scenarios using a groundwater numerical model, the closure and capping of AP-3 alone has a positive effect on the groundwater conditions. When combined with the closure and surface water improvements at AP-1 the volume of CCR below the potentiometric surface is reduced by 91% and groundwater flux is reduced by 97.7% relative to the pre-closure conditions. Georgia Power has opted to use the *TreeWell* system as an AEM to provide further reductions of (i) the volume of CCR below the potentiometric surface within AP-3 and (ii) groundwater flux through AP-3.

Groundwater modeling has been used at other sites to successfully approximate the hydraulic effects of a *TreeWell* system (Gatcliff et. al., 2016; Linton, 2018). Results of groundwater modeling included in **Attachments 3** and **4** of this report estimate that the *TreeWell* field installed downgradient of AP-3 will further reduce the volume of CCR below the potentiometric surface (i.e., approximately 1%) and groundwater flux (i.e., approximately 0.1%) relative to the combined closure of AP-3 and AP-1. Further, the *TreeWells* will also provide beneficial effects beyond the model boundary in the vicinity of the *TreeWell* field. As previously discussed, the *TreeWells* would require minimal long-term maintenance, offer the beneficial long-term hydraulic control without the need for above-ground water treatment, and would not impact the cover system or dikes of the AP-3 embankment.

TREEWELL REFERENCES

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ATTACHMENTS

Attachment 1 – Conceptual TreeWell Design

Attachment 2 – Conceptual Layout of TreeWell AEM

Attachment 3 – Groundwater Model Calculation Package

Attachment 4 – Groundwater Model Calculation Package Addendum

Attachment 5 – Reference Package

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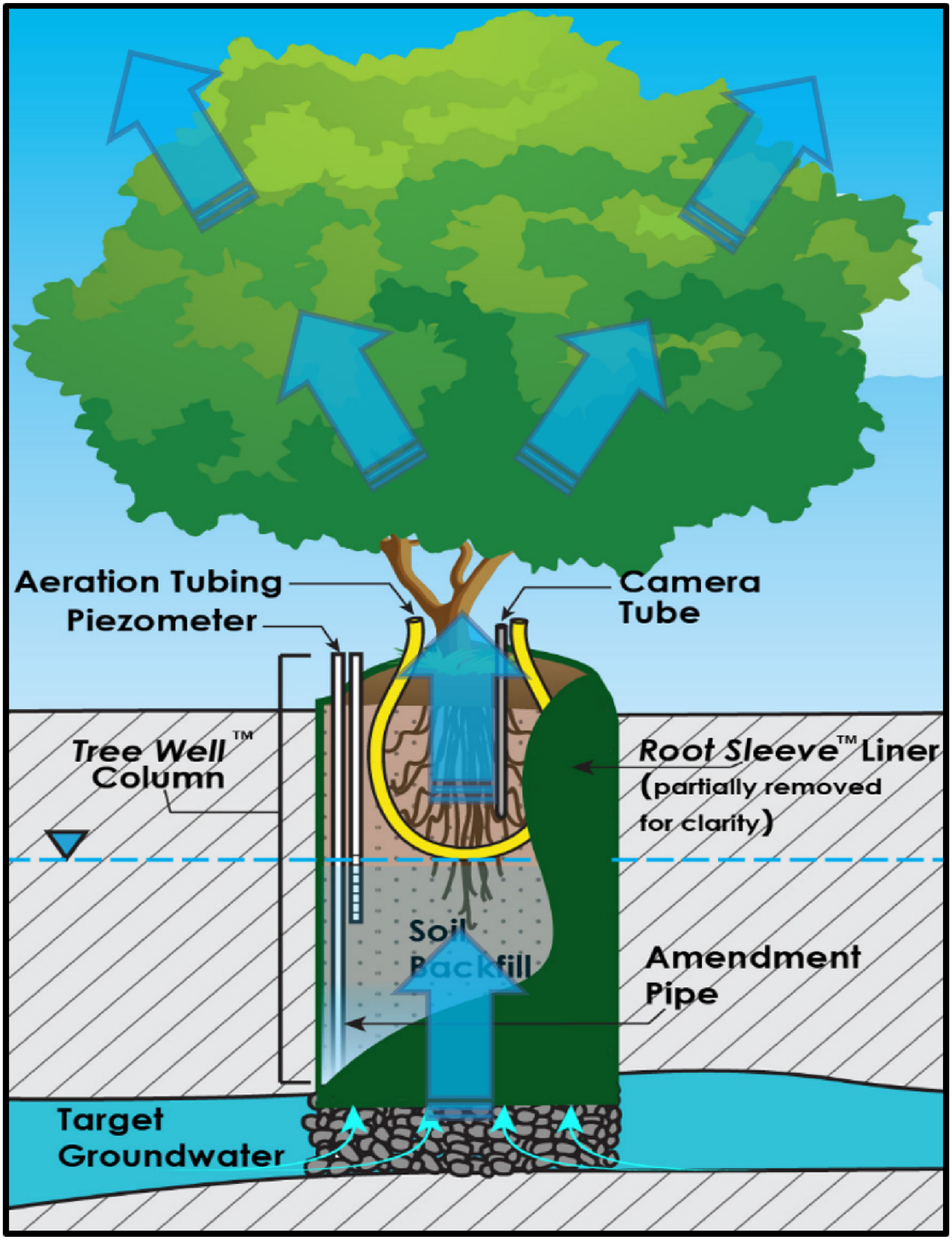
ATTACHMENT 1

Conceptual TreeWell Design



Note:
1. Final tree selection will be based on required water consumption rates, plant availability, health of plant materials, and further assessment of local plant material resources.
2. TreeWell Root Sleeve casing depth will vary dependent on target depth horizons, and may be adjusted in the field to account for variability in the subsurface conditions observed during drilling.

Aerial Photograph approximate date - August 2019 Source: Google Earth.

Conceptual TreeWell Design

Georgia Power Company
Plant Hammond AP-3
Rome, Floyd County, Georgia

Geosyntec consultants

Kennesaw, GA

December 2020

Attach.

1

N:\GA Power\Plant Hammond AP3\GIS\MXD\TreeWell\2020.11_Proposal\Figure1 Conceptual TreeWell Design.mxd 12/1/2020 9:26:31 AM

ATTACHMENT 2

Conceptual Layout of TreeWell AEM

▨ Conceptual TreeWell Field

┅ Approximate Limit of CCR

0 150 300 600
Feet

Aerial Photograph approximate date - August 2019 Source: Google Earth.

Conceptual Layout of TreeWell AEM

Georgia Power Company
Plant Hammond AP-3
Rome, Floyd County, Georgia

Geosyntec
consultants

Kennesaw, GA

December 2020

Attach.

2

N:\GA Power\Plant Hammond AP3\GIS\MXD\TreeWell\2020.11_Proposal\Figure1 AP-3 TreeWells Layout_Memo.mxd 12/1/2020 9:02:29 AM

ATTACHMENT 3

Groundwater Model Calculation Package

Prepared for

Southern Company
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GROUNDWATER MODEL CALCULATION PACKAGE PLANT HAMMOND AP-3

GEORGIA POWER COMPANY
Floyd County, Georgia

Submitted by

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engineers | scientists | innovators

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Project Number: GR6242
November 2019

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LIST OF ACRONYMS

3D	three dimensional
AP	ash pond
cm/s	centimeters per second
EVS	Environmental Visualization System
ft	feet
ft^2/d/ft	square feet per day per foot
Geosyntec	Geosyntec Consultants
GPC	Georgia Power Company
HAR	Hydrogeologic Assessment Report
NAVD88	North American Vertical Datum of 1988
NRMSE	normalized root mean square error
PEST	Parameter Estimation Software
REV	Representative Elementary Volume
SCS	Southern Company Services
USGS	United States Geologic Survey

1.0 INTRODUCTION

This *Groundwater Model Calculation Package* (Report) was prepared to document the construction and calibration of the finalized three-dimensional (3D), steady-state, groundwater numerical flow model used to evaluate the groundwater flow conditions in the vicinity of Ash Pond 3 (AP-3 or Site) at the Georgia Power Company (GPC) owned and operated Plant Hammond (the Plant) near Rome, GA. This Report documents the findings and conclusions of the calibrated groundwater flow model, which was used to simulate existing condition and capping of AP-3 with dewatering of AP-1 and evaluate the impacts of pond closure on the groundwater flow system at the Plant. The Report has been prepared by Geosyntec Consultants, Inc. (Geosyntec) on behalf of Southern Company Services (SCS).

1.1 Model Objectives

The objectives of the numerical groundwater flow modeling were three-fold:

- Construct a steady-state groundwater model of the Site that is calibrated to representative groundwater conditions recorded in the field;
- Simulate groundwater conditions within AP-3 under the current closure scenario using the calibrated model;
- Using the simulated results to evaluate the post-closure groundwater conditions.

2.0 MODEL CONSTRUCTION

2.1 Model Design

Based on the geologic information described in Section 3.0 of the *Hydrogeologic Assessment Report (Revision 01) – Ash Pond 3 (AP-3)* (HAR Rev. 01), the numerical groundwater flow model is conceptualized as being a single aquifer system, composed of five geologic layers (i.e. fill, terrace alluvium material, residuum, highly weathered rock, and unweathered limestone). The geological layers were further vertically discretized to better evaluate flow in the model domain **(Table 1)**. Generally, the geological layers, in addition to ash, were assigned to the numerical model layers as follows:

- Fill: Layer 1 and 2
- Ash: Layer 1 and 2
- Terrace Alluvium Material: Layer 3
- Residuum: Layer 4
- Highly weathered Rock: Layer 5
- Highly Fractured Rock (i.e. top 5 feet of Limestone): Layer 6
- Unweathered Limestone: Layers 7-9

Based on information provided in boring logs and a microgravity survey, the hydraulic properties of the geologic materials within the terrace alluvium material, highly weathered rock, and highly fractured rock were altered to more appropriately represent the materials (e.g., gravel or fractures that may indicate a greater than average hydraulic conductivity value than suggested by the geometric mean of measured values) found in these zones. These zones are shown in **Figures 1** through **9** and the justification for each zonation is provided in **Table 1**.

The bottoms of AP-1 and AP-3 were determined using historical as-built drawings published to GPC's webpage. Data from these sources were imported into the 3D visualization software Environmental Visualization System (EVS) and used to create the bottom of ash for AP-1 and AP-3.

The modular, 3D, finite difference groundwater flow model (MODFLOW), created by the United States Geological Survey (USGS), was used as the modeling program to simulate groundwater flow. Specifically, a Newton formulation of MODFLOW, MODFLOW-NWT (Niswonger, et al., 2011) was utilized because of its capabilities in solving non-linear equations associated with unconfined aquifers and non-linear boundary conditions, conditions relevant to the Site. The constant head package and the drain package (Niswonger, 2011) were used to simulate rivers/creeks and ephemeral steams, respectively. The recharge package (Niswonger, et al., 2011) was used to simulate recharge. Parameter estimation software (PEST) is a model independent parameter estimation program (Watermark Numerical Computing, 1994) that was used during the calibration process to assist in estimating model parameters such as hydraulic conductivity.

For the purposes of the MODFLOW groundwater flow model, the aquifer is assumed to act as an equivalent porous medium. However, a portion of the model domain is comprised of fractured rock. One rationale for this assumption is based on observed historical water levels and associated potentiometric surface maps that indicate a relatively smooth potentiometric surface without angular or sharp changes in the groundwater table.

Geophysical borehole logs were reviewed to evaluate the average open fracture spacing (**Table 3**). The evaluation indicated that in the borings where geophysics data were available that the average open fracture spacing varied from 0.25 to 0.65 fractures per foot with an average of 0.45 fractures per foot. These fracture spacings were used to calculate a representative elementary volume (REV). A REV is the smallest volume over which a measurement can be made that will yield a value representative of a whole. Since MODFLOW assumes groundwater flow in a porous medium (not fractures), it is necessary to understand the scale of the fractured rock system where groundwater flow is the same as in a porous medium. Generally, a REV of equivalent porous media flow occurs at scales of 30 to 50 times grain size diameter on a side. This same concept has been applied to fractured rock systems and for this Site would indicate that a REV for the portion of the limestone evaluated would range from a cube with sides measuring 7.5 feet to a cube with sides measuring 32.5 feet.

2.2 Model Grid and Layering

The model domain consists of 344 rows, 344 columns, and 9 vertical layers. The model cell size varies from approximately 10 ft by 10 ft Near AP-3 and telescopes outward toward the model boundary.

Model layers represent the 5 geologic units described in the HAR Rev. 01 and **Table 1** herein. Ground surface elevations were based on a combination of actual ground surface topography from publicly-available regional LIDAR data and a Site topo map provided by SCS. Lithology and layer elevations were based on subsurface lithologic/geologic boring log descriptions from Site-specific field investigation data, and historical maps of AP-3 construction. Data from these sources were imported using EVS and interpolated to create surfaces for the top and bottom of each model layer. The top of layer 1 is land surface and the elevations are based on LIDAR elevation data provided by the USGS (USGS, 2017) and a Site topo map[1]. Elevations for the bottoms of layer 1 through 9 were based on geological boring log data from the Site. The bottom of layer 9 (bottom of bedrock) was assumed to be at an elevation of 375 ft North American Vertical Datum of 1988 (NAVD88), which varies between 160 to 190 feet below the bottom of the highly fractured rock zone. **Figure 10b** though **Figure 15** show examples of EVS model layering along the cross section lines presented on **Figure 10a.**

In general, a minimum model layer thickness of 0.1 ft was applied to areas where interpolation of artificial pinch-outs were created due to a lack of geological data control points, or where physical pinch-outs of geologic units were observed (e.g. terrace alluvium material directly beneath AP-3). This minimum thickness was enforced because MODFLOW-NWT does not allow for a zero layer thickness in the model grid. For areas where a unit pinches out, cells with a minimum thickness of 0.1 ft were assigned hydraulic conductivity zones to match the geologic unit in the layer below. For example, the terrace alluvium material pinches out underneath AP-3, resulting in small layer thicknesses in model layer 3 beneath AP-3. Those cells were therefore assigned a hydraulic conductivity equal to that of the residuum in model layer 3.

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[1] The topographic contours and details shown inside of the Dike limits were obtained from the stamped as-built final cover survey conducted by Martin Survey and Associates, Inc. of Holly Springs, GA for Salla Construction Company, LLC of Birmingham, AL, Dated 25 October 2012, as provided by Southern Company Services in the CAD file titled “PH-Final 12-4-12.”

2.3 Model Boundaries

A conceptual level map of the boundary conditions is shown in **Figure 16** and the boundary conditions assigned to the model are shown in **Figure 16a**. The Coosa River was modeled by assigning a constant head boundary condition elevation of 561.45 ft NAVD88 to Layers 1-5. It should be noted that based on surface water elevation data collected by the USGS from 1 October 2007 until 20 May 2017 at a staff gauge located approximately eight miles east of Plant Hammond, the Coosa River stage has historically varied by 21.7 feet[2]. The depth of the Coosa River is not known adjacent to the Plant and was assumed to be approximately 17 feet deep and extend to the top of the highly-fractured limestone.

Cabin Creek is shown on the USGS topo (USGS, 1967) in **Figure 16** to be continually present and was also modeled as a constant head boundary condition. However, observations made during Site visits indicated that Cabin Creek is shallow. Furthermore, the elevation of Cabin Creek changes from approximately 570 ft to 561.45 ft NAVD88. Therefore, the constant head boundary condition that represents Cabin Creek is assigned to the uppermost active layer. For example, in one portion of the model the boundary condition would be assigned to layer 1. However, as Cabin Creek cuts down through the terrain, it reaches a point where it influences layer 2 and layer 1 is now dry. In these instances, the constant head boundary condition would be assigned to layer 2 instead of layer 1.

The USGS topo map indicates an ephemeral stream along the western portion of the model. Due to the ephemeral nature of the unnamed stream, it was assigned as a drain boundary condition. The drain elevations were derived from the Site-specific topo data and USGS topo and ranged from 590.6 ft NAVD88 near the northern edge of the model to the southern terminus of the Coosa River with a 9 February 2017 measured elevation of 561.45 ft NAVD88. The drain conductance was a calibrated value and set at 10 square feet per day per foot ($ft^2/d/ft$). Like Cabin Creek, this unnamed stream is shallow, and therefore the drain boundary condition was only assigned to the uppermost active layer.

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[2] https://nwis.waterdata.usgs.gov/usa/nwis/uv/?cb_00065=on&format=rdb&site_no=02397000&period=&begin_date=2007-10-01&end_date=2017-05-21

The USGS topo map in **Figure 16** shows that a topographic ridge is located north and west of the Site. It was assumed that this ridge functions as a no flow boundary condition as surface water runoff appears to collect in streams or water bodies on either site of the ridge.

AP-1 and AP-2 were both modeled as constant head boundary conditions. Ash was present in layers 1 and 2 in AP-1. Therefor the 9 February 2017 measured constant head boundary condition (585.09 ft NAVD88) was applied to both layers 1 and 2 in AP-1. Less information is available regarding AP-2 therefore the 9 February 2017 measured constant head boundary condition of 596.43 ft NAVD88 was applied only to the uppermost active cell. Similarly, little information is known regarding the industrial wastewater ponds to the east of Cabin Creek, which are not owned by GPC. Therefore, the surface water elevation derived from LIDAR data (588 ft NAVD88) was assigned to the uppermost active cell in these locations.

2.3.1 Model Recharge

The USGS performed a recharge study for the Coosa River basin (USGS, 1996). The study evaluated average recharge for the 4,040 square mile drainage basin that is represented by streamflow measurements made at a point on the Coosa River approximately 8 miles east of the Site. The recharge study estimated that the average recharge rate for the entire basin was 13.2 inches per year, but may be as low as 3.2 inches per year during droughts. It should be mentioned that these estimates are averages. Actual recharge will vary locally based on topography, surface water, run-off, man-made drainage features, rainfall intensity, etc. Therefore, these two recharge estimates were used as the upper and lower bounds for estimating recharge assigned to various zones within the model domain during model calibration. As shown in **Figure 17**, four recharge zones were assigned to the Site. The area south of the railroad tracks does not receive recharge as much of the area is covered with pavement or buildings and the remainder of the area is close to the Coosa River and is therefore in a discharge area. The area north of the railroad tracks was assigned a recharge value of 6.38 inches per year. This reflects the lower amount of recharge expected in the area due to runoff from relatively steep topography and the presence of man-made stormwater ditches. The area north of Cabin Creek was assigned a recharge of 13.2 inches per year as it is the headwaters area for Cabin Creek. Additionally, AP-3 was assigned a recharge rate of 3.7 inches per year in stormwater runoff is directed to an inner perimeter stormwater collection system. This recharge rate depicts baseline conditions for when the AP-3 cover system was incomplete (i.e., February 9, 2017). It should be noted that 0.57 inches of precipitation fell on nearby Rome, GA on February 8, 2017 (wunderground.com, 2017). This is one day before Geosyntec personnel were on Site collecting static groundwater and surface water measurements that were used to calibrate the model.

2.4 Hydraulic Conductivity Zones

In general, hydraulic conductivity zonation was based on a specific geologic material, which represented a layer in the model. The range, geometric mean and model calibrated hydraulic conductivity values for each geologic material are presented in **Table 1**. If available, well-specific hydraulic conductivity values were incorporated into the model (**Table 4**). However, model calibration was not possible using a single hydraulic conductivity for each geologic material as this produced unacceptable residuals in the residuum, highly weathered rock, and highly fractured rock. Therefore, the boring logs of monitoring wells with relatively high residuals were evaluated for the presence of material within the well screen that may be hydraulically different than that of the main geologic unit. Additionally, a microgravity survey was evaluated for the presence of bedrock zones that may contain open fractures/ solution voids (low density materials) or lower hydraulic conductivity zones (high density materials). Finally, where available, the measured hydraulic conductivity in wells with relatively high residuals were evaluated for differences from the value used in the model for the geologic unit. **Figures 1 through 9** show the hydraulic conductivity zones used in layers 1 through 9. A table of hydraulic conductivity zones is shown in **Table 1**.

2.5 Model Calibration

The model was calibrated to groundwater elevation targets based on measurements at monitoring wells and surface water locations made by Geosyntec on February 9, 2017. These measurements, well screen elevations, calibrated modeled values for each well are shown on **Table 5**. Wells were assigned to model layers based on their screen elevations. The groundwater flow model was calibrated to the actual on-site groundwater conditions by setting drain conductance to 10 ft^2/d/ft and then modifying recharge and hydraulic conductivity using PEST version 13.6 (Watermark, 1994) to allow the named parameters to vary within measured ranges until the best statistical fit between measured and observed head elevations was obtained. Following the use of PEST, zones within select geologic materials were adjusted according to available data as described in Section 2.4 to obtain a satisfactory fit. The model was considered calibrated once simulated output closely approximated observed field conditions (e.g. inferred groundwater flow directions, groundwater gradients, groundwater elevations at monitoring wells observed on Site), and when calibration statistics indicated a low residual mean error and a normalized root mean square error (NRMSE) less than 10%. NRMSE is used to measure the difference between observed groundwater values and model predicted values. The smaller the difference between observed and predicted values, the smaller the NRMSE percentage. Typically, groundwater models are considered calibrated when NRMSE is less than 10%.

Simulated groundwater elevation contours of the calibrated model are shown in **Figure 18** for the highly fractured rock zone and **Figure 19** for the terrace alluvium material. These zones were selected because most of the wells near AP-3 are screened in the highly weathered zone/highly fractured zone and most of the wells near AP-1 are screened at least partially in the terrace alluvium material. Simulated contours and flow directions generally matched historical potentiometric contour and flow direction maps generated from measured groundwater elevations. The simulated and the observed groundwater elevations were compared at the 36 monitoring well targets incorporated into the model by calculating the residual (observed groundwater elevation minus simulated groundwater elevation) for each well target (**Table 5**). The minimum residual head value was -3.81 ft and the maximum residual head value was 3.20 ft, over a range in observed head values of 20.76 ft. Comparison statistics for the well targets in **Table 5** show a residual mean error (ME) of -0.15 ft and a NRMSE of 9.9%); the proximity of these statistics to zero indicates a good match between observed and simulated heads and that the model is reasonably calibrated. The computed mass water balance error for the model was also small (-2.0 E-04%). **Figure 20** plots observed versus simulated head values for the 36 targets, and shows a good match between observed and simulated heads based on proximity of the results to the 1:1 correlation line. **Figure 21** shows observed head versus model residuals and shows that there is no strong bias to the residuals. Combined with the comparison statistics and negligible mass balance error, **Figure 20** and **Figure 21** support the conclusion that the flow model is a reasonable representation of actual Site conditions. Overall, simulated head contours, flow directions, calibration statistic, and model residuals indicates that the model is reasonably calibrated.

3.0 PREDICTIVE SIMULATIONS

After calibration, the groundwater model was used to evaluate the predictive scenario for pre-closure conditions (i.e., calibration run) and final closure design at steady state.

3.1 Scenario 1: Baseline Condition (Base Case, Pre-Closure)

This scenario is the calibrated model representing the conditions present at the Site before completion of the cover system, i.e. the "existing condition" at the time of model construction (i.e., February 9, 2017). **Figure 22** shows the baseline groundwater elevation contours generated from the model simulation.

3.2 Scenario 2: Install Cover at AP-3; AP-1 at Baseline Pool Level (Post-Closure)

Scenario 2 represents the conditions at the Site following completion of the cover system at AP-3 but prior to the dewatering and closure of AP-1. Under this scenario, recharge over AP-3 was reduced to zero and the constant head boundary condition at AP-1 was set at 585.09 ft to represent the pool water level measured February 9, 2017. **Figure 23** shows model predicted groundwater elevation contour map.

3.3 Scenario 3: Install Cover at AP-3 and Drain AP-1 (Post-Closure)

Scenario 3 represents the conditions at the Site following completion of the cover system at AP-3 and the anticipated closure of AP-1. Under this scenario, recharge over AP-3 was reduced to zero and the constant head boundary condition at AP-1 is removed to represent the removal of free water and closure of that unit. **Figure 24** shows model predicted groundwater elevation contour map.

Groundwater flow models are necessarily simplified mathematical representations of complex natural systems. Therefore, all groundwater models have limits to their accuracy and associated uncertainties in model predictions. The goal of this model was not to define precise predictive scenarios, but to provide relative groundwater elevation and flow information. The supporting calibration statistics and representative flow simulations provide an acceptable degree of confidence that the model is calibrated and suitable for its intended purpose.

4.0 SENSITIVITY ANALYSIS

A sensitivity analysis was performed to evaluate the effect that decreased horizontal and vertical hydraulic conductivity of the residuum would have on the calibration of the model. This parameter was chosen as the residuum is present beneath the ash in AP-3 and the hydraulic conductivity of the residuum plays a role in the feasibility of closure options. For the sensitivity analysis, the horizontal hydraulic conductivity of the residuum was reduced from 2.20×10^{-4} centimeters per second (cm/s) to 2.20×10^{-5} cm/s and the vertical hydraulic conductivity was reduced from 9.15×10^{-5} cm/s to 1.46×10^{-6} cm/s. The residuals between the calibrated head values and the sensitivity head values are shown in **Table 6**. The relatively small residuals (average residual is -0.06 ft and absolute average residual is 0.12 ft) between the simulations indicates that the model is not very sensitive to the hydraulic conductivity of the residuum. The implies that the potential for natural fluctuation of hydraulic conductivity within the residuum will not negatively impact the constructed model’s ability to accurately predict scenarios.

5.0 CONCLUSIONS

A three-dimensional steady state groundwater flow model was constructed to simulate various scenarios at the Site. Once calibrated, the model was used to simulate the groundwater flow conditions that would result from constructing a cap at AP-3 and draining AP-1 (Scenario 3). Under this scenario, the model predicts approximately a four-foot reduction in the groundwater elevation across the Site relative to the modeled pre-closure baseline conditions (Scenario 1).

6.0 REFERENCES

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TABLES

Table 1. Geologic Zones and Hydraulic Conductivity Values

Geologic Unit	Assigned Groundwater Model Layer	Data Source	Horizontal Hydraulic Conductivity, K_h (cm/s)				Vertical Hydraulic Conductivity, K_v (cm/s)			
			Geometric Mean	Model	Range of Values	Number of Observations	Geometric Mean	Model	Range of Values	Number of Observations
Residuum	**4**	Law Engineering (1977), Southern Company (2014) - K_h Golder (2016) & Geosyntec (2017) - K_v	2.01E-04	2.20E-04	6.10E-07 to 2.35E-02	13	2.91E-07	9.15E-05	1.00E-07 to 1.40E-06	6
Fill	**1, 2**	Law Engineering (1977) - K_h Golder (2016) & Geosyntec (2017) - K_v	3.33E-06	1.02E-05	7.62E-07 1.02E-05	8	4.12E-08	1.5E-07 at berm; 1.85E-06 elsewhere	1.50E-08 to 1.50E-07	4
Terrace Material	**3**	Law Engineering (1977) - K_h Golder (2016) & Geosyntec (2017) - K_v	1.21E-04	1.11E-03	4.27E-05 to 3.76E-04	4	9.47E-08	2.14E-04	6.40E-08 to 1.40E-07	2
Rock (+ some residuum)	**5, 6**	Law Engineering (1977) - K_h	3.38E-04	3.38E-03	5.08E-05 to 2.13E-03	3	-	3.38E-04	-	-
Limestone	**7, 8, 9**	Geosyntec (2017) - K_h	4.99E-04	3.53E-04	6.22E-05 to 2.82E-03	7	-	3.53E-05	-	-

Notes:
1) The samples tested for vertical hydraulic conductivity of the terrace material contained more clay than average and likely underestimate the vertical hydraulic conductivity.
2) The following additional hydraulic conductivity zones are shown on Figures 1 through 9. The hydraulic conductivities (cm/s) and rationale for changing the hydraulic conductivity are shown below:

Low Density Limestone Kh=1.76E-02 Kv=1.76E-03 Calibrated based on assumed increased fracture density from microgravity survey
High Density Limestone Kh=3.53E-05 Kv=3.53E-06 Calibrated based on assumed decreased fracture density from microgravity survey
High K Terrace Material Kh=5.00E-02 Kv=5.00E-03 Calibrated based on relatively high K values measured at AP1-MW6 and AP1-MW7, sand lense in APC1-5S, and sandy gravel in AP1-C4.
Low K residuum Kh=8.82E-0 6Kv=8.82E-07 Used lower range of K for residuum based on presence of only clay in this boring.
East of AP1 Low K Residuum Kh=3.38E-05 Kv=3.38E-06 Used lower range of K for residuum based on presence of only clay in this boring.
East of AP1 High K Residuum Kh=7.06E-03 Kv=7.06E-04 Calibrated based on presence of sandy gravel in well screen of AP1C-1
SW of AP1 Sand Kh=5.00E-02 Kv=5.00E-03 Calibrated based on sand seam in residuum at AP1C-6
SW of AP3 Highly Weathered Limestone Kh=8.42E-02 Kv= 8.42E-03 Calibrated based on partially weathered rock (shale gravel) AP3-MW21 and AP1-MW-1
SW of AP3 High K Highly Fractured Zone Kh=2.68E-02 Kv=2.68E-03 Calibrated based on partially weathered rock (shale gravel) AP3-MW21 and AP1-MW-1
water Kh=3.53E+00 Kv=3.53E+00 High K used to simulate water in Coosa River and Cabin Creek.

Table 2. Groundwater Elevations Near AP3-B-11 - February 9, 2017

Monitoring Well Name	Easting (ft)	Northing (ft)	Distance from AP3-B-11	Groundwater Elevation 2/9/17 (ft)	Reduction in Groundwater Elevation from AP3-B-11 (ft)
AP3-B-4	1942920.34	1550709.19	320	567.14	16.98
AP3-B-5	1942521.24	1550275.29	295	570.48	13.64
AP3-B-9	1942654.24	1550662.39	120	567.00	17.12
AP3-B-10	1942345.89	1550500.71	300	568.89	15.23
AP3-B-11	1942643.26	1550545.31	0	584.12	0.00

Notes:
1) Elevations are referenced to NAVD88
2) Northing and Easting reference the Georgia State Plane West (NAD83)

Table 3. Fracture Spacing Evaluation

Borehole Name	Length of Borehole Geophysics Data (ft)	Total Number of Open Fractures	Total Open Space (ft)	Fractures per Foot	Open Space per length (ft/ft)
AP3-B-2	59	32	2.85	0.54	0.048
AP3-B-3	44.5	11	1.03	0.25	0.023
AP3-B-4	3.1	2	0.50	0.65	0.161
AP3-B-9	2.75	1	0.65	0.36	0.236

Table 4. Well-Specific Measured Hydraulic Conductivity Values

Monitoring Well Name	Easting (ft)	Northing (ft)	Well Screen Midpoint Elevation (ft)	Model Layer	Measured Horizontal Hydraulic Conductivity (cm/s)		Measured Vertical Hydraulic Conductivity (cm/s)	
AP1-MW-1	1941590.75	1549936.41	563.10	6	2.68E-03	e	-	
AP1-MW-5	1942445.49	1548430.84	555.60	6	1.84E-03	e	-	
AP1-MW-6	1941686.57	1548381.22	554.30	6	1.14E-02	e	-	
AP1-MW-7	1941084.33	1548230.08	556.50	4	2.35E-02	e	-	
APA-4 (HGWA-4MW-19)	1939386.06	1549932.71	567.90	3	9.74E-04	e	-	
APA-2 (HGWA-1MW-20)	1940773.28	1550423.59	568.40	7	1.41E-03	e	-	
AP3-MW-21	1941812.40	1550265.01	565.50	5	8.42E-03	e	-	
HGWA-122 (AP3-MW-22)	1941892.64	1551247.62	565.70	6	2.50E-02	e	-	
AP3-MW-23	1942503.03	1551636.22	558.10	6	5.04E-02	e	-	
HGWC-124 (AP3-MW-24)	1942787.04	1551618.74	552.70	7	1.27E-03	e	-	
HGWC-8 (AP1C-2)	1942392.75	1549114.34	559.43	3	-		6.40E-08	e
HGWC-9 (AP1C-3)	1942215.01	1548692.82	538.62	5	-		1.50E-08	e
HGWC-11 (AP1C-5S)	1941146.65	1548477.54	560.33	4	-		6.10E-08	e
AP3-B-1	1942043.87	1550918.48	530.63	7	5.70E-04	b	1.40E-06	c
AP3-B-2	1941995.70	1551318.19	493.00	8	2.34E-04 (496.80'-491.80')	b	1.10E-07	c
AP3-B-3	1942862.68	1551280.14	507.00	7	2.82E-03 (549.15'-544.15')	b	2.90E-07	c
AP3-B-4	1942920.34	1550709.19	552.39	6	9.25E-04	b	2.10E-08	d
AP3-B-5	1942521.24	1550275.29	542.83	7	6.95E-04	b	7.60E-07	c
AP3-B-6S	1942122.65	1550542.92	581.95	1	4.13E-02	a	-	
AP3-B6I	1942123.35	1550538.41	546.48	5	9.75E-05	a	1.00E-07	c
AP3-B6D	1942124.44	1550530.98	523.76	7	6.22E-05	a	-	
AP3-B-8	1942521.40	1551323.29	519.59	7	5.15E-04	b	1.80E-07	c

Notes:
"-" = data unavailable
Source citation of hydraulic conductivity values:
a) Measured via slug test by Geosyntec, 2017
b) Measured via packer test by Geosyntec, 2017
c) Laboratory measurement of residuum vertical hydraulic conductivity by Geosyntec, 2017
d) Laboratory measurement of fill vertical hydraulic conductivity by Geosyntec, 2017
e) Provided by others

Elevations are referenced to NAVD88

Table 5. Observed and Modeled Groundwater Elevations February 9, 2017

Monitoring Well Name	Easting (ft)	Northing (ft)	Well Screen Midpoint Elevation (ft)	Model Layer	Observed Groundwater Elevation (ft)	Simulated Groundwater Elevation (ft)	Residual (ft)
AP1-MW-1	1941590.75	1549936.41	563.10	6	581.53	579.23	2.30
AP1-MW-5	1942445.49	1548430.84	555.60	6	562.79	562.23	0.56
AP1-MW-6	1941686.57	1548381.22	554.30	6	563.41	563.49	-0.08
AP1-MW-7	1941084.33	1548230.08	556.50	4	562.66	563.54	-0.88
APA-4 (HGWA-4MW-19)	1939386.06	1549932.71	567.90	3	583.42	582.87	0.55
APA-2 (HGWA-1MW-20)	1940773.28	1550423.59	568.40	7	580.12	583.39	-3.27
AP3-MW-21	1941812.40	1550265.01	565.50	5	581.45	578.25	3.20
HGWA-122 (AP3-MW-22)	1941892.64	1551247.62	565.70	6	578.57	579.14	-0.57
AP3-MW-23	1942503.03	1551636.22	558.10	6	574.61	574.37	0.24
HGWC-124 (AP3-MW-24)	1942787.04	1551618.74	552.70	7	570.50	570.83	-0.33
HGWA-1 (APA-2MW-20)	1940773.31	1550423.69	568.30	7	580.12	583.39	-3.27
HGWA-2 (APA-3S)	1939845.20	1549796.40	565.23	3	581.02	582.86	-1.84
HGWA-3 (APA-3D)	1939833.46	1549793.93	548.19	5	581.20	581.40	-0.20
HGWA-4 (APA-4MW-19)	1939386.17	1549932.76	567.90	3	583.42	582.87	0.55
HGWC-7 (AP1C-1)	1942319.97	1549520.39	556.32	5	575.77	572.93	2.84
HGWC-8 (AP1C-2)	1942392.75	1549114.34	559.43	3	577.42	574.39	3.03
HGWC-9 (AP1C-3)	1942215.01	1548692.82	538.62	5	566.10	566.85	-0.75
HGWC-10 (AP1C-4)	1941644.41	1548469.51	561.66	3	565.15	566.38	-1.23
HGWC-11 (AP1C-5S)	1941146.65	1548477.54	560.33	4	564.80	567.55	-2.75
HGWC-12 (AP1C-5D)	1941152.08	1548475.82	550.33	6	564.80	568.61	-3.81
HGWC-13 (AP1C-6)	1940900.41	1548628.52	554.76	4	576.53	573.48	3.05
HGWC-120 (P20-2016)	1942907.17	1551082.00	552.76	7	566.60	567.11	-0.51
AP1A-1	1941613.87	1550080.50	571.17	3	581.59	581.51	0.08
AP3-B-1	1942043.87	1550918.48	530.63	7	577.63	575.12	2.51
AP3-B-2	1941995.70	1551318.19	493.00	8	578.20	577.11	1.09
AP3-B-3	1942862.68	1551280.14	507.00	7	564.50	568.30	-3.80
AP3-B-4	1942920.34	1550709.19	552.39	6	567.14	566.28	0.86
AP3-B-5	1942521.24	1550275.29	542.83	7	570.48	568.80	1.68
AP3-B-6S	1942122.65	1550542.92	581.95	1	574.80	577.15	-2.35
AP3-B6I	1942123.35	1550538.41	546.48	5	574.70	572.83	1.87
AP3-B6D	1942124.44	1550530.98	523.76	7	572.87	573.11	-0.24

Table 5. Observed and Modeled Groundwater Elevations February 9, 2017

Monitoring Well Name	**Easting (ft)**	**Northing (ft)**	**Well Screen Midpoint Elevation (ft)**	**Model Layer**	**Observed Groundwater Elevation (ft)**	**Simulated Groundwater Elevation (ft)**	**Residual (ft)**
AP3-B-7	1942387.32	1551042.74	518.36	7	571.56	571.48	0.08
AP3-B-8	1942521.40	1551323.29	519.59	7	573.14	572.01	1.13
AP3-B-9	1942654.24	1550662.39	538.00	7	567.00	568.55	-1.55
AP3-B-10	1942345.89	1550500.71	552.69	4	568.89	572.44	-3.55
AP3-B-11 *	*1942643.26*	*1550545.31*	*539.62*	*6*	*584.12*	*568.90*	*15.22*

Min Residual	-3.81
Max Residual	3.20
Range	20.76
Mean Error	-0.15
NRMSE	9.9%

Notes:
*AP3-B-11 was not included in the statistical evaluations. The measured groundwater elevation in this well is approximately 15 feet higher than it's nearest neighbors

1) Elevations are referenced to NAVD88. Northing and Easting reference the Georgia State Plane West (NAD83)

Table 6. Sensitivity Evaluation

Monitoring Well Name	Calibrated Head (ft)	Sensitivity Analysis Head (ft)	Residual
AP1-MW-1	579.25	579.35	-0.10
AP1-MW-5	562.26	562.23	0.04
AP1-MW-6	563.58	563.51	0.06
AP1-MW-7	564.08	563.70	0.39
HGWA-4 (APA-4MW-19)	582.95	583.15	-0.20
APA-2 (HGWA-1MW-20)	583.43	583.58	-0.16
AP3-MW-21	578.26	578.40	-0.13
HGWA-122 (AP3-MW-22)	579.15	579.36	-0.20
AP3-MW-23	574.38	574.53	-0.15
HGWC-124 (AP3-MW-24)	570.83	570.90	-0.07
HGWA-1 (APA-2MW-20)	583.43	583.58	-0.16
HGWA-2 (APA-3S)	582.93	583.10	-0.17
HGWA-3 (APA-3D)	581.47	581.60	-0.13
HGWA-4 (APA-4MW-19)	582.95	583.15	-0.20
HGWC-7 (AP1C-1)	572.94	573.07	-0.13
HGWC-8 (AP1C-2)	574.40	574.45	-0.06
HGWC-9 (AP1C-3)	566.90	566.89	0.02
HGWC-10 (AP1C-4)	566.68	566.37	0.31
HGWC-11 (AP1C-5S)	567.75	567.60	0.15
HGWC-12 (AP1C-5D)	568.73	568.62	0.10
HGWC-13 (AP1C-6)	573.55	573.53	0.03
HGWC-120 (P20-2016)	567.11	567.12	0.00
AP1A-1	581.53	581.64	-0.11
AP3-B-1	575.14	575.29	-0.16
AP3-B-2	577.13	577.29	-0.16
AP3-B-3	568.30	568.30	0.00
AP3-B-4	566.28	566.30	-0.02
AP3-B-5	568.81	568.90	-0.09
AP3-B-6S	577.17	577.61	-0.45
AP3-B6I	572.84	572.94	-0.10
AP3-B6D	573.12	573.23	-0.11
AP3-B-7	571.49	571.53	-0.04
AP3-B-8	572.02	572.09	-0.08
AP3-B-9	568.55	568.59	-0.04
AP3-B-10	572.45	572.38	0.06
AP3-B-11	568.91	568.95	-0.05
		Average	-0.06
		Abs. Average	0.12

