Section 6
Groundwater Flow Model

A groundwater flow model was developed to evaluate groundwater flow patterns in the site area and to provide a basis for contaminant transport modeling.

6.1 Model Code

The DYNFLOW modeling code was used to develop the project groundwater flow model. The flexibility of DYNFLOW's finite element structure makes it easy to conform the model geometry to streams, ditches, ponds and other hydrologic features. The DYNSYSTEM groundwater modeling software includes DYNFLOW (single-phase groundwater flow), and DYNTRACK (solute transport). DYNFLOW is a fully three-dimensional, finite element groundwater flow model. This model has been developed over the past 25 years by CDM engineering staff, and is in general use for large scale basin modeling projects and site specific remedial design investigations. It has been applied to over 200 ground water modeling studies in the United States and has been reviewed and tested by the International Ground Water Modeling Center (IGWMC) (van der Heijde 1985, 2000). The code has been extensively tested and documented by CDM and is commercially available for purchase.

DYNFLOW accepts various types of boundary conditions on the groundwater flow system including:

- Specified head boundaries (where the piezometric head is known, such as at rivers, lakes, ocean, or other points of known head)
- Specified flux boundaries (such as rainfall infiltration, well pumping, and no-flow "streamline" boundaries)
- Rising water boundaries; these are hybrid boundaries (specified head or specified flux boundary) depending on the system status at any given time. Generally used at the ground surface to simulate streams, wetlands, and other areas of ground water discharge.
- Head-dependent flux (3rd type) boundaries including "River," "Drain," and "General Head" boundary conditions. Third-type boundaries can be used to represent drainage to local streams or surface water bodies if the piezometric head in a phreatic aquifer rises to the elevation of topmost model level, representing the streambed or land surface. Rising water fluxes at the conditional model boundary at the land surface elevation represent discharges of groundwater to surface water.

DYNFLOW uses a finite-element grid mesh built with a large number of tetrahedral elements. These elements are triangular in plan view, and give a wide flexibility in grid variation over the area of study. An identical grid is used for each level (surface) of the model, but the thickness of each model layer (the vertical distance between levels in the model) may vary at each point in the grid. Linear interpolation functions are applied in hydraulic computations within each element.

DYNFLOW can treat phreatic (unconfined), confined or mixed conditions, with the phreatic surface at each plan view node location occurring in any model layer, or moving between layers in a transient case. As such, model layers are not explicitly classified as “confined,” “unconfined,” etc. The phreatic surface defines the current model upper limit, and adjustments to the model grid geometry are made accordingly.

DYNFLOW is the core of an integrated set of modeling codes (DYNSYSTEM) that can simulate solute transport, non-aqueous phase liquid (NAPL) flow and density-driven aqueous-phase flow such as seawater intrusion. A graphical user interface, DYNPLOT, provides model building capabilities and rapid graphical displays of model inputs, simulation results, field data, and physical and geographical features.

6.2 Model Domain and Computational Grid

The model domain and computational grid are shown on **Figure 6-1**. The model domain has been extended to natural hydrologic boundaries at a considerable distance, 2 to 14 miles, from the site so that simulated groundwater flow near the site is not constrained by assumed model boundary conditions. The model extends to the Intracoastal Waterway to the north, the North Landing River and Currituck Sound to the east, Northwest River to the south and southwest, and to swampland and unnamed tributaries to the Northwest River to the west.

The finite element grid is comprised in plan view of 15,620 triangular elements defined by 7,932 node points at the vertices of the triangles. Aquifer and confining unit hydraulic properties are specified by element and layer. Fluxes, piezometric heads and layer top and bottom elevations are specified or computed at nodes and levels (layer top and bottom boundaries). Nodal spacing ranges from approximately 80 feet on site to 2,000 feet near the model boundaries. Nodal spacing was further refined to 15 feet in the vicinity of APT well, TW-1, for the purpose of simulating the aquifer performance test conducted by CDM in November 2009. The computational grid in the site area is shown in **Figure 6-2**.

6.3 Hydrogeologic Layers and Properties

The model includes the surficial aquifer, the Yorktown aquifer and the Yorktown confining zone that overlies the Yorktown aquifer and underlies the surficial aquifer. The Yorktown aquifer, the bottom layer of the model, is underlain by the St. Mary’s confining unit. The St. Mary’s confining unit is a low permeability layer with a thickness greater than 500 feet in the Battlefield USGS model domain (Heywood and Pope, 2009). Hence, hydraulic interaction between the Yorktown aquifer and deeper aquifers is insignificant for the purpose of this study.

