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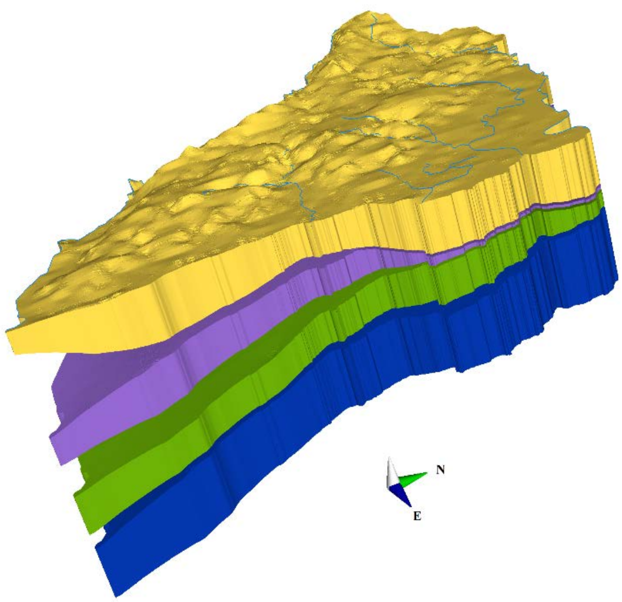
RESULTS OF GROUNDWATER FLOW SIMULATIONS IN THE EAST DOVER AREA, DELAWARE



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RESULTS OF GROUNDWATER FLOW SIMULATIONS IN THE EAST DOVER AREA, DELAWARE

INTRODUCTION

In 2015, staff of the Water Supply Section of the Delaware Department of Natural Resources and Environmental Control (DNREC) informed the DGS of their concerns about overpumping of the unconfined Columbia aquifer in an area east of Dover (Figure 1). In this area, the City of Dover's Long Point Road Wellfield (LPRW) and numerous irrigation systems pump water from the shallow Columbia aquifer. Overpumping is a cause for concern because it may 1) increase the risk for saltwater intrusion into the aquifer from saline tidal creeks and marshes and, 2) induce extra drawdown that could reduce the transmissivity of the aquifer and decrease well yields. The potential for overpumping will become more significant when an electric generating station served by the LPRW is expected to increase capacity and requires more water.

This report summarizes monitoring and modeling that were conducted to investigate the potential impacts of overpumping. Automated water level and salinity sensors were installed and operated in three monitoring wells, and a digital groundwater flow model was constructed. The model was run in both steady-state and transient modes. As is the case with most models, many assumptions and simplifications had to be made because of data limitations. The model was calibrated to a spatially limited set of data. Consequently, model outputs are meant to inform how the aquifers behave given the assumptions and simplifications and will not represent precise predictions of water pressures in the area represented by the model. Additional data are now being collected in the model domain to refine the accuracy and precision of model results.

General Hydrogeology

The study area is situated in the Atlantic Coastal Plain Physiographic Province, formed on a southeasterly sloping and thickening wedge of unconsolidated to consolidated sedimentary deposits ranging in age from Cretaceous to Quaternary. Table 1 lists the more permeable layers that host aquifers and less permeable layers that form confining beds in the Dover area. Readers interested in detailed descriptions of Coastal Plain geology and geologic units are referred to discussions in McLaughlin et al. (2014) and Ramsey (2007).

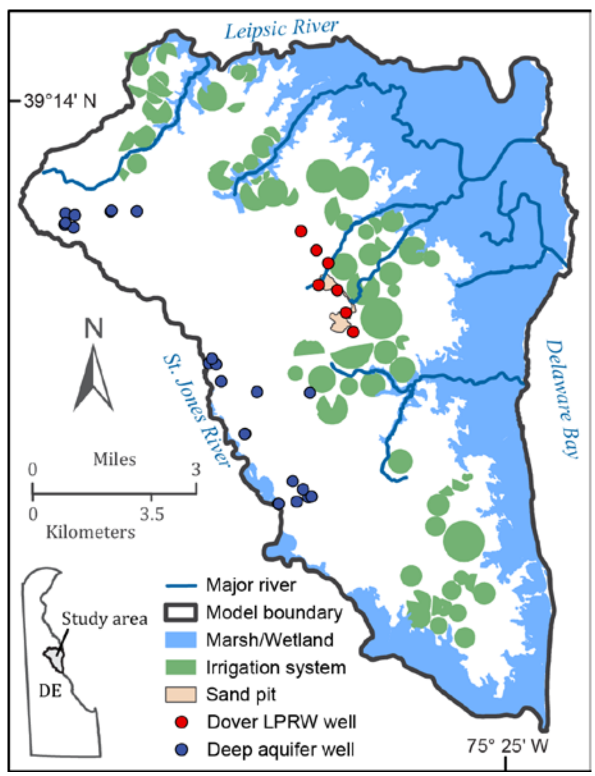


Figure 1. Location of study area and model boundary in the East Dover area, Delaware. LPRW is the Long Point Road wellfield.