FIGURES

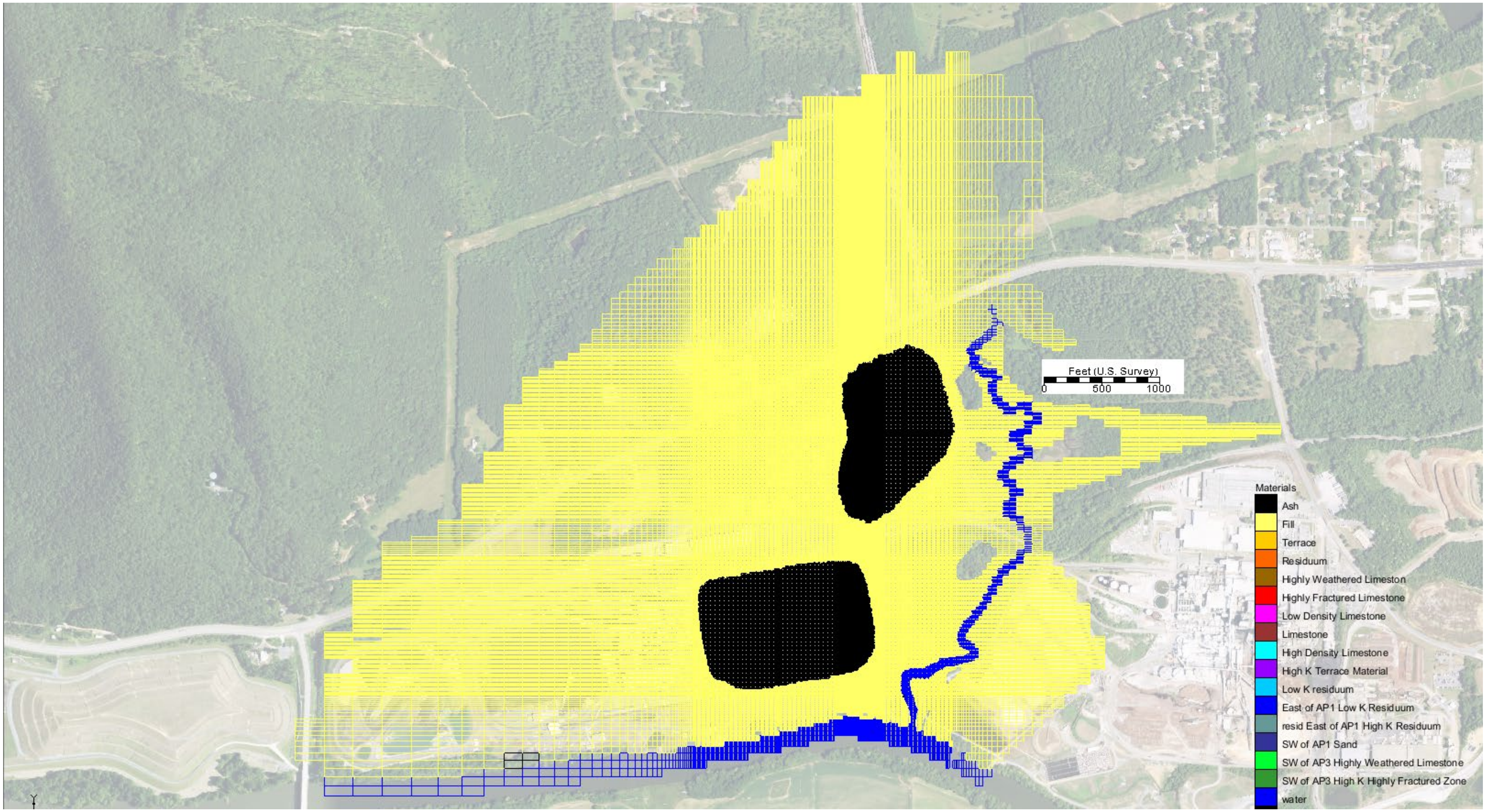

Figure 1: Layer 1 Hydraulic Conductivity Zones

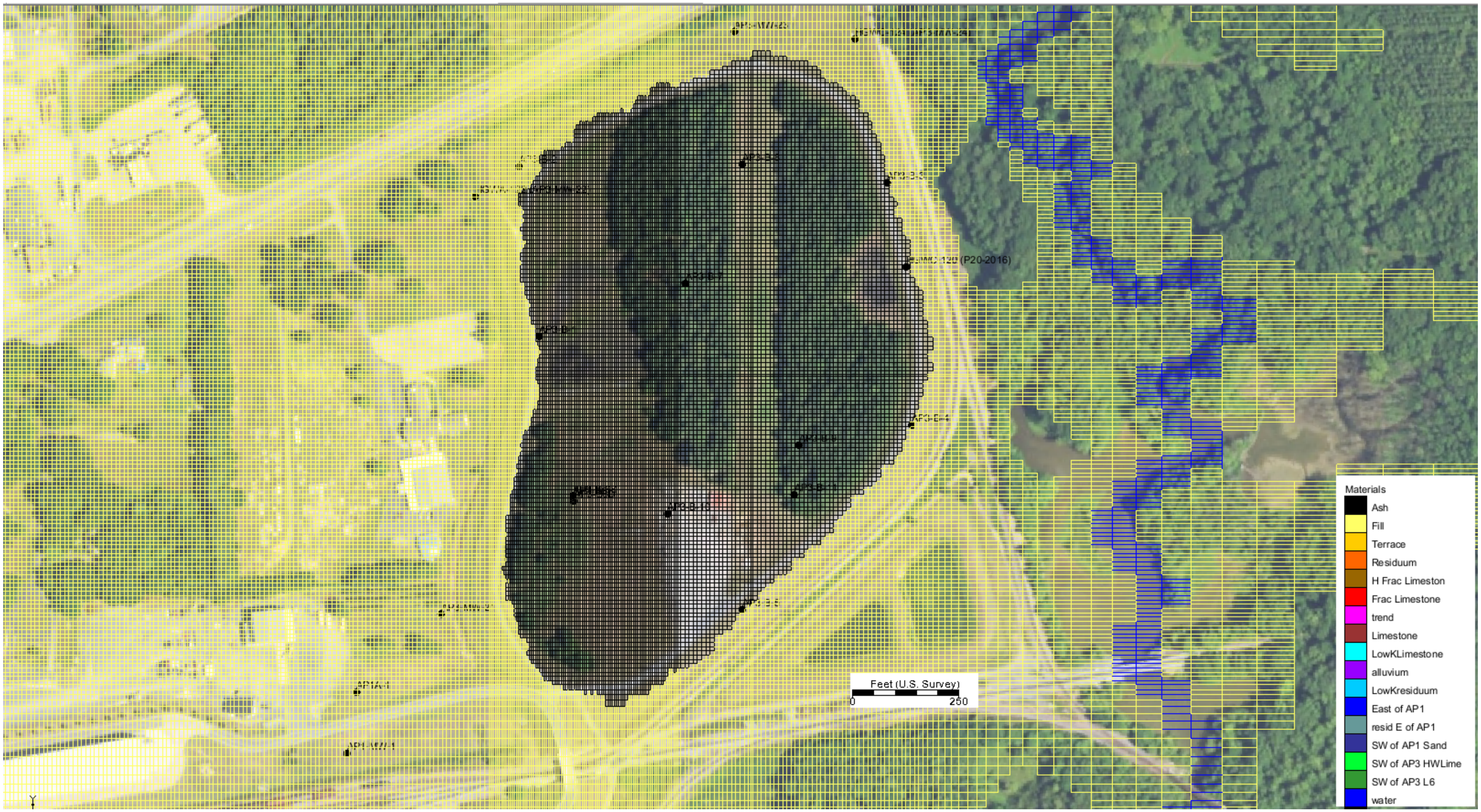

Figure 1a: Layer 1 Hydraulic Conductivity Zones Near AP-3

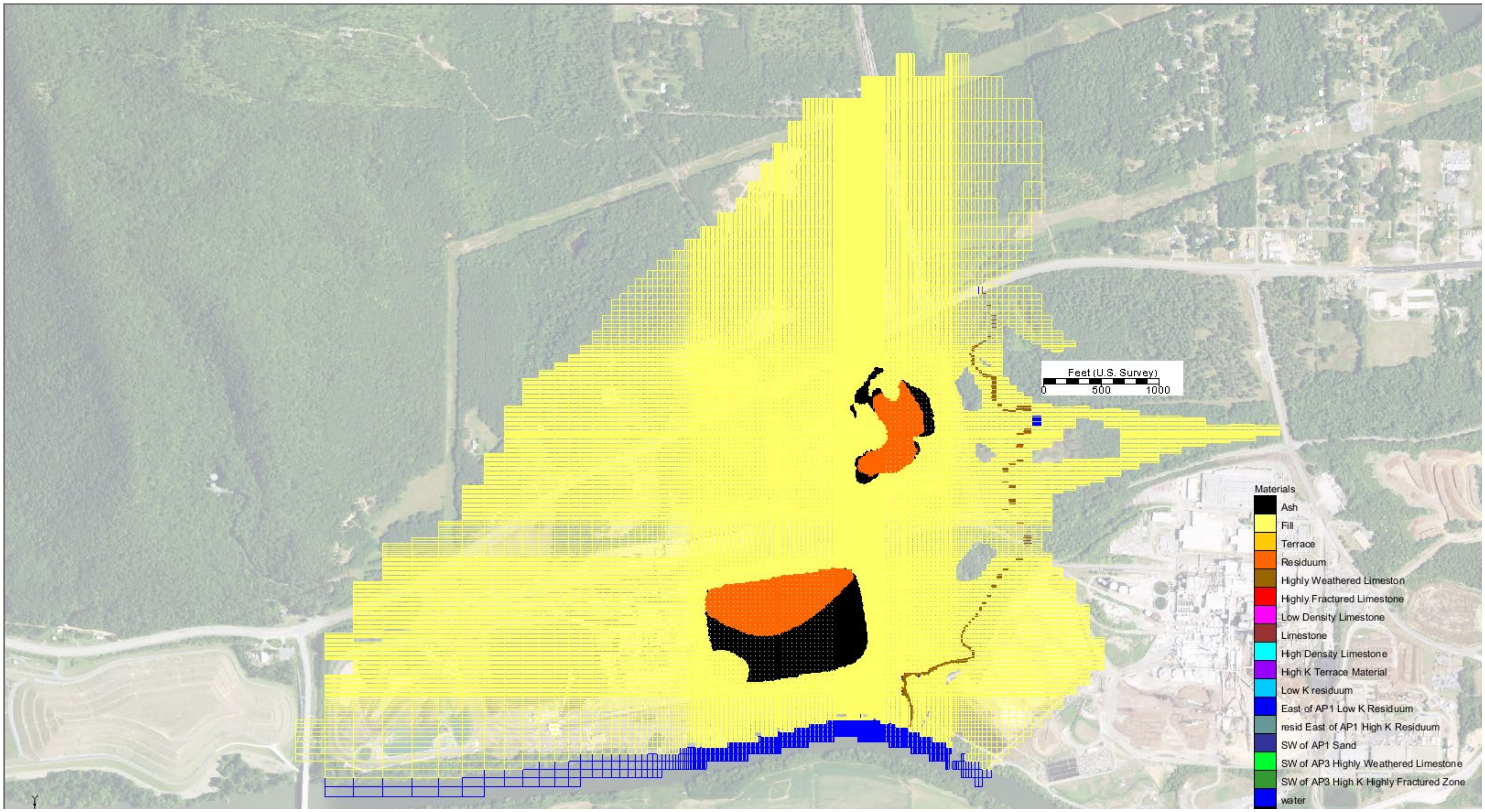

Figure 2: Layer 2 Hydraulic Conductivity Zones

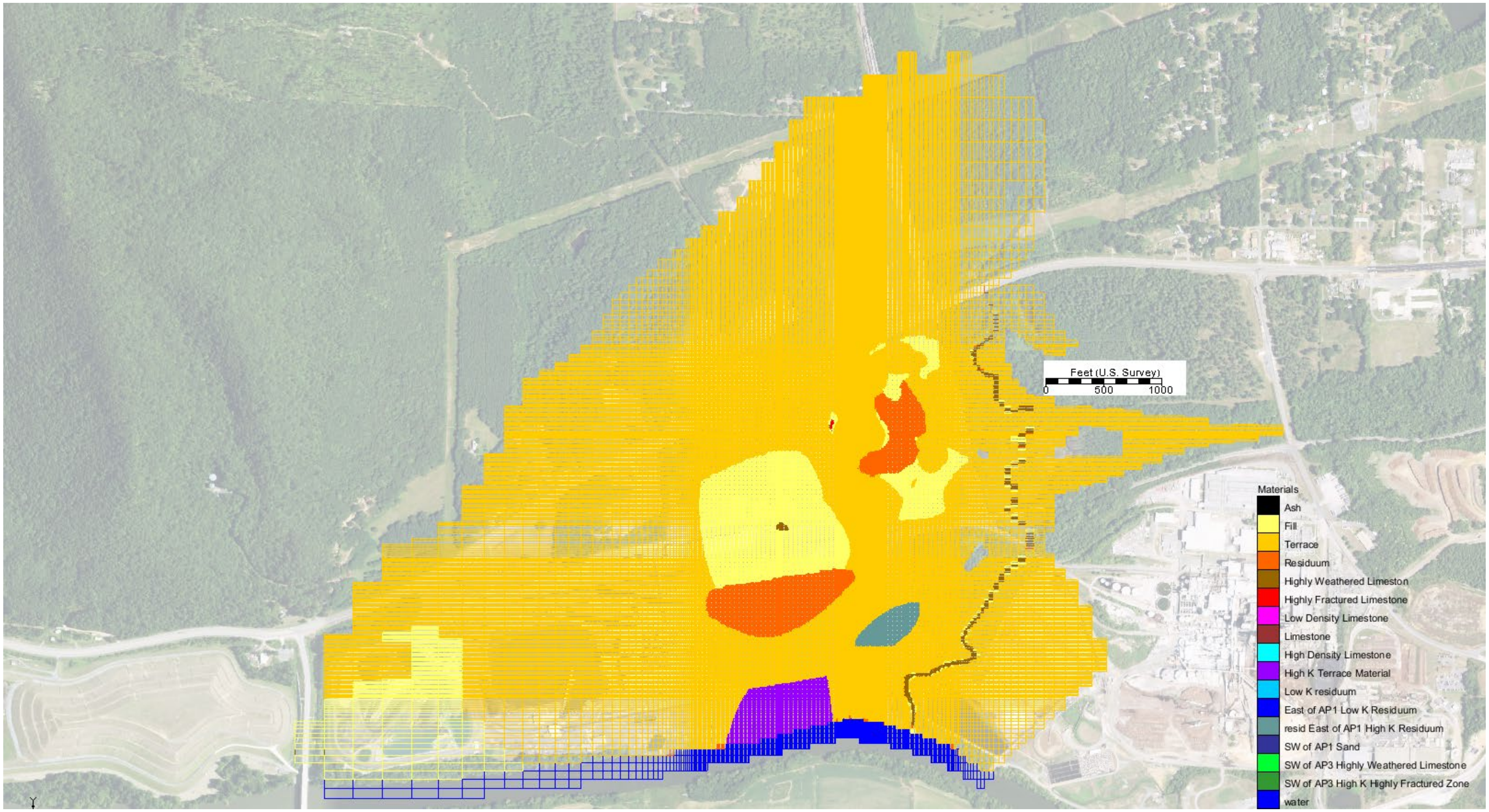

Figure 3: Layer 3 Hydraulic Conductivity Zones

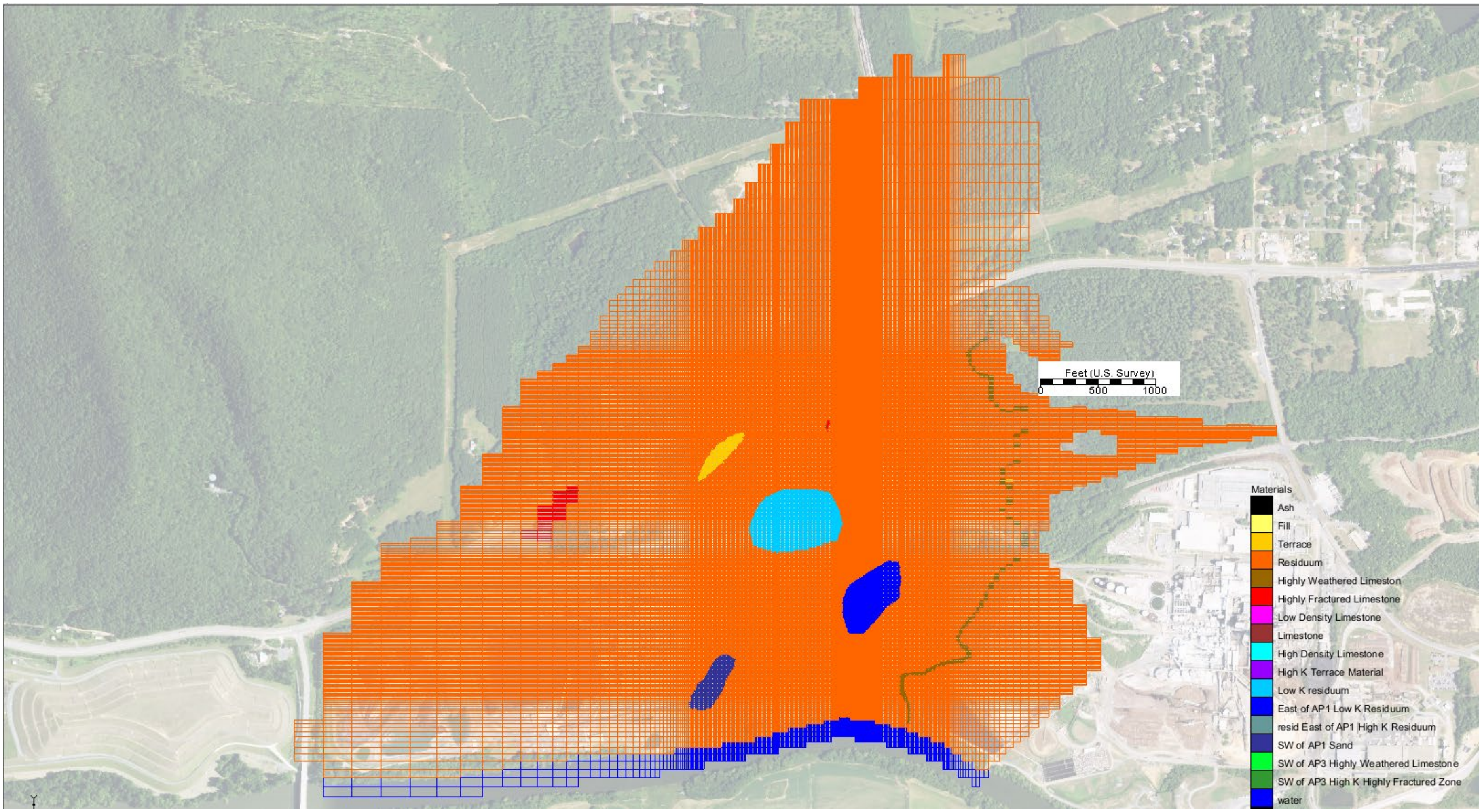

Figure 4: Layer 4 Hydraulic Conductivity Zones

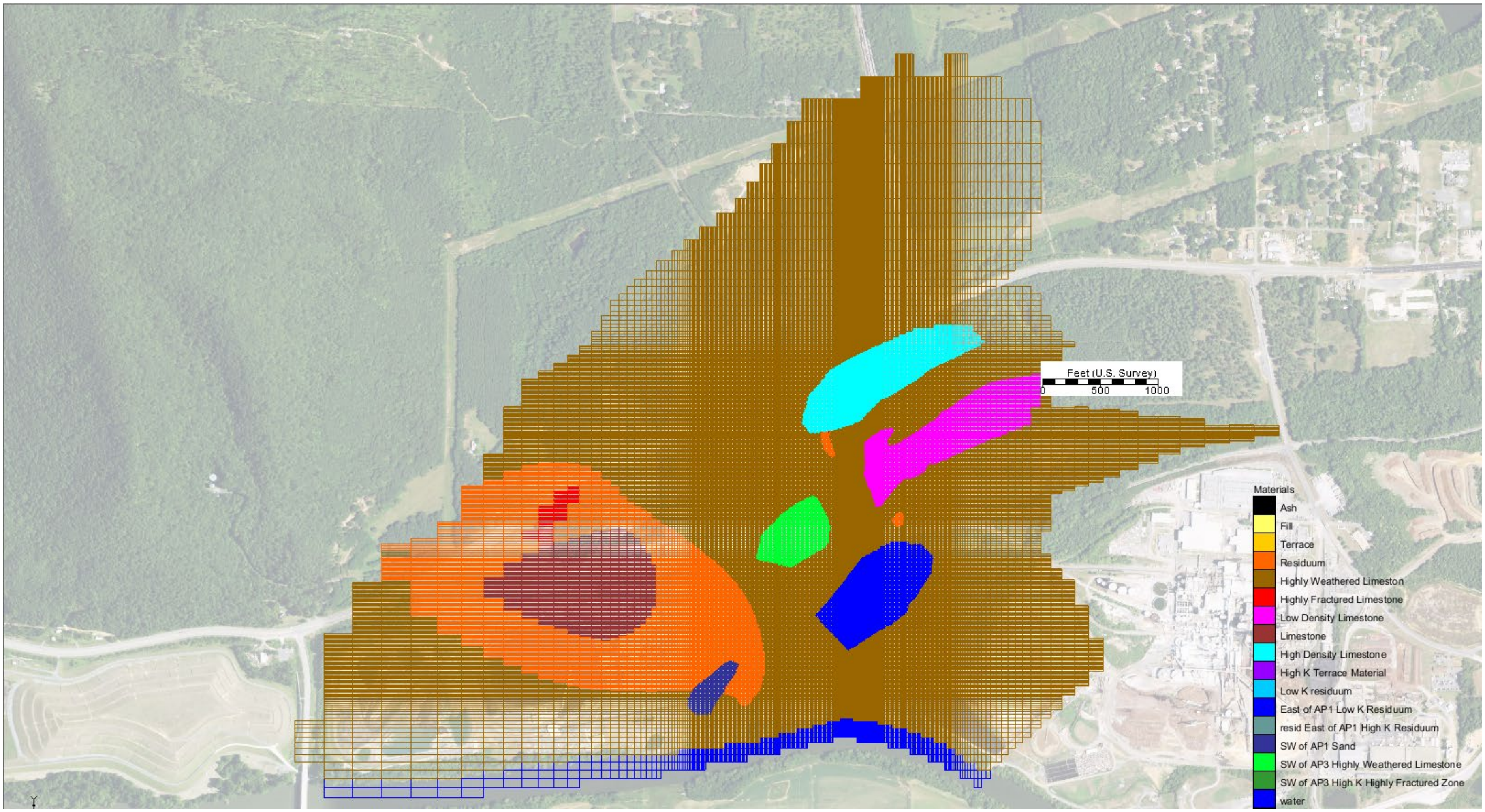

Figure 5: Layer 5 Hydraulic Conductivity Zones

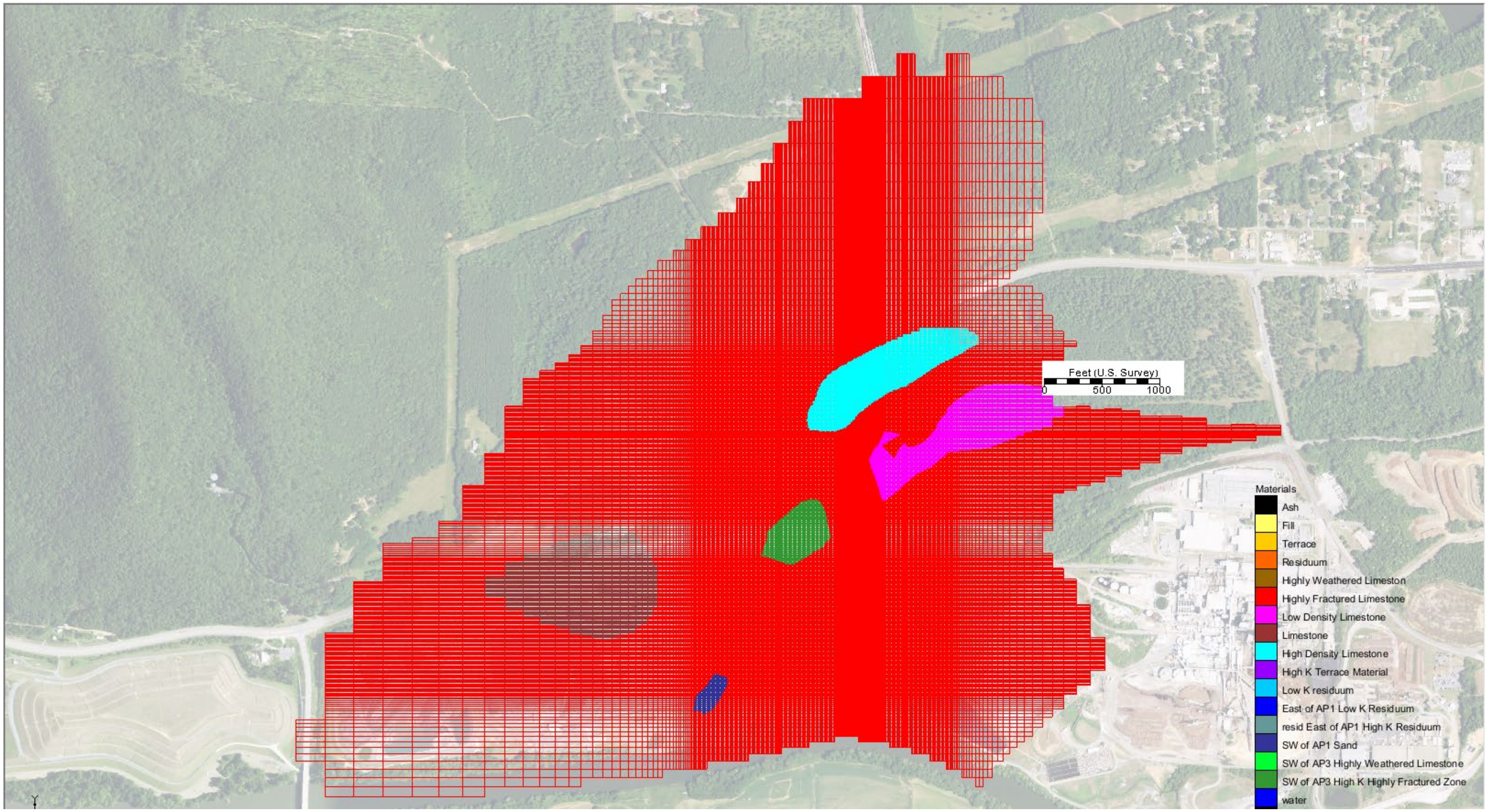

Figure 6: Layer 6 Hydraulic Conductivity Zones

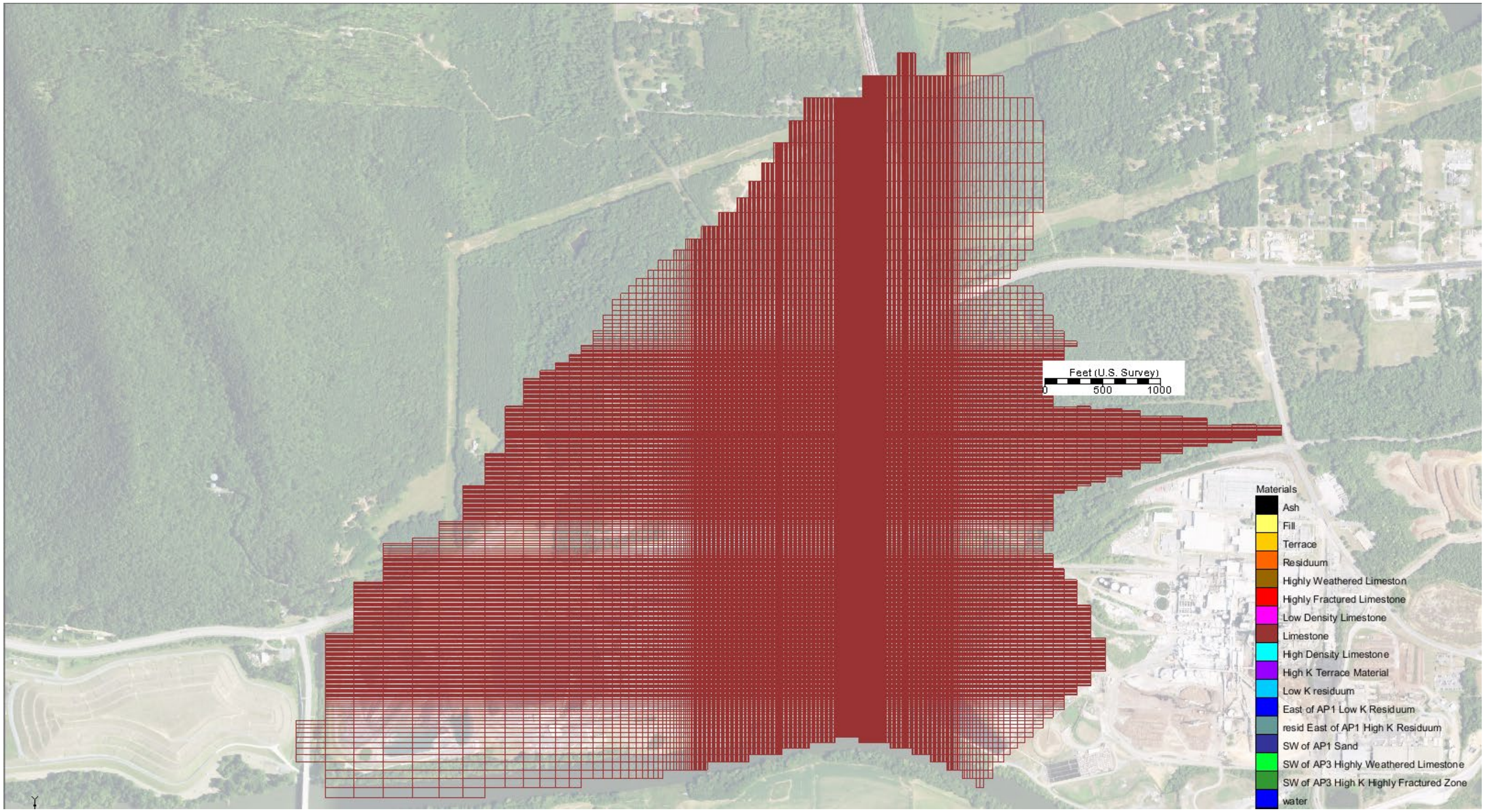

Figure 7: Layer 7 Hydraulic Conductivity Zones

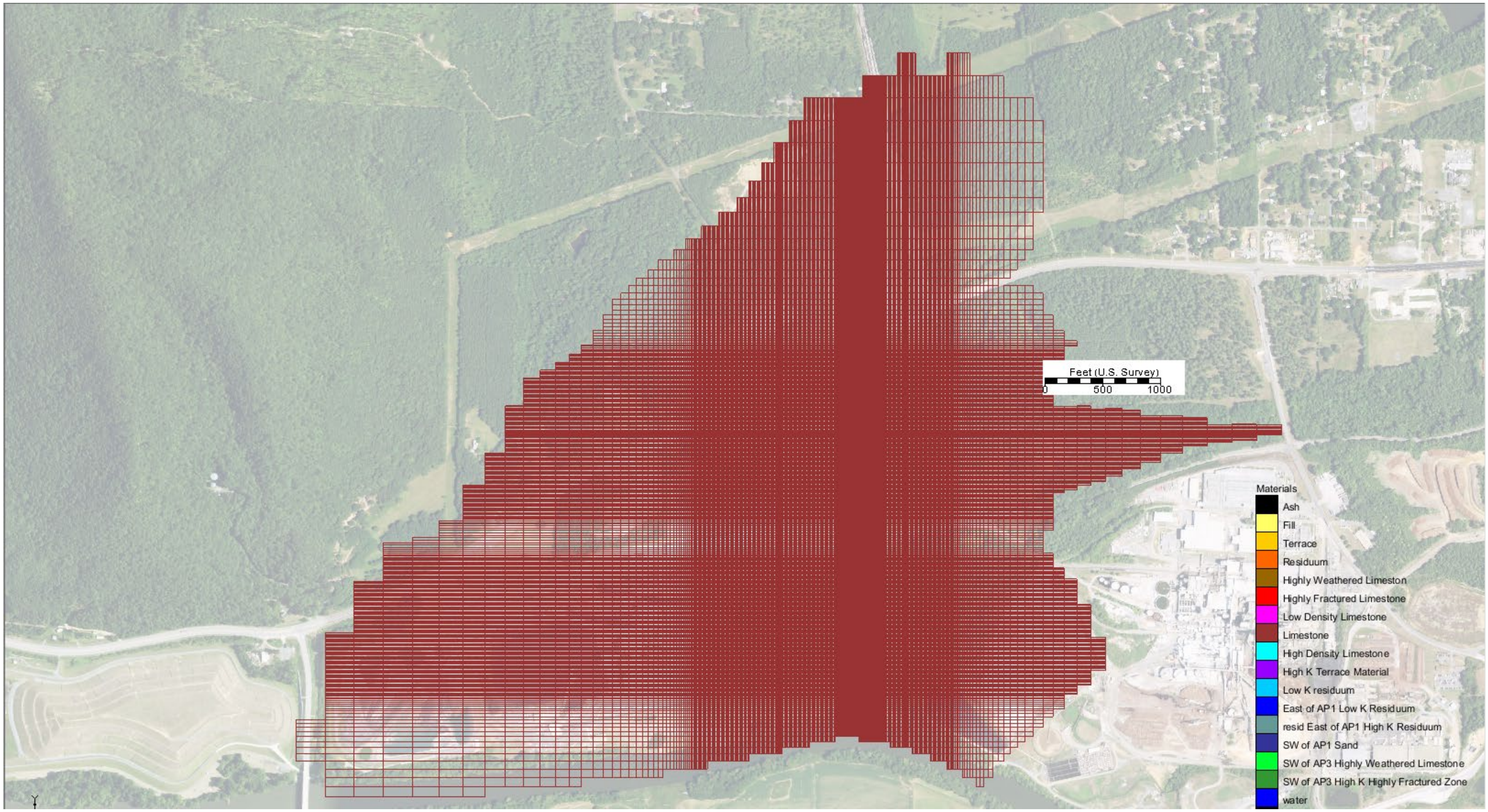

Figure 8: Layer 8 Hydraulic Conductivity Zones

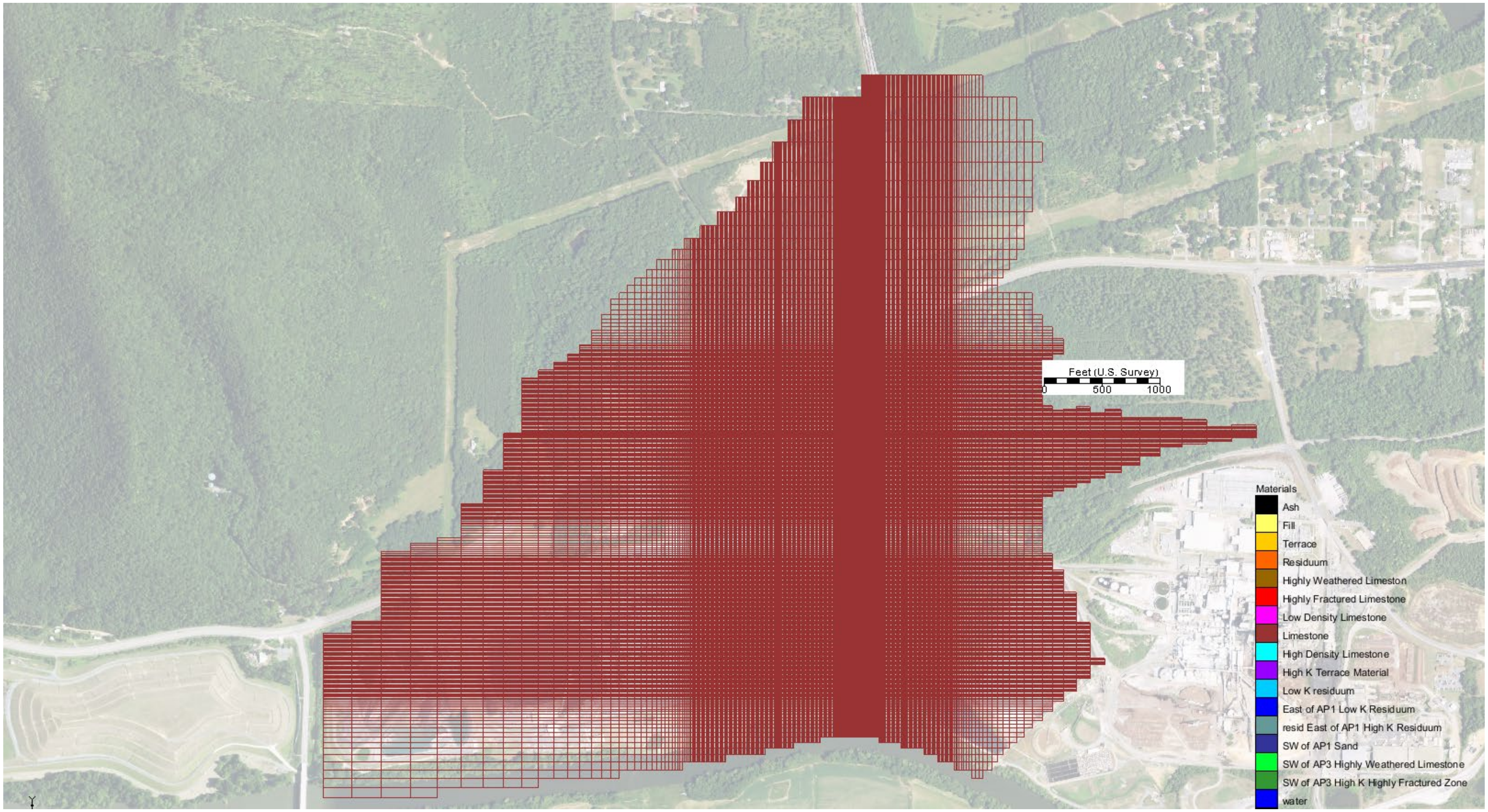

Figure 9: Layer 9 Hydraulic Conductivity Zones

● Boring (Installed 2017)

● Boring (Installed 2015)

● Boring (Installed 1976-1977)

⊕ Well/Piezometer (Installed 2016)

⊕ Monitoring Well (Installed 2015)

⊕ Well/Piezometer (Installed 2014)

● Piezometer (Installed 2010)

⊕ Piezometer (Installed 1976-1977)

⊕ Observation Well (Installed 1976-1977)

—— Ground Surface Elevation (5 ft interval)

— — Georgia Power Property Boundary

N

Notes:
1. Aerial Photograph approximate date - February 2017
Source: Google Earth.
2. Topographic Contour Source: City of Rome and Floyd County, Georgia and a site topographic map provided by Southern Company Services.
3. AP3-1, AP3-2, AP3-3, AP1-MW-2, AP1-MW-3, AP1-MW-4, AP3-MW-25 through AP3-MW-27, and HGWC-121 were abandoned.

0 580 Feet

Plan View of Geologic Sections in EVS (A-A', B-B', C-C', D-D', D'-D'', E-E', and F-F')

Georgia Power Company
Plant Hammond AP3
Rome, Floyd County, Georgia

Geosyntec consultants

Kennesaw, GA | July 2017

Figure
10a

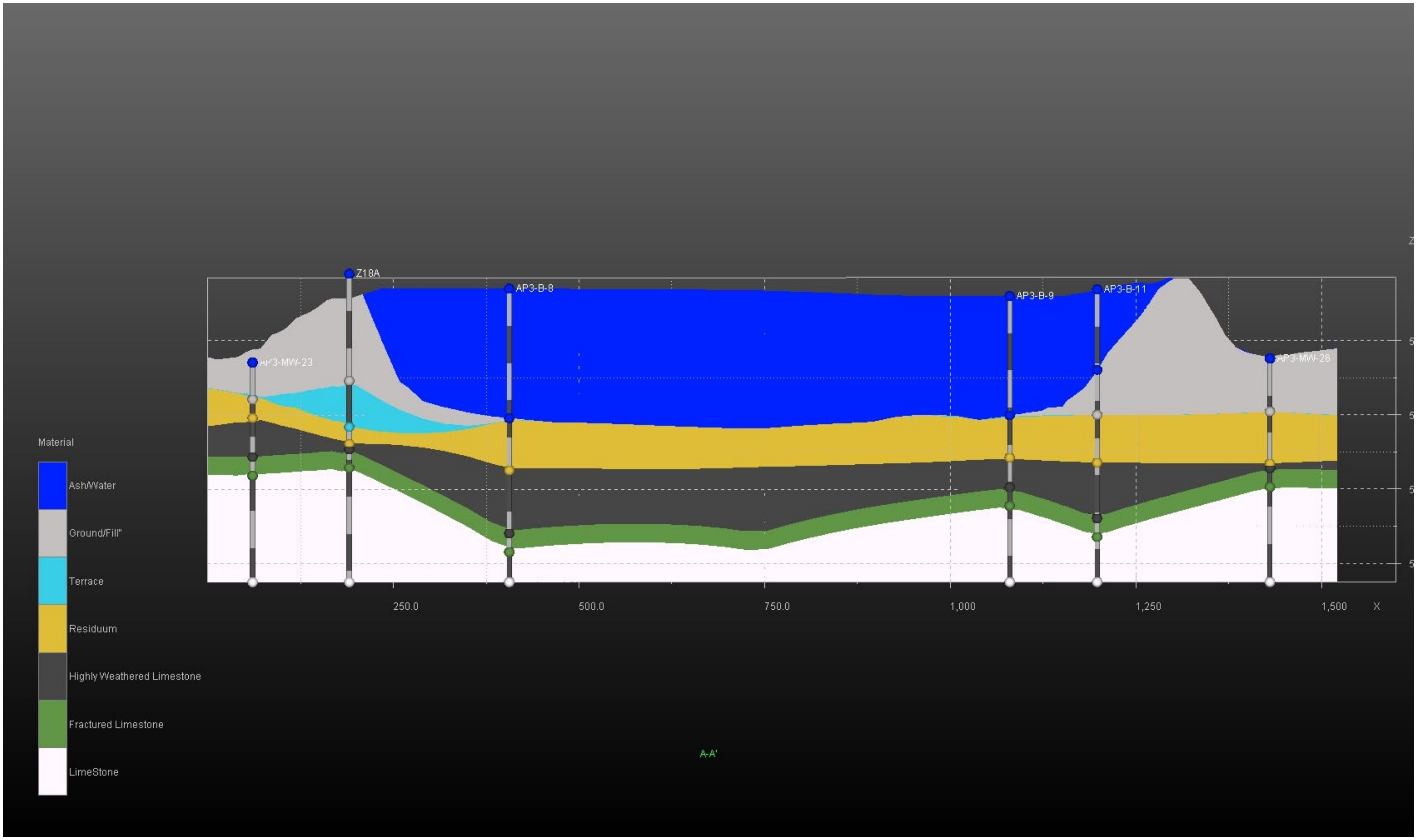

Figure 10b: EVS Cross-Section A-A’

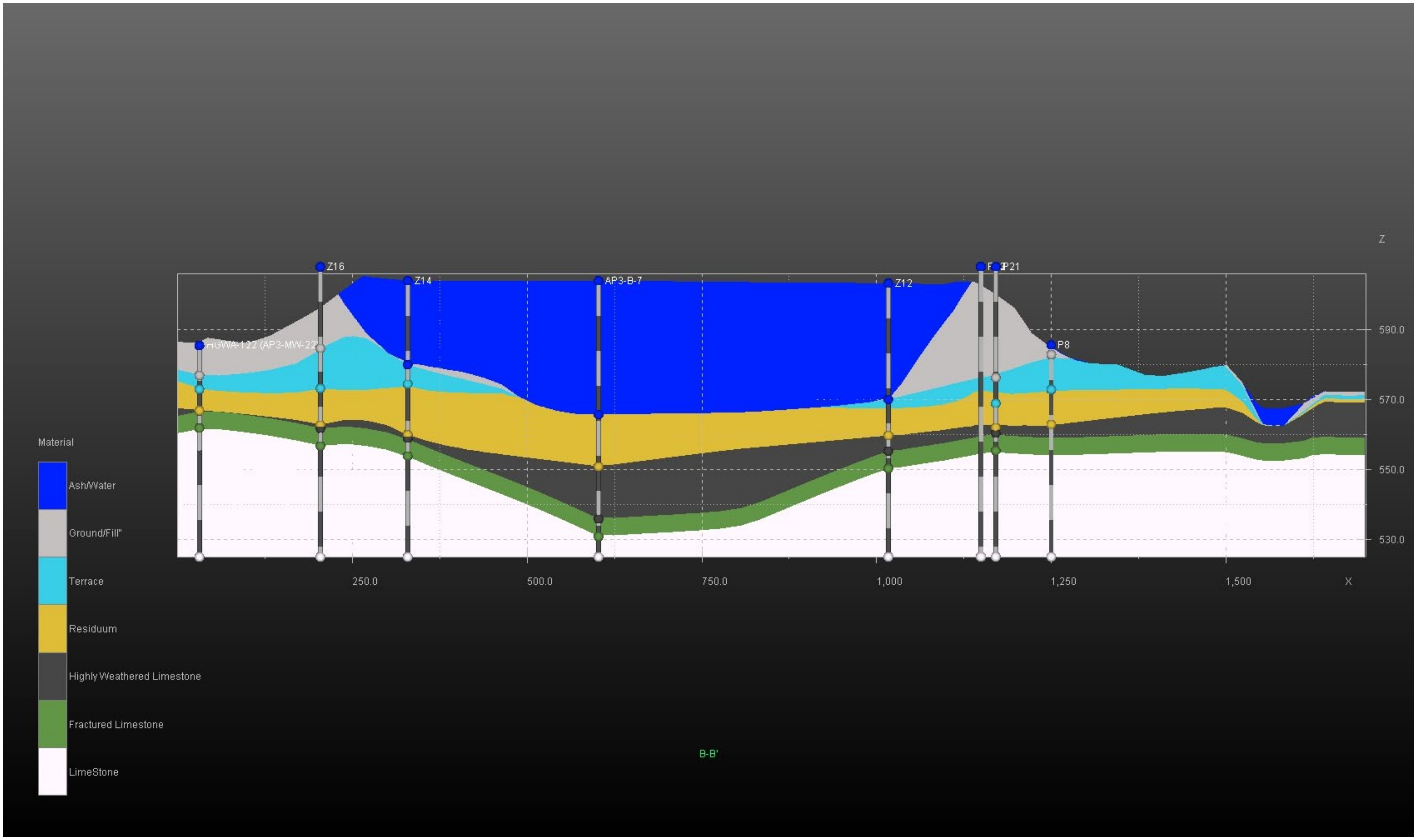

Figure 11: EVS Cross-Section B-B’

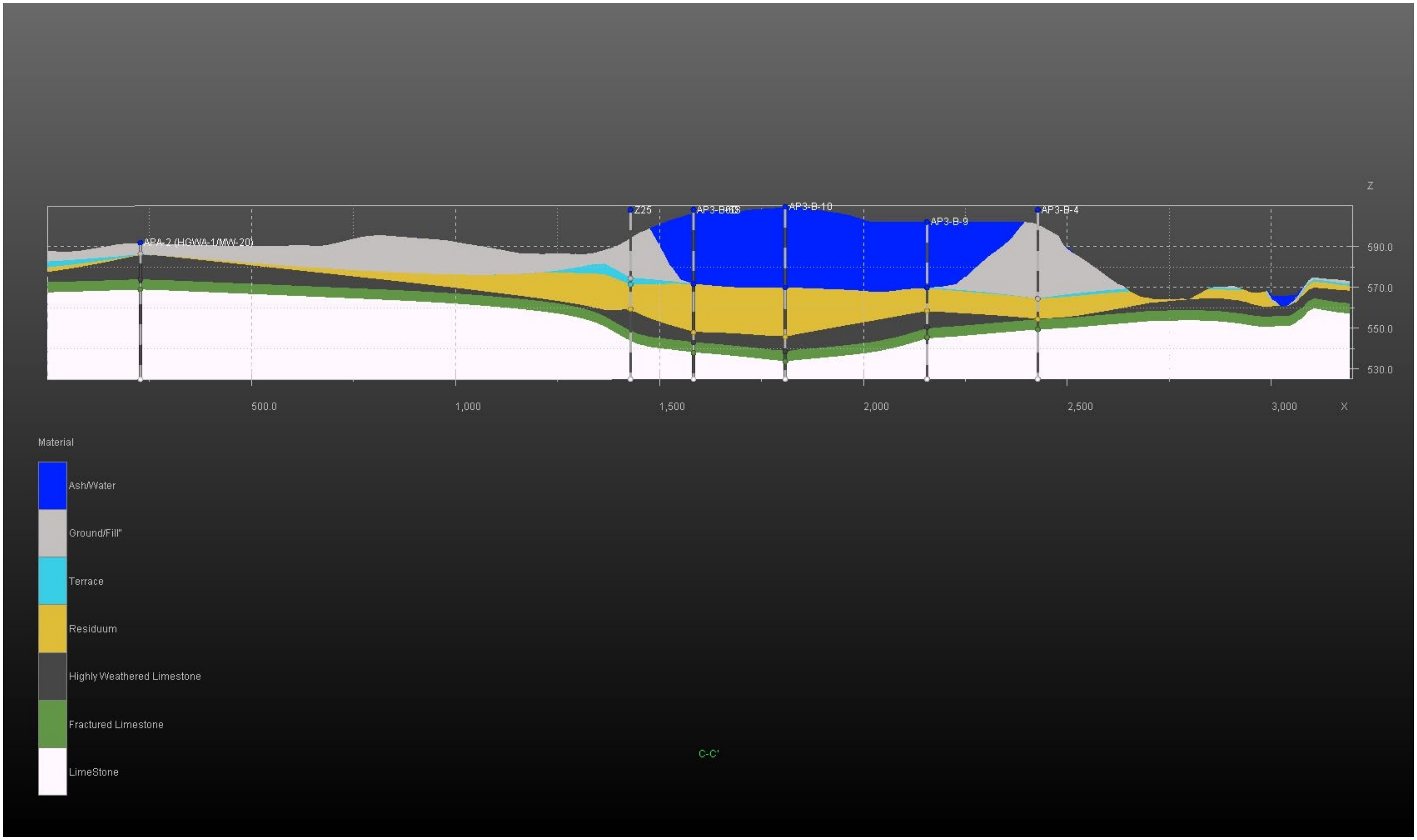

Figure 12: EVS Cross-Section C-C’