In addition, the model explicitly incorporates an approximately five-foot thick layer of relatively low permeability silt and clay at the unimproved land surface at and near the site, as identified in the soil borings. The surficial aquifer is subdivided into four computational model layers to better represent the vertical component of flow and transport in that aquifer. Model layers are numbered from bottom to top in DYNFLOW. The model layers are summarized in **Table 6-1**.

The model layering is illustrated on **Figures 6-3** and **6-4**, which are cross-section plots showing model layering with the boring logs superimposed. Cross-section A-A′ shown in Figure 6-3 is an east-west cross-section along the southern perimeter of the golf course. Cross-section B-B′ on Figure 6-4 is a north-south cross-section, approximately through the middle of the golf course.

The top of the model represents the land surface. The distribution of land surface elevations was taken from the National Elevation Dataset (USGS) except at the Battlefield golf course and nearby drainage ditches. The land surface at the golf course, shown in **Figure 6-5**, was assigned based on design contours for the site (MJM_Golf_Documents), since as-built topography was not available. The elevations along the drainage ditch immediately west and south of the golf course, were assigned based on interpolation of available staff gage data as described in Section 6.4.3.

The top of the surficial aquifer is represented by the land surface, except in the vicinity of the site where a surficial silt-clay layer is explicitly represented. The top of the computational model is automatically located at the water table in DYNFLOW. The elevation of the bottom of the surficial silt-clay layer (and top of the surficial aquifer) was interpolated from soil boring logs, as illustrated in cross-section Figures 6-3 and 6-4. The spatial distributions of (1) the bottom elevation of the surficial aquifer, (2) the Yorktown confining zone, and (3) the Yorktown aquifer were assigned to the model based on interpolation of data from site and regional borings. These elevation distributions are shown in **Figures 6-6** through **6-8**. The bottom of the model domain is defined by the bottom of the Yorktown aquifer.

Table 6-2 lists the model hydraulic property assignments. These assignments were based primarily on model calibration, as described below in Section 6.5. The K_h and K_v, specific storativity (S_s) and specific yield (S_y) shown in Table 6-2 are within the expected range of values for these hydrogeologic units presented by Heywood and Pope (2009).

A range of hydraulic conductivity values is shown for some of the stratigraphic units. The lower value is based on the APT calibration, as described in Section 6.5.1. The higher value is based on an alternative model developed during the model calibration and sensitivity analysis as described in Section 6.5.2 that represents higher groundwater flow rates in the aquifer system. Note that in the APT calibration, different hydraulic conductivity values were assigned to the upper half and lower half of the surficial aquifer.

The S_s and specific yield S_y values were taken from the USGS Coastal Virginia regional SEAWAT groundwater model. These parameters do not affect the steady-state simulations used for the transport modeling or steady-state calibration. The transient aquifer performance test simulation was somewhat sensitive to the S_s value assigned to the surficial aquifer.

6.4 Boundary Conditions

Boundary conditions were specified for the model perimeter, model top and model bottom. These boundary conditions include rivers and streams, drainage ditches, onsite ponds, recharge, evapotranspiration, and groundwater withdrawals.

6.4.1 Model Perimeter

Discharge to a river or stream is represented along almost the entire model perimeter in the surficial aquifer, thus providing a natural boundary condition. A specified fixed head boundary condition was assigned to model perimeter nodes in the Yorktown aquifer (layer 1). The specified head values were interpolated from the initial Yorktown aquifer heads assigned in the USGS Coastal Virginia regional SEAWAT model.

A no-flow boundary condition is applied to the bottom of the model. As noted above, vertical flow between the Yorktown aquifer and the underlying St. Mary's confining unit is assumed to be very small compared with the flow in the Yorktown aquifer.

The top of the model, computationally, is the water table. A drain boundary condition, or conditional rising water boundary condition described in Section 6.4.2, was assigned to the top of the model. The computed water table level is free to rise and fall depending on hydrologic and hydraulic conditions, except that it is constrained to not rise above the land surface. Recharge and evapotranspiration fluxes are applied at the water table as described below.

6.4.2 Rivers and Streams

Groundwater discharge to rivers and streams is represented using conditional "rising water" boundary conditions. A rising water node is a "free" node, with specified recharge or discharge and computed head, unless the computed water table tends to rise to or above the land surface. In that case, a specified head boundary condition is invoked with the head fixed to the land surface elevation and discharge from groundwater to surface water is automatically computed. In this way, groundwater discharge is automatically simulated at low points in the topography coincident with streams or wetlands. This is analogous to a drain boundary condition with the drain level set at the land surface with negligible hydraulic resistance between the groundwater and surface water. When assigning land surface elevations to nodes, care was taken to ensure that local low points in the DEM topography were incorporated into the model land surface elevation assignments. Because of a generally shallow water table within the model domain, no significant outflow from streams to groundwater is expected.