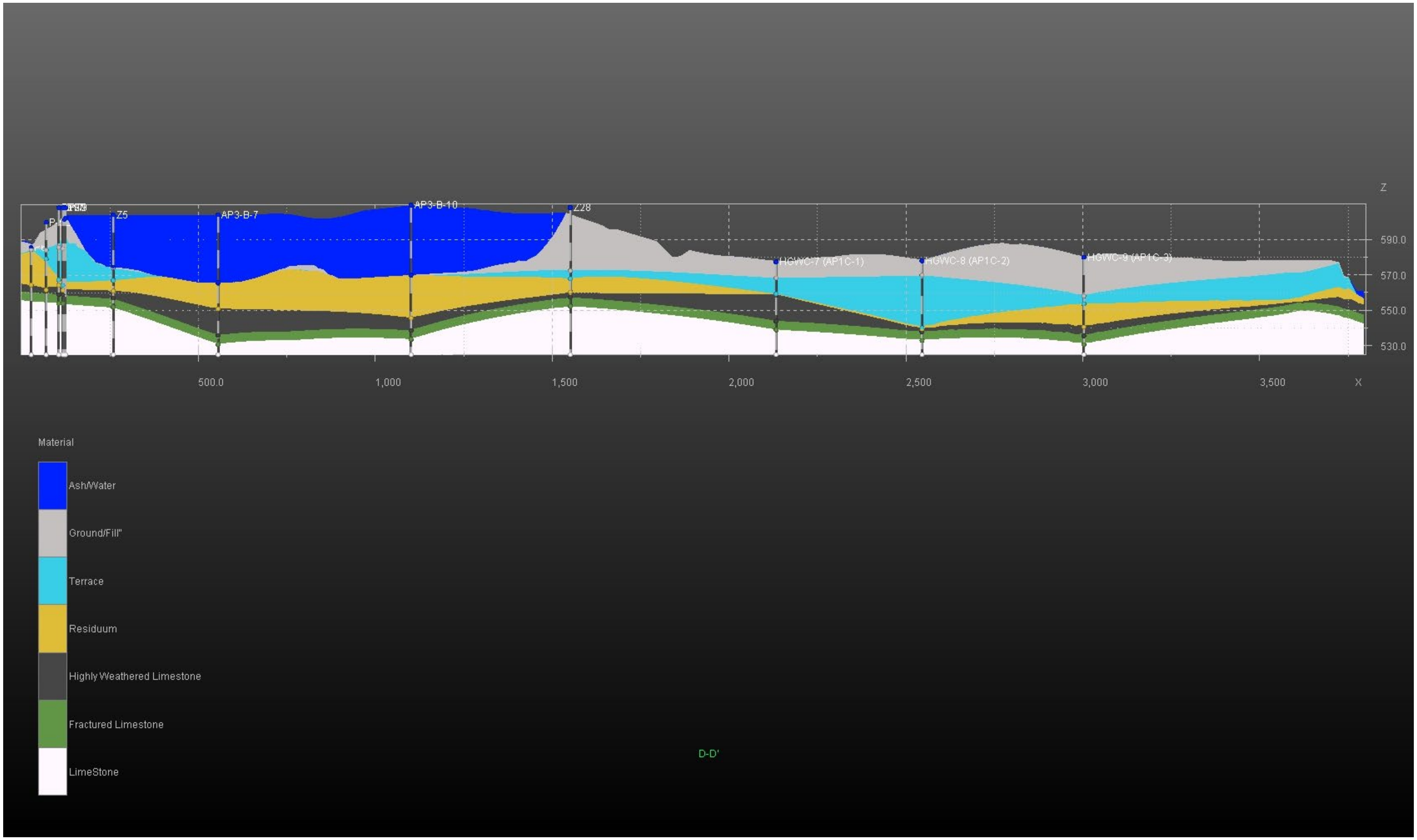

Figure 13: EVS Cross-Section D-D’

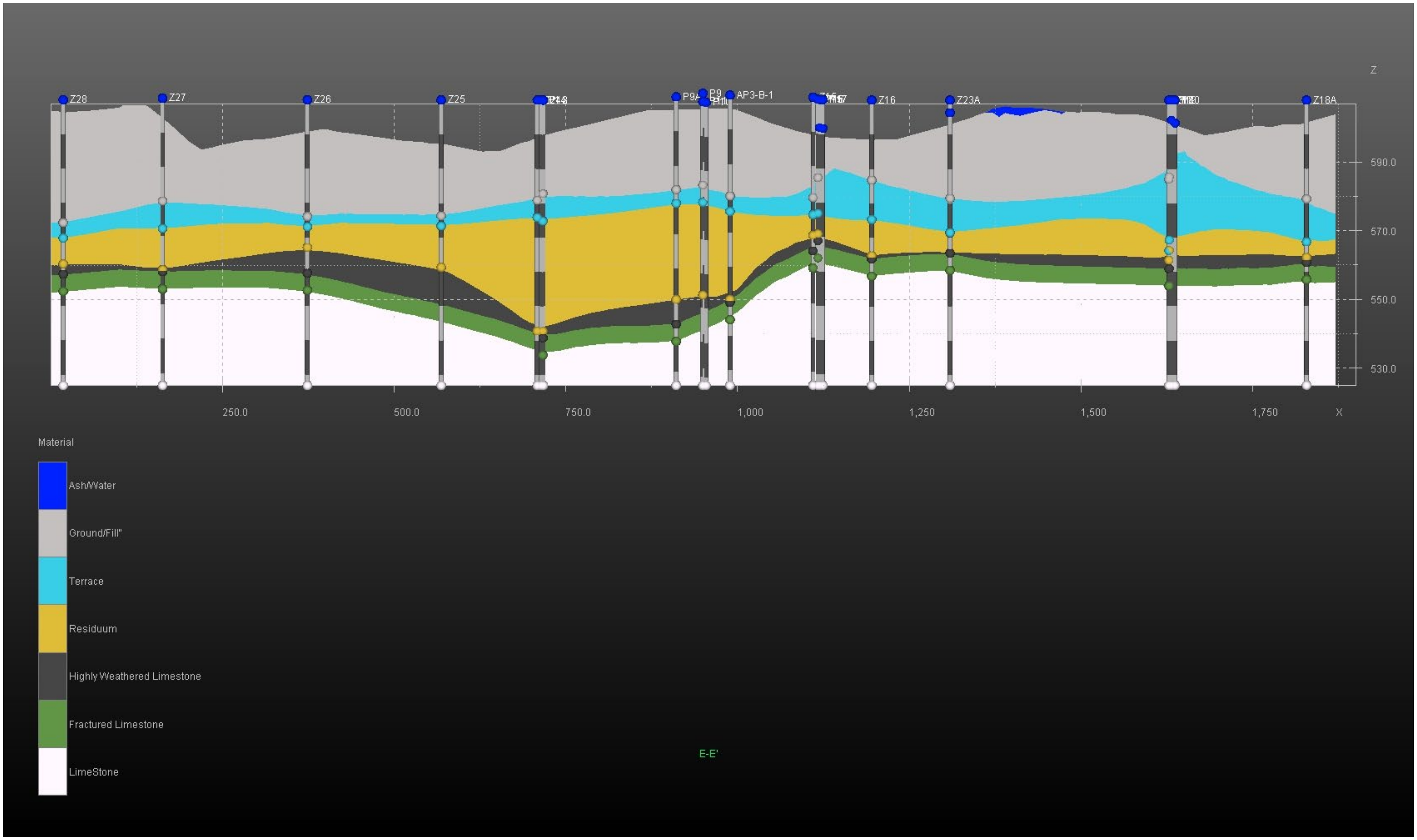

Figure 14: EVS Cross-Section E-E’

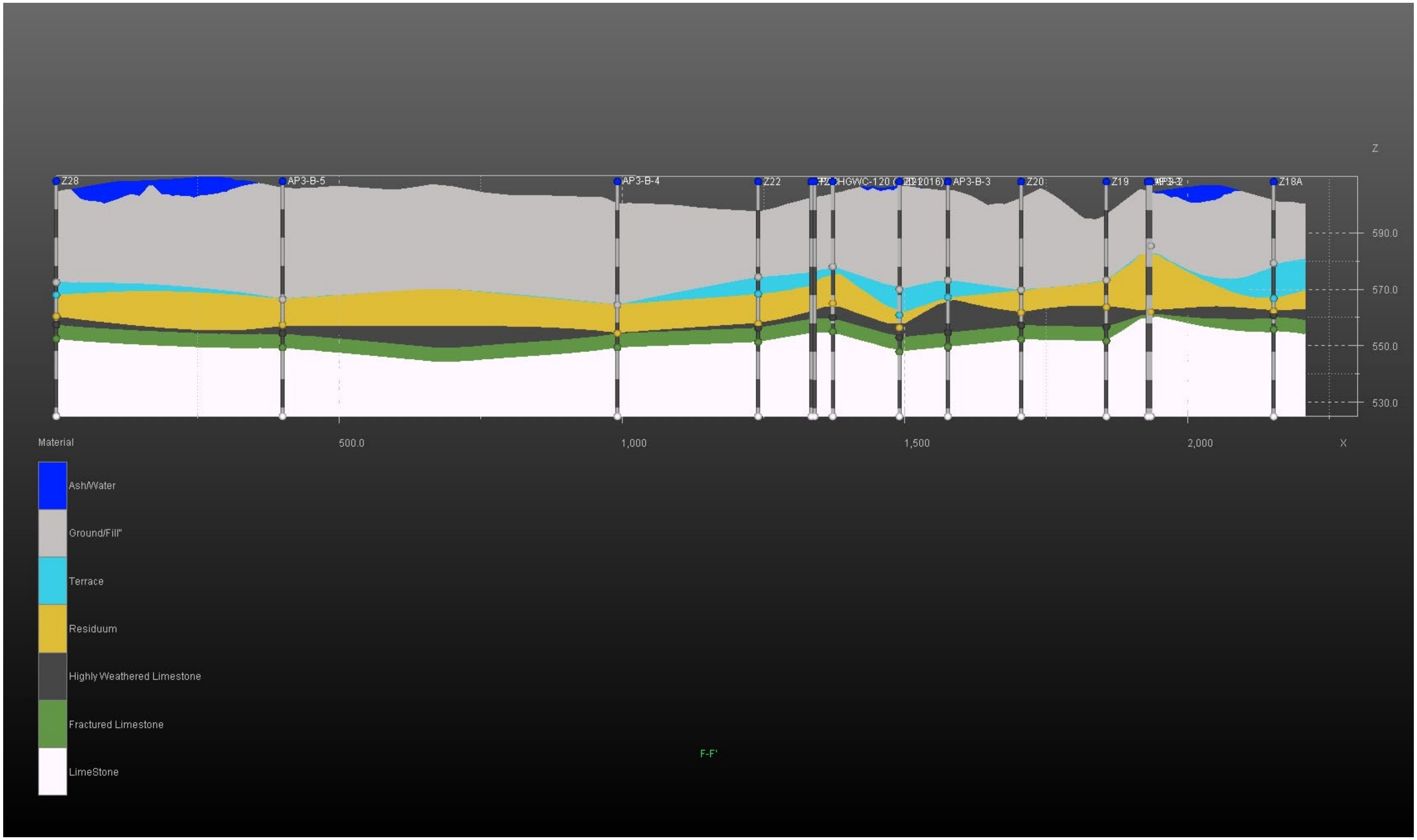

Figure 15: EVS Cross-Section F-F’

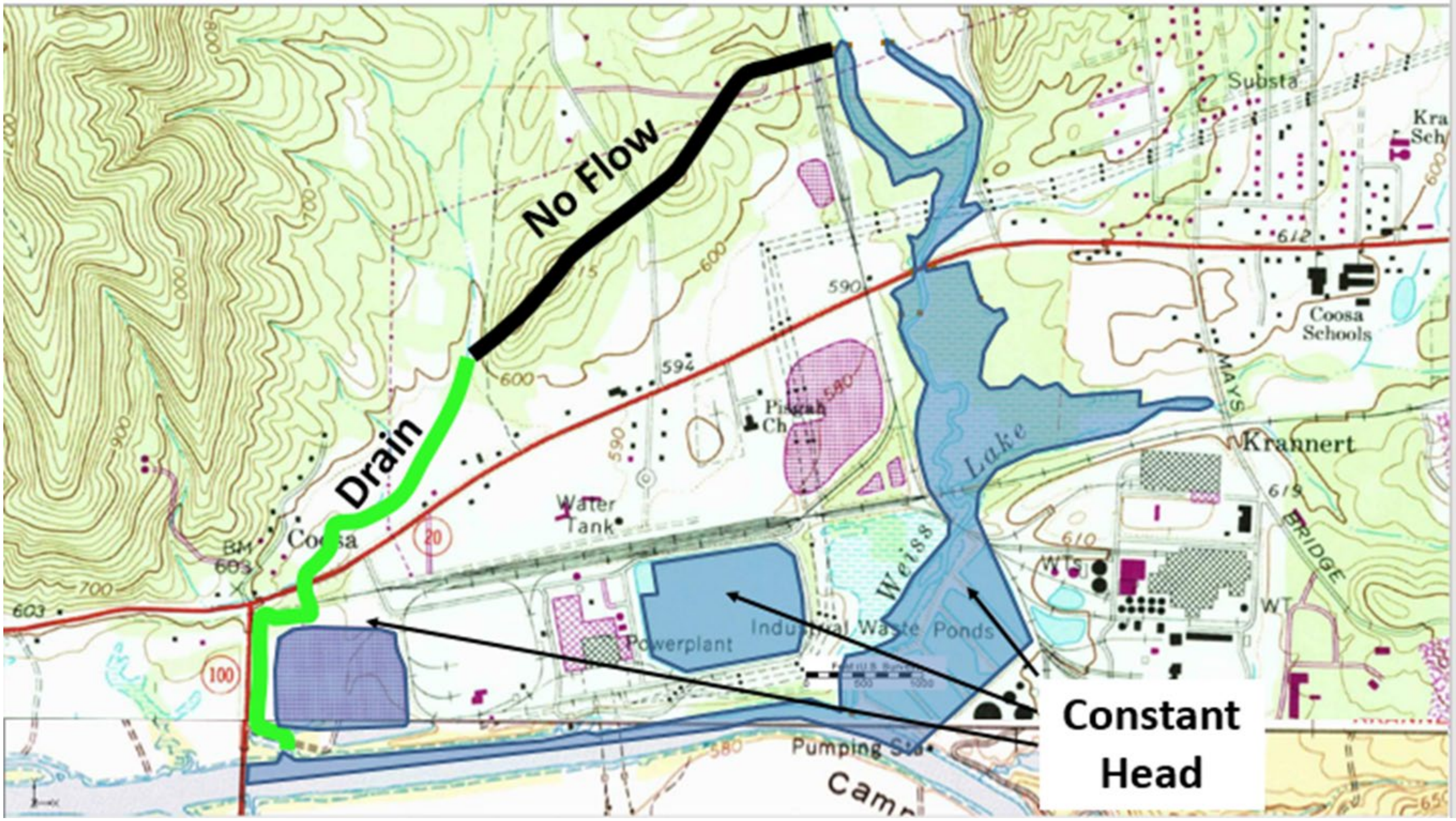

Figure 16: Conceptual Model Boundary Conditions

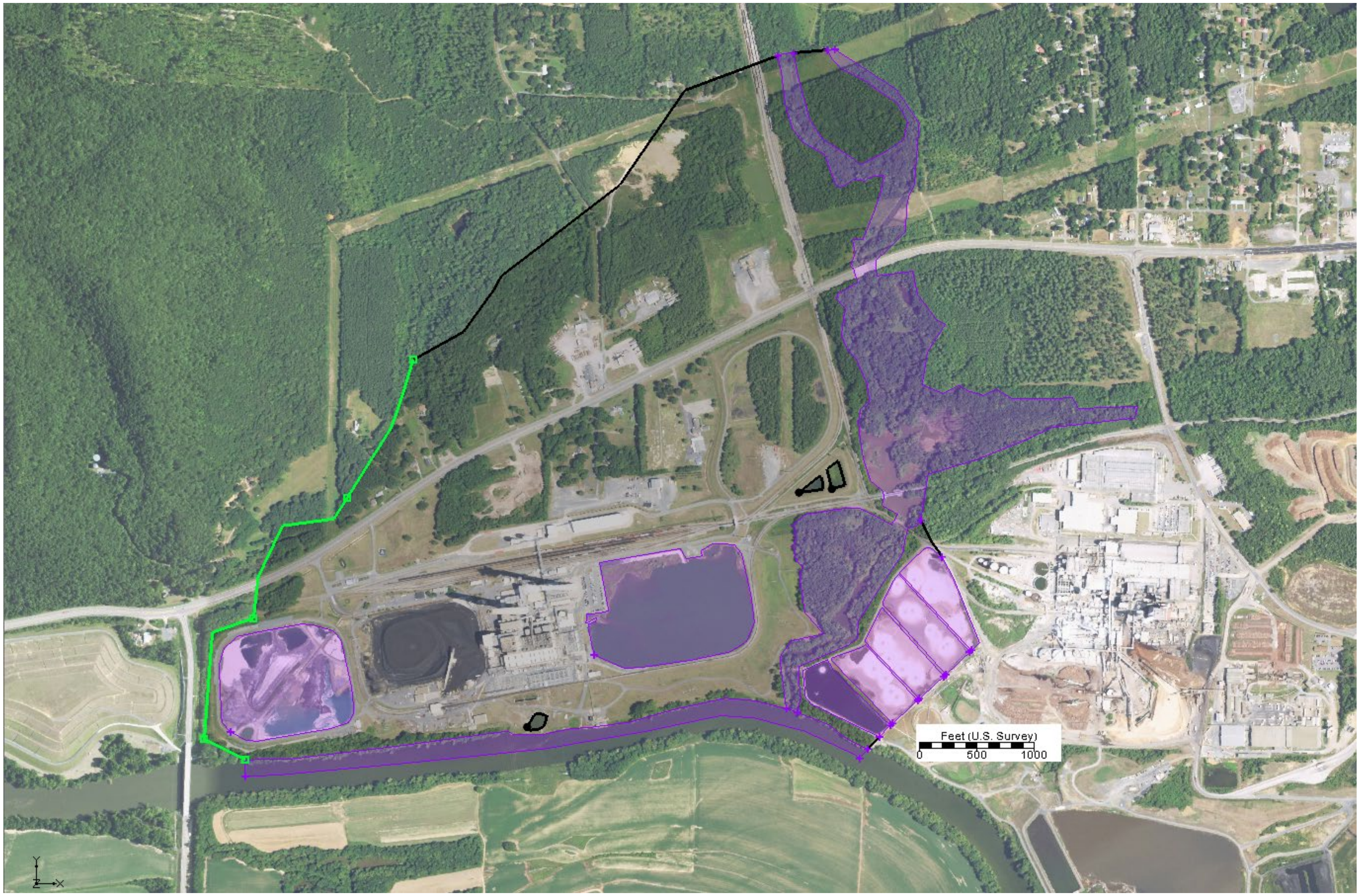

Figure 16a: Model Boundary Conditions

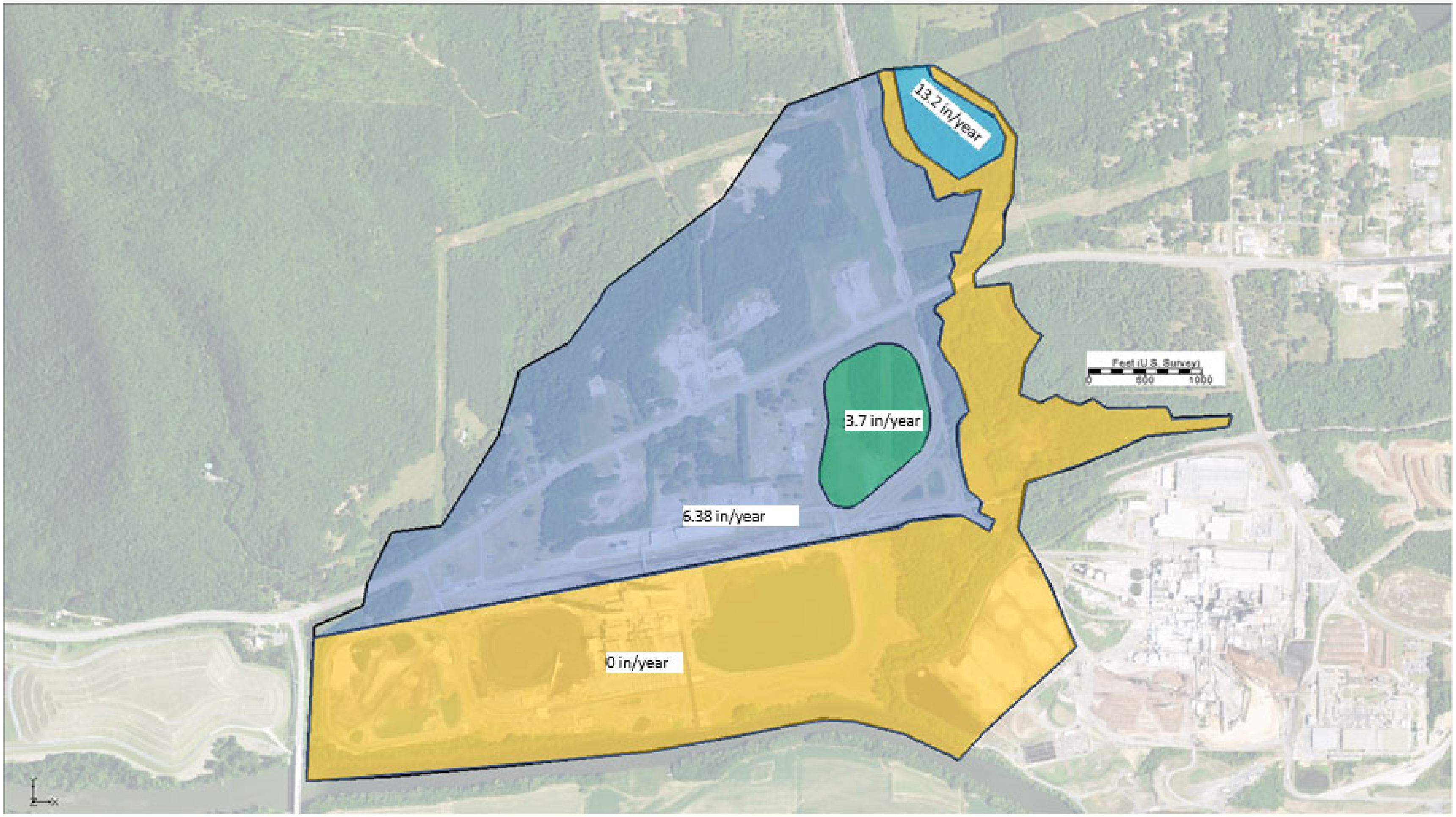

Figure 17: Model Recharge Zones

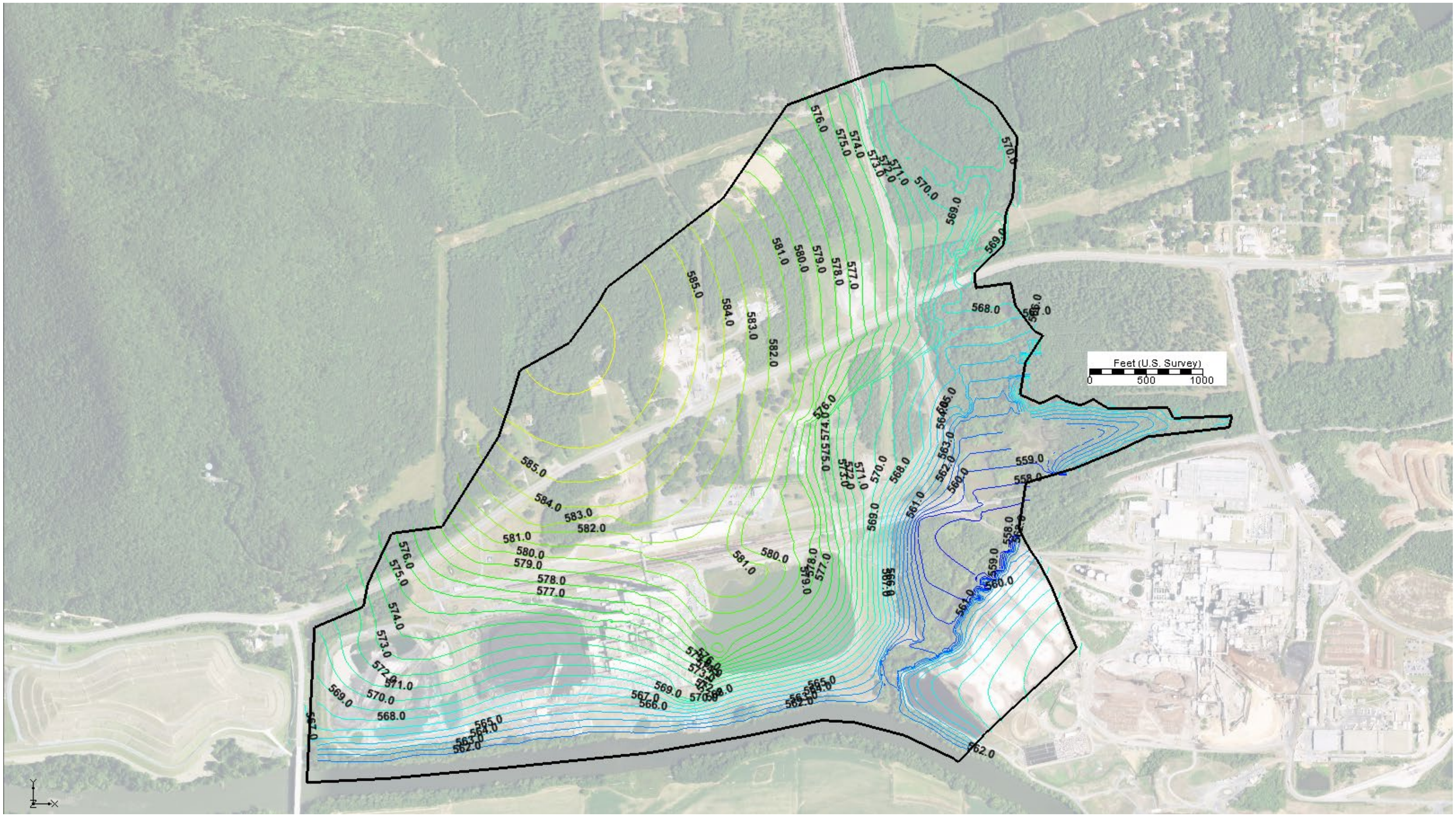

Figure 18: Modeled Groundwater Elevations for the Highly Fractured Limestone

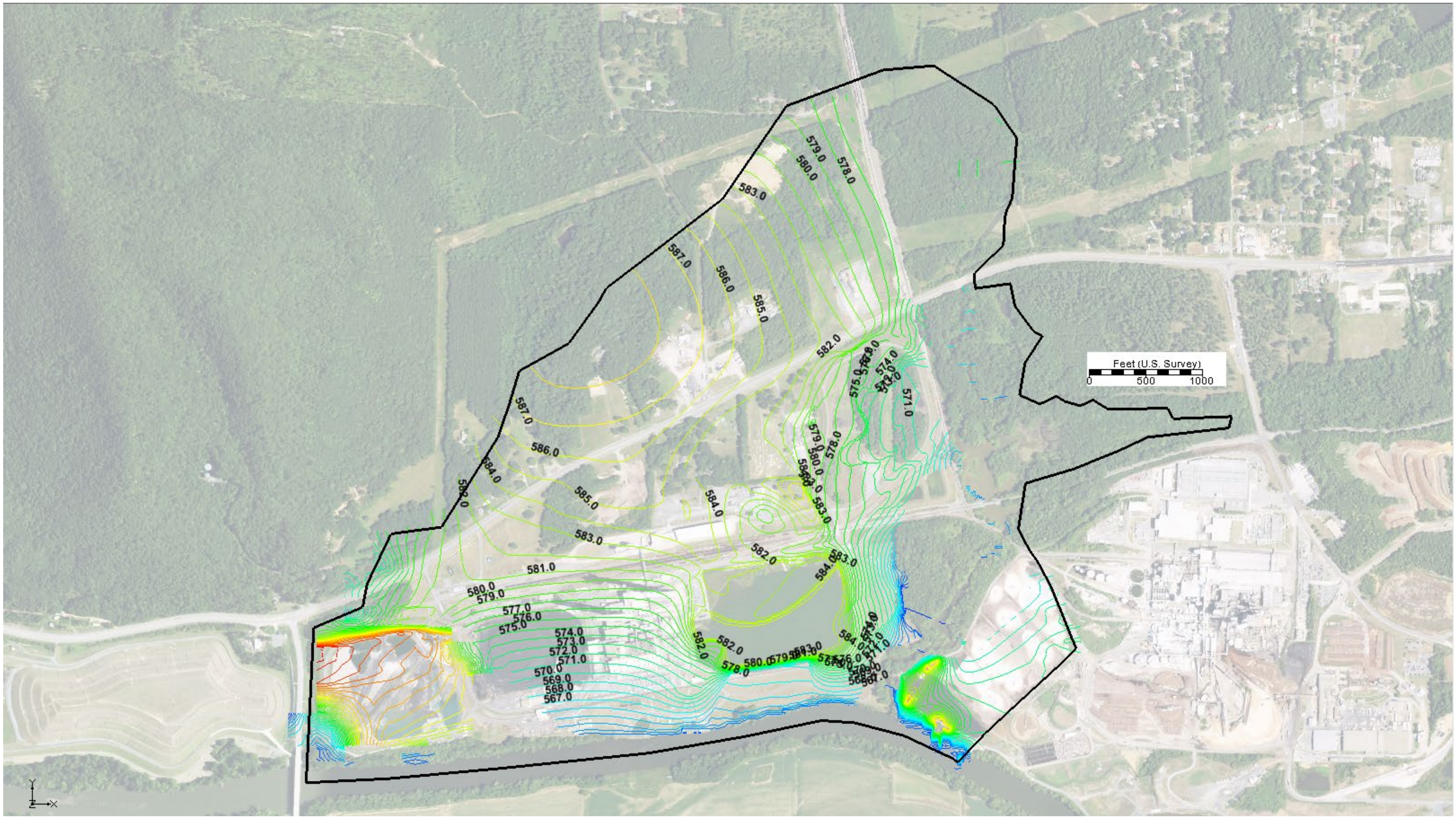

Figure 19: Modeled Groundwater Elevations for the Terrace Alluvium Material

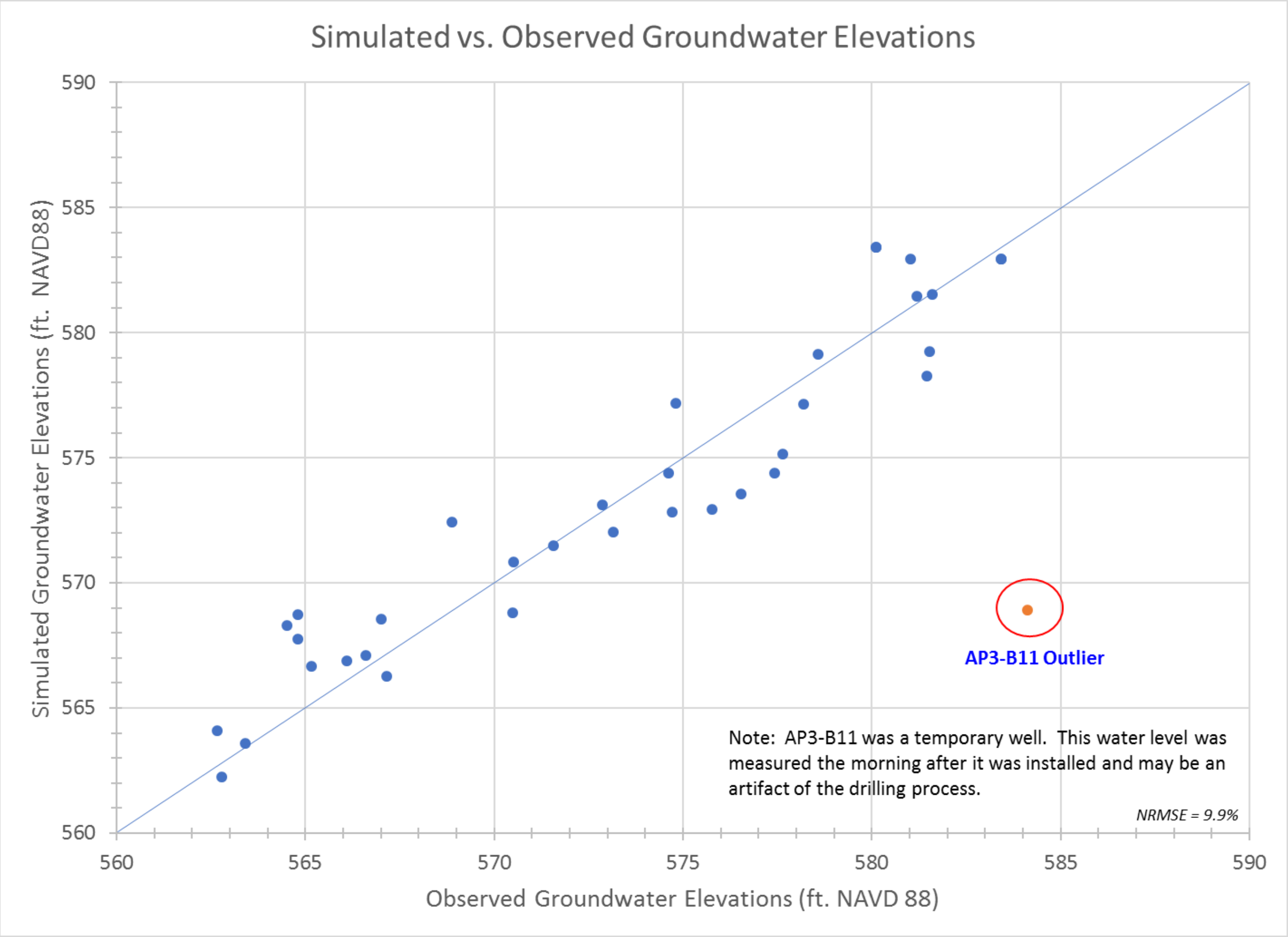

Figure 20: Simulated vs. Observed Groundwater Elevations

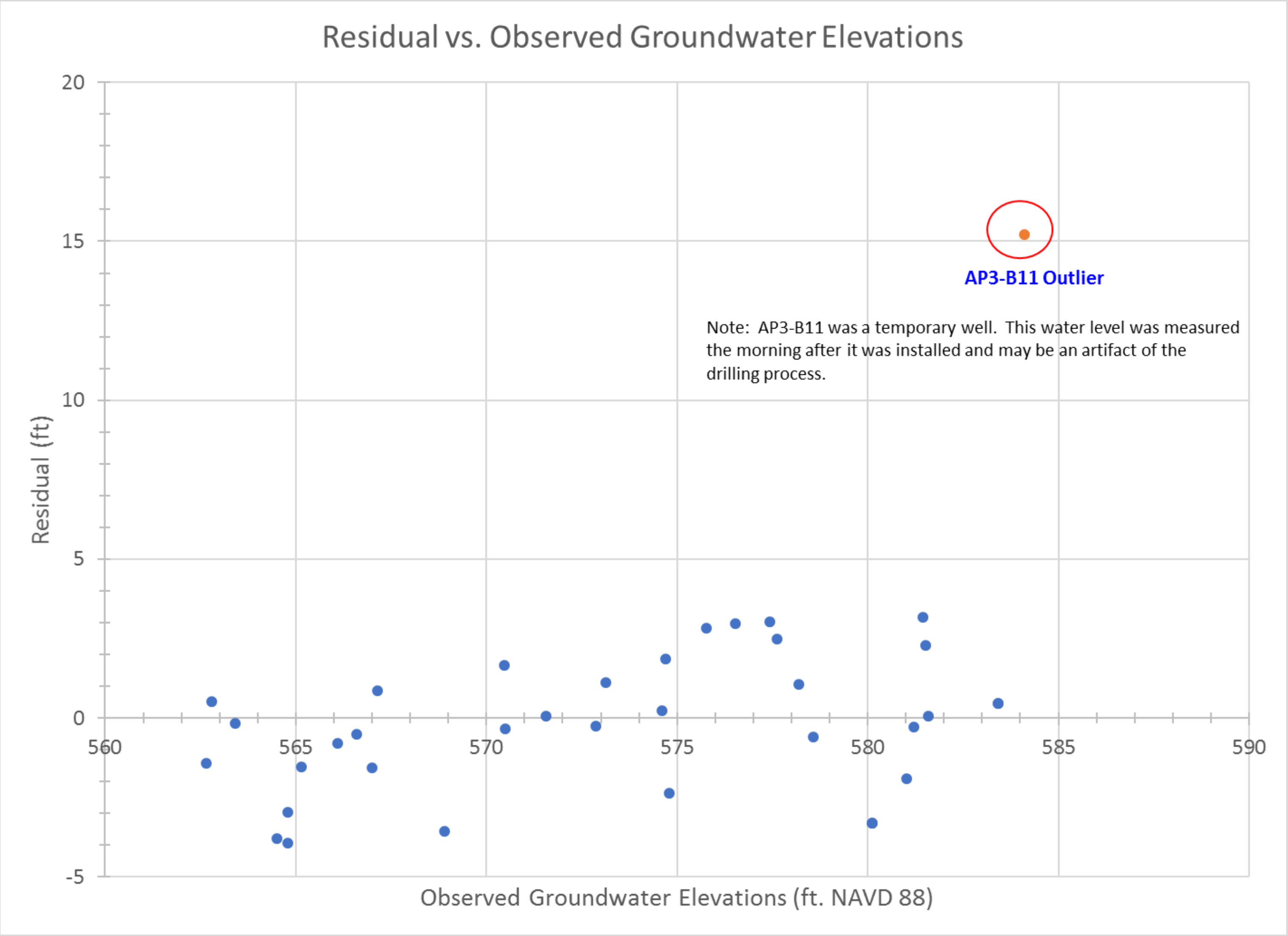

Figure 21: Residual vs. Observed Groundwater Elevations

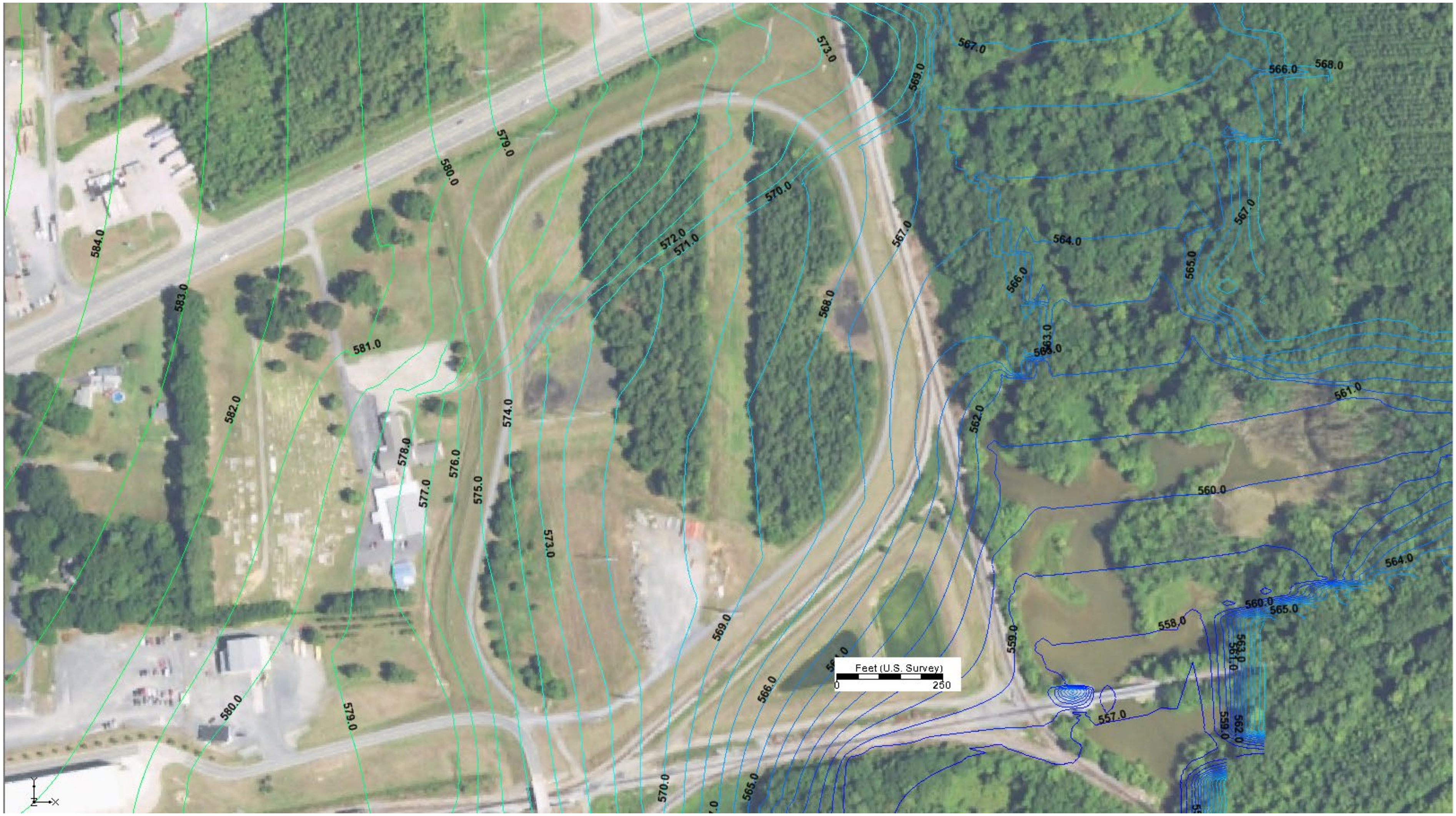

Figure 22: Scenario 1 – Model Predicted Groundwater Elevation Contour

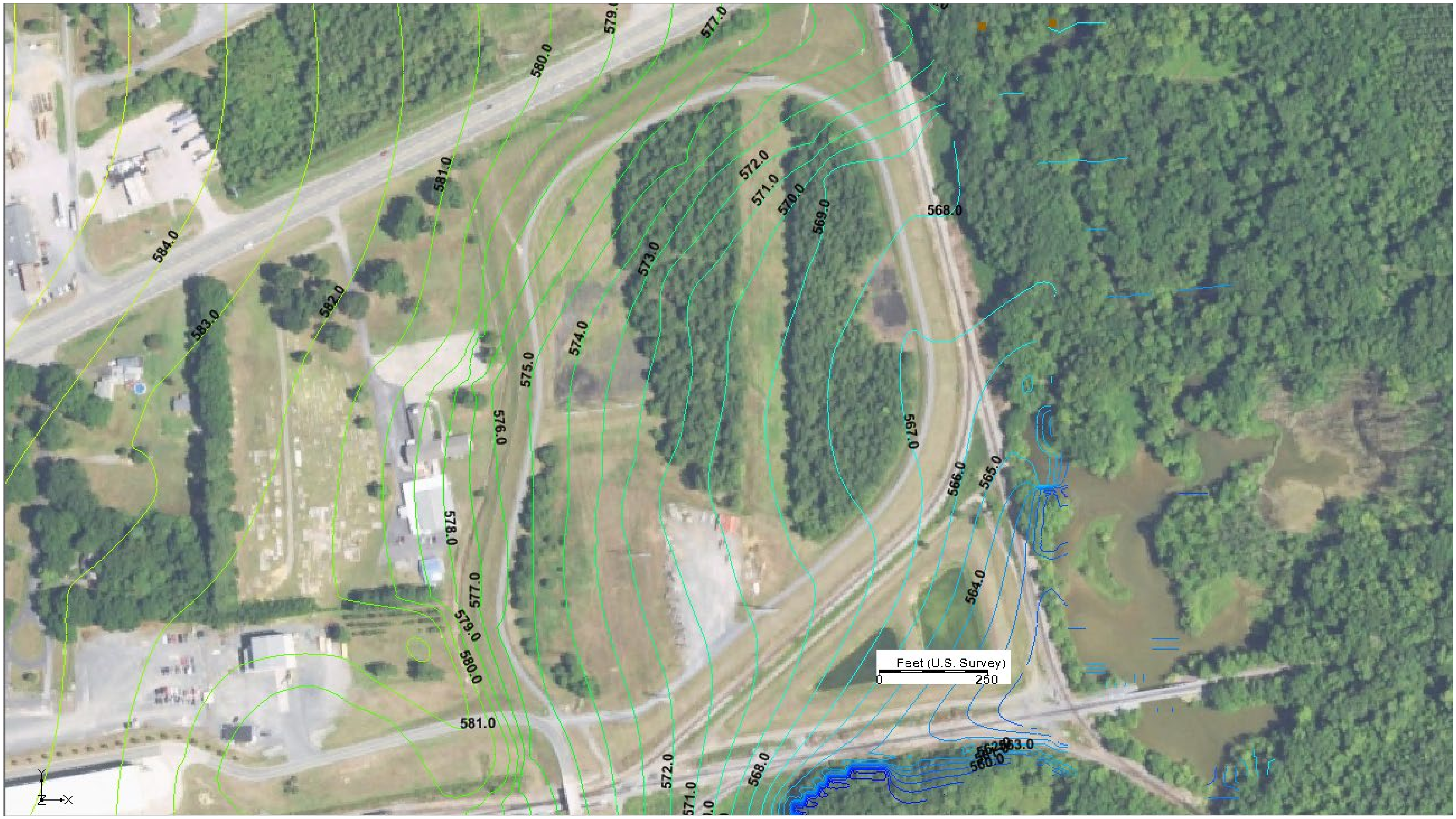

Figure 23: Scenario 2 – Model Predicted Groundwater Elevation Contour

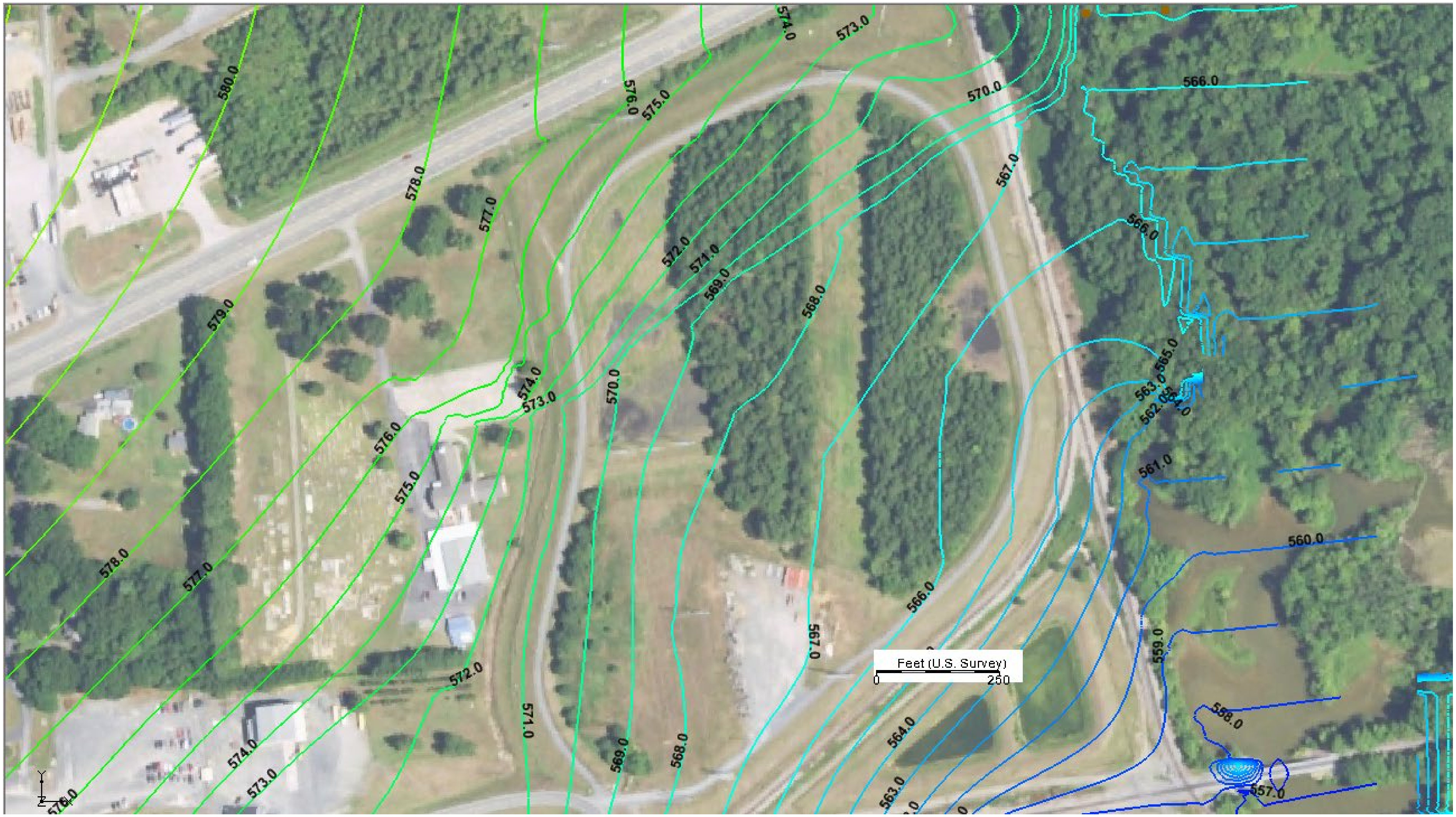

Figure 24: Scenario 3 – Model Predicted Groundwater Elevation Contour

ATTACHMENT 4

Groundwater Model Calculation Package Addendum

Prepared for

Southern Company
241 Ralph McGill Blvd NE
Atlanta, Georgia 30308

GROUNDWATER MODEL CALCULATION PACKAGE ADDENDUM PLANT HAMMOND ASH POND-3 (AP-3)

GEORGIA POWER COMPANY
Floyd County, Georgia

Submitted by

Geosyntec consultants

engineers | scientists | innovators

1255 Roberts Boulevard, Suite 200
Kennesaw, Georgia 30144

Project Number: GR6242
November 2020

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LIST OF ACRONYMS

AEM	Advanced Engineering Method
AP	Ash Pond
CCR	Coal Combustion Residuals
CSM	Conceptual Site Model
ft	feet
Geosyntec	Geosyntec Consultants
Georgia Power	Georgia Power Company
gpd	gallons per day
SCS	Southern Company Services

1.0 INTRODUCTION

This *Groundwater Model Calculation Package Addendum* (Report) was prepared to document the results of an advanced engineering method (AEM) model scenario conducted for the groundwater flow conditions in the vicinity of Ash Pond 3 (AP-3 or Site) at the Georgia Power Company (Georgia Power) owned and operated Plant Hammond (the Plant) near Rome, GA. The AEM includes the use of *TreeWells*®. The hydrogeologic conceptual site model (CSM) and groundwater model construction and calibration were documented in the *Groundwater Model Calculation Package*, dated November 2019, and included in the *Hydrogeologic Assessment Report Revision 1*, prepared by Geosyntec Consultants (Geosyntec) and submitted to Georgia Environmental Protection Division in November 2019. This Report has been prepared by Geosyntec on behalf of Southern Company Services (SCS).

1.1 Model Objectives

The objective of the numerical groundwater flow modeling was to simulate the future conditions of groundwater near AP-3 relative to pre-closure conditions under the following scenarios:

- AP-3 closed and closure by removal of AP-1 (modeled by removing the constant head boundary conditions representing the historical pool from AP-1),
- the above conditions in conjunction with the AEM of an engineered *TreeWell* system.

The scenarios were evaluated with respect to (i) height of the potentiometric surface above the bottom of the AP-3 unit, (ii) volume of CCR below the potentiometric surface, (iii) percent reduction of CCR below the potentiometric surface relative to pre-closure conditions, (iv) the aerial extent of CCR below the potentiometric surface, (v) percent reduction in AP-3 groundwater flux, and (vi) simulated particle travel time to the permit boundary.

2.0 PREDICTIVE SIMULATIONS AND RESULTS

The calibrated groundwater model was used to predict groundwater conditions for three scenarios at steady state. These scenarios were as follows:

- Scenario 0: Pre-closure conditions with partial cover at AP-3 and AP-1 at historical pool elevation (585.09 ft, relative to North American Vertical Datum 1988, to represent the pool water level measured February 9, 2017);
- Scenario 1: Surface water improvement where AP-3 is capped by reducing recharge to zero over capped area and removing the constant head boundary conditions representing historical pool at AP-1[1]; and
- Scenario 2: 107 *TreeWells* screened in the highly fractured rock/fractured limestone and installed on the downgradient side of AP-3, each "pumping" at 40 gallons per day (gpd) per tree[2]. Modeled with the same boundary conditions as Scenario 1.

The results of the calibrated model for pre-closure conditions (Scenario 0), the post-closure conditions at AP-3 with removal of the historically present pool of AP-1 (Scenario 1), and the AEM *TreeWell* option (Scenario 2) are summarized in **Table 1**.[3] The table presents data to evaluate, per modeled scenario, (i) the maximum thickness and volume of CCR below the maximum predicted potentiometric surface; (ii) the percent reduction the calculated volume of CCR relative to pre-closure conditions; (iii) the amount of pumping modeled (specific to the *TreeWell scenario);* and (iv) the amount of time, as

---

[1] The modeled hydraulic conductivities for residuum and fly ash are closely similar (i.e., 2.2×10^{-4} centimeters per second (cm/sec) and 5.0×10^{-4}cm/sec, respectively). Therefore, the model layer cells beneath AP-1 were unchanged between Scenarios 0 and 1, as reclassifying or removing the cells would not constitute a fundamental change in the modeled results. The removal of the constant head boundary (representing removal of the free liquids from AP-1) resulted in the notable changes in hydraulic conditions at AP-3.

[2] This is based on commonly accepted estimates of evapotranspiration of approximately one million gallons per year per acre of full canopy forested land (McCutcheon and Schnoor, 2003), and a planting density of approximately 60 trees per acre. This results in an estimate of 45 gpd per tree, therefore a conservative estimate of 40 gpd per tree was used for the groundwater model.

[3] The modeled effects shown in this table are focused on conditions at or within the AP-3 permit boundary. Due to the location of the *TreeWell* field downgradient of AP-3 and the current permit boundary, additional beneficial effects of the *TreeWell* system, such as reduction in the potentiometric surface and in groundwater flux, may not be evident in these model results.

predicted by the groundwater model, it would take a conservative tracer (water particle) to travel from the location of the greatest thickness of CCR below the potentiometric surface to the AP-3 permit boundary[4]. Figure 1 provides a comparison of modeled potentiometric surfaces between Scenarios 0 and 2. Figures showing the particle tracking discussed above are shown on **Figures 2** and **3.**

Table 1 also presents a conservative measurement of reduction in AP-3 groundwater flux. The baseline value was the modeled flux of groundwater per day that flowed out of the bottom of the model cells representing the CCR below the potentiometric surface in Layer 1. The modeled groundwater flux from the bottom of model cells representing CCR below the potentiometric surface for each additional scenario was also extracted from the model and compared to the baseline flux to obtain the reported reduction in flux[5].

---

[4] Particle tracking requires the use of MODPATH which in turn requires the user to input values of porosity. The values used for AP-3 in the area under consideration are as follows: Ash 0.2 (EPRI, 2012), Residuum 0.1 (Domenico and Schwartz, 1990), Highly Fractured Limestone 0.3 (Baedke and Krothe, 2001).

[5] It should be noted that most of the groundwater exited the ash through the bottom of the cells and only a de minimis amount exited laterally.

3.0 REFERENCES

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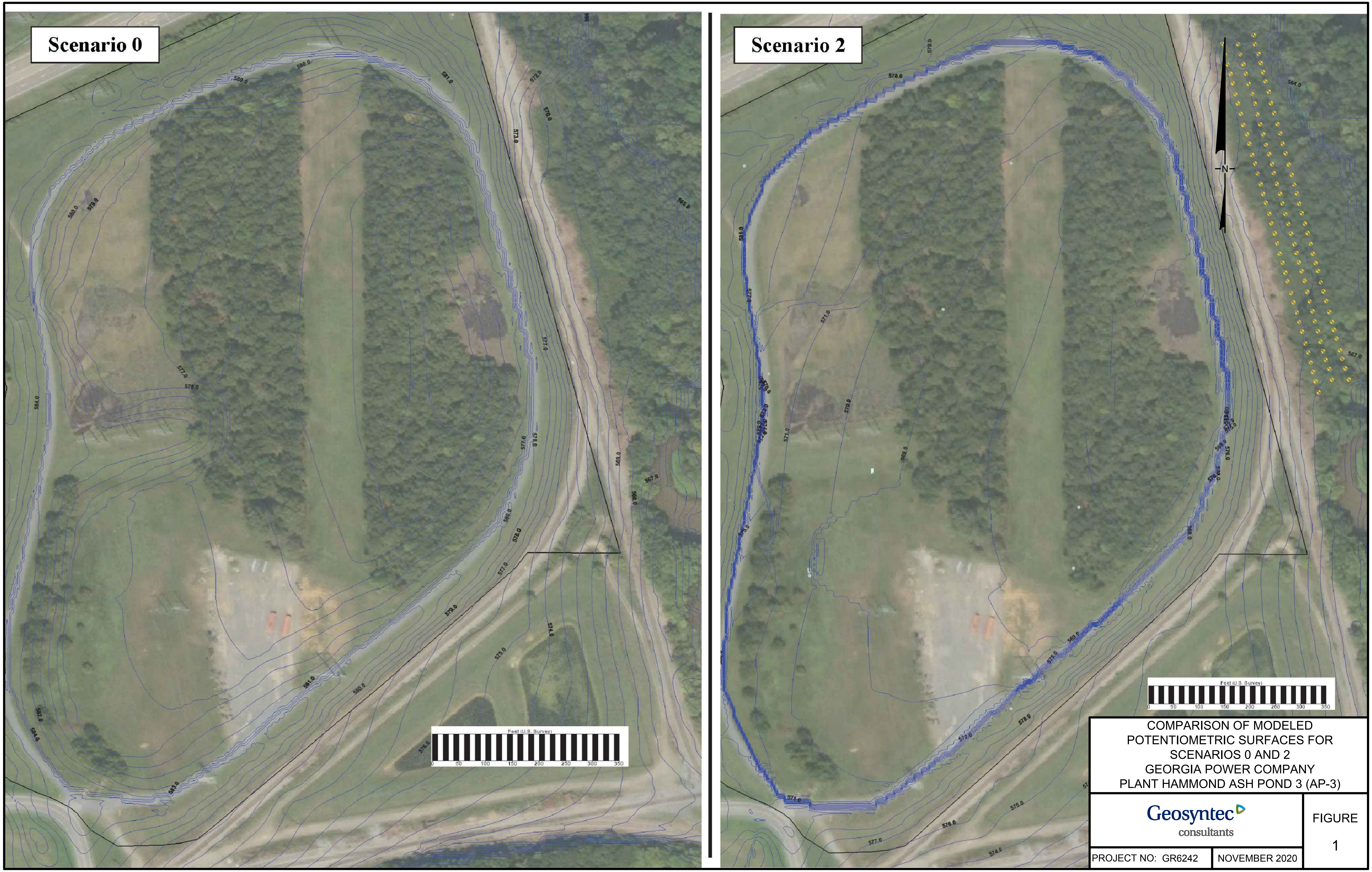
TABLE

Table 1
Summary of Modeling Results
Plant Hammond AP-3, Floyd County, Georgia

Scenario No.	AP-3 Conditions	AP-1 Pool Elevation	Enhancement	Description of Enhancement	Maximum Height of Potentiometric Surface Above Bottom of Unit (ft)	Volume of CCR Below Potentiometric Surface (CY)	% Reduction in Volume of CCR Below the Potentiometric Surface	Pumping Rate (gallons per minute)	% Reduction in Groundwater Flux	Time for Particles to Cross AP-3 Permit Boundary (years)
0	Partial Cover Installed	Historical Elevation	-	-	9.6	101,585	-	-	-	20
AP-3 Closure Conditions										
1	Cover installed	Removed	AP-1 Closure	Engineered cover at AP-3 Stormwater diverted away from AP-3 Eliminates hydraulic influence of historical AP-1 pool	3.7	8,657	91%	-	97.7%	>100
AEM Scenario										
2	Cover installed	Removed	TreeWells®	107 *TreeWells* Screened in HFR/Fractured Limestone and "Pumping" at 40 GPD/tree (collectively 3 gpm for the entire field)	3.7	8,143	92%	3.0	97.8%	>100

Notes:
1. These values were obtained from groundwater flow modeling results. It is noted that groundwater flow models are necessarily simplified mathematical representations of complex natural systems. Because of this, all groundwater models have limits to their accuracy.
2. These model results were intended for use as relative comparisons between scenarios and not as precise predictions of post-closure conditions.
3. Particle tracking represents a theoretical particle of water traveling by advection only and does not account for geochemistry, retardation, or diffusion.
4. Flux estimates were calculated in the model by the volume of water passing through the bottom of model cells in the CCR layer.

FIGURES



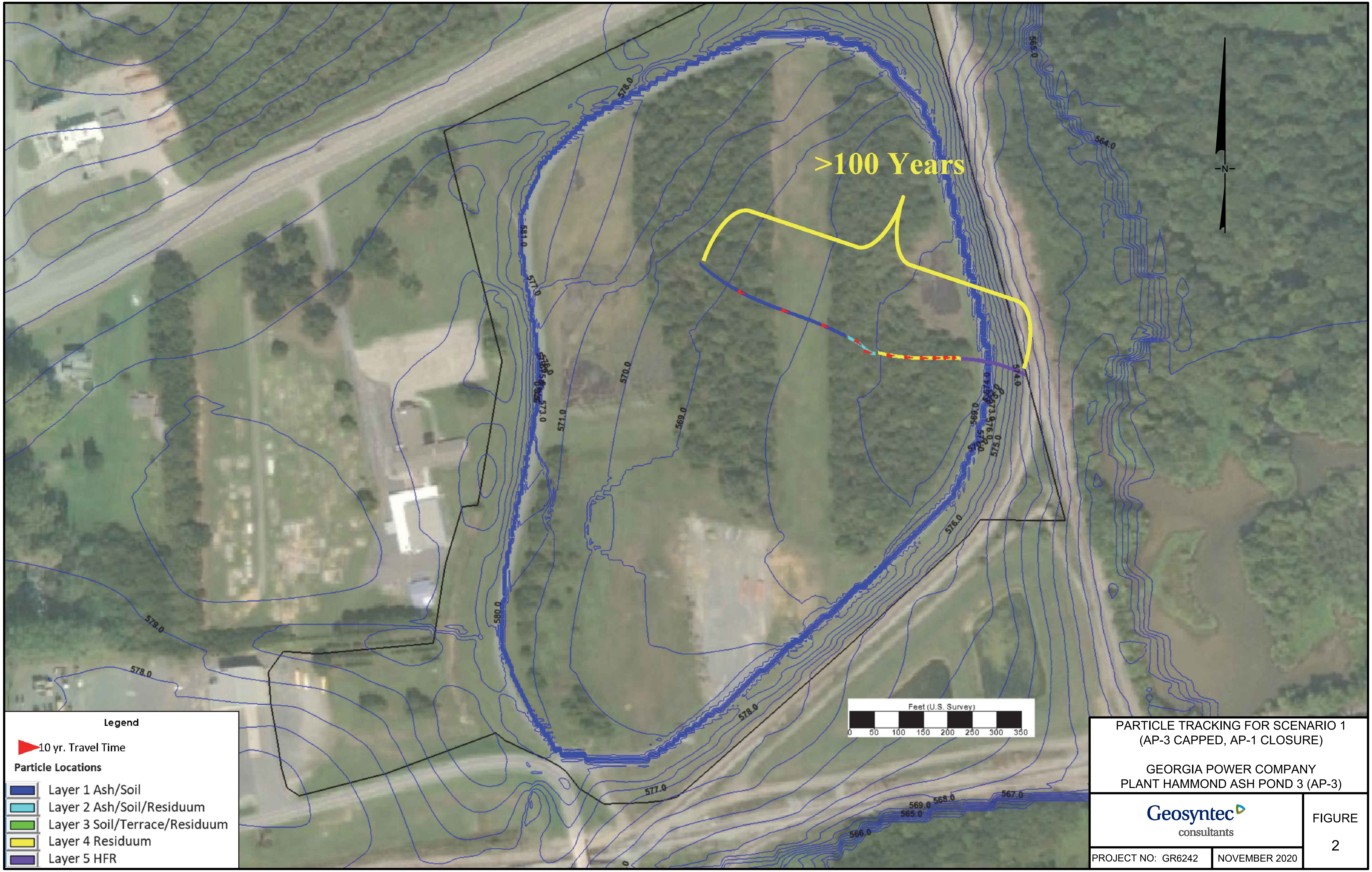
COMPARISON OF MODELED
POTENTIOMETRIC SURFACES FOR
SCENARIOS 0 AND 2
GEORGIA POWER COMPANY
PLANT HAMMOND ASH POND 3 (AP-3)

Geosyntec consultants

FIGURE
1

PROJECT NO: GR6242
NOVEMBER 2020

L:\CADD\GEORGIA POWER\PLANT HAMMOND GR6242\VOLUME\FIG 1 SCEN 2



PARTICLE TRACKING FOR SCENARIO 1
(AP-3 CAPPED, AP-1 CLOSURE)

GEORGIA POWER COMPANY
PLANT HAMMOND ASH POND 3 (AP-3)

Geosyntec consultants

FIGURE
2

PROJECT NO: GR6242

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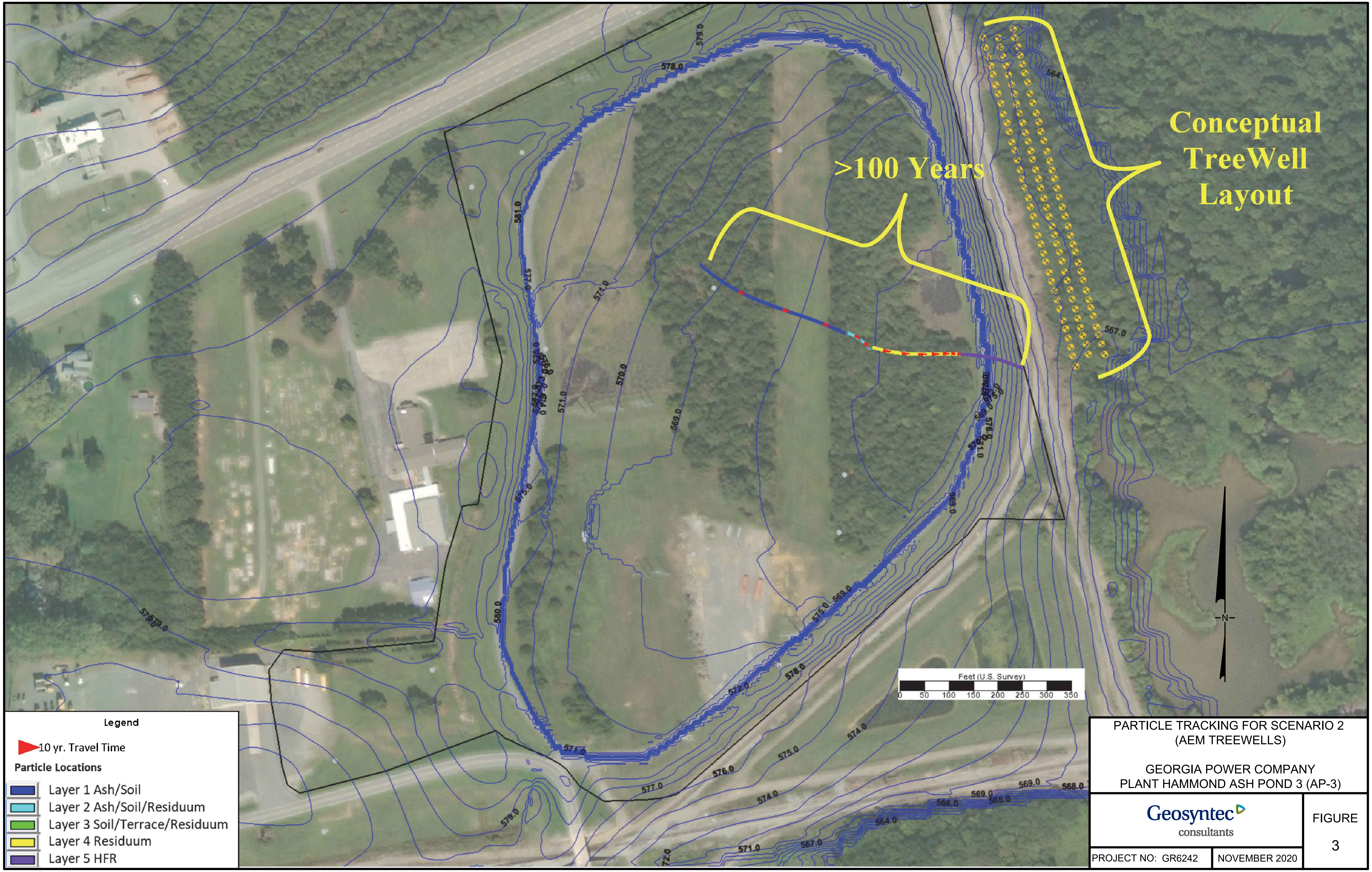
L:\CADD\G\GEORGIA POWER\PLANT HAMMOND GR6242\VOLUME\FIG 5 SCEN 1



PARTICLE TRACKING FOR SCENARIO 2
(AEM TREEWELLS)

GEORGIA POWER COMPANY
PLANT HAMMOND ASH POND 3 (AP-3)

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FIGURE 3

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\\KEN-CADD\CADD\CADD\GEORGIA POWER\PLANT HAMMOND GR6242\VOLUME\FIG 6 SCEN 2

ATTACHMENT 5

Reference Package

Gatliff et. al. (2016)

Phytoremediation of Soil and Groundwater: Economic Benefits Over Traditional Methodologies

23

PHYTOREMEDIATION OF SOIL AND GROUNDWATER: ECONOMIC BENEFITS OVER TRADITIONAL METHODOLOGIES

Edward Gatliff[1], **P. James Linton**[2], **Douglas J. Riddle**[3], **Paul R. Thomas**[4]
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Geosyntec, Clearwater, Florida, USA[2]
RELLC, Mountain Center, California, USA[3]
Thomas Consultants, Inc., Cincinnati, Ohio, USA[4]

1 PHYTOREMEDIATION HISTORY

Phytoremediation is the use of plants in environmental restoration. It can refer to applications ranging from treatment wetlands to urban green roof systems. The term *phytoremediation* is used here to describe environmental restoration of soils and groundwater using trees.

The general application of phytoremediation began in the early 1990s and was performed concurrently with active research at that time. Nearly all of the applications were applied to hazardous substances of low risk and thus low potential for impact to the public health and safety. Accordingly, most early applications and research focused on remediation of:

- Agricultural chemicals (Banuelos, 1994; Burken and Schnoor, 1996; Jordahl et al., 1995; Schnoor and Licht, 1991);
- Heavy metals (Baker et al., 1991; Chaney et al., 1997);
- Trinitrotoluene (TNT);
- Petrochemicals (Banks et al., 1994); and
- Volatile organic compounds (VOCs) (Ferro et al., 1996; Rock, 1996).

The history of phytoremediation requires the discussion of roughly concurrent events in the mid- to late 1980s. Two groups were considering the feasibility of remediating agricultural chemical sites in the midwestern United States using plants. These groups included Edward Gatliff and Paul Thomas on sites in Illinois and Jerry Schnoor and Louis Licht in Iowa. One reason that these early field applications were possible was that agricultural chemical sites were regulated differently than other waste sites. In the states of Illinois, Minnesota, and Iowa, for example, agricultural chemical sites fell under the jurisdiction of the respective states' departments of agriculture as opposed to the state regulatory agencies that oversaw typical properties with hazardous waste issues. The departments of agriculture were generally receptive to some of the early applications of plant-based bioremediation. Early plantings confirmed

Bioremediation and Bioeconomy. http://dx.doi.org/10.1016/B978-0-12-802830-8.00023-X

that herbicides and levels of excess nutrients could be reduced by establishing vegetative cover (Gatliff, 1997; Thomas and Buck, 1999).

One very important finding from the early applications was that hybrid poplar trees could be deep planted in soils contaminated with herbicides and salts. In these situations, the root system of the poplar tree would be buried deeper than the near-surface contaminated soil where conditions would prevent the germination of seed and/or impede growth of shallow-rooted plants. Both the *Populus* and *Salix* genuses have rooting characteristics that allow this type of deep planting.

At about the same time as the early work with agricultural chemicals, Scott Cunningham of Dupont identified hyperaccumulator plants appearing spontaneously at sites containing soils contaminated with heavy metals. Analysis of some of these plants showed that levels of heavy metals in the tissues were extremely high, which indicated the possibility that metals could actually be mined from shallow soils using plants.

Other concurrent work was being performed by Department of Defense researchers who found that TNT sites that had been dormant for a number of years showed substantial reductions in soil contaminant concentrations. These reductions were associated with encroaching vegetative growth around the periphery of the sites as the concentration of TNT in soil was reduced. Similar conclusions were drawn with regard to organic chemical sites both by early research and forensic examination of contaminated sites and facilities that had become naturally vegetated. Since 1990, phytoremediation has been progressing with researchers attempting to catch up with field applications that often demonstrated very positive reductions in contaminant concentrations (Erickson et al., 1994; Fletcher et al., 1995; McCutcheon, 1996; Negri et al., 1996). Much of the early field applications of phytoremediation were possible because of the "voluntary" nature of these pilot projects and because there was generally no immediate risk to human health or the environment that would require removal and other intrusive types of remediation.

2 TRADITIONAL VERSUS DESIGNED AND CONSTRUCTED SYSTEMS

Traditional phytoremediation as discussed here involves the use of plants (usually *Populus* and/or *Salix* tree species) planted as live cuttings, unrooted whips, bare-rooted whips, or bare-rooted trees. The potential objective of phytoremediation is the reduction of contaminant mass in soil and/or groundwater. This contaminant reduction is achieved by:

- Rhizodegradation (contaminant degradation/transformation in the root zone through cometabolism with microbes or through enzyme reactions);
- Phytodegradation (uptake of contaminant by plant followed by degradation or transformation in plant tissues);
- Phytovolatilazation (uptake of contaminants followed by translocation to leaves and transpiration);
- Phytosequestration (immobilization of contaminants in the near-root zone); and
- Phytoaccumulation (uptake followed by sequestration of unmodified contaminants in plant tissues).

The remediation objectives are achieved by planting trees in open holes or trenches so that the roots will be in contact with the capillary fringe (the zone of partial saturation in contact with groundwater). If the capillary fringe is too deep, irrigation may be necessary for the trees to survive until roots reach the capillary fringe or become sufficiently established to allow survival from the consumption of water from rainfall events. Irrigation has the potential to be counterproductive to phytoremediation function if the consumption and treatment of groundwater is an objective. If the goal is soil remediation, the plant roots must be in contact with the impacted soils. If the goal is groundwater remediation, the plants must be able to exert a hydraulic influence over the impacted groundwater in order to move the water into the root zone of the plants where it is subject to remediation mechanisms.

Designed and constructed systems were initially used to force the root systems of plants (typically trees) to develop to deep groundwater. In New Jersey in 1990-1991, the authors designed and constructed a prototype system to allow trees to primarily utilize groundwater about 5 m below ground surface in a climate where annual rainfall averages 1140 mm/year; an amount that easily satisfies the water requirements of the trees. To make the system functional and timely, access to rainwater had to be limited, and roots would be required to reach the top of the aquifer by penetrating 5 m of fairly dense sandy clay subsoil in a short time. To overcome these challenges, 90-cm-diameter boreholes were developed to the top of the aquifer, cased with metal corrugated drainage pipe that extended 15 cm above the ground surface and backfilled with topsoil. Relatively large hybrid poplar trees, about 40-60 mm caliper, were installed in these cased holes. The system forced the trees to develop roots vertically and reach the capillary fringe of the aquifer at about 4 m below ground surface within the first year (as determined by the substantial increase in the size of the uppermost leaves, which indicates luxury consumption of water) (Figure 1).

Since the early 1990s, the prototype system has been refined and substantially enhanced to allow targeting of specific horizons of the vadose and saturated zones. In addition, the authors have trademarked the terms TreeMediation and TreeWell to identify their designed and constructed systems. These refinements have substantially increased the efficacy of the system in many ways. The most significant innovation allows plants to utilize water from specific subsurface horizons in which contamination is migrating. Trichloroethylene (TCE) and other organic compounds that are heavier than water are commonly found near the base of permeable aquifers. Plants drawing water from the top of these aquifers will generally have little effect on contaminant concentrations that are in deeper horizons (Figures 2 and 3).

FIGURE 1

Boreholes were developed to the top of the aquifer, cased with metal corrugated drainage pipe.

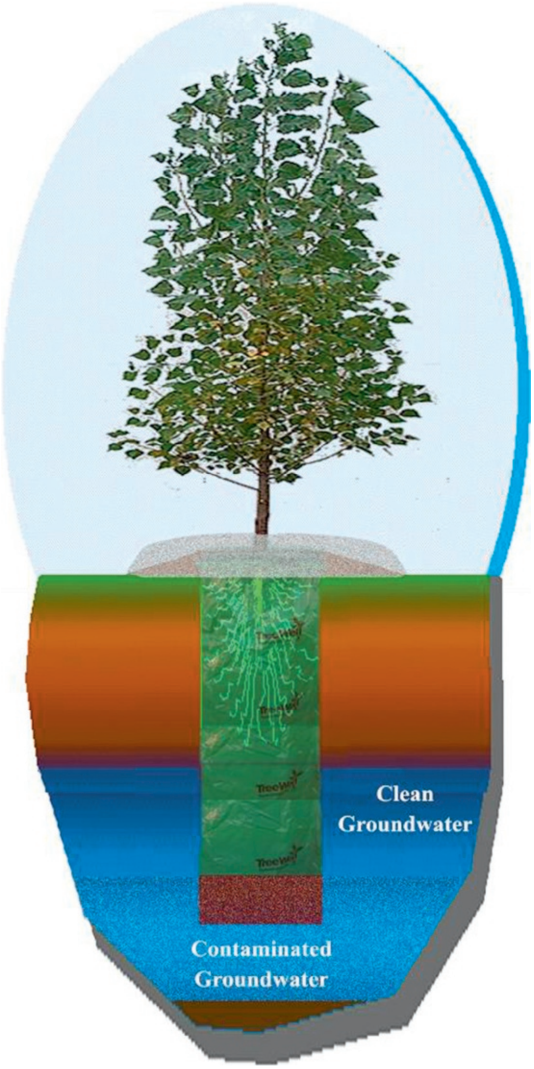


FIGURE 2

Plants roots penetrating into aquifers (Clean and contaminated).

Other refinements allow the plants to utilize contaminated water that would normally be phytotoxic. As the tree pumps water from the soil column, groundwater passes through bioreactor media in the soil column as it flows upward toward the root system. Depending on the constituent(s) and the residence time, there can be substantial contaminant reduction before the groundwater solution reaches the roots thereby reducing or eliminating phytotoxic effects (Figure 4).

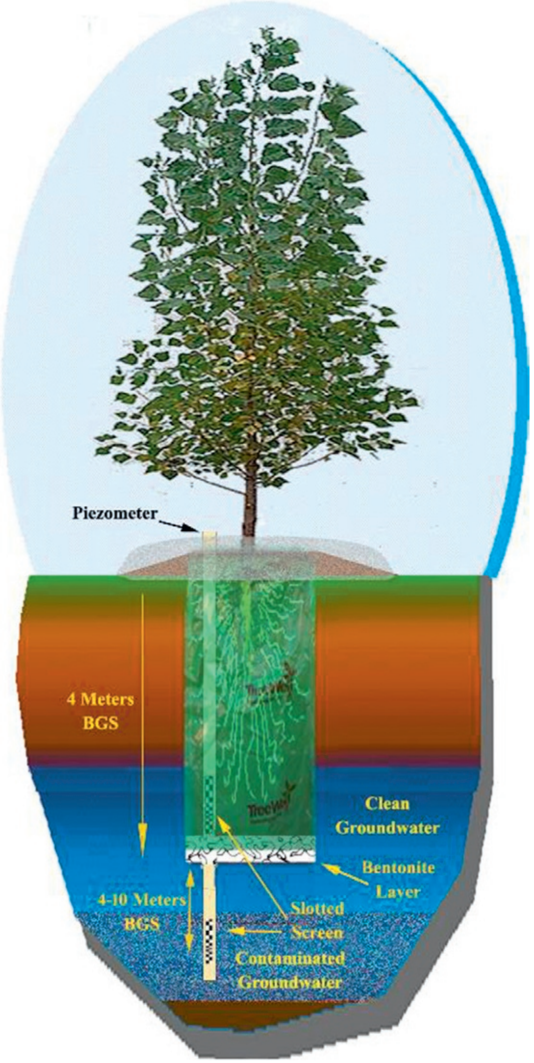


FIGURE 3

Plants drawing water from the top of the aquifers. Please note the bentonite later between clean and contaminated water.

3 OVERCOMING THE LIMITATIONS OF PHYTOREMEDIATION

Designed and constructed systems significantly expand the opportunities available for phytoremediation. While limitations remain, this chapter will focus on the opportunities in order to offset many preconceived biases with regard to the limitations of phytoremediation.

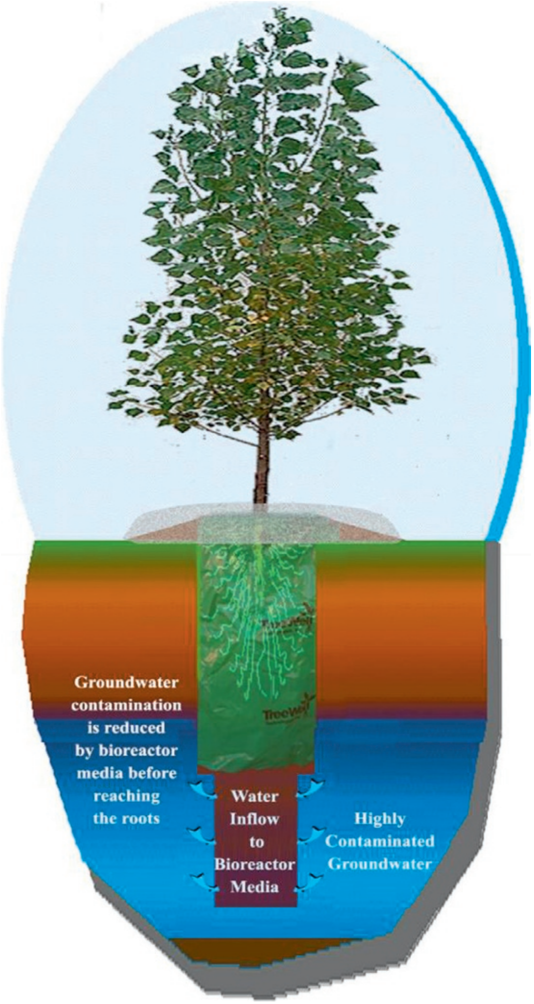


FIGURE 4

The tree act as hydraulic system to pump groundwater. Ground water passes through bioreactor media in the soil column as it flows upward toward the shoot system. Depending on the constituent(s) and the residence time, there can be substantial contaminant reduction before the groundwater solution reaches the roots thereby reducing phytotoxic effects.

3.1 TIGHT FORMATIONS

Phytoremediation has a distinct advantage over pump and treat systems in tight formations. The ability of the root system to explore and utilize capillary water is a significant advantage to soil and groundwater cleanup in tight formations. Pumping systems only extract free water and must rely on pulse pumping to impact contaminants held in the capillary solution. Roots actually pump from the capillary system thereby directly treating contaminants in the capillary solution.

3.2 SINKING CONTAMINANTS

Sinking contaminants would be impossible to treat with traditional phytoremediation systems. However, designed and constructed systems can target these contaminants in many situations. Obviously, tighter formations would enhance the viability of a designed and constructed system over a pump and treat system but opportunities are not limited to tight formations. While phytoremediation systems are limited in water use capacity, they still offer treatment-free water removal.

3.3 HIGH-YIELDING OR FAST-MOVING AQUIFERS

Opportunities do exist for phytoremediation in high-yielding or fast-moving aquifers, especially with the designed and constructed systems. One approach effectively creates a biobarrier by having multiple rows of the bioreactor columns that extend vertically through the aquifer media. These series of bioreactor columns must have comparable or higher porosity than the surrounding media to insure groundwater pass-through. The pumping by the trees further enhances the system by creating a hydraulic gradient toward the column as well as enhancing the flushing of the column. While this approach is feasible, the elevated installation costs may prove to be a limitation.

3.4 PHYTOTOXICITY

Phytotoxicity is a significant issue regarding the potential for treating highly contaminated soil and groundwater. However, some mitigation techniques can be successfully employed depending on the constituent of issue.

3.4.1 Organic contaminant levels

There are effective mitigation techniques available for organic contaminants depending on the constituent of issue. In some cases, selecting the right plant is all that is required. As noted earlier, in situ pretreatment is also possible by selecting the right treatment media.

3.4.2 Salt levels

High salt levels are a problem at many industrial sites. While treatment opportunities are limited or nonexistent, plant selection offers an effective means of overcoming this issue. Halophytes or facultative halophytes can perform well in conditions with fairly high salt levels.

3.4.3 Metals

Not only is the remediation of metals difficult or highly impractical for phytoremediation systems, they are also quite toxic for many plants. As with elevated salt levels, there are plants that can deal with potentially phytotoxic levels of metal constituents, and there are pretreatment systems that can be employed especially with metals in solution but opportunities to use plants for metals remediation remain quite limited.

4 CASE HISTORIES

4.1 OCONEE, ILLINOIS: REMEDIATION OF AGRICULTURAL CHEMICALS IN SOIL

An 0.4-ha agricultural chemical dealership near Oconee, Illinois, was closed in 1986 in response to neighbor concerns about chemical releases. Subsequent site characterization activities indicated that soil and groundwater were impacted by spills of liquid chemical fertilizers and herbicides. In 1987, phytoremediation of site soils was proposed as an alternative to excavation and disposal. The site was planted with corn in 1988. Corn was selected because a large component of the soil contamination was herbicide to which corn was known to have resistance. Unfortunately, the salts and other herbicides present in the soil prevented a significant portion of the corn from germinating and the corn that did germinate was adversely impacted. In 1989, an 8-cm-thick layer of sawdust was tilled into the surface of the site to provide a source of organic matter, to improve soil structure, to mitigate the effects of salinity, and to provide a nitrogen sink.

In 1991, 2-m-tall hybrid poplar trees were planted with bare roots located approximately 1 m below the surface where it was known that the salinity and herbicide concentration would be significantly less than at the surface. The trees grew well, and in 1995 an irrigation system was installed that extracted contaminated groundwater from the downgradient end of the site. The intent of the irrigation system was to recirculate groundwater impacted with herbicides and fertilizers in order to reduce the mass of contaminant available for downgradient transport. It was understood that the salinity of the irrigation water would ultimately result in tree mortality and the intent was to allow the salts to reach a level at which the trees no longer survived, then to stop irrigating and allow the salts to naturally flush out of the system. The irrigation system was shut down in 2002, and trees were replanted in 2008. Soil sampling in 2011 showed that the contaminants in site soils had been reduced to the point that the Illinois Environmental Protection Agency requires no further soil remediation. Figure 5 shows the concentration reduction in soil nitrate nitrogen (upper 0.5 m) between 1987 and 2011.

Phytoremediation of soil at Oconee eliminated the need for excavation and disposal resulting in a cost savings of approximately $375,000 (1987 cost basis) for the 0.4-ha site. The cost savings account for phytoremediation costs (including construction and monitoring) of approximately $200,000.

4.2 ABERDEEN PESTICIDE DUMPSITES: REMEDIATION OF LINDANE IN GROUNDWATER

Pilot planting and full-scale phytoremediation systems were installed in Aberdeen, North Carolina, at the Aberdeen Pesticide Dumps Superfund Site (APDS) in 1997 and 1998, respectively. The record of decision (ROD) issued in 1993 originally specified excavation and thermal desorption of contaminated soils, replacement of treated soils back into the excavations from which they had been removed, and a mechanical groundwater extraction and treatment (pump and treat) system to contain and remediate groundwater contaminated with chlorinated volatile organic compounds (CVOCs) and residual pesticides.

The APDS site resulted from the operation of a pesticide reformulation and packaging facility where pesticides from various manufacturers were combined with other compounds to act as carriers and to reduce the percentage of active ingredient to desired levels. VOCs used in formulation as well as off-specification pesticide products were disposed of in trenches on and near the facility, resulting in soil and groundwater contamination. The primary site remedy involved the excavation of soils contaminated with hexachlorocyclohexane (Lindane), which were thermally treated and returned to the excavation (Figure 6).