6.4.3 Agricultural Drainage

The land use of more than half of the model area is agricultural. This can be seen on Figure 6-9, which shows land use within the model domain based on the National Land Cover Database (NLCD) land cover/use maps for 2001, downloaded from http://www.mrlc.gov/. A dense surface drain network in the agricultural areas can be seen in aerial photographic images. Assuming that surface and sub-surface drainage systems have been constructed in the agricultural land, a drain boundary condition was assigned to all nodes within agricultural areas shown in Figure 6-9. Due to a lack of available design/construction data for the agricultural drainage network, the drain elevation was set to be 3 feet below land surface. A high conductance value (50,000 square ft/d) was assigned, resulting in little computed head loss (hydraulic resistance) between the groundwater and drain.

Special attention was focused on the representation of significant drainage ditches near the golf course. These are shown in dark blue in Figure 6-10. In particular, the drain that runs along the western and southern perimeter of the golf course significantly affects simulated groundwater flow from the golf course. These ditches were represented using the drain boundary condition. Model nodes were specifically placed along the alignment of these ditches. The surface water elevation assignments for the ditch that runs along the western, southern and eastern golf course perimeter were based on the available surface water staff gage data. The elevations along the drainage ditch approximately 3,200 feet south of the golf course, were estimated based on available data at a single staff gage (SG-15), DEM land surface elevations, and the elevations of the drain along the south perimeter of the golf course.

6.4.4 Onsite/Golf Course Ponds

The locations and identifiers of ponds on the golf course are shown on Figure 6-11. Following the convention of MACTEC (2009), the ponds are identified by the number of the staff gage installed for a given pond.

Two of these ponds, SG-3 and -16, discharge to surface drainage ditches and are assumed to behave essentially as groundwater drains. The range of measured staff gage water level readings for these ponds is less than 0.5 feet and 0.8 feet for SG-3 and -16, respectively. Drain boundary conditions were assigned to all nodes associated with these ponds, with the drain water level assigned equal to the average of measured staff gage water level values for these ponds, except for ponds SG-3 and -16, a drain boundary condition was not assigned to the pond nodes.

Ponds SG-9, -10 and -12 are indicated by MACTEC (2009) to be deep enough that the pond bottoms are in direct contact with the surficial aquifer with no intervening silt-clay layer. Although depth data is not available for ponds SG-3, -11, -16 and -17, they were also assumed to be hydraulically well connected with the surficial aquifer based on the close similarity of measured pond levels to heads measured in nearby monitoring wells. For model elements associated with these ponds, the relatively low hydraulic conductivity associated with the surficial silt-clay layer was not assigned to the top model layer. Instead, a very high horizontal hydraulic conductivity of 1,000 ft/d was assigned to account for the negligible resistance to flow within the pond. This results in a relatively flat simulated water table corresponding to the pond surface. The assignment of the 1,000 ft/d "pond" hydraulic property set can be seen in cross-section Figure 6-4.

6.4.5 Recharge and Evapotranspiration

A specified groundwater recharge flux was applied at the water table. Conceptually, groundwater recharge is the remaining precipitation after subtracting runoff and evapotranspiration from the vadose zone, land surface and vegetation surface. Infiltration from irrigation return flow, septic tanks and leaking water pipes can also contribute to groundwater recharge.

For the Virginia coastal plain as a whole, average net recharge is estimated to be approximately 10 in/year based on analysis of measured stream flow using base flow separation techniques (Heywood and Pope, 2009). A HELP model analysis conducted for this study described in Section 5.2 indicated a range of recharge rate, depending on surface soil conditions, of 7.5 to 15.8 in/yr for the site.

As described in Section 6.5, two alternative groundwater models were developed. One model incorporates aquifer hydraulic properties resulting from analysis of the APT conducted by CDM in 2009. Based on model calibration using this set of hydraulic properties, an average recharge rate of 3.1 in/yr is specified for the entire model domain. Since this recharge rate is lower than expected, a second model was developed that incorporates higher values of hydraulic conductivity and recharge. Based on model calibration using this set of hydraulic properties, an average recharge rate of 10.1 in/yr is specified for the entire model domain, except that a recharge rate of 16 in/yr is assigned to the Battlefield golf course area based on the upper limit recharge rate estimated by HELP model analysis.

For the onsite pond areas, a net recharge of 22 in/yr was specified, which is simply the difference between average precipitation of 46 in/yr, multiplied by 1.2 to account for runoff into the ponds from surrounding areas, and an average evaporation of 32 in/yr. Because the pond areas are limited, the model simulations were not very sensitive to the pond recharge assignment.