One of the functions of the pump and treat system was to be the remediation of any residual Lindane in the treated soil or in contaminated soil that might have been missed during excavation. The potentially responsible parties (PRP) group was successful in obtaining a modification to the ROD through explanation of significant difference (ESD). The ESD changed the remedy to include phytoremediation

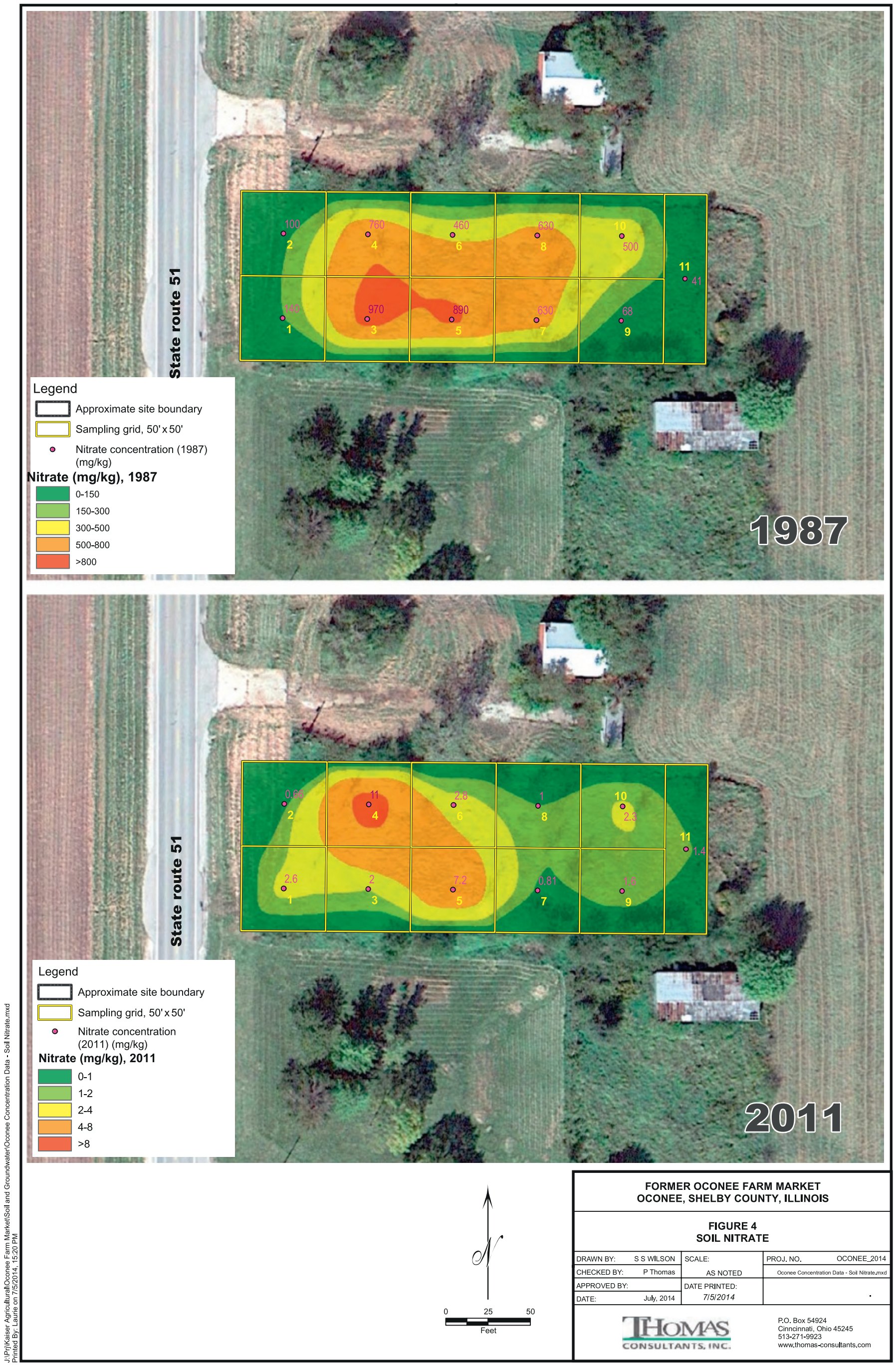


FIGURE 5

Shows reduction in soil nitrate nitrogen concentration between 1987 and 2011.

FIGURE 6

Soils contaminated with hexachlorocyclohexane (Lindane), were excavated and thermally treated.

and natural attenuation, significantly reducing the scope of groundwater extraction and treatment. Phytoremediation has been used principally for hydraulic containment of the shallow aquifer and for "polishing" treatment to remove residual organic contaminants following the removal of most of the contaminated soil in 1998.

The pilot phytoremediation system installed in 1997 was approximately 0.1 ha in size. The pilot plot was located on a slope where the depth to water ranged from approximately 2 m at the bottom of the slope to approximately 5 m at the top of the slope. Bare-rooted hybrid poplar trees ranging from 2 to 5 m were planted in 0.3-m-diameter holes ranging in depth from 1 to 4 m. The primary objective of the pilot system was to establish whether or not the trees, particularly the trees planted in the up-slope locations, would survive without irrigation. In order for the phytoremediation system to function as designed, it would be necessary for the trees to obtain a significant portion of the water they needed for survival from near the surface of the water table. Given the extremely high sand content of site soils (greater than 90%), hybrid poplar trees would not be expected to survive on percolating precipitation. Local plants that survive where depth to groundwater exceeded 2 m is limited to those species that are highly adapted to the sandy soil conditions. The pilot project resulted in the conclusion that the selected species and planting methods would function as required.

The full-scale phytoremediation system installation was performed over a 6-week period in March and April of 1998. Approximately 1.75 ha were planted with bare-rooted hybrid poplar trees to depths ranging from 1.5 to 4 m depending on the depth to groundwater (Figure 7).

Sap flow sensors were used to quantify the volume of groundwater consumed by the system in 1998, 1999, 2000, and 2012. An approximate water consumption rate of 1 L/m^2 of leaf area was established. Measurements from 2013 suggest that peak leaf area was achieved by year three (Figure 8).

Excavations were performed in 2013 to assess the extent of tree root development. In particular the excavations were to confirm that the deeply planted trees (4 m) were actually rooted into the capillary fringe. The excavations showed that the trees planted in 1998 to a depth of 4 m had developed roots at depth and continue to consume groundwater as required for the proper function of the phytoremediation system.

FIGURE 7

The full-scale phytoremediation system was established in March and April of 1998. Approximately 1.75 ha were planted with bare-rooted hybrid poplar trees to depths ranging from 1.5 to 4 m depending on the depth to groundwater for removal of ground water contaminants.

FIGURE 8

Sap flow sensors were used to quantify the volume of groundwater consumed by the trees. Approximate water consumption rate of the planted trees was about 1 L/m 2 of leaf area.

The pilot planting, including reporting, cost approximately $50,000. The full-scale planting cost approximately $350,000, including design, construction, and engineering oversight. Subsequent maintenance, monitoring, and reporting costs associated with the phytoremediation system have totaled approximately $425,000 over 17 years. The use of phytoremediation technology as a substitute for the original pump and treat system is estimated to have saved from $15 to $17 million over the 17-year period since the system was installed.

4.3 SARASOTA: REMEDIATION OF A 1,4-DIOXANE PLUME IN FRACTURED BEDROCK

The Sarasota site is located in west-central Florida near the Gulf Coast and was operated as a manufacturing facility for speed and proximity sensors during the 1970s through approximately 2008. During that period of operation, the facility utilized chlorinated solvents trichloroethene (TCE) and tetrachloroethene (TCA) in the process, and employed an on-site recovery still to recycle the solvent products. No catastrophic releases were recorded; however, accumulated spills and other small releases over time have resulted in groundwater impacts in multiple areas of the site.

1,4-Dioxane is a cyclic ether that was used as a stabilizer in TCA to prevent the degradation of the solvent during storage and use, at concentrations of up to 4% by volume. It is a Lewis base with electrons available for sharing, and is subsequently highly soluble (miscible) in water. The ring structure and position of the oxygen molecules in the ring make 1,4-dioxane highly stable and relatively immune to both abiotic and biotic transformation under normal environmental conditions. These characteristics also prevent 1,4-dioxane from readily sorbing to the soil matrix or other media, and it tends to move in the groundwater at a higher rate than the associated solvents and their breakdown products. This generally results in a mature plume configuration with residual solvent and daughter products close to the source area, and a dilute 1,4-dioxane "halo" that can potentially extend for a considerable distance beyond the residual solvent plume.

These same characteristics also make 1,4-dioxane difficult to recover and treat. The general extent of the dilute plume can require a significant extraction system to capture and contain the plume. Standard air stripping is not effective due to the miscible nature of the compound. Sorption media, such as activated carbon, are ineffective for removal, and the structure of the ring requires considerable energy to break. Treatment systems designed to treat 1,4-dioxane generally require an aggressive (and expensive) component, such as ultraviolet photolysis or chemical oxidation.

The configuration of the groundwater contaminant plume at the Sarasota site generally fits that described earlier, with very little residual degradation products of the chlorinated solvent and an associated extensive, dilute 1,4-dioxane plume downgradient from the "source" area, extending off site. Several smaller residual plumes that may have initially been connected with the main plume are also present on adjacent parcels. In addition, the geochemical changes associated with the biodegradation associated with the solvent component mobilized arsenic from the aquifer matrix.

The "main plume" extends onto an adjoining property, generally beneath an area of what was a distressed wetland overrun with nonnative invasive tree and understory species. A portion of the plume with concentrations of 1,4-dioxane greater than the Natural Attenuation Monitoring (NAM) default concentration, technically considered a source area, remains at the upgradient end of the plume located beneath a low, intermittently inundated area of native oak trees. Lithology within the area of the plume consists of approximately 5-8 ft of silty/sandy soil grading to a more silty layer. A low permeability, fractured limestone is beneath the silt to a depth of up to 12 ft. This is underlain by a tight calcareous clay.

In 2006 an extraction and treatment system was installed at the site to control migration of contaminants further downgradient, and to eventually reduce concentrations to levels that would allow site closure. The system consisted of groundwater extraction wells and an extraction trench, conventional air stripping, photochemical oxidation (ultraviolet light and peroxide), ion exchange, followed by discharge through an infiltration gallery.

The system was designed to operate at approximately 50 gallons per minute (GPM) and was initially effective at both hydraulic containment and mass removal. Low groundwater recovery rates and limits to volume that could be discharged, due to low hydraulic conductivity of the aquifer matrix, resulted in a much lower operation condition (10 GPM) that dramatically reduced the potential efficiency of the system. Mass removal rates had become asymptotic with contaminant concentrations remaining well above cleanup target requirements. Operation and maintenance (O&M) for this system had been in excess of \$300,000 year^{-1}, and operation of this system would have been required for many years to reach the remedial requirements for this site.

The political and regulatory climate surrounding this site would not allow site closure or long-term monitoring options without some form of ongoing active remediation. A feasibility study was conducted to evaluate numerous alternatives that had potential for application to the site, and the TreeWell system was selected for further evaluation on the basis of:

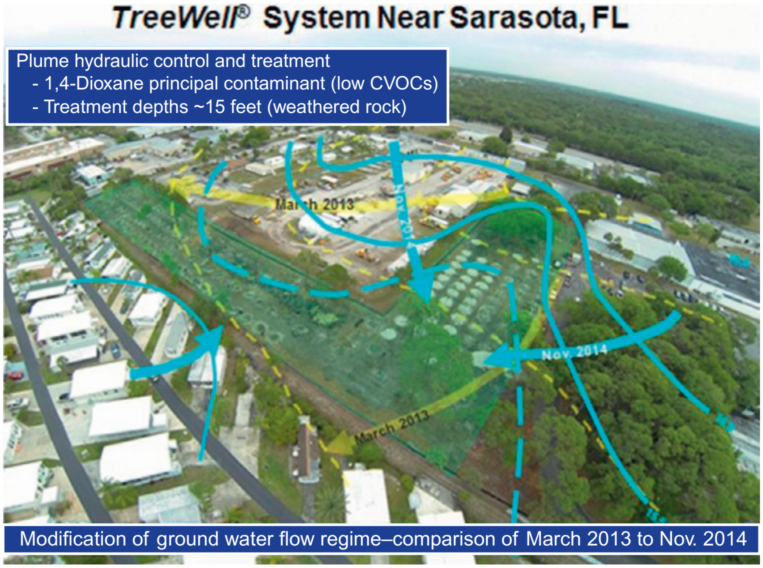
1. A high probability of success under the site conditions;
2. The engineered approach is an active remedial alternative with a low projected O&M expense component (essentially landscape maintenance); and
3. It will remain an active system for the life of the trees.

Additional studies were then conducted to confirm the applicability of this technology, and to provide data for the engineering design. High-resolution sampling and lithology evaluation determined that the bulk of the hydraulic flow at the site is through the fractured rock, and that the contaminant impacts are within this zone, most likely due to back-diffusion from the underlying calcareous clay. Agronomic sampling indicated that soil conditions and chemistry would support the application of the TreeWell system. A groundwater flow model was also developed to evaluate the potential for hydraulic capture using variable numbers of TreeWell trees, anticipated evapotranspiration rates at different stages of growth, and different targeted extraction depths (Figure 9).

The resulting design included 154 TreeWell units spaced on 20-ft centers within a 2.5-acre portion of the property containing the distressed wetland. The wetland was initially cleared of the overgrowth of nonnative invasive species, and the TreeWell units were installed to target the depth corresponding to the fractured rock zone. The TreeWell units were then planted with native species adapted to the conditions at the site (slash pine, willow, sycamore, cypress), with inherent resistance to pests and diseases. The small “source area” was also isolated from the downgradient plume using an impermeable barrier wall, and additional TreeWell trees were installed within this area to supplement the existing oak trees.

Installation was completed in March 2013. The initial effects of the installation were seen within the first quarter following that installation and were well established by the end of the first year. Groundwater flow direction, previously to the west-northwest, has been altered in response to a hydraulic low created by the planting area, and now flow is coming into this area from all directions—downgradient flow has been reversed.

The TreeWell system is also removing contaminant mass. The IMW-10, a monitoring well within the midpoint of the main plume, had historically been approximately one order of magnitude above



TreeWell® System Near Sarasota, FL

Plume hydraulic control and treatment
- 1,4-Dioxane principal contaminant (low CVOCs)
- Treatment depths ~15 feet (weathered rock)

Modification of ground water flow regime–comparison of March 2013 to Nov. 2014

FIGURE 9

TreeWell system at near Sarasota, Florida showing modification of groundwater flow regime - comparison from March 2013 to 2014. Evapotranspiration rates were dependent upon the stages of plant growth and different extraction depths.

the remedial goal for 1,4-dioxane of 3.2 μg/L. By the end of the first year, concentrations detected in this well had dropped below the remedial goal and have remained at this level. Concentrations of 1,4-dioxane in IMW-24R, located downgradient from the source and a few yards outside of the planting area, historically two orders of magnitude above the remedial target, have been reduced to less than 10 μg/L (Figures 10 and 11).

These trends have continued through the second year of "operation" and have demonstrated that:

1. Hydraulic capture has been achieved, and
2. Mass reduction is underway.

The effects seen in the first two seasons have been consistent with those predicted by the groundwater flow modeling. The initial planting used a species mix that was somewhat experimental to determine which species would do best under the site conditions that would also adapt to growth in the TreeWell system. A small percentage of the trees required replacement following the first growing season, but the planting is now established and should require little maintenance beyond weed control, occasional fertilization, and pruning.

The success of the TreeWell system enabled the Florida Department of Environmental Protection to issue a natural attenuation with monitoring order for the site and allowed shutdown of the remedial system in July 2014. Groundwater modeling has predicted that conditions at the site will allow a Risk-Based Conditional Closure by 2020 (or 7 years from installation).

The installation and operation of the interim groundwater pump and treat system was essentially mandated by the regulatory agency. As might be expected given the circumstances, the economics of the system were not optimal. Both the capital and operations costs were also significantly increased

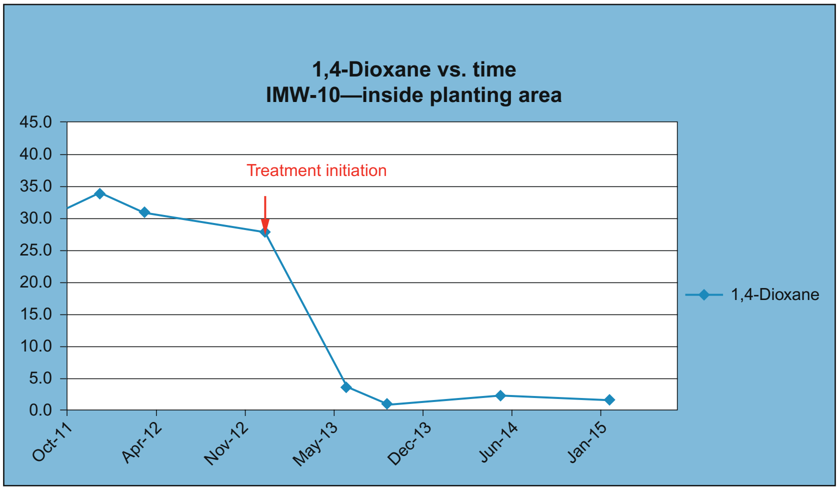


FIGURE 10

The TreeWell system is also removed 1,4-Dioxane (1,4-Dioxane vs time with in IMW-10, a monitoring well).

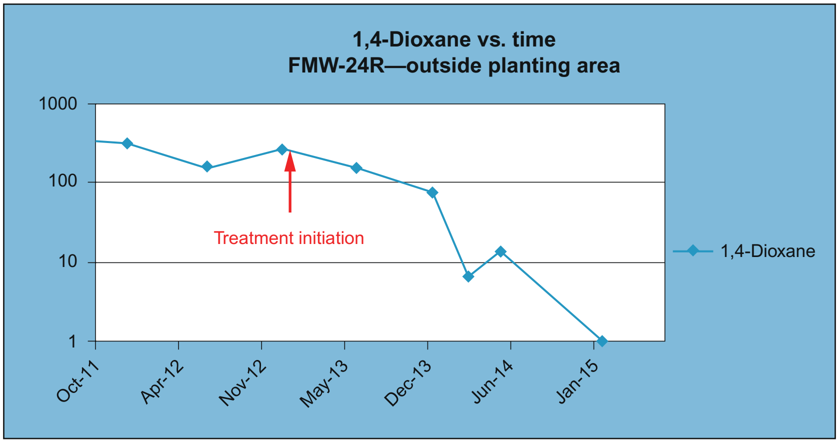


FIGURE 11

The TreeWell system is also removed 1,4-Dioxane (1,4-Dioxane vs time, outside planting area (FMW-24R).

by the requirement that all treated groundwater returned to the site infiltration galleries had to meet groundwater cleanup target levels (GCTLs; i.e., the drinking water standards). As such, naturally occurring compounds had to be treated as well as the constituents of concern. This required the installation of additional treatment media.

In terms of operational data, the interim pump and treat system operated for a period of approximately 8 years from 2006 through 2014. During this period the 1,4-dioxane mass (plume) was reduced by approximately 80% by the extraction (and treatment) of 8,540,547 gallons of groundwater (June 2006 through mid-July 2014). The average groundwater withdrawal rate of the system was 2883 Gallons per day (GDP) for the 2962 days of the operating period. Actual yearly averages are shown in Table 1.

Table 1 Interim pump and treat system operated for a period of approximately 8 years from 2006 through 2014. During this period the 1,4-dioxane mass (plume) was reduced by approximately 80%

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014
Gallons per year	427,330	1,239,770	1,181,000	929,170	1,133,730	1,637,000	1,144,100	689,900	158,547
Gallons per day	2374	3397	3236	2546	3106	4485	3135	1890	672

Based on the extraction volume and the measured influent and treated effluent concentrations, the system removed 2.5 kg of 1,4-dioxane; 1.1 kg of arsenic; and 0.63 kg of CVOCs during operations. It is also estimated that between one and two pore volumes were extracted (between 4.3 and 7.0 million gallons) in the area of the 1,4-dioxane plume. Pore volume estimates were based on effective porosities of either 15% or 25%. It is worth noting that significantly lower extraction rates occurred post-2012.

System costs inclusive of design, construction, operation, and maintenance until system shutdown in July 2014 were \$4.24 million. On a gallon-treated basis this equates to \$0.50 per gallon. Average O&M costs for the period from 2007 through 2013 (full years of operations) were \$314K year^{-1}. Figure 12 provides a summary of capital and O&M costs for the system operating period.

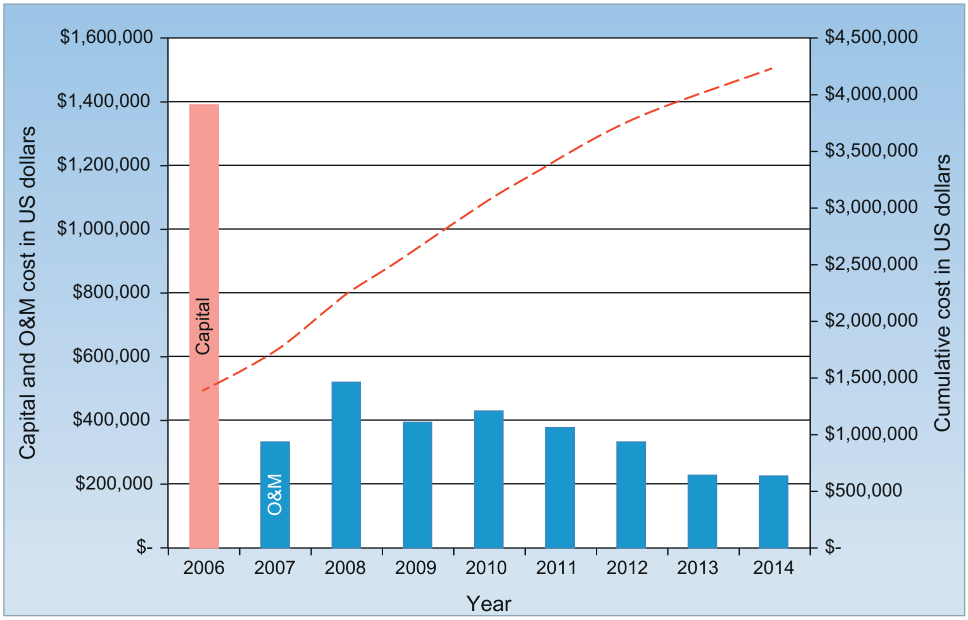


FIGURE 12

Summary of capital and Operation and Maintenance (O&M) costs in US \$ for the system operating period.

The system was installed with the primary goal of achieving natural attenuation default concentrations (NADCs) in the groundwater. Once NADCs were achieved, and it could be demonstrated that no rebound occurred, the intent was to turn off the system and (hopefully) begin monitored natural attenuation (MNA). However, once NADCs were achieved, the length of time predicted to be required for MNA to remediate groundwater to the GCTLs became problematic, both in terms of cost and general acceptability to the agency. While by no means universally defined by the regulatory community, the generally accepted time period for MNA to achieve remediation goals is typically on the order of 5 years. In this case, in excess of 20 years was more likely.

A number of options were considered in the evaluation of the path forward. The goal of the effort was to select an option that would reduce the timeframe required for MNA or eliminate MNA entirely. Importantly, the estimated MNA 20 year timeframe served as the principal baseline for comparing the costs of possible remedies on a net present value (NPV) basis.

In the end, the enhancement of extraction infrastructure and continued operation of the interim system were selected to be compared to a designed and constructed phytoremediation system. In the case of the continued operation of the existing system it was assumed that after extraction enhancements were completed, the system would operate for a minimum of 2 years (based on pore volume removal) and MNA would follow. In the case of the designed and constructed phytoremediation, the performance of the system is expected to achieve GCTLs without the need for a period of MNA. In simple terms, the capital cost of enhancing the existing system combined with the anticipated 2-year minimum operating timeframe was comparable to the cost of installation of a designed and constructed phytoremediation system. Therefore, the O&M cost of the designed and constructed phytoremediation system was able to be directly compared to the O&M cost of MNA.

The designed and constructed phytoremediation system is expected to achieve GCTLs in 7-12 years following implementation. The range in timeframe is based on the predicted pore volume extraction rate. Figure 13 provides the comparison of the NPV cost of designed and constructed phytoremediation at 7 and 12 years after planting with the NPV cost of 20 years of MNA (note: inflation assumed at 3%). As can be seen in Figure 13, the anticipated completion of phytoremediation in 2020 results in a NPV cost of $636K. This compares with the estimated NPV cost of MNA of $1432K.

There were a number of clear advantages to the implementation of the designed and constructed phytoremediation system. Besides providing a broader groundwater capture zone than the "enhanced" existing system option, the system, as designed, outperforms the extraction rates achieved by the pump and treat system. Based on the current groundwater elevation contours, the installed phytoremediation system has already outperformed the previous system within the first 2 years.

For illustrative purposes, it is worth evaluating how the designed and constructed phytoremediation system would have performed if installed in 2006 instead of the interim pump and treat system. Figure 14 has been prepared to provide a comparison to the capital and O&M costs presented in Figure 14 for the interim pump and treat system. Figure 14 utilizes actual capital costs for the installation of the designed and constructed phytoremediation system as well as current and predicted O&M costs.

Based on the current groundwater data, we know that the designed and constructed phytoremediation system is conservatively capable of achieving withdrawal of one pore volume (based on original plume size) in 1-2 years once the trees have reached an age of 2 years. If a 2-year startup period is allowed for establishment of the trees, then it can be assumed that the system would be able to achieve the same level of withdrawal (i.e., one to two pore volumes) in an additional 2-4 years as compared to the 8 years that was required of the pump and treat system. Therefore, the phytoremediation system

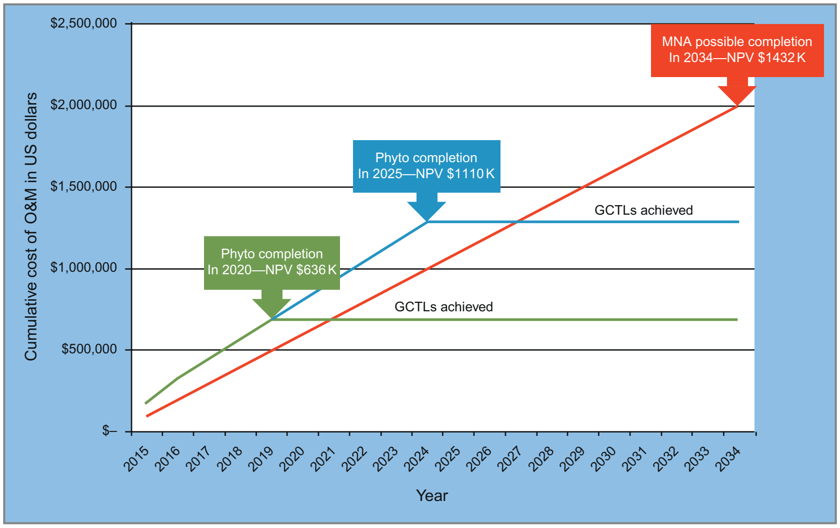


FIGURE 13

Comparison of the net present value (NPV) cost of designed and constructed phytoremediation at 7 and 12 years after planting with the NPV cost of 20 years of monitored natural attenuation (MNA) (note: inflation assumed at 3%).

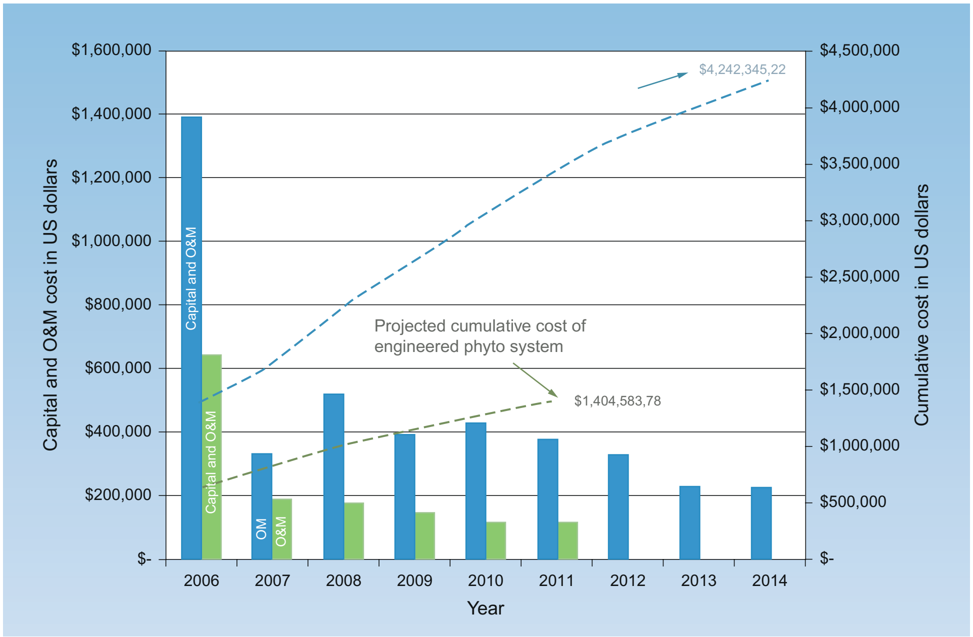


FIGURE 14

Projected cumulative cost of engineered phytosystem for 2006–2014.

would have been able to achieve the same level of cleanup in 4-6 years and at substantially lower annual O&M costs. Figures 12–14 demonstrates that a potential savings on the order of $2.83 million could have been realized if a designed and constructed phytoremediation system was implemented in 2006 instead of the pump and treat system.

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Goldemund and Gestler (2019)

Phytoremediation Using TreeWell® Technology: An Innovative Approach to Groundwater Remediation at CCR Sites

Phytoremediation Using *TreeWell*® Technology: An Innovative Approach to Groundwater Remediation at CCR Sites

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KEYWORDS: CCR units, groundwater remediation, engineered phytoremediation

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ABSTRACT

Some coal combustion residual (CCR) disposal units regulated by the Federal CCR Rule may require groundwater remedies based on statistically significant levels of constituents regulated in Appendix IV of the Rule. These inorganic constituents cannot be destroyed or degraded, but only captured/contained, rendered immobile, or allowed to migrate into the environment at concentrations deemed acceptable. This, in turn, affects (and also limits) the selection of potentially applicable groundwater remedial alternatives. One of these technologies involves the use of phytoremediation. Traditional phytoremediation methodologies, however, have often been limited in their effectiveness due to constraints including inaccessibility to deep groundwater, poor growing conditions and/or highly elevated (and potentially phytotoxic) levels of contaminants. More recently, an engineered approach to phytoremediation, the *TreeWell*® system, has been shown to overcome typical limitations of applying phytoremediation to groundwater cleanup. This phytoremediation system targets specific groundwater strata, at depths of 50 feet (15 meters) below ground surface (or more), and forces roots to use only water from a specific targeted zone. *TreeWell* technology has great potential for groundwater remediation applications at CCR sites, especially as an enhancement to source control measures. The *TreeWell* system can be used for both hydraulic control of contaminant plumes and for groundwater contaminant treatment via degradation (for organic constituents) or immobilization/ containment mechanisms (for organic and inorganic constituents). This paper discusses mechanisms utilized in phytoremediation systems applied to address sites impacted by inorganic contaminants, including those typically encountered at CCR sites, and also presents case studies demonstrating the successful use of engineered phytoremediation systems.

INTRODUCTION

Some coal combustion residual (CCR) disposal units regulated by the Federal CCR Rule[1] may require groundwater remedies based on statistically significant levels of constituents regulated in Appendix IV of the Rule. Groundwater below basins that have been used to store CCR materials may have concentrations of certain groundwater constituents in excess of applicable regulatory standards and/or background conditions. These include mostly inorganic constituents such as metal(loid)s (e.g., arsenic [As], selenium [Se], mercury [Hg], iron [Fe], manganese [Mn], and boron [B]) and anions (e.g., chloride [Cl], or sulfate [SO_4]). While some of these constituents may not require remediation under the Federal Rule, they may be regulated by individual states and require some form of remedial action.

Once released or mobilized, inorganics cannot be destroyed or degraded, but only captured/contained, rendered immobile or allowed to migrate into the environment at concentrations deemed acceptable. This, in turn, affects (and also limits) the selection of potentially applicable remedial alternatives. One of these technologies involves the use of phytoremediation.

PHYTOREMEDIATION

Phytoremediation is the use of plants to degrade or contain contaminants in soil, groundwater, surface water, and sediments. Over recent decades, phytoremediation has emerged as a feasible alternative to more active and costly environmental cleanup technologies, especially for large areas with relatively low levels of contamination in shallow soils or groundwater. In general, six main mechanisms are involved in the application of phytoremediation:[2]

1) Phytosequestration (inorganic and organic contaminants) is the ability of plants to sequester contaminants in the rhizosphere (an area a few millimeters away from a root surface). This is a containment mechanism.
2) Rhizodegradation (organic contaminants) refers to the microbial breakdown of contaminants in soil through the bioactivity that exists in the rhizosphere (an area a few millimeters away from a root surface). This is remediation by destruction.
3) Phytohydraulics is the ability of plants to capture and evaporate water. This is hydraulic control of a groundwater plume through plant root uptake and is considered a containment mechanism.
4) Phytoextraction (mostly inorganic contaminants) is the process of contaminant uptake into the plant. This is remediation by removal.
5) Phytodegradation (organic contaminants) is the ability of plants to take up and break down of contaminants in the transpiration stream. This is remediation by destruction.
6) Phytovolatilization (mostly organic, but some inorganic contaminants) is the mechanism of plant uptake and translocation of contaminant into the leaves with subsequent transpiration of volatile contaminants. This is remediation by removal.

Typically, a combination of these mechanisms acts in concert to achieve successful applications of phytoremediation for site cleanup. For example, phytohydraulics may act in conjunction with phytoextraction for remediation of inorganic contaminant plumes, while phytohydraulics coupled with phytovolatilization can together achieve effective remediation of 1,4-dioxane plumes and can also address inorganic constituents such as selenium and mercury plumes.

More recently, the term “phytotechnologies” has been introduced to more broadly describe a wide variety of plant-based environmental tools, including those used for site cleanup (i.e., phytoremediation). Phytotechnologies encompass a number of plant-based technologies and applications and includes any plantings that enhance the environmental goals for a given site.[3] Conceptually, phytotechnologies include a variety of applications ranging from constructed wetlands to alternative landfill covers, from tree plantations for hydraulic control to the use of plants for slope stabilization, from planted (riparian) buffers for nutrient management and sediment control to the classical applications of contaminant uptake and degradation. However, this paper does not discuss the use of phytoremediation for cleanup of soils and/or its use in the larger variety of applications listed above but focuses instead on the use of this technology for groundwater applications. In particular, this paper focuses on the use of an innovative and proprietary phytoremediation technology and its feasibility for application to CCR sites.

THE *TREEWELL* SYSTEM

The effectiveness of groundwater remediation using traditional phytoremediation approaches may be limited by compacted soil conditions that impede root penetration, target groundwater that is too deep for root access, or phytotoxicity due to excessively high contaminant concentrations. More recently, an engineered approach to phytoremediation, the *TreeWell* system, has been shown to overcome these constraints by utilizing a specialized lined planting unit constructed with optimum planting media designed to promote downward root growth, encourage contaminant treatment, and focus groundwater extraction from a targeted depth interval. Developed and patented by Dr. Edward Gatliff of Applied Natural Sciences, Inc., the *TreeWell* system uses a proprietary design to focus groundwater extraction from a targeted depth interval; targeted groundwater is drawn upward through the planting unit and into the root zone, creating a hydraulic connection between impacted groundwater and the phytoremediation system. Advanced techniques have been developed to address groundwater typically too deep for root contact, at depths greater than 50 feet (15 meters) below ground surface, enabling *TreeWell* systems to target groundwater normally inaccessible to plant roots and therefore out of reach for effective phytoremediation. A schematic illustrating the typical construction of a *TreeWell* unit is presented on Figure 1.

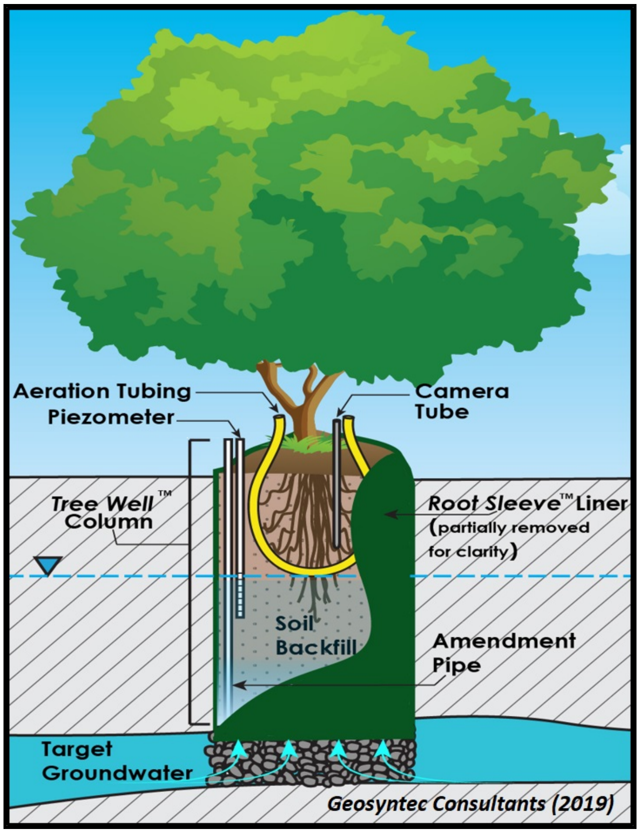

Figure 1: Schematic of a typical *TreeWell* unit.

The *TreeWell* system can be used for both hydraulic control of contaminant plumes and for groundwater contaminant treatment via degradation (for organic constituents) or immobilization/containment mechanisms (for organic and inorganic constituents). By contrast, in traditional hydraulic control/containment systems, such as a groundwater pump and treat (P&T) technology, extraction wells or trenches are used to capture groundwater, which may subsequently require above-ground treatment and discharge to a receiving stream, reinjection into the groundwater, or reuse at a given site. Groundwater P&T is often slow and costly as a means to restore groundwater quality but can be effective in providing hydraulic control to limit contaminant migration, while addressing a variety of inorganic constituents typically encountered at CCR sites.

Hydraulic control can also be achieved without the need for mechanical above-ground extraction and treatment of groundwater, however, through the use of an engineered phytoremediation technology such as the *TreeWell* system. This type of system installs a tree within a cased (i.e., sleeved) boring, which allows for groundwater to be extracted from a targeted zone which then enters the root system of the trees. This method forces the tree to use groundwater rather than meteoric/surface water to meet its water needs and encourages downward root growth to the saturated zone. By installing a cased “well” for tree planting using large diameter auger (LDA) technology, extraction of deeper groundwater zones (i.e., in excess of 50 feet [15 meters] below the ground surface) can be achieved, since the surface of the “well” is sealed and only groundwater from a targeted zone is allowed into the cased-off borehole.[4] This type of system mirrors a traditional mechanical extraction system with the trees acting as solar-driven pumps. The advantage of the system includes no above-ground water management needs and minimal long-term operations and maintenance (O&M) requirements following the establishment of the tree system. Such systems have been observed to meet design hydraulic control parameters typically by the end of the third growing season, when properly designed and spaced. The layout for a *TreeWell* plantation is generally based on groundwater flow modeling, and typically assumes a design uptake rate of approximately 40 to 60 gallons per day per unit. Due to the relatively low concentrations of constituents in groundwater surrounding CCR units, contaminant uptake and accumulation within the aboveground biomass is generally not of concern but can be monitored if warranted under certain circumstances.

Typical installation of *TreeWell* units consists of drilling to target depth using an LDA. The boring from the LDA is then lined with a fabricated plastic liner and backfilled with imported agricultural-grade soils. Down-hole components, such as tubing and instrumentation for gas exchange, fertilizer injection and groundwater monitoring, are installed during the backfilling, and one or more selected trees are then planted at the top of the backfilled boring. The *TreeWell* unit is then completed at the ground surface per the *TreeWell* design and stabilized. Figure 2 presents a newly installed *TreeWell* system showing typical aboveground completion at a site in North Carolina. Figure 3 presents the same *TreeWell* system two years post-installation. The rapid growth and excellent health observed in trees at this site are typical of the results achieved at other sites using the *TreeWell* system, thanks to the optimized growing conditions created by this engineered phytoremediation system.

Figure 2: Newly completed *TreeWell* units at North Carolina site.

Figure 3: *TreeWell* phytoremediation system two and a half years post-installation at North Carolina site.

FEASIBILITY OF *TREEWELL* TECHNOLOGY FOR CCR SITES

TreeWell technology has great potential for groundwater remediation applications at CCR sites, especially as an enhancement to source control measures. Observed groundwater impacts around CCR sites are generally limited and concentrations of groundwater contaminants are typically low. Typical constituents observed in groundwater underlying basins used to store CCR materials include metal(loid)s such as As, Se, Hg, Fe, Mn, B and anions such as Cl and SO_4. While concentrations of these contaminants may be in excess of applicable regulatory standards and/or background conditions, they may however be within the range that is suitable for phytoremediation with *TreeWell* technology. By directly targeting the impacted water-bearing zone of interest, the *TreeWell* system can achieve hydraulic control of contaminant plumes in as little as two growing seasons post-installation,[5] and more typically within three to four years post-installation. In addition, the *TreeWell* system can concurrently address the mix of inorganic constituents found in groundwater associated with CCR sites through one or more of the key phytoremediation mechanisms described above. The exact mechanism(s) involved will be constituent-specific and may also be impacted by speciation or form of the metal(loid) or anion. Some examples include the following:

- Fortuitously, several of the typical groundwater constituents encountered at CCR sites are essential (micro-) nutrients for plants, such as Fe, Mn, B and SO_4. Thus, these constituents may be absorbed by plant roots and translocated throughout the plant (i.e., phytoextraction) to support its growth;
- Plants can effectively remove Se from impacted sites by uptake of selenate or selenite. Once absorbed by roots, plants have the capacity to (i) sequester the metal in plant tissue and/or (ii) phytovolatilize the Se as volatile and non-toxic dimethyl selenide. Further, both plants and their associated soil microbes

contribute to the biosynthesis and emission of volatile Se gases, e.g., dimethyl selenide.[6]

- Select amendments may be utilized when constructing the *TreeWell* units in order to immobilize or precipitate specific constituents. These amendments include sulfide- and zero-valent iron-based reactive treatment technologies, which can be emplaced as backfill in the *TreeWell* units during construction. For example, sulfide-based amendments can be used to promote the formation of stable and insoluble sulfide-metal complexes, effectively immobilizing metals such as iron and manganese in the *TreeWell* column;[7] and
- Production of root exudates (labile organic compounds including sugars, polysaccharides, polypeptides and organic acids) can establish conditions favorable to the reduction of sulfate to sulfide.[8] This sulfide may, in turn, lead to formation of stable and insoluble sulfide-metal complexes, thus effectively immobilizing both the sulfate and metal constituents of concern within the *TreeWell* column.

Specific metal(loid)s and/or anions may potentially pose adverse or phytotoxic risks to plants at higher concentrations, depending on speciation or form and the specific plant under consideration; as noted above, pre-treatment options may be necessary to sorb and immobilize some contaminants in the soil column of *TreeWell* units prior to potential root uptake. The exact type and amount of pre-treatment material would be dependent on constituents of concern and would take into consideration the planned lifespan of the phytoremediation system (typically 30 years or more).

Plant selection is often a critical design consideration when developing a phytoremediation system, including those using *TreeWell* technology. When designing a phytoremediation system for CCR sites, careful selection of plant species should be performed to tailor the plants used in the system to the constituents observed in groundwater. For example, at CCR sites where Cl concentrations are high relative to other groundwater constituents, the use of halotolerant or halophytic plant species may be warranted to mitigate against the potentially adverse accumulation of Cl in plant tissues. Likewise, at CCR sites where high B groundwater concentrations are observed, the use of plant species known for elevated tolerance to B should be considered, to mitigate against potential phytotoxicity from this constituent.

SELCT *TREEWELL* PHYTOREMEDIATION CASE STUDIES

Case Study 1: Phytoremediation of Mercury-Impacted, High-Salinity, High-pH Groundwater at a Former Outfall Pond (Confidential Client)

A *TreeWell* phytoremediation system was successfully applied at a confidential site in California to prevent flux of mercury-impacted groundwater to a sensitive waterbody. The site once housed a chloralkali unit consisting of multiple mercury cells used for production of chlorine and sodium hydroxide. The chloralkali unit ceased operations in the 1970’s, but a former outfall pond (FOP) associated with the unit had significant mercury impacts to both soil and groundwater. Groundwater underlying the FOP had total mercury concentrations ranging from 245 ng/L to 540,000 ng/L, pH ranging from 7 to 12, and chloride and sodium concentrations ranging from 1.2 to 12.5 g/L and 0.9 to 10.0 g/L, respectively. A cap system (an impermeable geotextile and 12" of clean cover) was installed over the FOP in 2000 to prevent recharge to the underlying shallow aquifer. While the cap was successful in reducing recharge, the hydraulic gradient of the aquifer indicated that groundwater continued to flow towards the adjacent waterbody. Based on the results obtained from groundwater modeling, a *TreeWell* phytoremediation system was installed at the FOP in 2013, with its primary objectives being hydraulic control and contaminant sequestration (i.e., phytosequestration). These objectives were achieved through plant uptake and transpiration of target groundwater concomitant to metal sequestration in the root zone around each planting. The system was installed directly through the FOP cap to establish an inward hydraulic gradient, mitigating potential off-site migration of contaminants. The innovative phytoremediation design maintained the integrity of the FOP cap, minimizing recharge, while simultaneously promoting downward root development, targeting the impacted water-bearing zone. A total of 271 engineered *TreeWell* units were installed over a one-acre area of the FOP. Each unit contained two salt-tolerant plant species (Saltbush and Afghan Pine) previously identified as being well suited to groundwater conditions at the site.

The effects of the phytoremediation system on groundwater flow conditions were rapidly observed. An inward hydraulic gradient began to develop in the interior of the planting area by the end of the first growing season. The magnitude of the inward hydraulic gradient continued to increase with each growing season as the system's plants matured and transpired larger volumes of water, leading to the desired goal of hydraulic control of impacted groundwater. Sequestration of mercury in the root zone was indirectly confirmed by semi-annual sampling of groundwater concentrations and through plant tissue analysis (to confirm that no mercury accumulation was occurring in above-ground plant tissues). The green and sustainable remediation approach used at this site was not only successful in meeting the remediation objectives but was also very cost-effective versus more conventional technologies initially considered for the site (e.g., P&T).

Case Study 2: Phytoremediation of Groundwater Impacted by Arsenic, Chlorinated Volatile Organic Compounds and 1,4-Dioxane at a Former Manufacturing Facility (Confidential Client)

The groundwater at this former manufacturing facility in Florida contained elevated levels of arsenic, chlorinated volatile organic compounds (CVOCs) and 1,4-dioxane (constituents of concern [COCs]) resulting from historical facility activities. Conditions at the site were complex and included residual source areas and multiple plumes both on- and off-site. Key remedial goals for the site were (i) reduce contaminant concentrations within the plume to levels that would be acceptable to the regulatory agency for a risk-based conditional closure, and (ii) provide hydraulic control to prevent the COC plumes from migrating off-site, and to allow shut-down of the existing P&T system within a reasonable time frame.

Initially, a P&T system was installed and operated for 12 years at the site. However, due to aquifer properties, the system was only able to extract and treat at a very low rate (10 gallons per minute [gpm]) and was not effectively reducing concentrations within the groundwater plume. A minimum of 25 years of additional costly operations and maintenance were anticipated to obtain site closure. Therefore, alternative remediation technologies were evaluated to determine if a more cost-effective and sustainable strategy could be implemented to obtain site closure more quickly. Vertical geologic and groundwater profiling, pump testing, and groundwater flow modeling were completed to refine the conceptual site model and develop a final remedy for the site that included an engineered *TreeWell* phytoremediation system comprised of 150 units designed to reduce COC concentrations and capture the flow of affected groundwater.

As part of the phytoremediation approach, a distressed wetland area was reclaimed by removing solid waste and invasive species and installing *TreeWell* units employing native species. Within the second growing season, monitoring of the *TreeWell* system demonstrated complete capture of the affected groundwater flow and decrease in groundwater COC concentrations by up to two orders of magnitude. Based on these results, it was recommended to shut down and remove the existing P&T system, which was approved by the Florida Department of Environmental Protection (FDEP). By the end of the fourth growing season, contaminant concentrations in the source area and downgradient plume had been reduced to slightly above the State Cleanup Target Levels, and a conditional No Further Action proposal was submitted and approved.

CONCLUSIONS

While phytoremediation is often applied to address organic contaminants, it can also be an appropriate remedial strategy for the metal(loid)s and anions typically observed in groundwater at CCR sites. Plant-based remediation technologies can be effective as either a hydraulic control strategy or a sequestration/containment strategy for metal(loids) and other inorganics from groundwater.

While traditional phytoremediation methodologies have often been limited in their effectiveness due to constraints including inaccessibility to deep groundwater, poor growing conditions and/or highly elevated (and potentially phytotoxic) levels of contaminants, the *TreeWell* system has been shown to overcome typical limitations of applying phytoremediation to groundwater cleanup. *TreeWell* technology has great potential for groundwater remediation applications at CCR sites, especially as an enhancement to source control measures. The *TreeWell* system can be used for both hydraulic control of contaminant plumes and for immobilization/containment of inorganic constituents. Remediation practitioners should consider keeping these versatile technologies in their toolbox.

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Linton (2017)

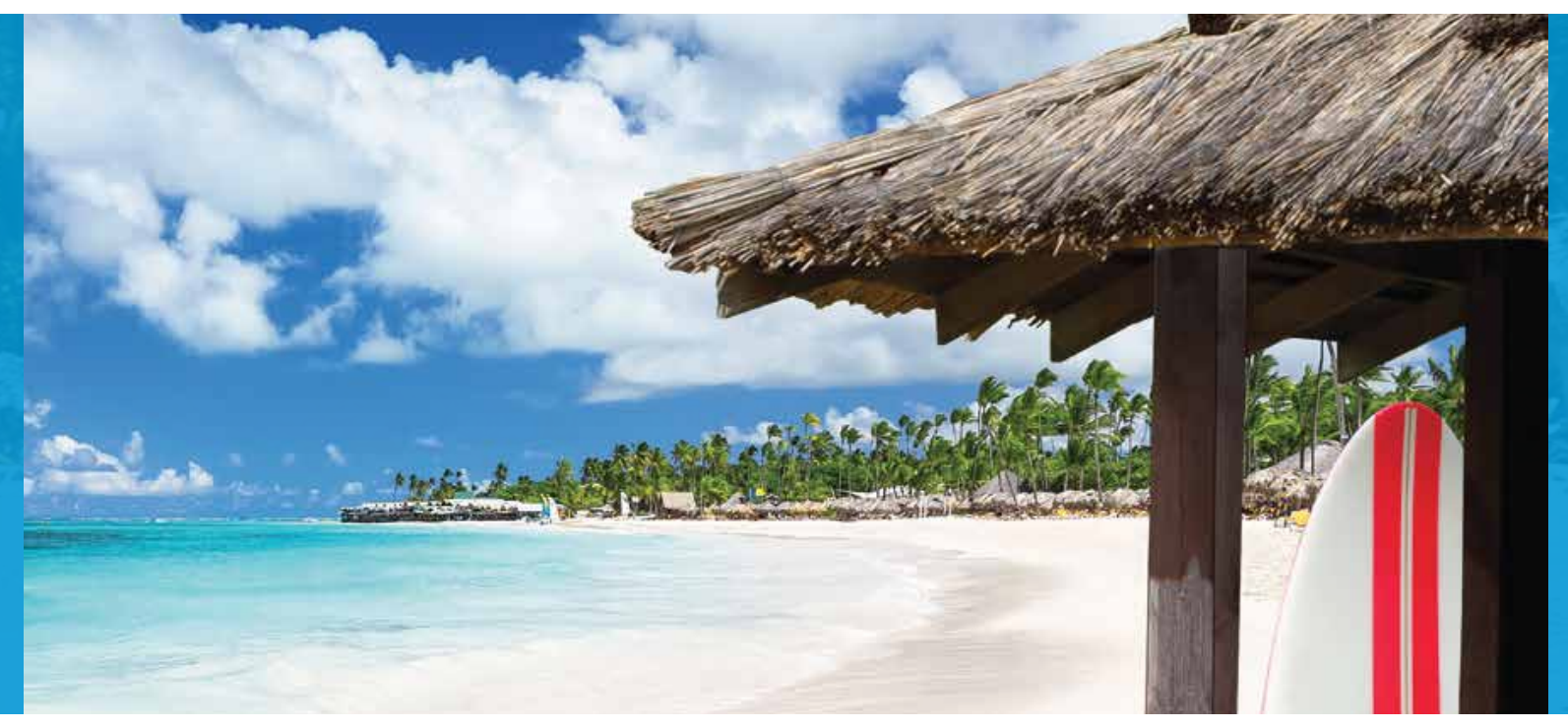
Integrated Source Isolation and Targeted Phytoremediation to Address a 1,4 Dioxane and Arsenic Plume in Fractured Bedrock

draft -for review only

Geosyntec consultants

Integrated Source Isolation and Targeted Phytoremediation to Address a VOC/1,4-Dioxane and Arsenic Plume in Fractured Bedrock

P.J. Linton, E. Gatliff, P. Thomas, and D. Riddle. - Geosyntec Consultants



Background

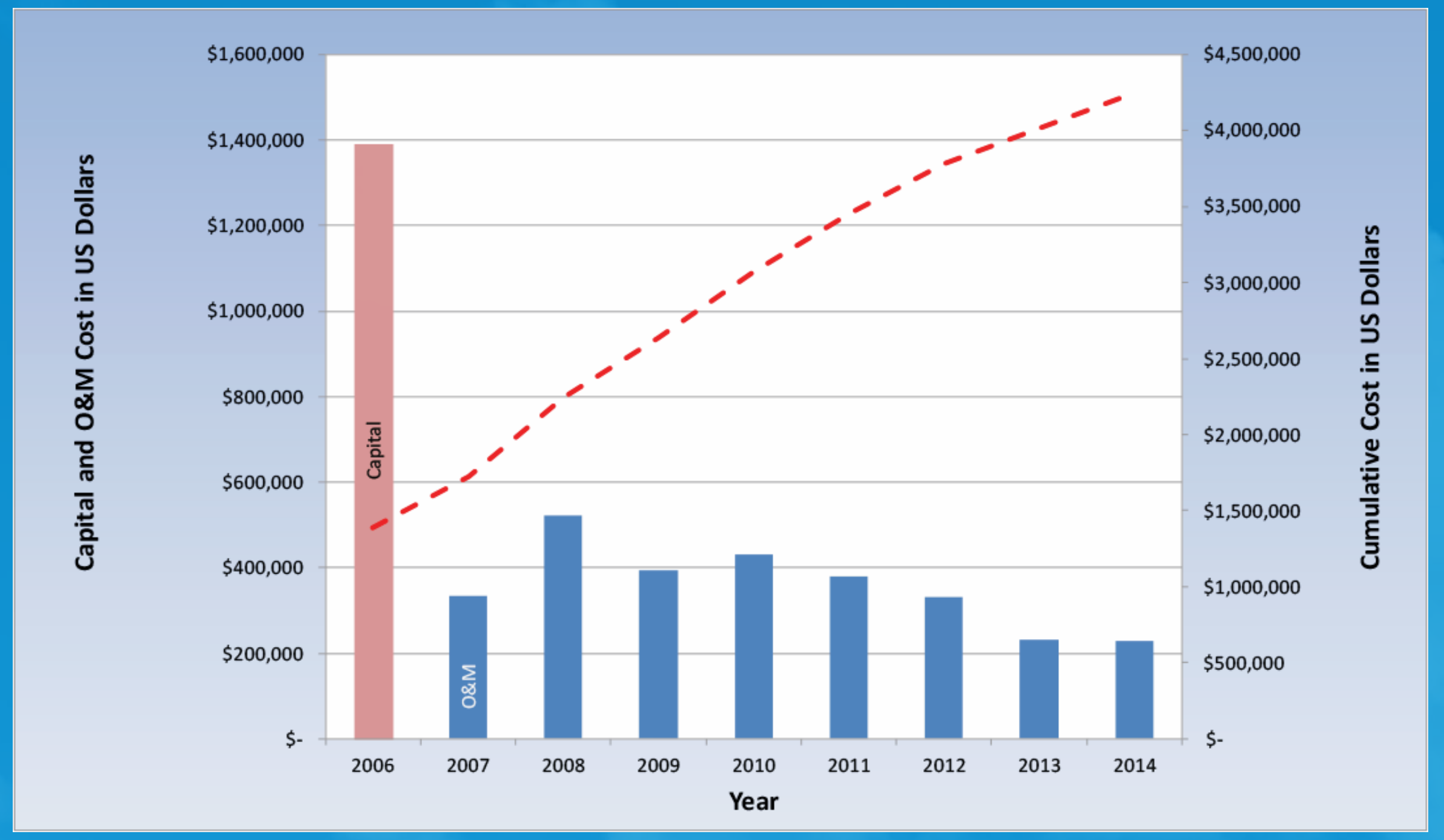


FIGURE 1 - Cumulative cost graph for the pump and treat

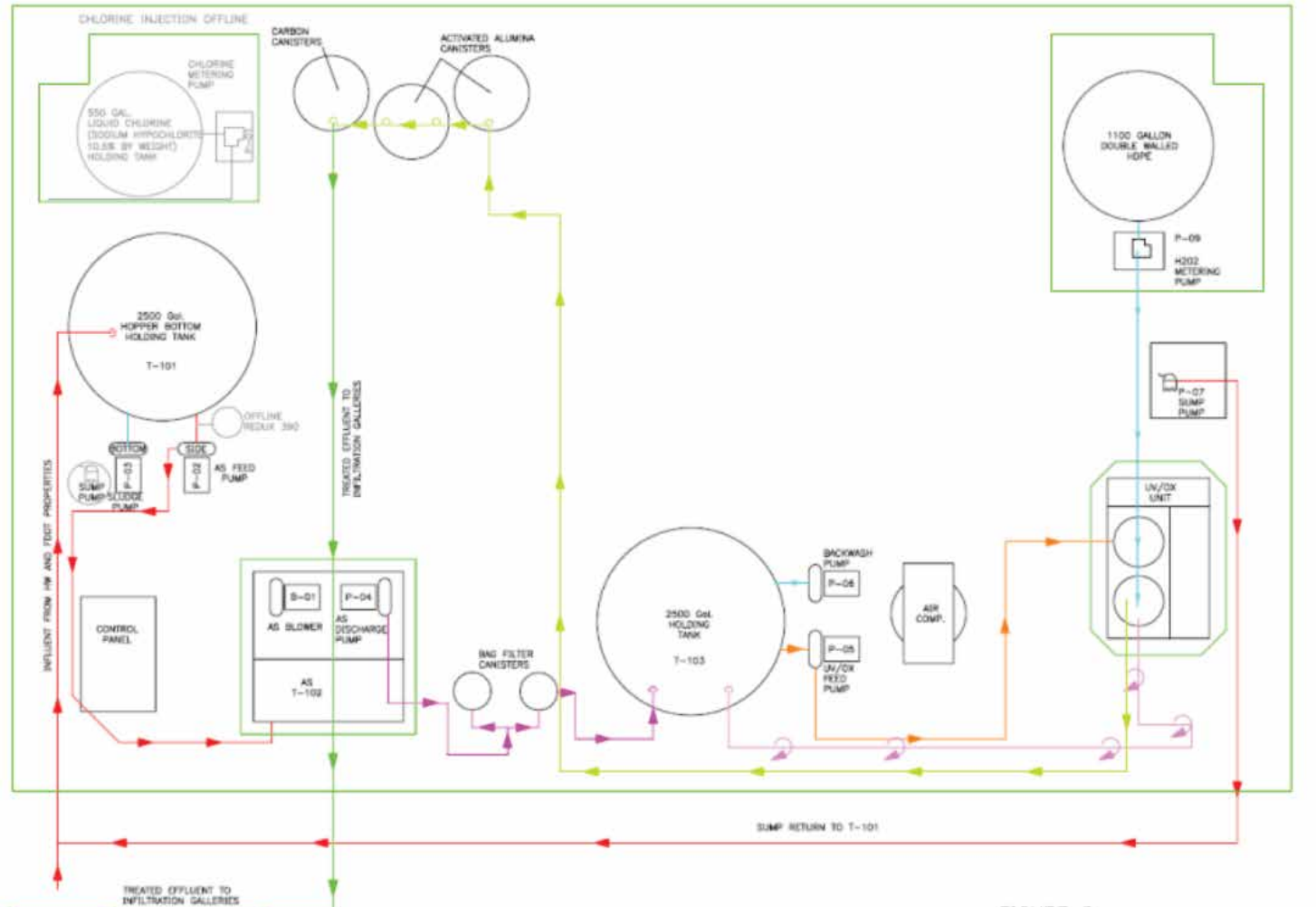
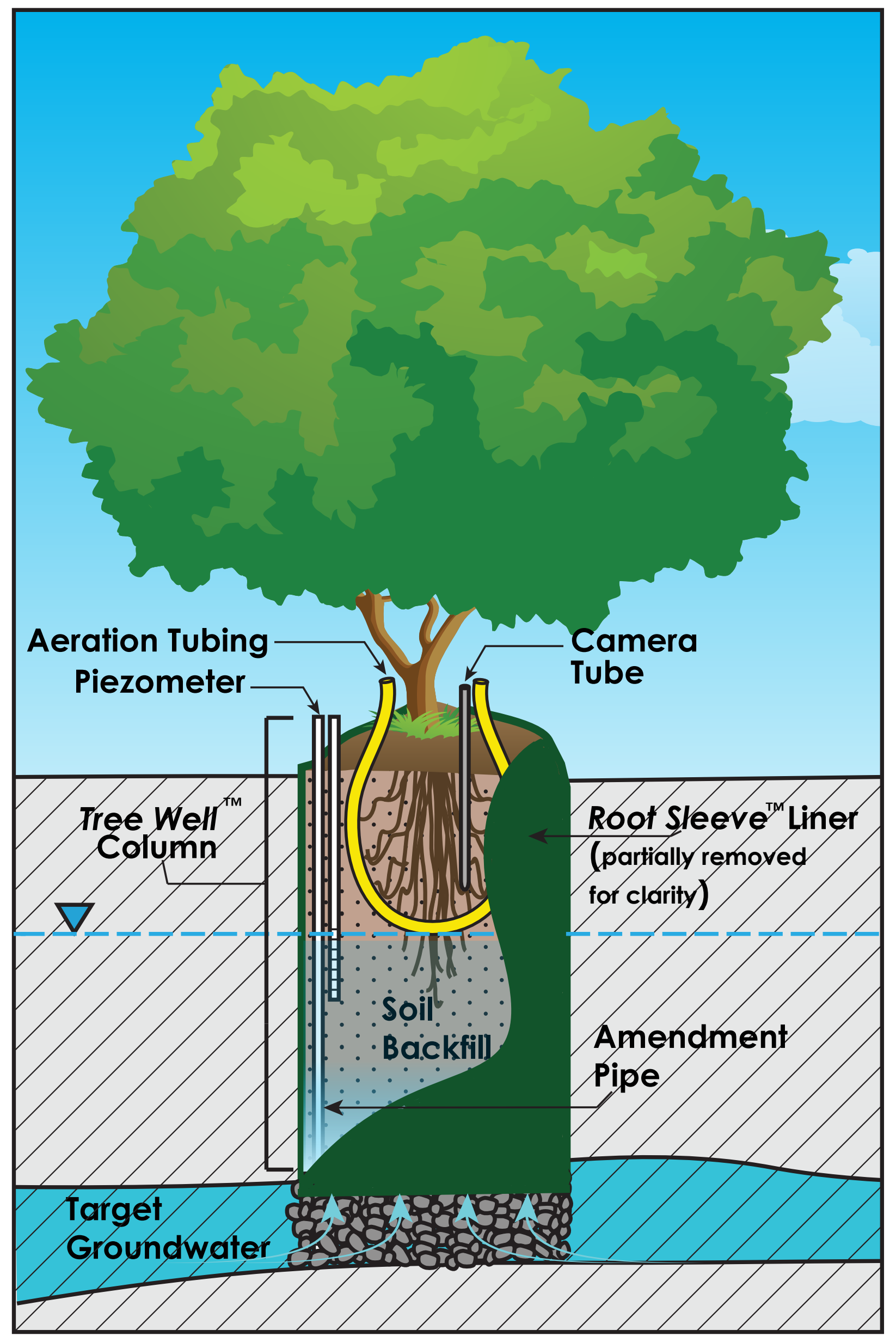


FIGURE 2 - Schematic

- Pump and Treat operated 8 years with little effect
- Treatment was via air stripping, particulate filtration, UV/OX, GAC and AA before discharge to groundwater infiltration trenches
- Design, construction and O&M costs from startup until shutdown in July 2014 were $4.24 million (approximately $0.50/gallon treated).
- Average O&M Costs during full operation years were $314K per year.

TreeWell® System – How it Works



- Creates an environment that only allows water from the targeted zone to enter the root-zone
- Encourages downward root growth to the target saturated zone (in this case fractured limestone)
- Capillary pressure draws contaminated GW to root zone

Benefits of the Engineered Phytoremediation Approach

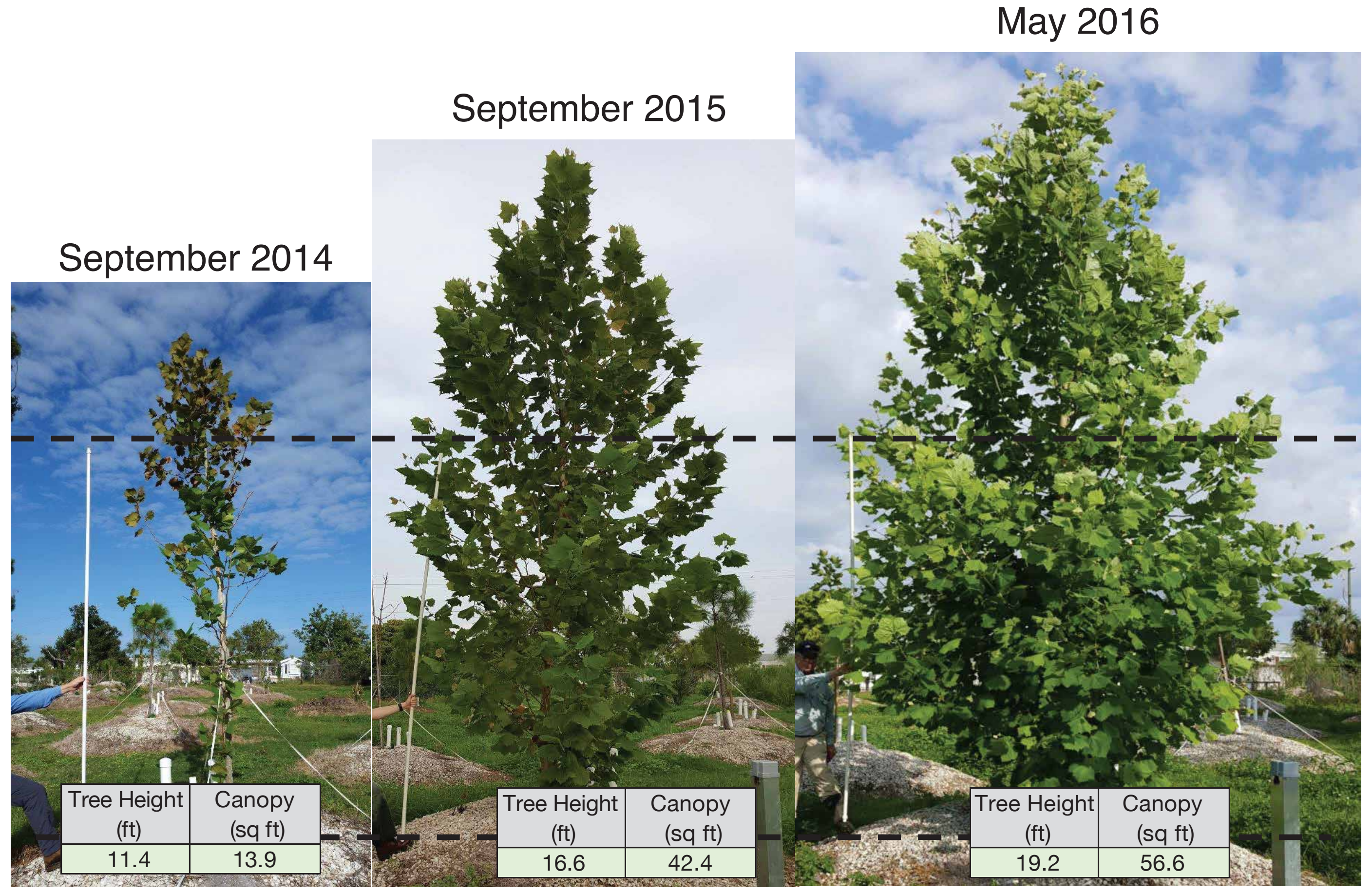
Primary Benefits

- Substitute for P&T system,
- More effective then P&T in low permeability zones
- "Active" remediation
- Low O&M costs

Secondary Benefits

- Aesthetic appeal to community
- "Enthusiastic" regulatory acceptance
- Green and sustainable

FIGURE 3



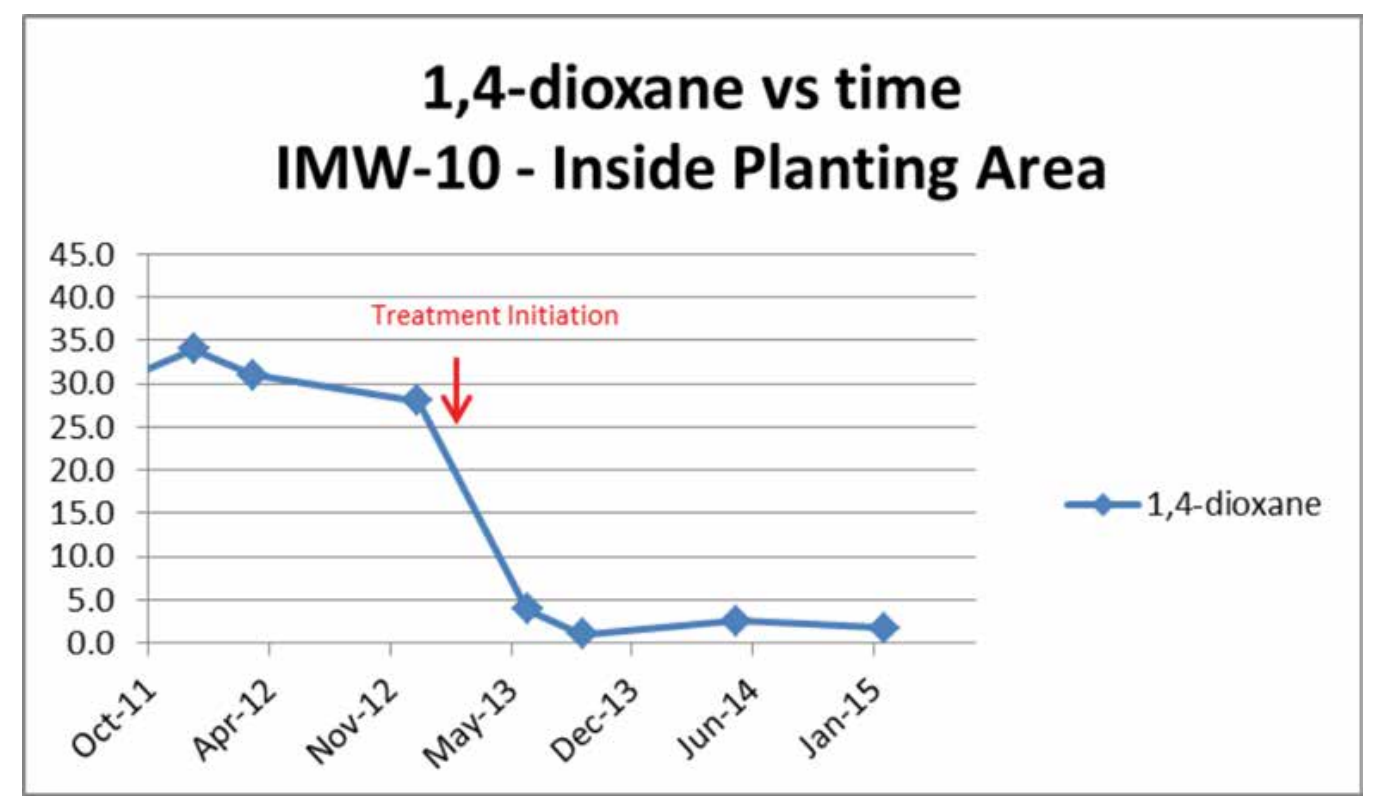
Tree Height (ft)	Canopy (sq ft)
11.4	13.9

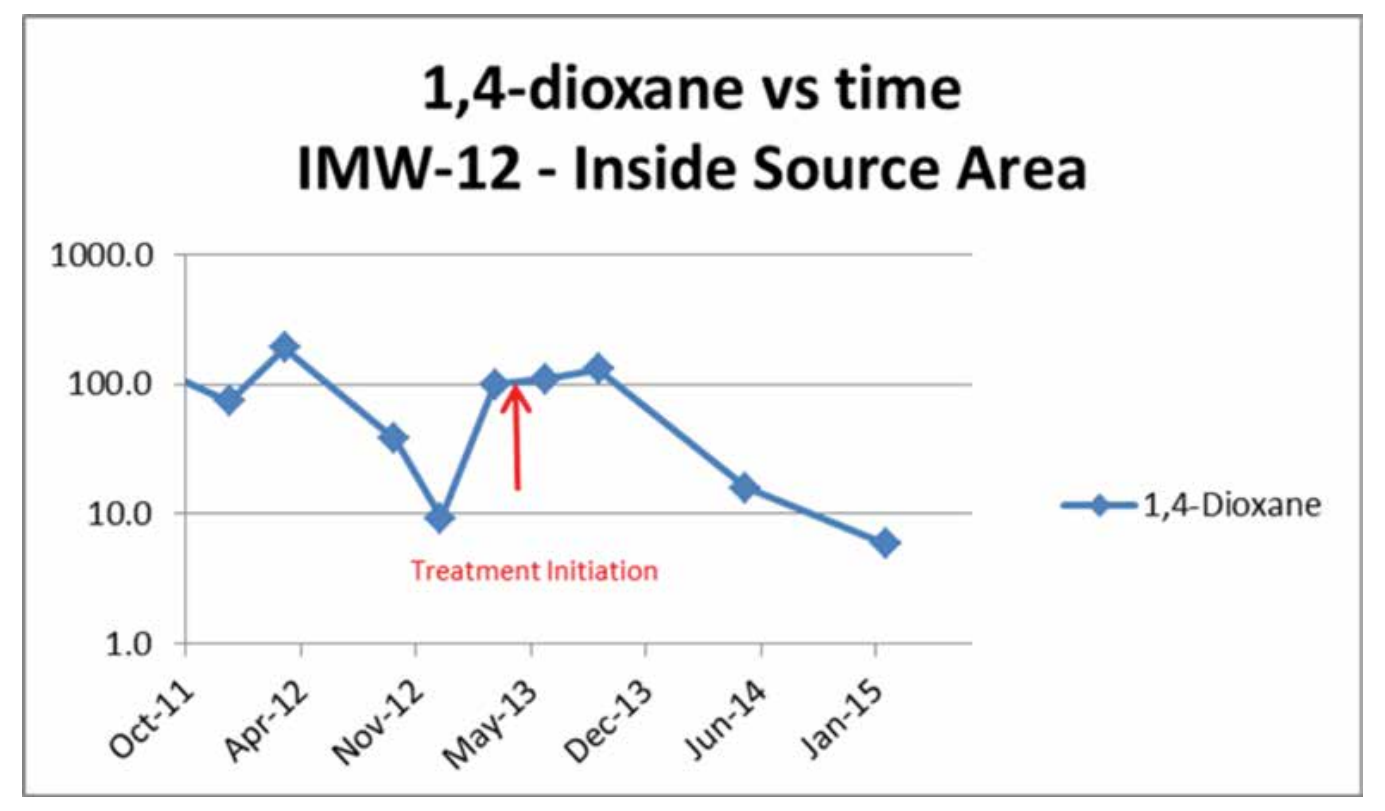
Tree Height (ft)	Canopy (sq ft)
16.6	42.4

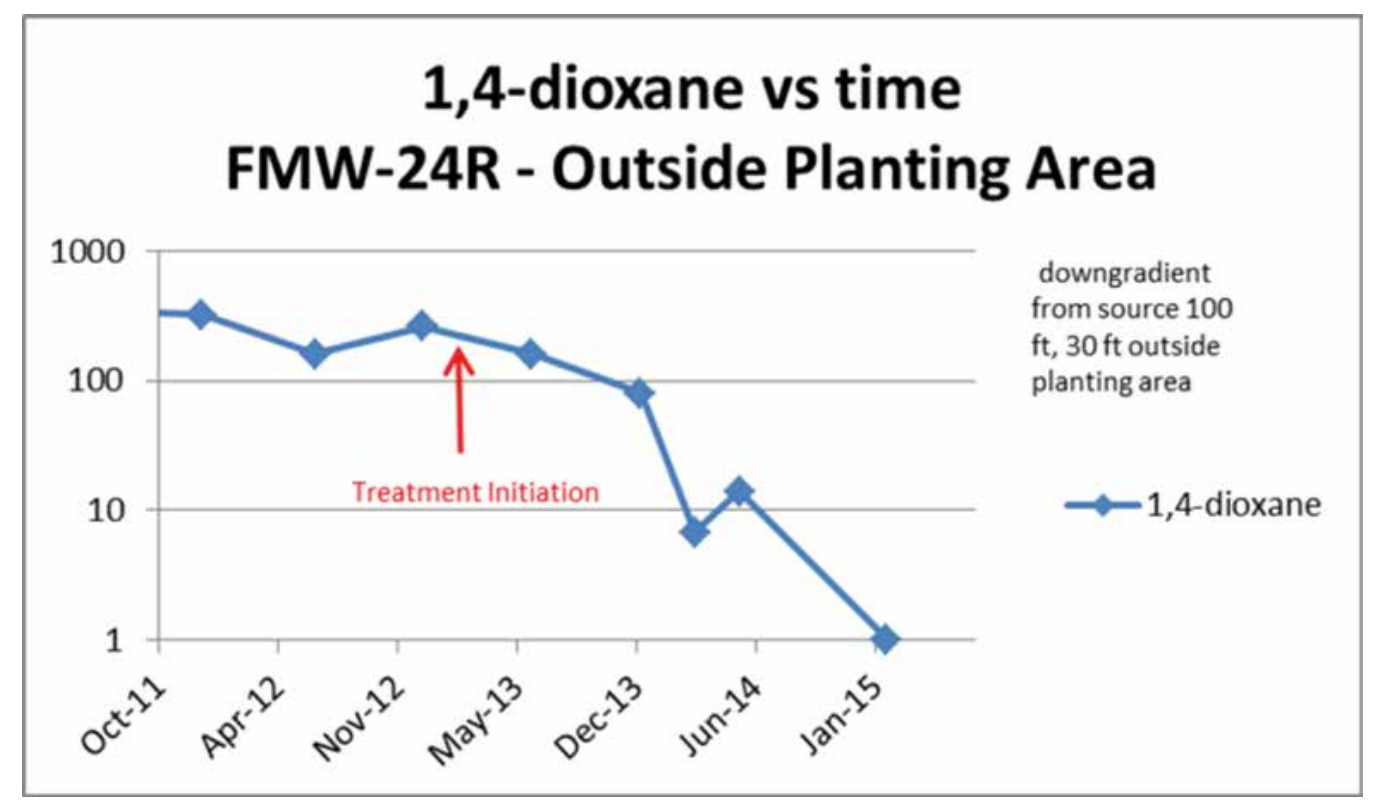
Tree Height (ft)	Canopy (sq ft)
19.2	56.6

FIGURE 4 - Sarasota - Growth of Sycamore D-11

Changes in Contaminant Concentrations vs Time



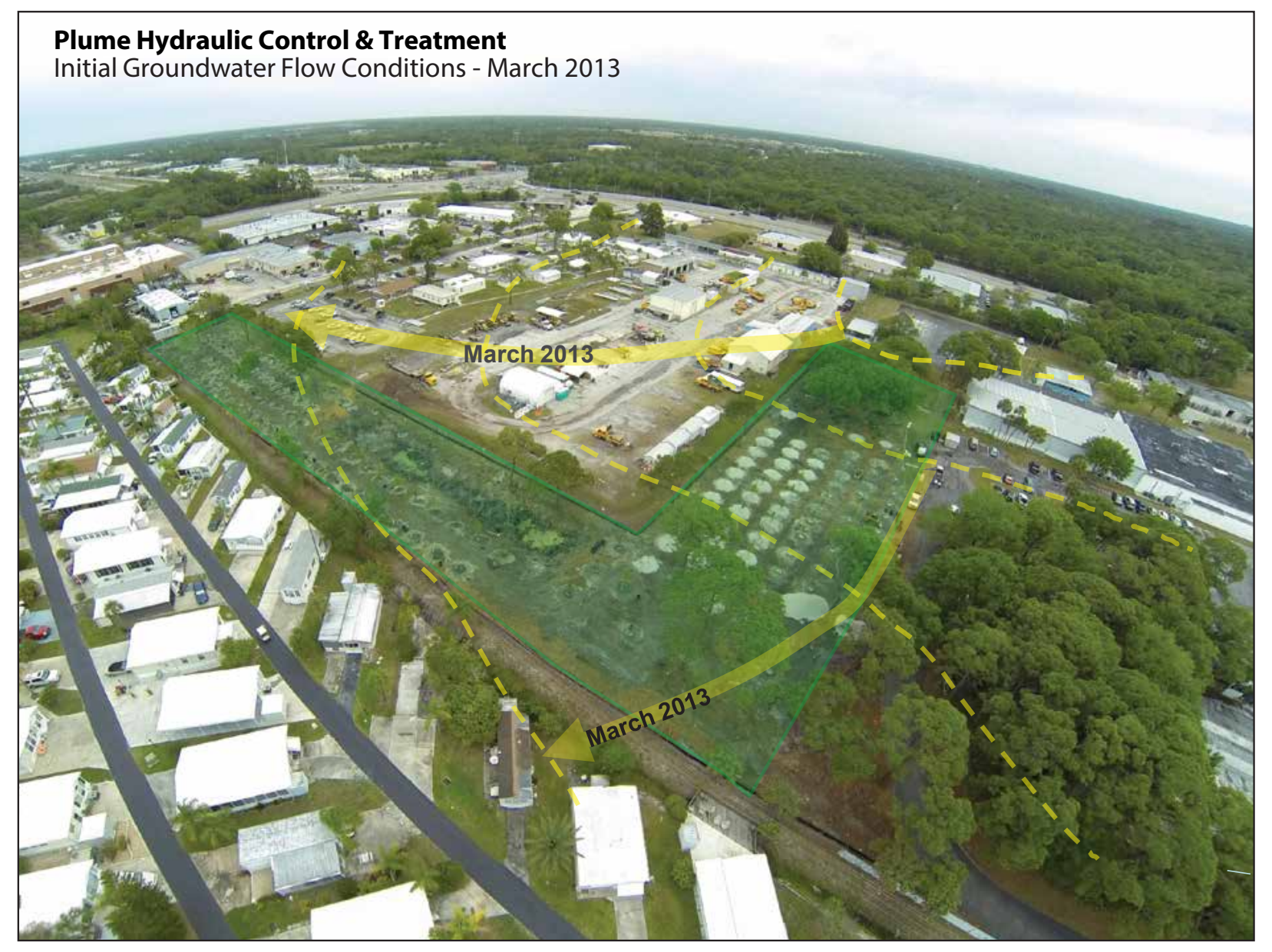




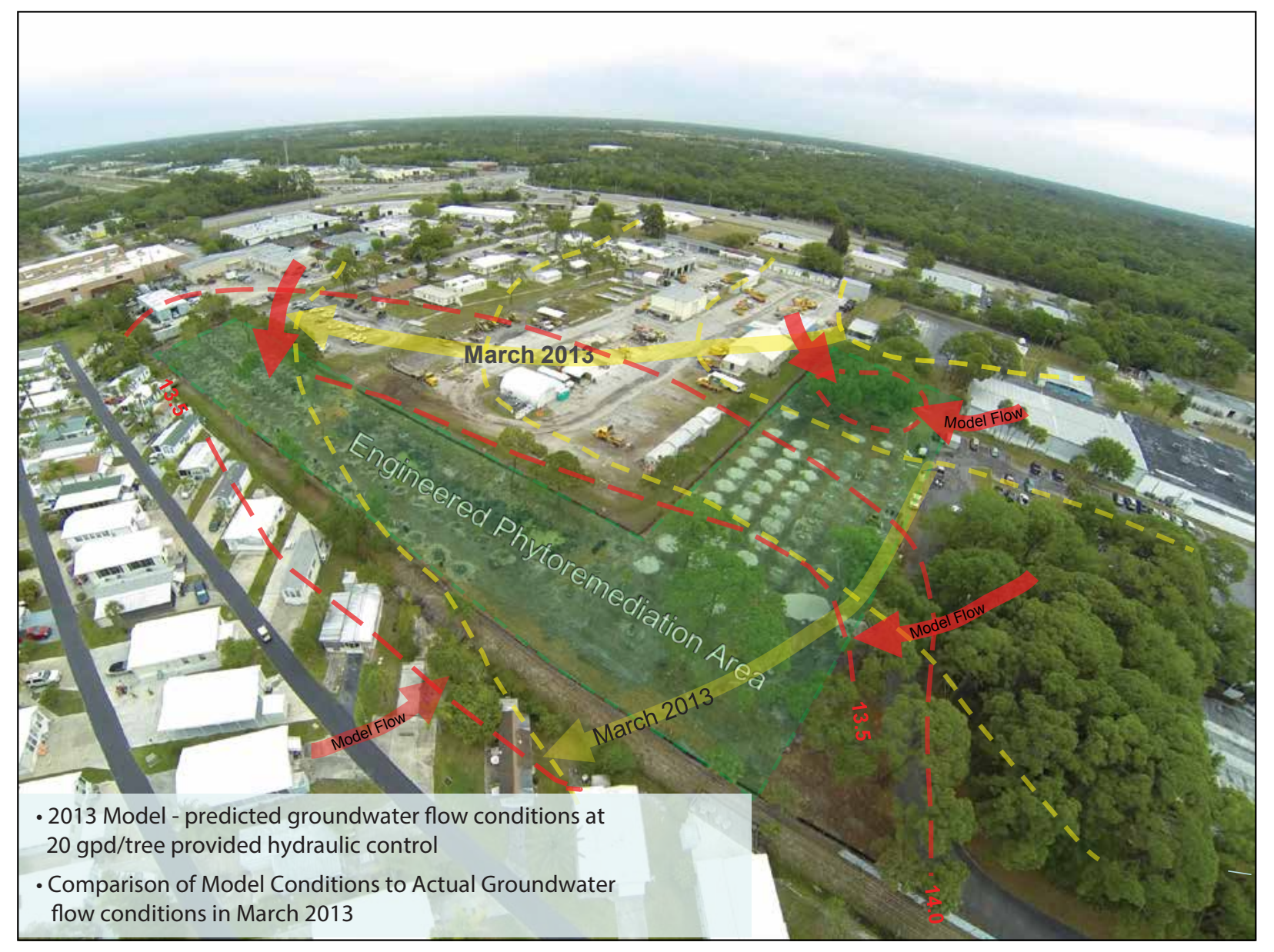
Sarasota - Performance of Phytoremediation System

Actual versus Groundwater Model Prediction

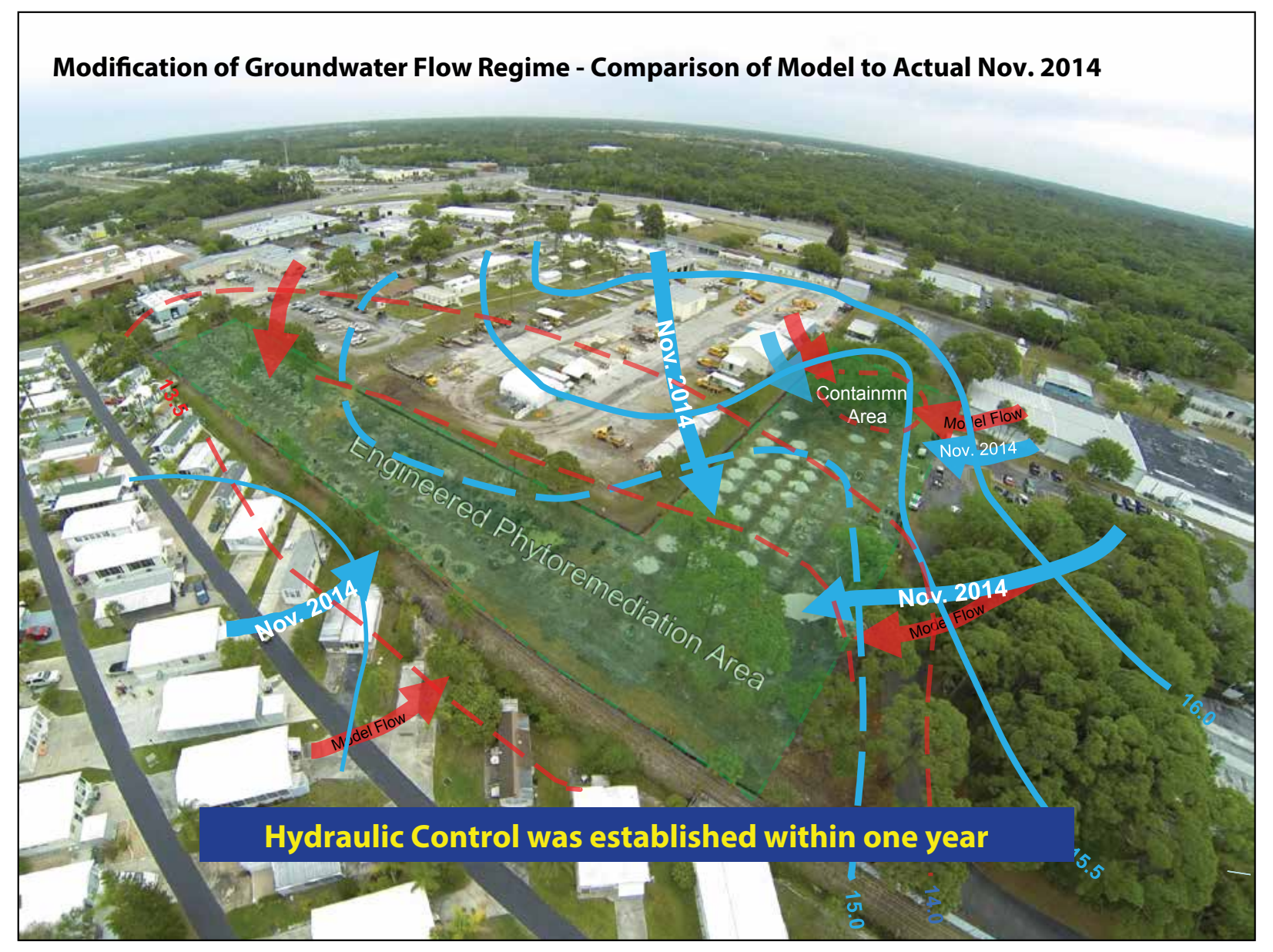
Note: Experience at Sarasota with predicted groundwater response versus actual has been applied to modeling of other sites with similar success