Where the water table is sufficiently close to the land surface, an evapotranspiration flux may be subtracted directly from the water table. Evapotranspiration from the water table can be significant in this region of Virginia, because there is a relatively shallow water table at many locations. In the model, evapotranspiration from the water table is computed as a function of the depth of the water table below land surface. With the water table at the land surface, computed evapotranspiration is at the specified maximum value of 32 in/yr, based on studies conducted by the Virginia State Climatology Office, as reported by Heywood and Pope (2009). The computed evapotranspiration decreases linearly with depth of the water table below the land surface to a value of zero at a specified root extinction depth.

Extinction depth is a function of crop or vegetative cover, and also soil type and land use. A uniform extinction depth of 3 feet was assigned to the entire model area. However, the evapotranspiration computations are not invoked at the agriculture land use nodes in the model. This is because the drain boundary conditions assigned to agricultural area nodes prevent the water table from rising to an elevation less than 3 feet below the land surface. In effect, the drainage system is assumed to prevent groundwater from saturating the root zone of the crops.

6.4.6 Groundwater Withdrawals

Approximately 63 known residential wells in the site vicinity are used for water supply. The well depths for 17 if these wells are known and the wells were assigned to these depths in the groundwater flow model. The remaining 46 residential wells that do not have available well depth data were simulated as pumping from the surficial aquifer as a conservative measure. All residential wells were assumed to pump continuously at the average residential water usage rate of 0.45 gpm based on typical City of Chesapeake water use rates. This non-intensive, dispersed pumping exerts a negligible overall effect on the groundwater flow field in the vicinity of the site, which is dominated by recharge and discharge to drainage ditches.

The USGS eastern Virginia regional model includes no municipal or industrial pumping from the surficial aquifer within the model domain. The USGS model includes two wells pumping a total of 180 gpm from the Yorktown-Eastover aquifer within the project groundwater model domain. This Yorktown aquifer pumping is assigned to the project groundwater model in the same location as assigned in the USGS model shown on Figure 6-12.

6.5 Flow Model Calibration and Sensitivity

The flow model was calibrated using:

- The results of the Columbia aquifer performance test conducted by CDM in 2009; and
- Comparison of the average measured heads in monitoring wells to model computed heads for steady state simulations representing average hydrologic conditions.

6.5.1 Aquifer Performance Test Transient Calibration

CDM conducted an APT in November 2009 to help define appropriate hydraulic parameters of the surficial aquifer. Discussion of the APT analysis is detailed in Section 4.2.1. Groundwater potentiometric surface response to the pumping monitored in wells MW-3A and MW-3B and piezometers PZ-1 and PZ-2 was analyzed. The relative location of these wells is shown on Figure 6-13. TW-1 was designed to nearly fully penetrate the entire thickness of the surficial aquifer. Well MW-3A monitors the upper surficial aquifer; Well MW-3B, PZ-1 and PZ-2 monitor the lower surficial aquifer. The distances of the monitoring wells from the test pumping well are listed in Table 4-2.

A traditional analysis of the aquifer performance test results using type-curve fitting analytical methods was performed. The computations and curve fitting were done using the AQTESOLV program as described in Section 4.2.1. The results using the Hantush leaky aquifer solution are summarized in Table 4-2. They indicate a surficial aquifer K_h in the 50 to 80 ft/day range. The analysis results were not sensitive to the assumed vertical hydraulic conductivity in the surficial aquifer.

A more comprehensive analysis of the APT results was conducted using the numerical groundwater flow model. The numerical model is not as limited to idealized conditions as the analytical models are. In particular, the numerical model explicitly accounts for vertical flow and gradients and interactions with overlying and underlying layers.

Numerous trial transient simulations using different hydraulic parameters were made with the objective of achieving reasonable agreement between simulated and measured drawdown patterns. Figure 6-14 shows measured and simulated time-drawdown plots at the key monitoring wells for this aquifer performance test. The distribution of simulated drawdown at the end of the pumping period is shown in Figure 6-15. The hydraulic properties listed in Table 6-2 (lower value of ranges) were applied in this simulation.

As indicated in Table 6-2, a relatively lower K_h was applied to the upper half of the surficial aquifer to achieve this result. The APT simulation was sensitive primarily to K_h and K_v of the surficial aquifer, and secondarily to S_s of the surficial aquifer, K_v of the upper silt-clay layer, and K_h/K_v) of the Yorktown confining zone.