Plume Hydraulic Control & Treatment
Initial Groundwater Flow Conditions - March 2013

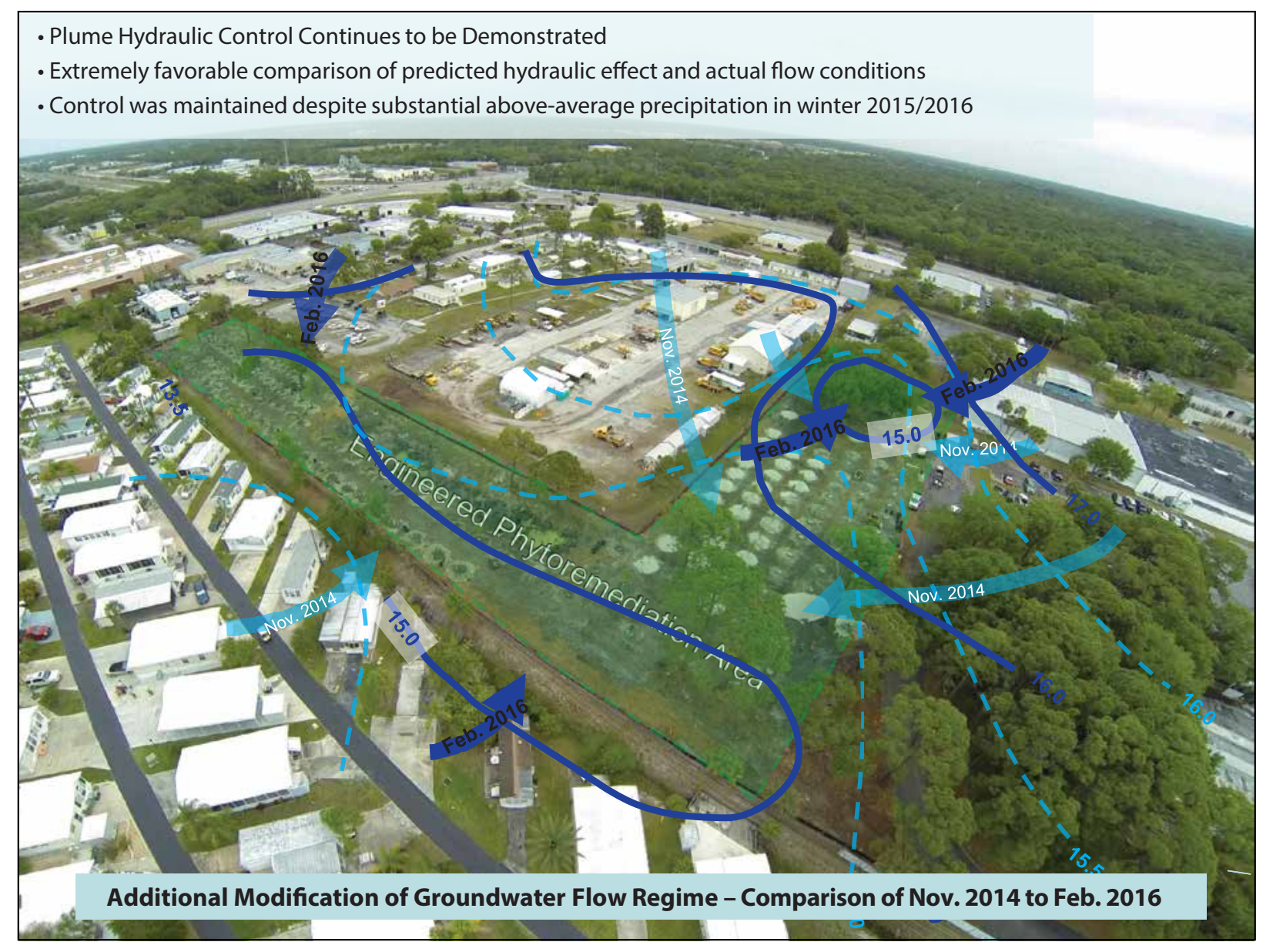


- 2013 Model - predicted groundwater flow conditions at 20 gpd/tree provided hydraulic control
- Comparison of Model Conditions to Actual Groundwater flow conditions in March 2013



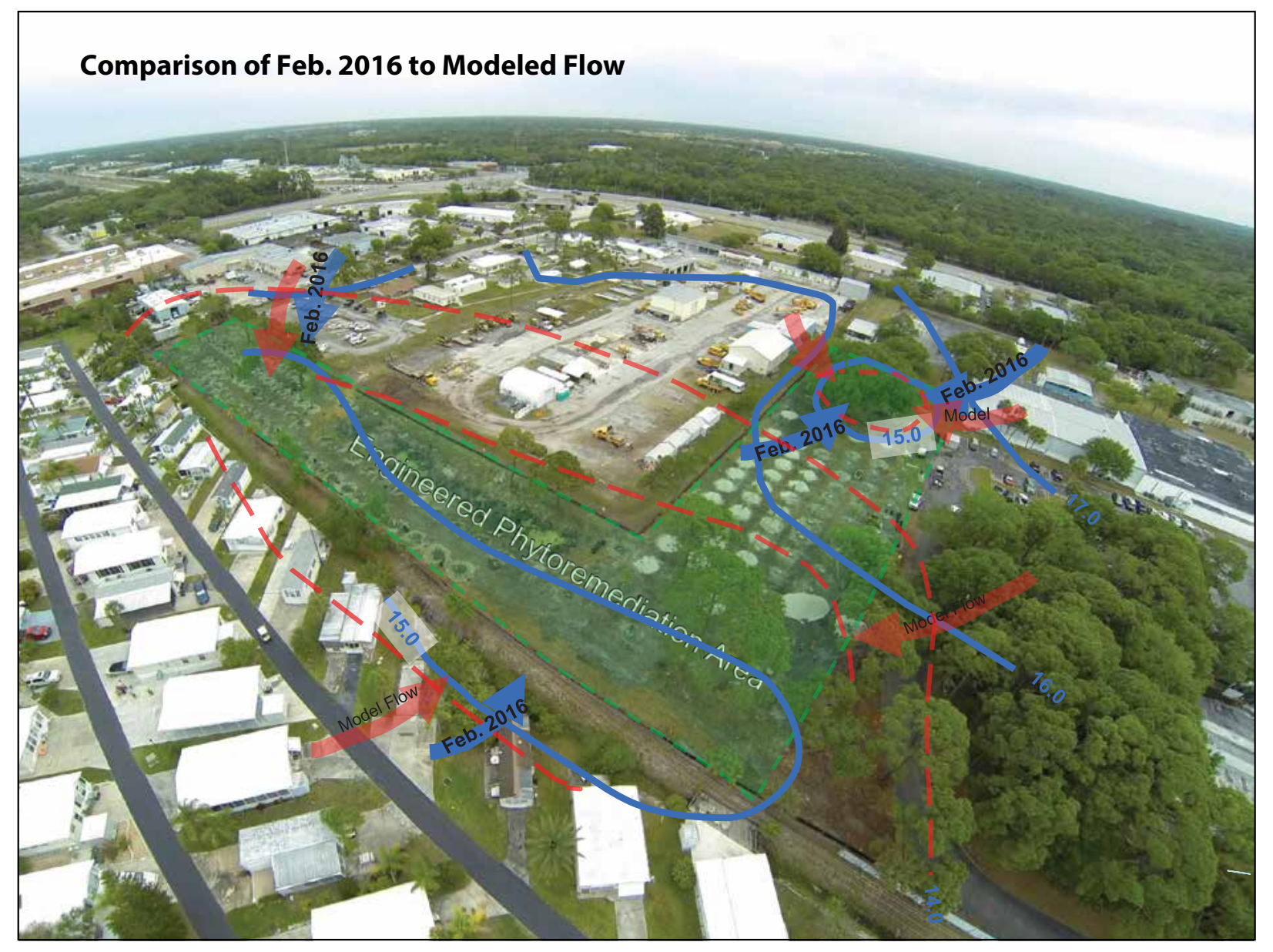
Modification of Groundwater Flow Regime - Comparison of Model to Actual Nov. 2014

Hydraulic Control was established within one year



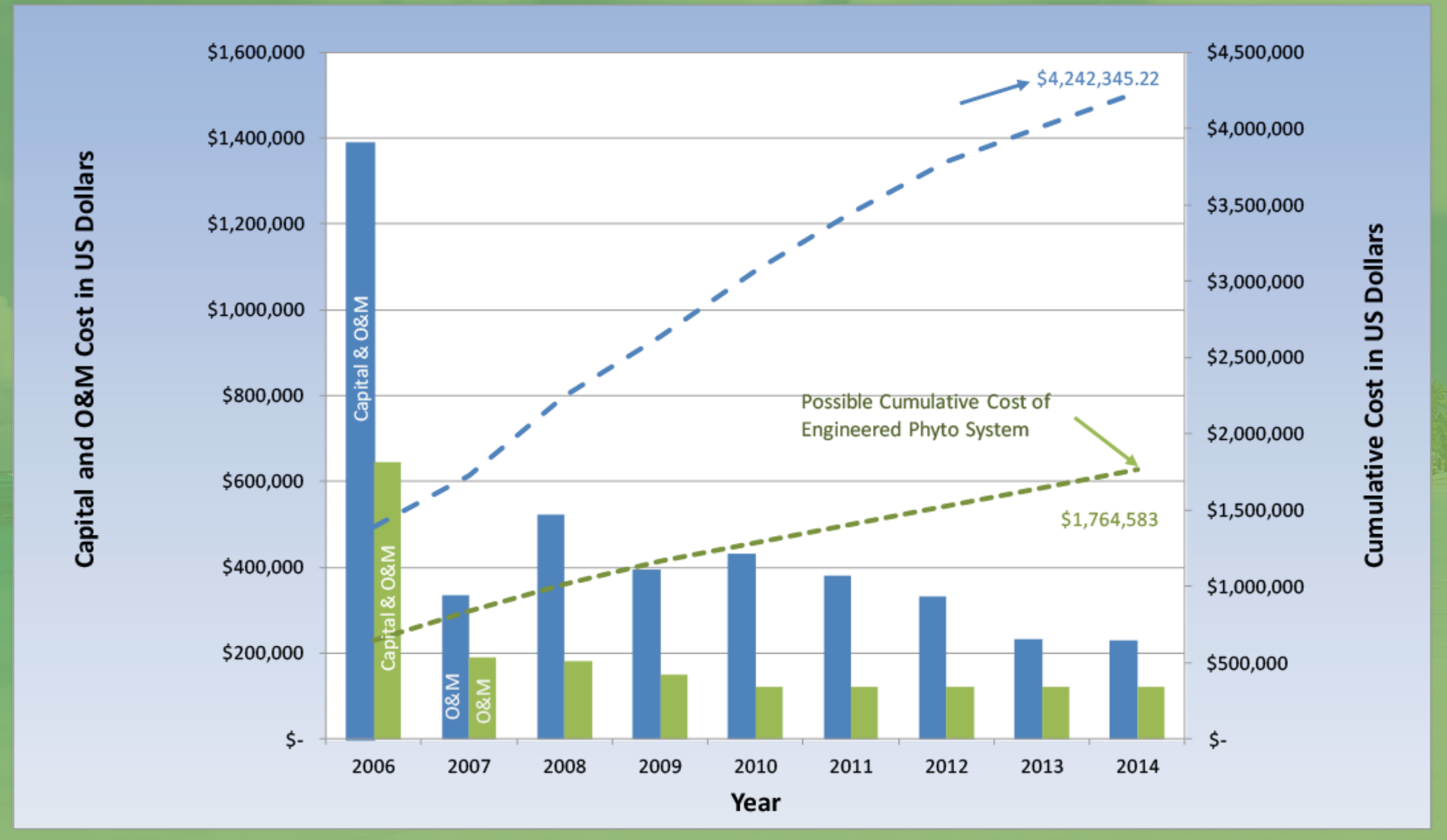
- Plume Hydraulic Control Continues to be Demonstrated
- Extremely favorable comparison of predicted hydraulic effect and actual flow conditions
- Control was maintained despite substantial above-average precipitation in winter 2015/2016

Additional Modification of Groundwater Flow Regime – Comparison of Nov. 2014 to Feb. 2016



Comparison of Feb. 2016 to Modeled Flow

What if we had started with Engineered Phytoremediation?



engineers | scientists | innovators

Linton (2018)

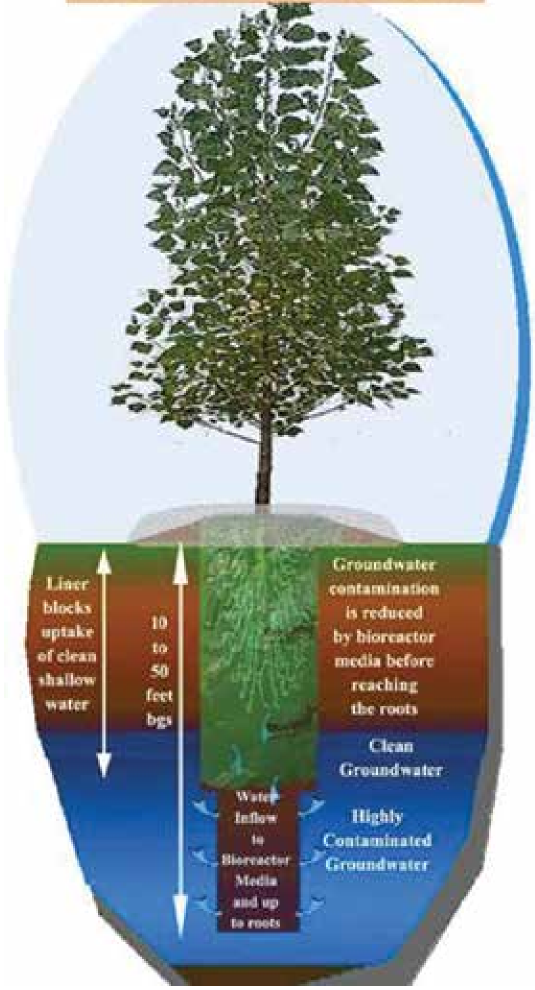
Engineered Phytotechnology for Plume Control and Treatment: Adapting a Natural System to Meet Remediation Goals

Engineered Phytotechnology for Plume Control and Treatment

Adapting a Natural System to Meet Remedial Goals

By P. James Linton

Model of the *TreeWell* Unit



Historically, remediation practitioners have been limited in their options for management and control of groundwater contaminant plumes. Mechanical pump-and-treat systems have often been employed for hydraulic control and treatment of impacted groundwater, but the high cost and limited success of these "active" groundwater treatment systems has emphasized the need for alternative technologies. Phytoremediation systems can be used to control plume migration and hydraulic gradients of impacted groundwater at sites where contaminants are accessible to tree roots, typically in shallow unconfined aquifers; however, at some locations, impacted groundwater may be inaccessible to tree roots due to depth of contaminants, compacted soil conditions that impede root growth, confined aquifers, and other factors that limit effectiveness of conventional approaches to phytoremediation. In such situations, engineered systems that allow for greater root penetration and access to groundwater at deeper depths or in confined aquifer units can be highly successful. By targeting only the depth interval requiring remediation, these designed phytoremediation systems can be a very effective strategy for hydraulic control of contaminant plumes.

The engineered phytotechnology system employed for the case studies presented in this article is the *TreeWell*® system developed by Applied Natural Sciences-ANS. A *TreeWell* unit in this system is constructed as a large-diameter well (usually 36-42 inches in diameter) that is advanced to the targeted depth. An impermeable liner is installed in the borehole to slightly above the targeted depth, and the borehole is then backfilled with a permeable growth media, and any desired amendments. Infrastructure to allow air penetration, access for fertilization, etc., are installed, and the tree is planted at the top of the

column. The top of the liner is then closed, effectively sealing the unit, and forcing the tree to seek water from the targeted zone.

The biological community that becomes established within the root zone creates an environment where contaminants are degraded, immobilized, or otherwise treated, with residual mass taken into the tree through the root system and either metabolized and fixed within the tree, or transpired out to the atmosphere.

The use of engineered phytotechnology also has esthetic advantages. The technology is both "green" and "sustainable," creates habitat for wildlife, and often is met with enthusiastic regulatory acceptance.

The primary benefit of engineered phytotechnology is that, where conditions render it applicable, it can be used to replace an ineffective or operation and maintenance intensive pump-and-treat system. It is considered an "active" form of remediation; however, the operation and maintenance costs are significantly less, and essentially limited to landscape maintenance and monitoring.

The use of engineered phytotechnology also has esthetic advantages. The technology is both "green" and "sustainable," creates habitat for wildlife, and often is met with enthusiastic regulatory acceptance.

Case Study #1 – Sarasota, Florida

The Sarasota facility manufactured speed and proximity sensors and was operational at this location since the early 1970s until plant operations ceased in 2008. Trichloroethene was historically used as a degreasing agent in the operations until the early 1980s, when it was replaced by 1,1,1-trichloroethane. Groundwater at the site is contaminated with elevated levels of chlorinated solvents, 1,4-dioxane, and arsenic resulting from facility activities and geochemical changes created by those activities. Conditions at the site are very complex with residual source areas both on and off site, multiple plumes both on and off site, and multiple contaminants.

A pump and treat system consisting of nine extraction wells and an extraction trench, air-stripping, ion exchange, and UV/Peroxide treatment, an infiltration gallery and alternative NPDES-permitted discharge, had been operating at the site for approximately 12 years, at a cost of approximately $350,000 annually. Due to aquifer

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Engineered Phytotechnology for Plume Control and Treatment

continued from page 23

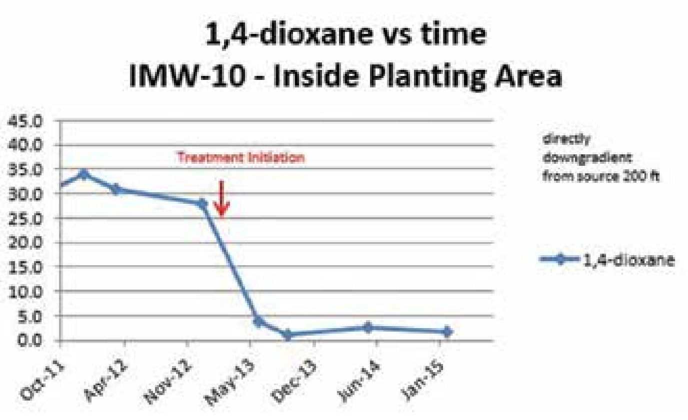
properties, the system was only able to extract and treat at a very low rate (10 gallons per minute [gpm]) and was not effectively reducing concentrations within the groundwater plume. A minimum of 25 years of additional operation were predicted to reach site closure conditions. The remedial goals for the site were:

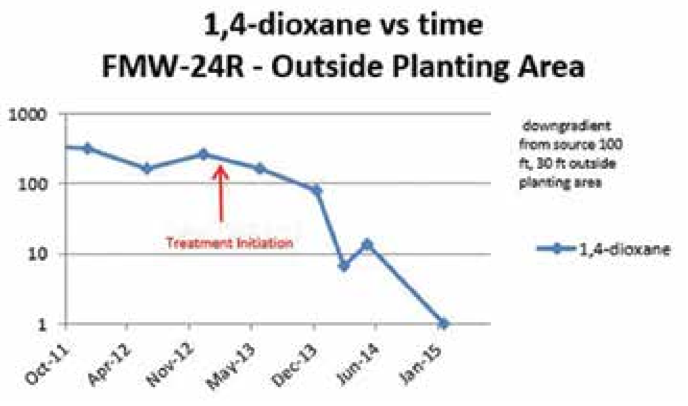
- Reduce contaminant concentrations within the plume to levels that would be acceptable to the regulatory agency for a risk-based conditional closure, and
- Provide hydraulic control to prevent the plume, in particular 1,4-dioxane, from migrating off-site, and to allow shut-down of the existing pump and treat system within a reasonable time frame.

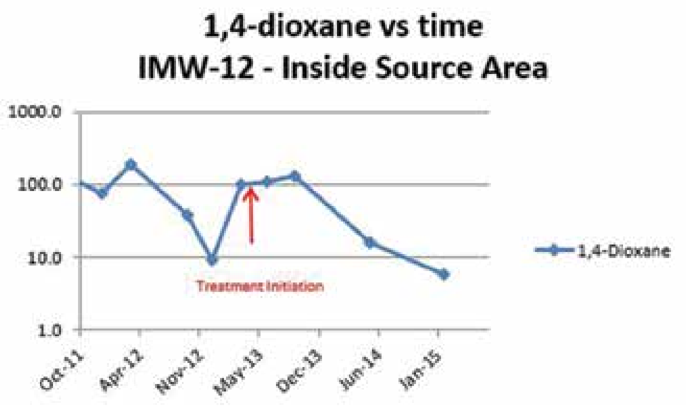
Vertical lithology profiling determined that groundwater flow in the surficial aquifer was actually limited to a permeable zone from approximately 5 to 7 feet depth. A pump test of this permeable zone was conducted, and a groundwater flow model was developed to estimate the location of the potential 1,4-dioxane source area. Vertical profile data for contaminant distribution using discrete interval groundwater sampling were collected in this area to assess the horizontal extent of the elevated groundwater impacts and to precisely define the relationship between contaminant distribution and lithology. A remedy was implemented, on the basis of this information, that included:

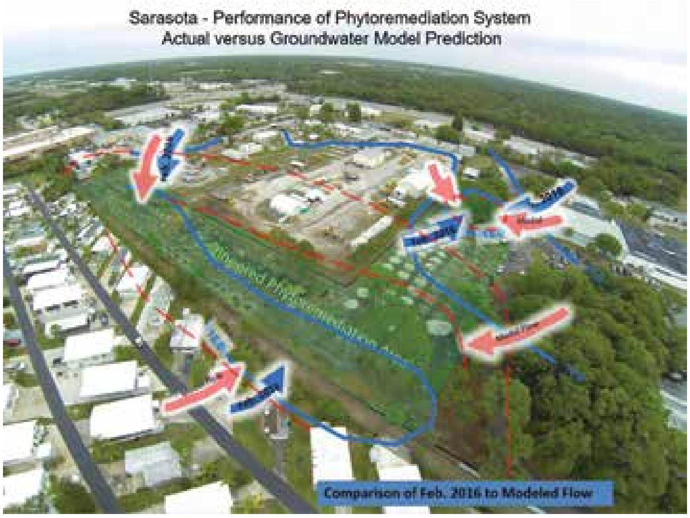
- Isolation of the remaining 1,4-dioxane source (HDPE liner installed within a vertical trench), and
- Phytoremediation through reclamation of an on-site distressed wetland, using native species in an engineered planting targeting the permeable lithologic zone, to both treat the dissolved plume, and provide hydraulic control.

Hydraulic control was established by the second growing season, allowing termination of the existing mechanical pump and treat system operation. Installation of the isolation barrier essentially created a closed lysimeter which forced existing mature trees to seek water in the deeper permeable zone. By the end of the fourth growing season, contaminant concentrations in the source area and downgradient plume had been reduced to slightly above the State Cleanup Target Levels, and a conditional No Further Action proposal was submitted and approved.









Case Study #2 – Danville, Illinois

The Danville, Illinois case study is for a facility that produced and repackaged chlorofluorocarbon refrigerants from 1955 until present. In 1978, a significant release of carbon tetrachloride was identified in the site rail loadout area, and an Interim Remediation Measure pump-and-treat system was installed and activated to prevent off-site migration of the plume and address the source—an area of free-phase carbon tetrachloride within some thin gravel and sand lenses 18 to 25 feet below ground surface in tight glacial till. The tight nature of the formation created difficulties for operation of the pump-and-treat system,

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Engineered Phytotechnology for Plume Control and Treatment

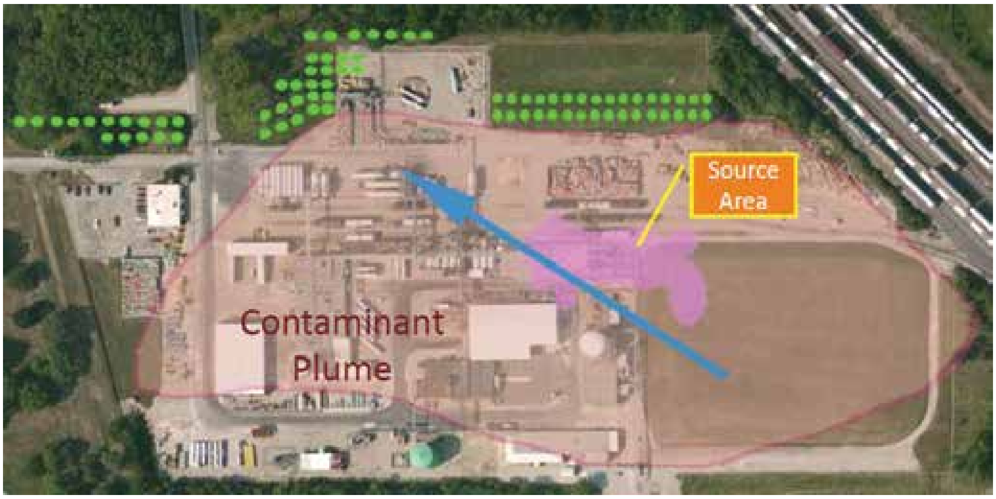
continued from page 25

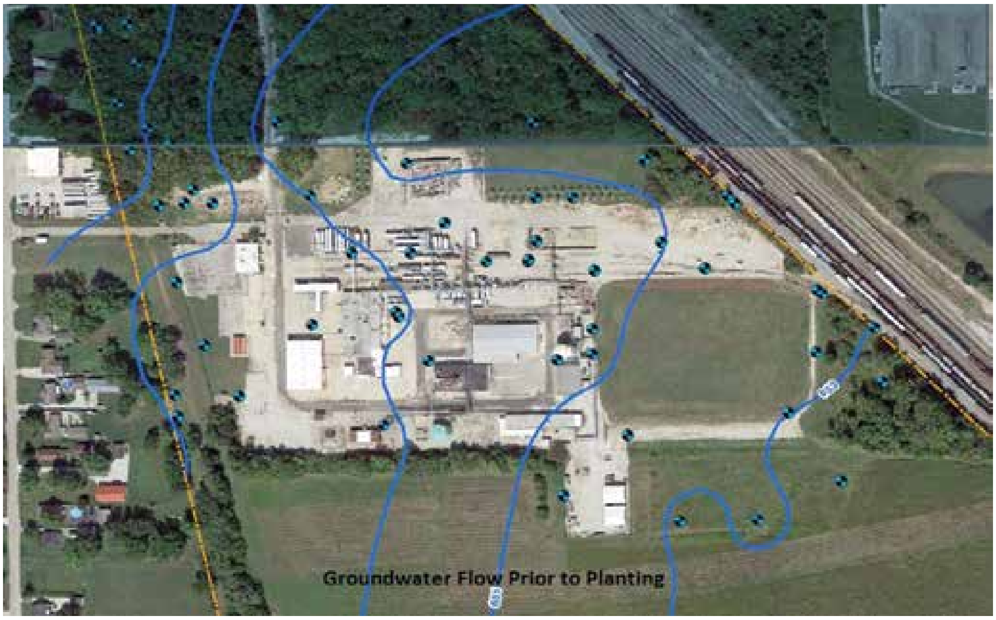
A site assessment was conducted during 2008 and 2009, and it was determined that the pump-and-treat system was ineffective.

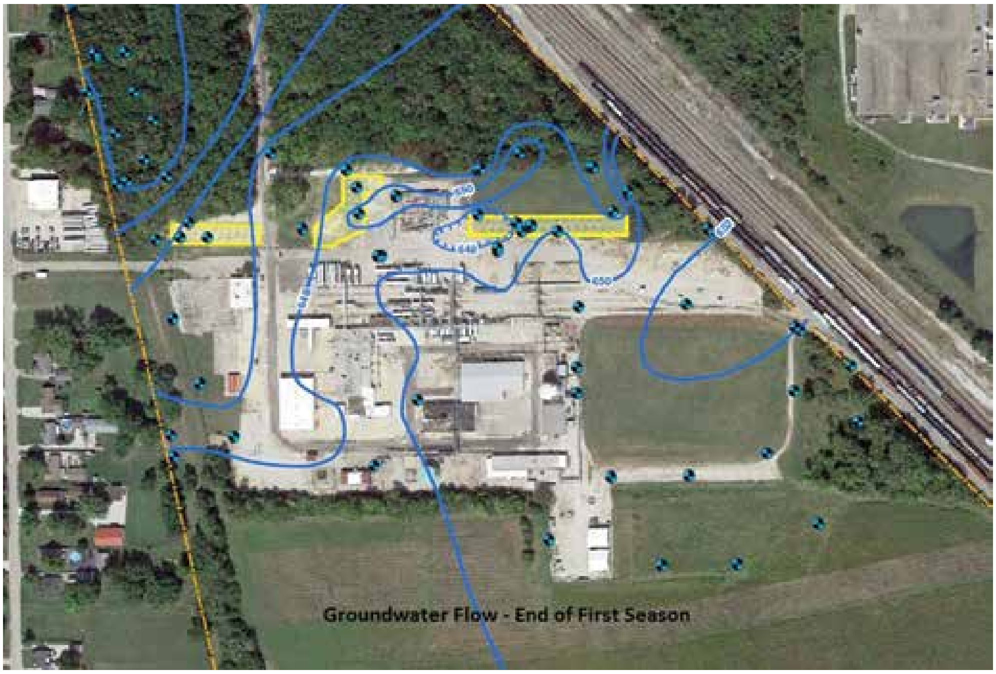
that had to be run as a batch process, with an overall average extraction rate of 0.2 gpm. A site assessment was conducted during 2008 and 2009, and it was determined that the pump-and-treat system was ineffective. Remedial goals were established that included:

- Mass reduction in the source area, and
- Hydraulic control of the downgradient plume to prevent off-site migration of contaminated groundwater.

A Remedial Alternatives Evaluation was completed in 2014. One complicating factor was the location of the source area beneath the active rail loadout area—the selected remedy needed to be able to be applied without demolishing the rail yard or disrupting plant operations. A change in ownership and operations was planned for late 2017 that would result in a temporary shutdown of the facility in 2018. On this basis, electrical resistive heating (ERH) was







selected as the remedy to address the source area.

Trees are very efficient at extracting water. The *TreeWell* system was evaluated as the means for establishing the hydraulic control portion of the remedy. A groundwater flow model was created to determine the number of *TreeWell* units that would be required, and the optimal placement of those units. A total of 79 *TreeWell* units were installed. Hydraulic control was becoming established by the end of the first growing season, confirming the predictive model.

The pump-and-treat system (with the associated O&M cost) was idled after the first growing season. Source area treatment is currently underway.

Case Study #3 – Shelby, North Carolina

The Shelby, North Carolina case study is an active electronic manufacturing facility that produces switches and electrical products for the automotive, appliance, and climate control industries. The facility began operation in 1974, and employed 1,1,1-trichloroethane (and associated 1,4-dioxane) for degreasing baths. Sludge from a solvent recovery still and used hydraulic oil were disposed in a ditch on-site until 1982. Contaminated soil was excavated and removed in 1983, and groundwater assessment was initiated in 1986. An air-sparging system was installed and operated from 1996 through 2006. In 2007, and continuing to recently, groundwater remediation had been addressed through the operation of an Accelerated Remediation Technologies, LLC (ART^{TM}) in-well circulation system with ozone enhancement to address the 1,4-dioxane. Mass reduction resulting from operation of this system had become asymptotic with groundwater concentrations remaining an order of magnitude above regulatory levels. In addition, groundwater with concentrations greater than surface water criteria was discharging to an adjacent stream, the only risk pathway/receptor associated with the site.

The remedial goal for the site was to develop a final

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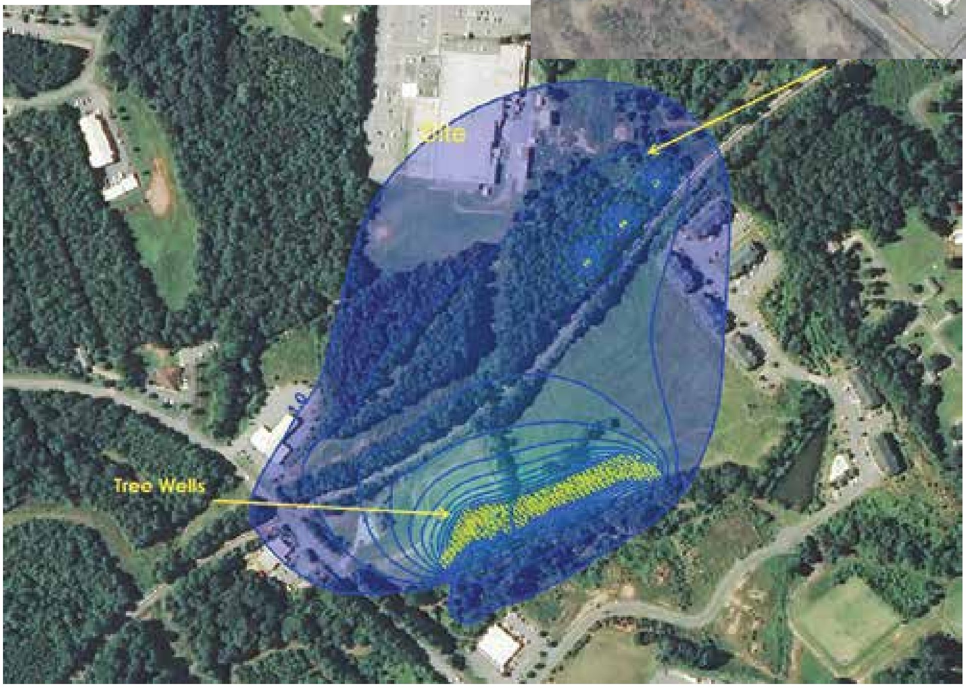

The remedial goal for the site was to develop a final remedy for plume treatment and control that would reduce the flow and concentration of contaminated groundwater so that it would not exceed surface water criteria at the discharge to the adjacent stream.

Engineered Phytotechnology for Plume Control and Treatment

continued from page 27

The TreeWell system has demonstrated effectiveness for prevention of discharge to surface water.

remedy for plume treatment and control that would reduce the flow and concentration of contaminated groundwater so that it would not exceed surface water criteria at the discharge to the adjacent stream. Steps taken during a remedial alternatives evaluation included:

- Definition of the relationship between contaminant distribution and lithology,
- Development of an understanding of lithologic and hydrogeologic characteristics influencing the fate and transport of the contaminants in groundwater, and
- Evaluation of the potential for the use of phytoremediation as a final remedy for plume treatment and control.

Vertical lithology and geochemical profiling determined that the contaminant concentrations were primarily contained in the saprolite zone immediately above the bedrock, and that the bedrock was acting as an aquiclude. A pump test was then conducted to evaluate the hydraulic characteristics of the saprolite. These data were used to prepare a groundwater flow model to aid in the design of a *TreeWell* system to meet the remedial goal.

A 152-unit *TreeWell* system was installed in the spring of 2015. The *TreeWell* system has demonstrated effectiveness for prevention of discharge to surface water. The ART^{TM} system (and associated O&M costs) has since been disabled and abandoned, and a conditional No Further Action is being negotiated for the site.

About the Author:

P. James Linton is an environmental scientist with over 30 years of experience in the environmental field in Florida, including wetland and upland ecological studies, and assessment and remediation of contaminated sites. With a strong background in botany, horticulture, and chemistry, Jim has become a strong advocate for the application of engineered phytotechnology for the reclamation of contaminated and stressed property. He has successfully applied these concepts at multiple sites in varying climates around the country, including Florida.

USEPA (2020)

Phytoremediation at 317/319 Area, Argonne National Laboratory in Illinois (CLU-IN Profile)

U.S. EPA Contaminated Site Cleanup Information (CLU-IN)

CLU-IN | Databases | Phytotechnology Project Profiles | Phytoremediation at 317/319 Area, Argonne National Laboratory in Illinois

Phytotechnology Project Profiles

Phytoremediation at 317/319 Area, Argonne National Laboratory in Illinois

- Home
- Search Profiles
- Submit a New Profile
- Update an Existing Profile
- Description of Web Site
- Disclaimer

Last Updated: Fall 2004

Site Information

Site Name, Location:	Argonne National Laboratory, Lemont, IL, United States
Site Type:	Federal Facility
Is this a Federal Superfund Site?	Yes
ROD Date, if applicable:	09/29/1998
Is this a Federal or Military Site?	Yes
Entity Responsible for Cleanup:	DOE

Project Information

Project Name:	Phytoremediation at 317/319 Area, Argonne National Laboratory in Illinois
Site History and Background:	The 317/319 Area at Argonne National Laboratory contains several sites used in the past to dispose of solid and liquid waste from various laboratory activities. Because of these past activities, VOCs and tritium have been released in the groundwater at depths of approximately 6-9 m and have been detected in groundwater offsite.
Scale:	Full
Project Status:	Ongoing
Project Start Date:	1999

Media Treated:

Media	Qty.	Geology	Comments
Soil		Geology at the site consists of 10 feet silty clay at the top, followed by 2 foot shallow aquifer, 8 foot silty clay, 10 foot silt and finally silty clay deep aquifer at the bottom.	
Ground Water		Groundwater at 25 to 30 feet below ground surface; aquifer 5 feet	

Contaminants Treated:

Contaminant	Initial Concentration	Depth	Media	Comments
Arsenic			Soil	
Arsenic			Ground Water	
Carbon tetrachloride			Soil	
Carbon tetrachloride			Ground Water	
Chloroform			Soil	
Chloroform			Ground Water	
Lead			Soil	
Lead			Ground Water	
Tetrachloroethene			Soil	

Tetrachloroethene	Ground Water
Trichloroethene	Soil
Trichloroethene	Ground Water
Zinc	Soil
Zinc	Ground Water
Tritium	Soil
Tritium	Ground Water

Phytotechnology Mechanism(s):

Phytoremediation
Hydraulic Control
Phytoextraction
Phytostabilization
Rhizodegradation
Phytodegradation

Plants and other Vegetation Used:

Hybrid Poplar
Eastern Gamagrass
Golden Weeping Willow
Hybrid Prairie Cascade Willow
Laurel-Leaved Willow

Planting Description:

800 whips planted. 420 poplars installed in deep, lined boreholes (TreeWells). 389 willows and poplars planted at or near surface. Used patented TreeWells and TreeMediation (Applied Natural Sciences Inc.) In 1999 Argonne installed a series of engineered plantings consisting of a vegetative cover system and approximately 800 hybrid poplars and willows rooting at various predetermined depths. Because of the peculiar stratigraphy at this site and the depth of the target contamination, the plants were installed using various methods including Applied Natural Sciences? TreeWell® system.

Planting Area:

4 acres

O & M Requirements:

Fertilization, replanting, and significant Health/Safety expenditures because of radiological and other concerns

Performance Data:

Qualitatively results are good. Hydraulic control is apparent and VOCs have been detected in the plant tissue indicating uptake. But no quantitative results are available. From these data it is apparent that the trees have begun to influence the area. Only months after planting, both TCE and PCE were detected in branch tissue of trees growing in the source area soil. Correspondingly, trichloroacetic acid, a degradation intermediate, was consistently detected in leaves of these same plants. Two years after planting, TCE and PCE began to be detected also in tissue of several trees targeting the downgradient contaminant plume, and the number of detections has continued to increase with time. By the fall of 2002, several trees showed significantly higher tritium concentrations that approached the concentration of the groundwater in the area. Soil sample evidence shows that roots had developed at to at least 4 m by the fall of 2001.

Cost of the Phytotechnology Project:

$1,200,000

Lessons Learned:

Tree Wells installed in effort to achieve hydraulic control. During a warm period in September 2000, the plantation began exhibiting diurnal fluctuations (up to 7 cm) in groundwater elevation at selected monitoring wells. The diurnal fluctuations continued during the 2001 growing season and varied in amplitude with the amount of daily solar radiation. In 2001 water levels of some wells gradually lowered during days of high sunlight resulting in strong diurnal fluctuations. On cloudy days water level changes were less pronounced. These water level changes were an early indicator that the maturing trees will exert an increasing effect on the site?s hydrology, which will ultimately result in hydraulic containment of the contaminant.

Comments:

This progression was expected as a consequence of the time necessary for the roots to develop to the capillary fringe. Results of this modeling suggest that despite leaf-off winter periods, the plantation will provide full containment on the larger western (317 Area) side of the plantation, and a strong degree of containment on the eastern (319 Area) side.

Point(s) of Contact

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Applied Natural Sciences, Inc.
Hamilton, OH United States
Telephone: (513) 895-6061
E-mail: ans@treemediation.com

Information Source(s):

Negri, M.C. et al 2003. Root Development and Rooting at Depths, in S.C.

McCutcheon and J.L Schnoor, eds., Phytoremediation: Transformation and Control of Contaminants: Hoboken, NJ, John Wiley & Sons, Inc. p, 233-262, 912-913

Quinn, J.J., et al 200 Predicting the Effect of Deep-Rooted Hybrid Poplars on the Groundwater Flow System at a Phytoremediation Site: International Journal of Phytoremediation, vol. 3, no. 1, p. 41-60.

Phytoremediation at Argonne
http://web.ead.anl.gov/phyto/

Project update provided to Ellen Rubin by Cristina Negri. October 2004

Negri, M. Cristina; John Quinn; Casey Hamilton; Edward G. Gatliff. 2003. Phytoremediation for Plume Control of Deep Groundwater. From International Applied Phytotechnologies Conference, March 3-5.
http://www.cluin.org/studio/2003phyto/abstracts.htm

EPA. 2005. Use of Field-Scale Phytotechnology for Chlorinated Solvents, Metals, Explosives and Propellants, and Pesticides. EPA 542-R-05-002.
http://www.epa.gov/tio/download/remed/542-r-05-002.pdf

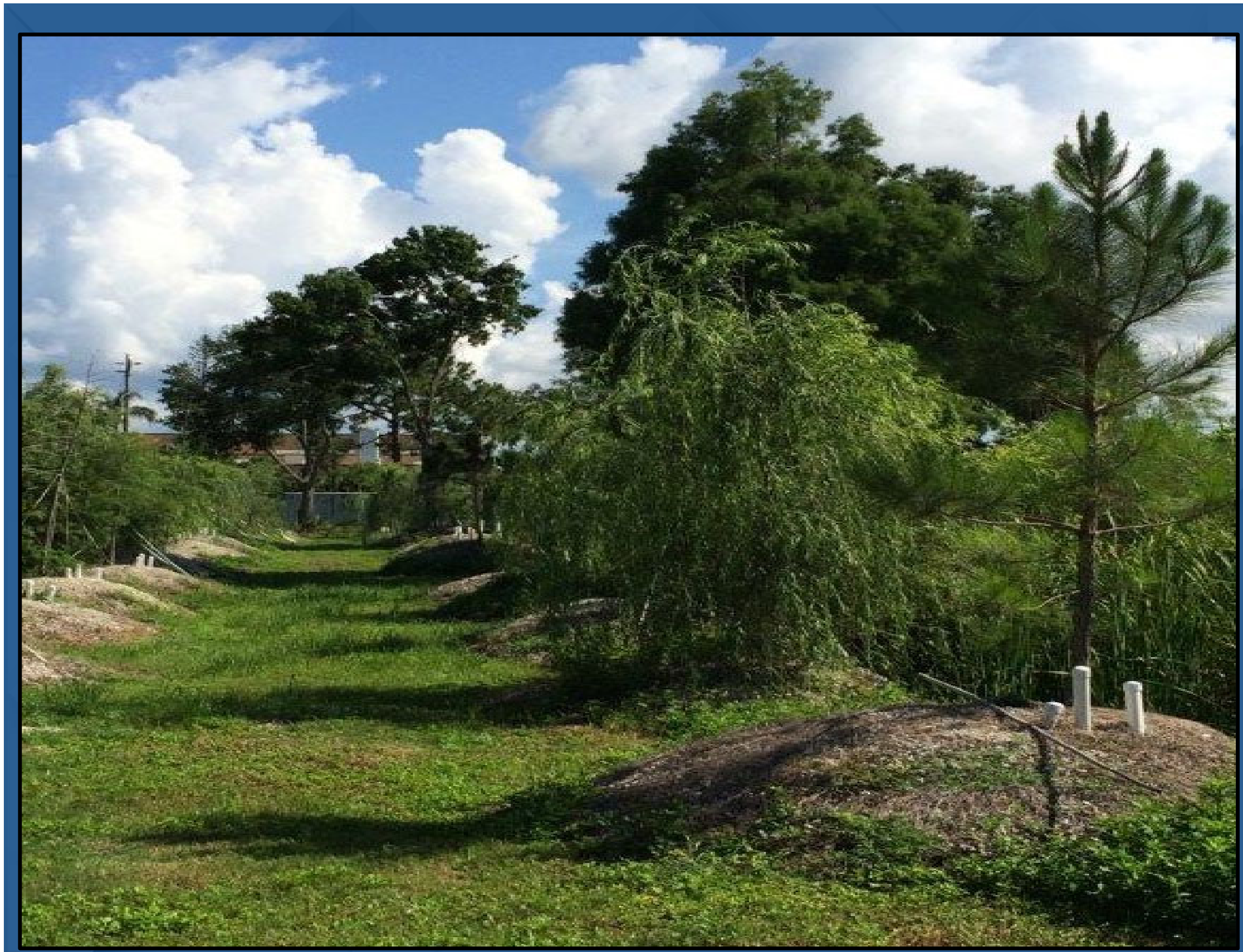
Associated Vendor(s) or Consultant(s): Applied Natural Sciences

RETURN TO LIST

Top of Page

Wissler (2019)

Water Management Using Engineered Phytoremediation with TreeWell Technology. Presentation to the Florida Association for Water Quality Control, 14 June 2019



Water Management Using Engineered Phytoremediation with TreeWell™ Technology

Geosyntec
consultants

Matthew Wissler, P.G.
Florida Association for Water Quality Control
14 June 2019

Outline

- Phytoremediation Background
- Introduction to the *TreeWell*® System
- System Design Basics
- Phyto System Performance Case Studies:
  - Sarasota, FL
  - Danville, IL
  - Shelby, NC

What is Engineered Phytotechnology?

- Use of plants to degrade or immobilize contaminants in soil and groundwater.
- First-generation suffered from misapplication due to:
  - Wrong tree species
  - Improper/ineffective planting or growing methods
  - Incomplete site characterization
  - Hydrogeology
  - Distribution of COCs
- Second-generation phytoremediation considers:
  - System hydraulics
  - Contaminant characteristics
  - Species considerations – form, growth patterns, tolerances
  - Overall end-point objectives

You cant just “plant a tree and hope for the best”

Key Mechanisms of Phytoremediation

Phytovolatilization

VOCs volatilize off leaf surface (1,4-Dioxane, TCE)

Phytoextraction

Uptake and removal of contaminants through the roots

Typically a combination of these mechanisms at work concurrently

Phytodegradation

In Planta degradation (TCE, TNT)

Phytosequestration

In Planta sequestration or accumulation (salts, metals/metalloids)

Rhizodegradation/Rhizofixation/Chelation

Microbial degradation in the rhizosphere (salts, metals, organic contaminants)

Chemical Reduction

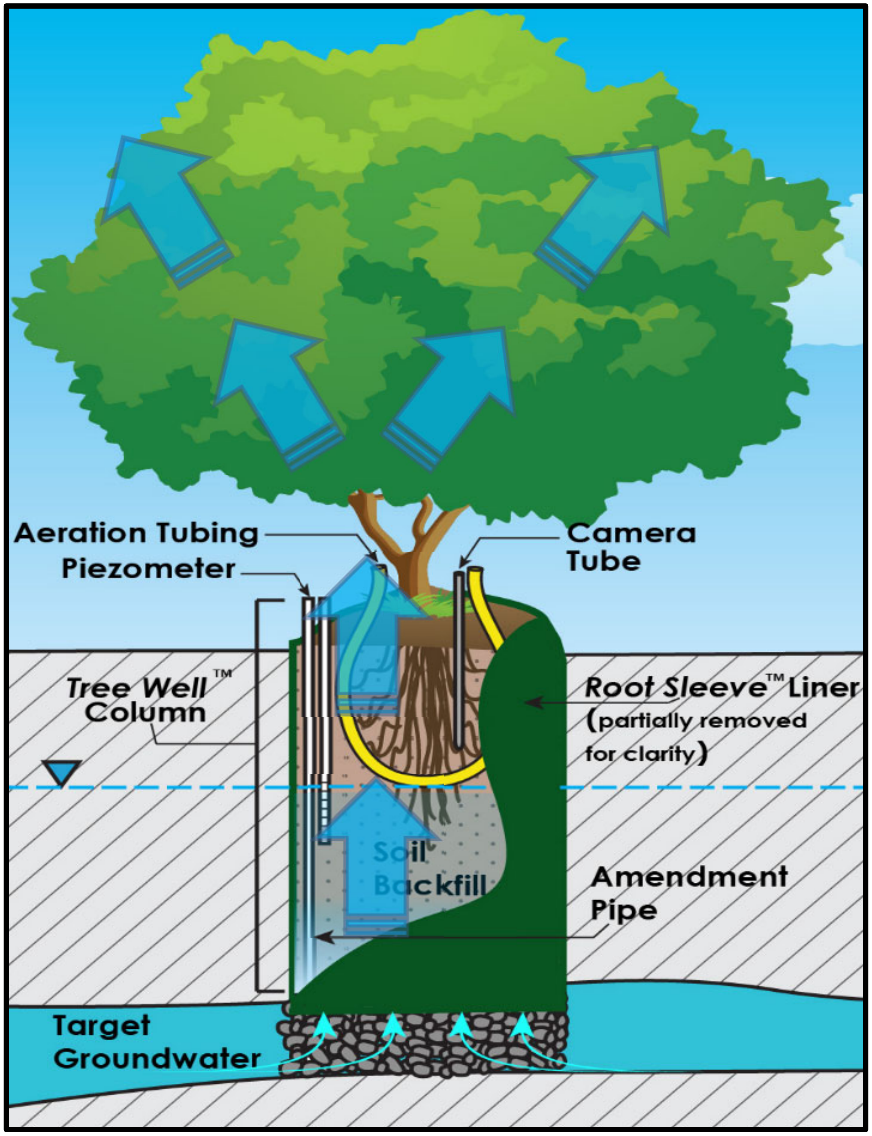
Strongly reducing conditions (organic contaminants)

Phytohydraulics

Groundwater uptake

Engineered Phytotechnology: The *TreeWell*® System

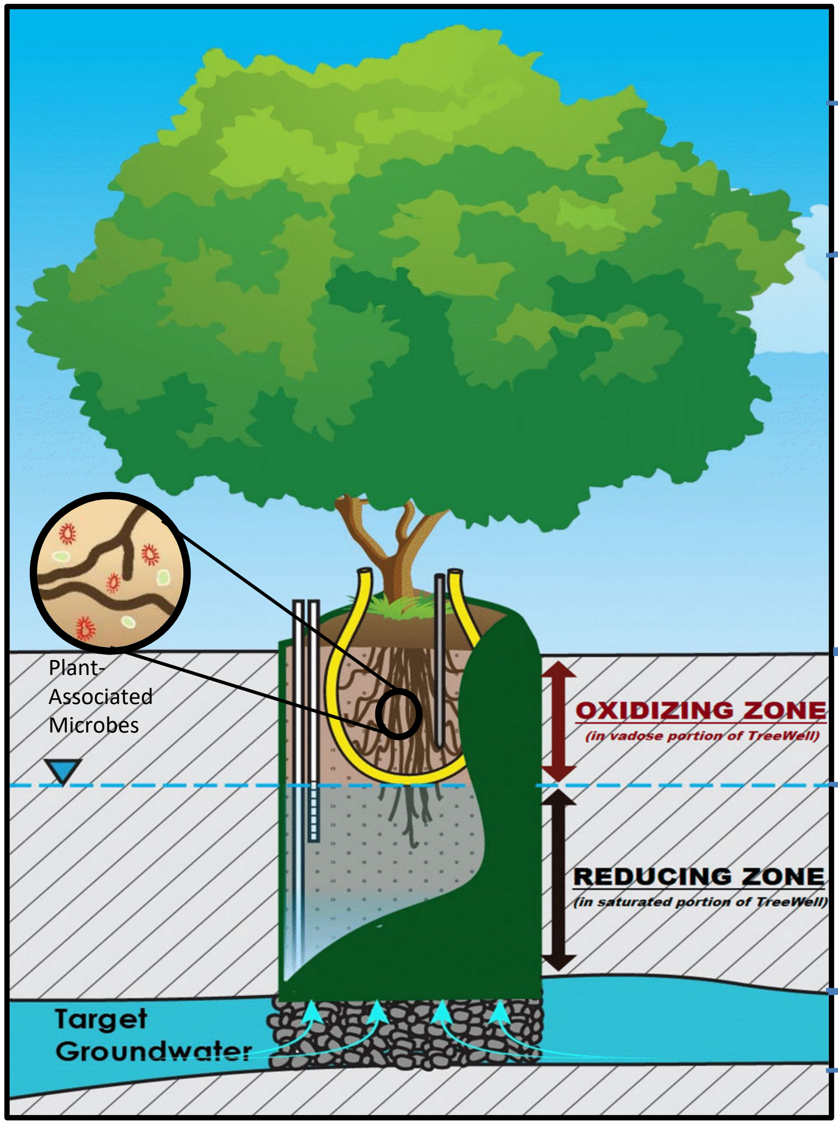
Geosyntec consultants



- Patented by Applied Natural Sciences, Inc. (ANS)
- Targets specific groundwater depth zones by directing root growth downward
- Optimizes growing conditions
- Bioreactor effect – both oxidizing and reducing zones in each unit
- Increases soil temps – enhances biodegradation rates in vadose
- Highly adaptable – can be tailored to specific site conditions
- *Active* treatment – in a *passive* manner

Key Mechanisms of Phytoremediation: The *TreeWell*® System

Geosyntec consultants



Phytovolatilization

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Typically a combination of these mechanisms at work concurrently

Phytosequestration

In Planta sequestration or accumulation (salts, metals/metalloids)

Rhizodegradation/Rhizofixation/Chelation

Microbial degradation in the rhizosphere (salts, metals, PHCs, DCE, VC)

Chemical Reduction

Strongly reducing conditions – ISCR/ISB (PCE, TCE, more fully chlorinated organics)

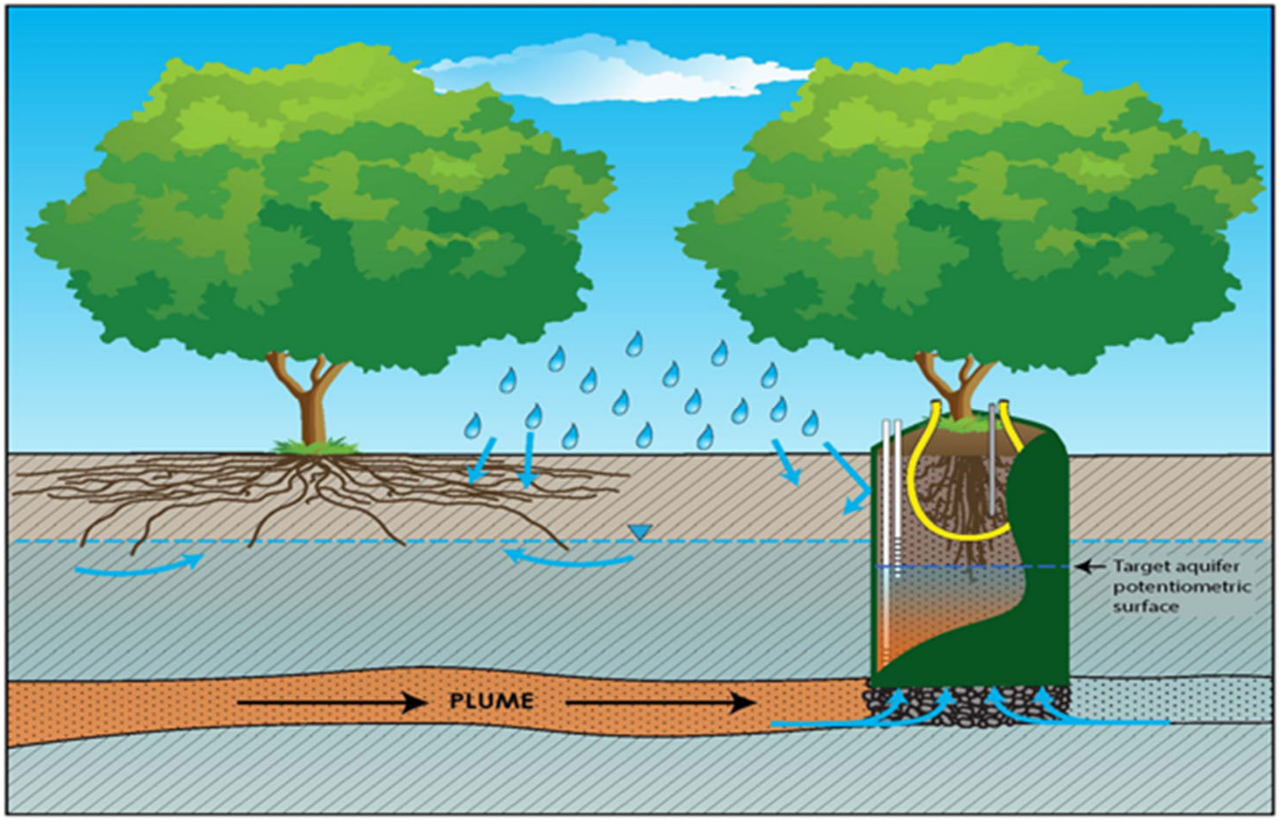
Phytohydraulics

Groundwater uptake

Why Use Engineered Phytotechnology?

Limitations of Conventional Phytoremediation

- Target groundwater too deep
- Site soils too poor, too compacted
- Concentrations too high
- Reliance on precipitation



Benefits of Engineered Phytoremediation using the *TreeWell*® System

- Control plant growth, manage site conditions, target the zone of remedial effect and recharge dilution
- For GW as deep as 50’ bgs (or more)
- Treat high contaminant concentrations
- Can reduce the time to meet remedial goals
- Enables plants to ***THRIVE***
- Objective is to control the hydrology and allow phyto properties to address groundwater within the *TreeWell* units.

What are the limitations?

- Chemistry: Phytotechnology is versatile and can be adjusted via tree species to address a wide range of contaminants
  - pH range between 3 and 10
  - TDS range from fresh to seawater conditions
  - High nutrient metals levels and
  - Successful implemented in environments with:
    - Free phase DNAPL
    - Landfill leachate
    - Nutrient rich stormwater
- Climate: Transpiration variation is to be expected between summer and winter growing seasons.
- Hydrogeology: Most successful in thin aquifers or water bearing zones with lower hydraulic conductivity.

System Installation

Basic Approach

- Borehole advanced to the horizon of interest
- Safety platform set
- Liner, aeration tubing other desired infrastructure are added
- Borehole is backfilled with topsoil and selected amendments
- Tree is then planted, and unit is finished

Benefits of the Engineered Phytoremediation Approach

Geosyntec consultants

Primary Benefits

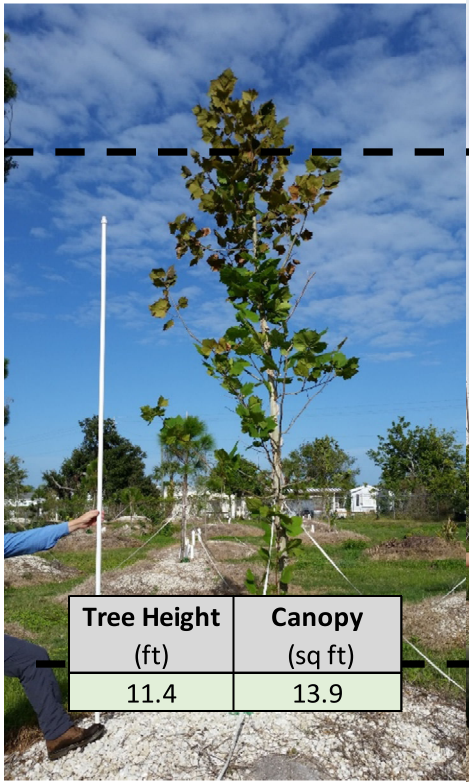
- Substitute for P&T system
- More effective then P&T in low permeability zones or thin aquifers
- “Active” remediation
- Low O&M costs

Secondary Benefits

- Aesthetic appeal to community
- “Enthusiastic” regulatory acceptance
- Defined as “Green and Sustainable” by USEPA

Typical Growth

September 2014

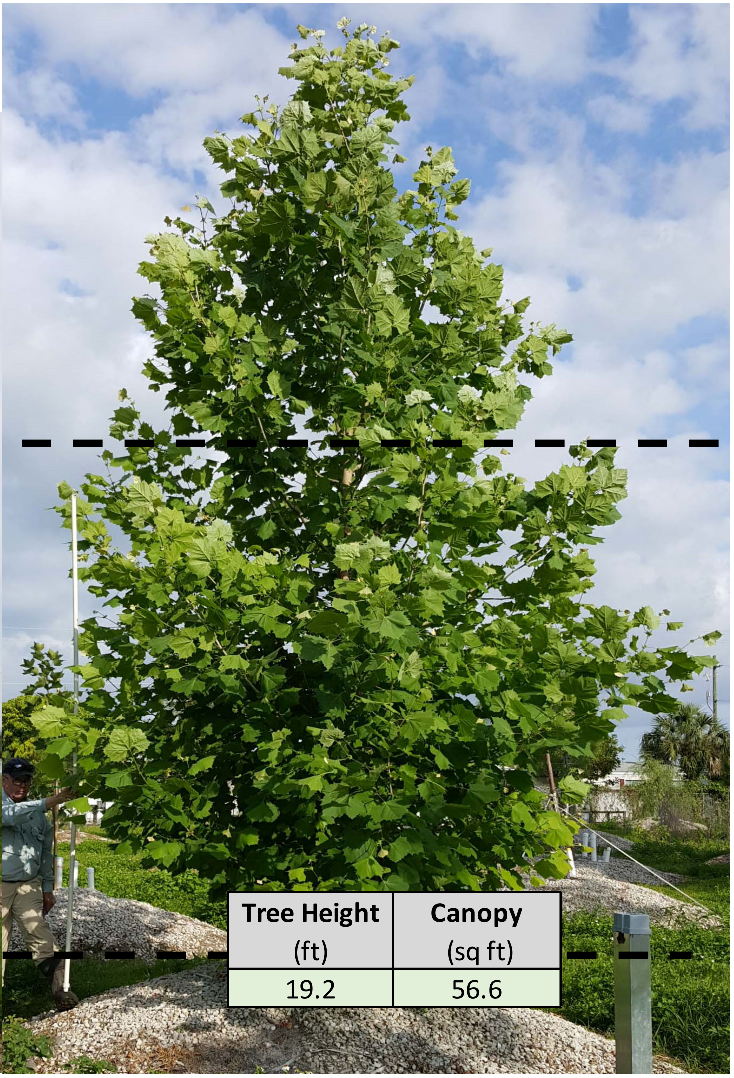


Tree Height (ft)	Canopy (sq ft)
11.4	13.9

September 2015

Tree Height (ft)	Canopy (sq ft)
16.6	42.4

May 2016



Tree Height (ft)	Canopy (sq ft)
19.2	56.6

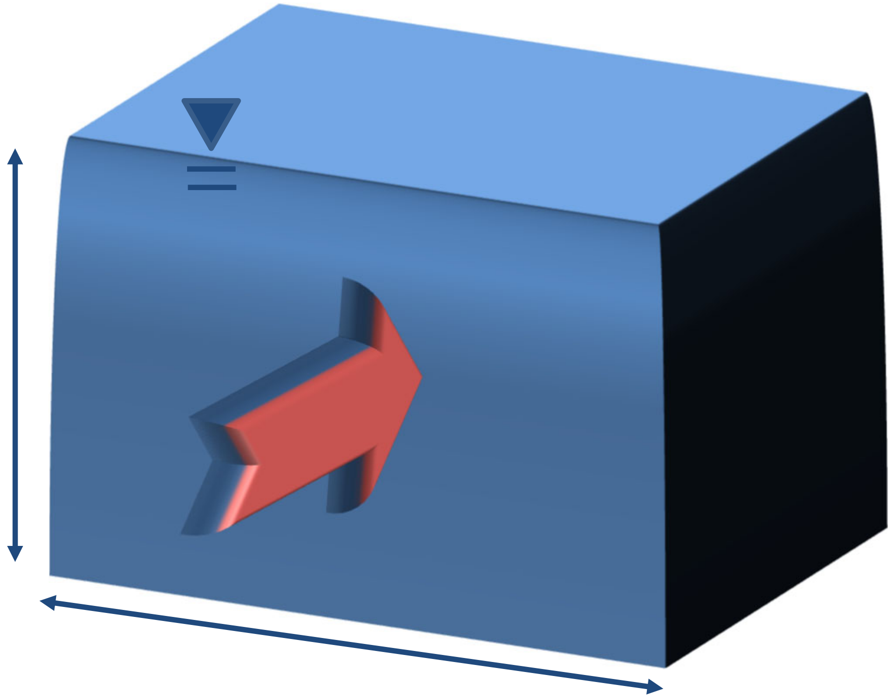
System Design Basics

Design Requirements

1. Define System Objective(s)
2. Conceptual Site Model
    - Target Contaminant Footprint
    - Lithology
    - Permeability
    - Groundwater Flow

Design Approach Options

1. Hand calculations (determine groundwater flux across a plane)
2. Groundwater modeling



$$Q = KiA$$

where:
Q = groundwater flux
K = hydraulic conductivity
I = hydraulic gradient
A = cross sectional area of aquifer

Case Study #1: Sarasota, FL

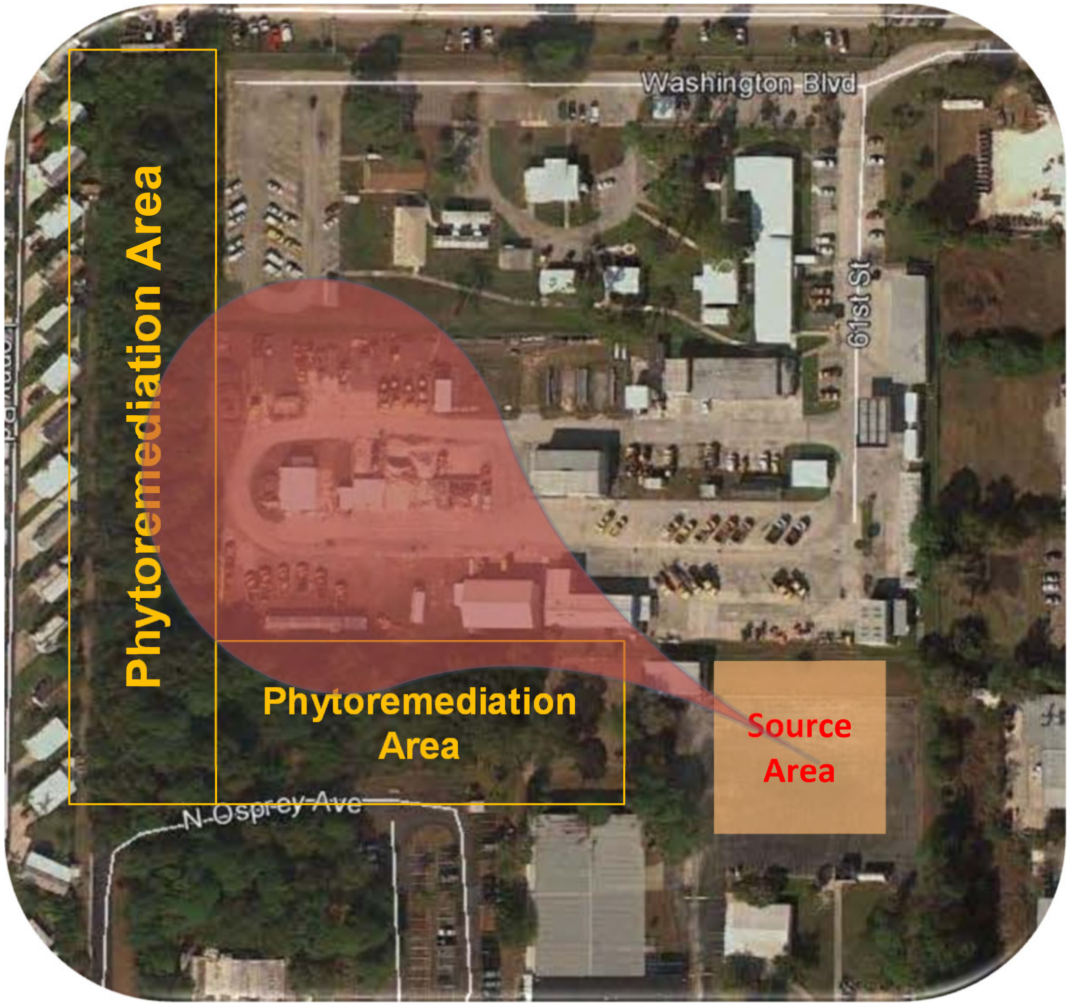
Geosyntec consultants

System Design

1. Aquifer Characterization
    1. Thin water bearing zone
    2. Used existing P&T system to conduct APTs (K=<1 ft/d)
2. Groundwater Modeling

System Installation: 2013

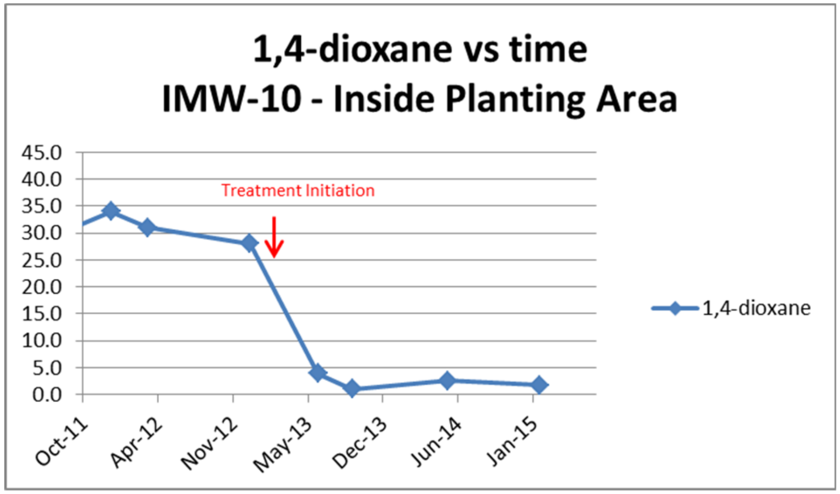
1. 154 units installed 20' on center
2. Projected withdrawal rate between 2 and 4 GPM

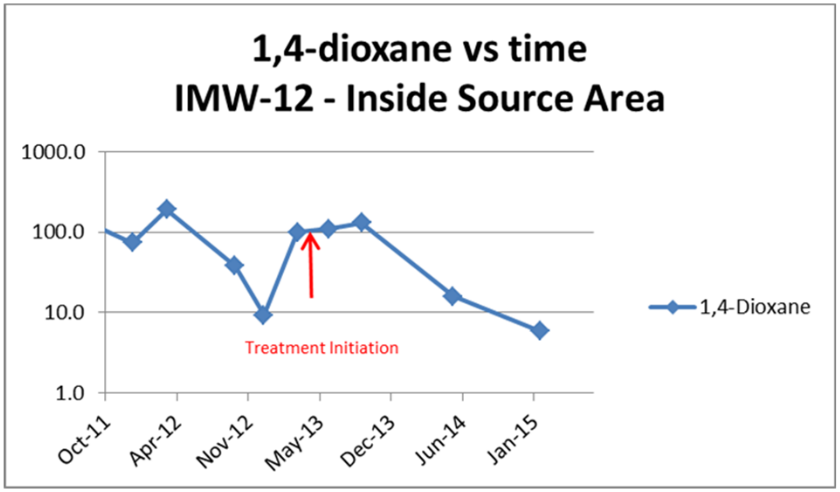


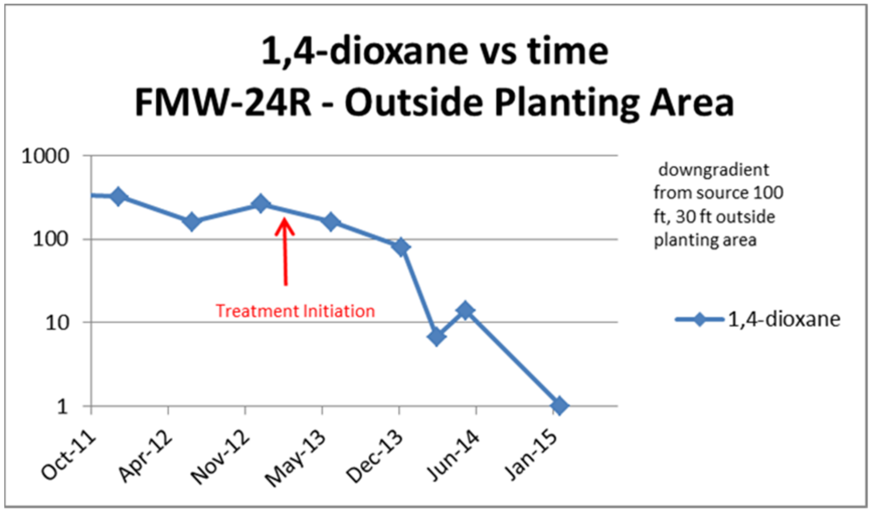
Case Study #1: Sarasota, FL

Modification of Groundwater Flow Regime – Comparison of March 2013 to Nov. 2014

Case Study #1: Sarasota, FL







FROM THIS:

1,4-dioxane

UV/OX

VOCs

Stripper

Arsenic

GAC/Ion Exchange

$1.3 MM Capital and $350K/ year OM&M

TO THIS:

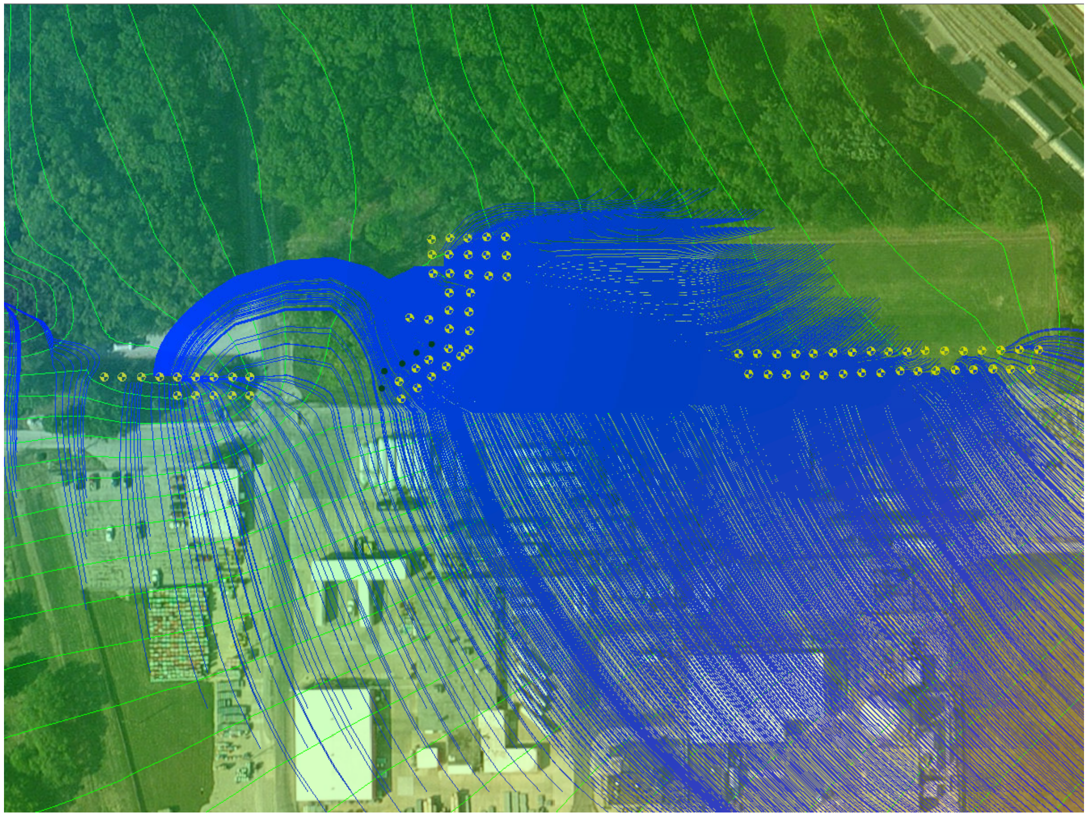
154 TreeWell ® Units and barrier wall

FDEP SRCO in March 2019

Case Study #2: Danville, IL

System Design

1. Aquifer Characterization
    1. Primarily low K glacial till with sporadic sand zones
    2. Used APTs and slug testing to estimate K (K=<0.1 ft/day)
2. Groundwater Modeling

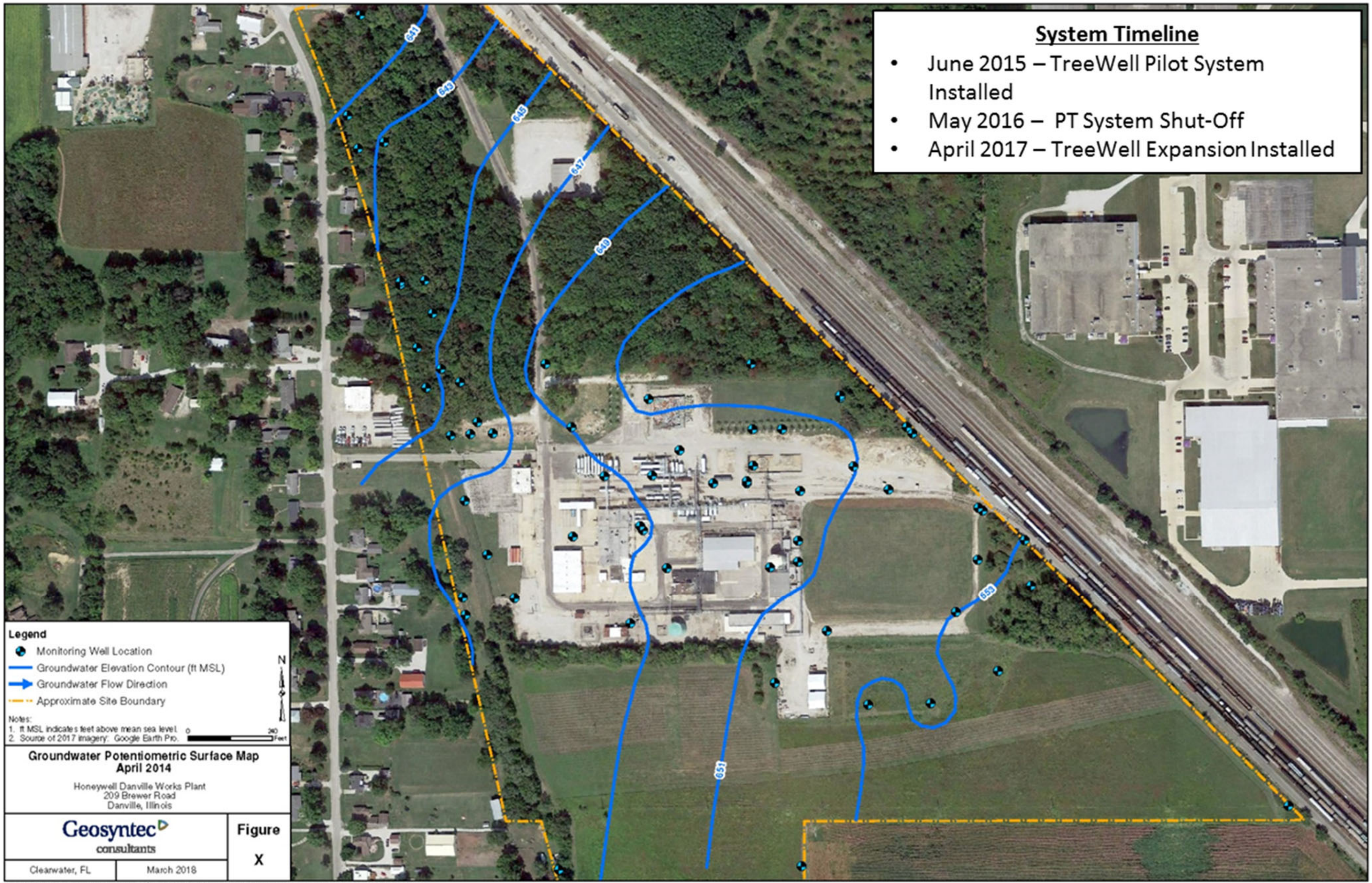


System Installation: 2015 and 2017

1. 90 units installed 20’ on center to provide hydraulic capture
2. Projected withdrawal rate between 1.5 and 3 GPM

Case Study #2: Danville, IL

Geosyntec consultants



System Timeline

- June 2015 – TreeWell Pilot System Installed
- May 2016 – PT System Shut-Off
- April 2017 – TreeWell Expansion Installed

Notes:
1. ft MSL indicates feet above mean sea level.
2. Source of 2017 imagery: Google Earth Pro.

Groundwater Potentiometric Surface Map
April 2014

Honeywell Danville Works Plant
209 Brewer Road
Danville, Illinois

Geosyntec consultants

Clearwater, FL | March 2018

Figure

X

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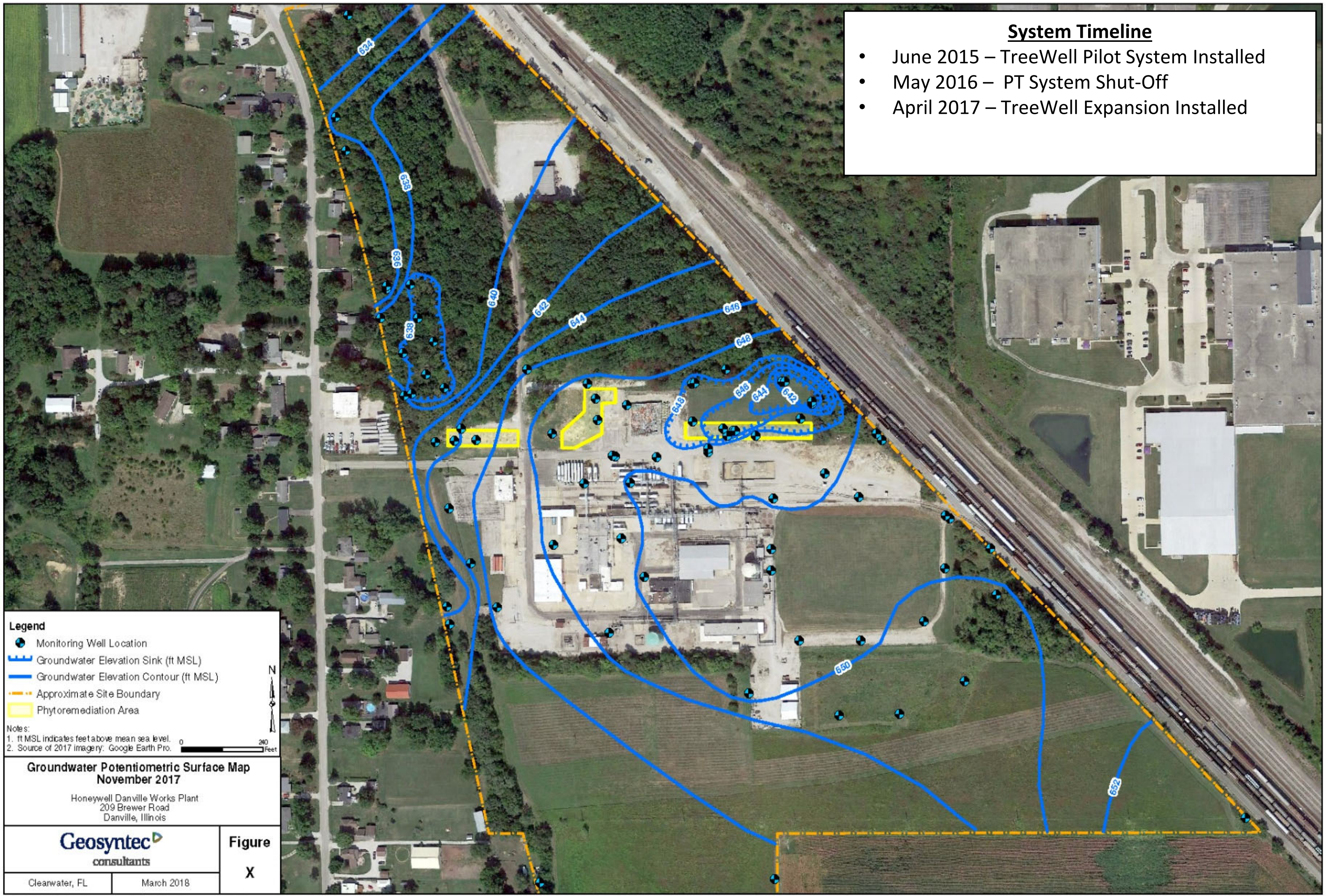
Case Study #2: Danville, IL

System Timeline

- June 2015 – TreeWell Pilot System Installed
- May 2016 – PT System Shut-Off
- April 2017 – TreeWell Expansion Installed



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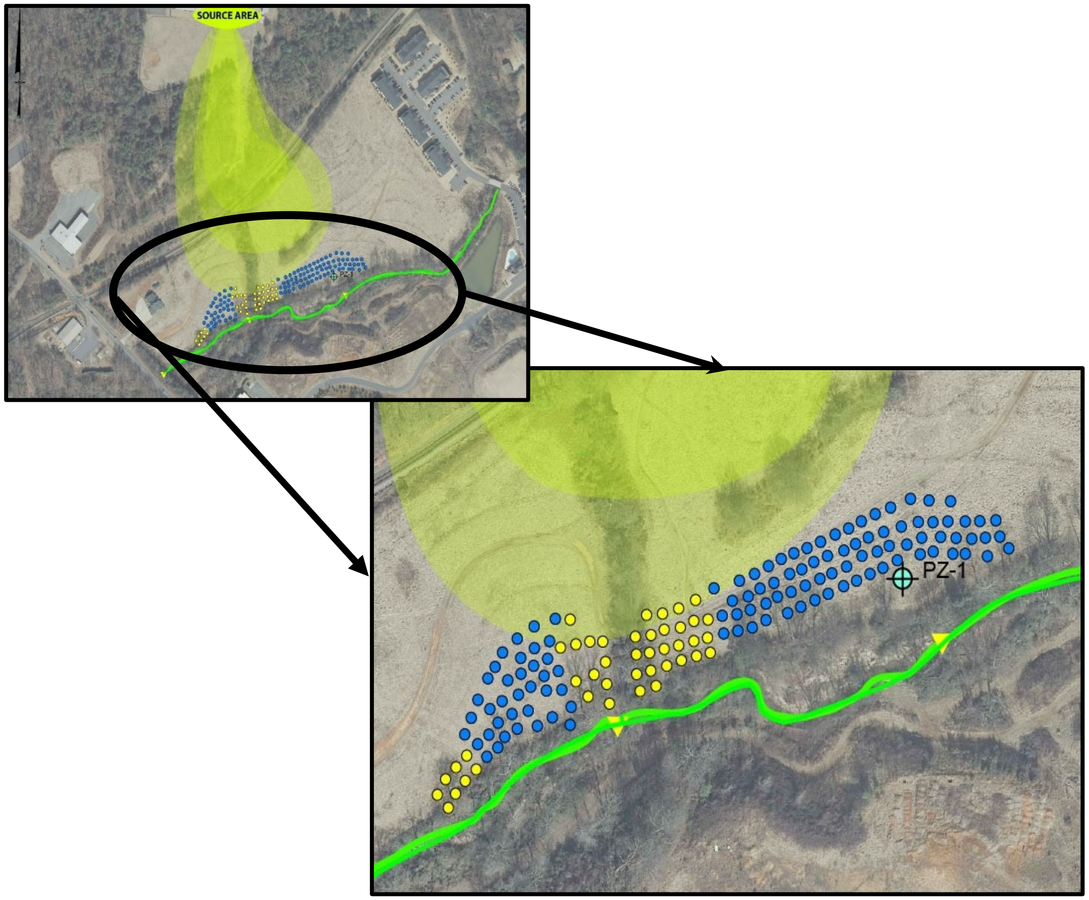
Case Study #3: Shelby, NC

System Design

1. Aquifer Characterization
    1. Thin water bearing zone within transition zone
    2. Used existing P&T system to conduct APTs (K=<1 ft/day)
2. Groundwater Modeling

System Installation: 2015

1. 150 units installed 20’ on center to serve as “Phyto-barrier”
2. Projected withdrawal rate between 2 and 4 GPM



Questions??