6.5.2 Steady State Calibration

The steady state calibration was initially conducted using the surficial aquifer, Yorktown confining zone, and surficial silt-clay layer properties resulting from the APT calibration. Recharge, evapotranspiration, and Yorktown aquifer K_h and K_v were adjusted to provide reasonable agreement between simulated and measured head. The hydraulic properties listed above in Table 6-2 (lower value of ranges) were applied in this simulation. The calibrated recharge rate was 3.1 in/year. This model is called the "Aquifer Performance Test Model" because it incorporates the hydraulic properties developed by the APT calibration.

The calibration results are summarized in **Table 6-3**. Overall, the mean difference between simulated and measured head (termed the residual) was 0.048 feet, with a standard deviation of 1.721 feet. The spatial distribution of simulated head near the site and calibration residuals is shown in Figures 6-16 through 6-18. Figure 6-16 shows simulated head contours near the top of the surficial aquifer, along with color coded symbols at monitoring wells screened in the corresponding vertical interval (A wells) indicating the calibration residual at that location. Figure 6-17 shows simulated head contours and residuals near the bottom of the surficial aquifer (B wells). Figure 6-18 shows simulated head contours and residuals near the top of the Yorktown aquifer (C wells). **Table 6-3** lists the calibration monitoring wells with the average measured head. The steady state calibration target was based on heads measured in monitoring wells on and near the site during 2008 and 2009.

6.5.3 Model Sensitivity

The steady state flow model calibration is very sensitive to the recharge and K values specified. However, the steady state calibration was not unique, in that a similar distribution of simulated head could be achieved using a higher recharge rate in combination with higher K values. Calibration using the APT calibration hydraulic properties required assignment of a lower than expected recharge rate. Because the extent of the APT analysis was limited to a small area of the aquifer within 300 feet of well TW-1, the K values indicated by the APT may not be fully representative of the aquifer as a whole.

Therefore, an alternative model was developed and calibrated (steady state) in which higher recharge rates and higher K values were assigned. For this alternative model, the K_h values in the surficial and Yorktown aquifer were assigned to be 100 ft/d, at the upper limit of the reasonable range of published values for these aquifers presented by the USGS (Heywood and Pope, 2009). The upper value of parameter ranges shown in Table 6-2 were used, except for within approximately 700-1000 feet of APT TW-1 where K values developed for the APT model were assigned. This model is called the "High Flow Model" because the simulated rate of recharge and flow in the aquifers is greater than for the APT Model.

The High Flow Model incorporates a recharge rate in the expected range and resulted in better calibration statistics than the aquifer performance test calibration model. It also provides a basis for more conservative contaminant transport simulations, because higher groundwater flow rates and velocities are simulated. Also, because the higher recharge and higher K_h in the Yorktown aquifer will induce higher flows in that aquifer, the potential for downward flow (and transport) to the Yorktown aquifer is increased.

The calibrated recharge rate for this model was 10.1 in/yr. The calibration results are summarized in **Table 6-4** for the High Flow Model. Overall, the mean difference between simulated and measured head was 0.139 feet, with a standard deviation of 1.158 feet.

The spatial distribution of simulated head near the site for the calibrated steady-state High Flow Model and calibration residuals is shown in Figures 6-19 through 6-21. Figure 6-19 shows simulated head contours near the top of the surficial aquifer, along with color coded symbols at monitoring wells (A wells) indicating the calibration residual at that location. Figure 6-20 shows simulated head contours and residuals near the bottom of the surficial aquifer (B wells). Figure 6-21 shows simulated head contours and residuals near the top of the Yorktown aquifer (C wells).

6.6 Simulated Groundwater Flow Field and Water Budget

Figure 6-22 shows simulated upper surficial aquifer flow direction arrows and head contours (High Flow Model). The flow simulation results indicate that flow in the upper surficial aquifer from beneath the site and surrounding area converges toward the drainage ditch that runs along the south perimeter of the site.

An east-west cross-section A-A′ along the south perimeter of the site is shown in Figure 6-23. Simulated head contours in the surficial aquifer for the High Flow Model are shown, along with average measured head posted at monitoring well locations. A slight upward gradient is indicated by both the measured heads and simulated contours. Simulated head contours and average measured head values are shown for north-south cross-section B-B′ in Figure 6-24. On this figure, a mix of upward and downward head gradients in the surficial aquifer beneath the site are indicated.

The overall water budgets for the APT Model and High Flow Model steady state calibration simulations are summarized in Table 6-5. Positive values indicate flux into the groundwater model domain, negative fluxes indicate flux discharging from the groundwater model domain. The greater simulated flow rates in the High Flow Model are evident in Table 6-5.