In the east Dover area, the shallow Columbia aquifer is the primary source of water used for irrigation and as a potable water supply by the City of Dover. The composition of the thick (>40 ft) gravelly sands and sandy gravels that form the Columbia aquifer at the LPRW and surrounding area is consistent with multiple lithostratigraphic units, including the Columbia Fm, Beaverdam Fm, and Scotts Corners Fm, or with the unusually coarse grained beds of the Frederica sand member of the Calvert Fm. However, exposures of the units forming the aquifer are limited to a few shallow excavations. No diagnostic fossils or radiometric age data exist that could differentiate one unit from another. Therefore, in this report, all of the sandy deposits mentioned above are simply referred to as the Columbia aquifer.

Muddy beds of the Calvert Formation function as a confining bed and form the bottom of the Columbia aquifer. Total thickness of the Columbia aquifer is spatially variable due to the heterogeneous compositions of the units forming the aquifer and the sloping geometry and variable thickness of the underlying confining bed.

Additional important aquifers used for water supply in the study area are, from shallow to deep, the Frederica, Federalsburg, Cheswold, and Piney Point (Table 1). The Frederica, Federalsburg, and Cheswold aquifers occur within coarser-grained sand and shell beds of the Miocene-age Calvert Formation. Muddy beds of the Calvert Formation separate these aquifers from each other and the underlying Piney Point aquifer. All of the sub-units in the Calvert Formation thicken and dip to the southeast, and their tops are truncated by erosional disconformities associated with the base of the overlying Pliocene to Quaternary sediments. Where the disconformities intersect the Cheswold, Federalsburg, and Frederica aquifers they are in close hydraulic connection to the Columbia aquifer. As a result, only the Cheswold aquifer is present throughout the study area and the Federalsburg and Frederica aquifers are present only in the southern half of the study area. Muddy beds of the lower Calvert Formation beneath the Cheswold aquifer form a continuous confining unit that separates it from the Piney Point aquifer. The Piney Point aquifer occurs within coarse-grained sand beds of the Eocene-age Piney Point Formation.

Groundwater Development

The LPRW was developed in the 1980s and 1990s under the guidance and detailed work of Betz Converse Potomac, Inc. The LPRW includes both production and observation wells that are screened in the Columbia aquifer and a few observation wells finished in the Frederica aquifer. Dover has routinely measured water levels and collected samples for water quality analysis since the mid-1990s. Reported pumping from the LPRW was fairly limited, ranging from 2.5 to 160 million gallons per year (MG/Yr) and averaging about 82 MG/Yr between 1996 and 2015 (DNREC unpublished data). Reported pumping has been increasing at a rate of about 2 MG/Yr since 2000. The latest (2014) water allocation for the LPRW permits the withdrawal of up to 630 MG/Yr.

Some of the earliest records (1950s) in the DGS and USGS well databases are of large-capacity irrigation wells located around the LPRW. Through investigation of records in the state's well permitting program and observations of aerial photography, it is clear that the number of irrigation wells and irrigation systems has steadily increased over time. Analyses of aerial photographs collected in 2007 and 2012 (UD Agricultural Experiment Station, 2012) have provided detailed maps of the locations and sizes of irrigation systems. Reported water-use data and methods to estimate unreported use are discussed in later paragraphs.

Surface-water features in the study area range from freshwater man-made ditches and ponds, swamps, marshes, and streams to brackish to saline tidal streams, marshes, streams, and the Delaware Bay. Several large man-made impoundments that were

Table 1. Stratigraphic units and major aquifers in the study area. Stratigraphic units adopted from McLaughlin et al. (2014).

System	Series	Geologic units	Aquifer
Quaternary	Pleistocene	Scotts Corners Fm. Beaverdam Fm.	Columbia
Tertiary	Miocene	Calvert Fm	Leaky and discontinuous confining beds
			Frederica
			Leaky and discontinuous confining beds
			Federalsburg
			Leaky and discontinuous confining beds
			Cheswold
			Leaky confining bed
	Eocene	Piney Point Fm.	Piney Point

constructed for wildlife management purposes are present east of the LPRW. All of the streams in the study area drain to Delaware Bay.

INPUT DATA AND MODEL DEVELOPMENT

A groundwater flow model was constructed to simulate hydrogeologic conditions of the east Dover area. The model domain is wedge shaped and is bounded on the east by Delaware Bay, on the southwest by the St. Jones River, and on the north by the Leipsic River (Figure 1).

Conceptual model and numerical model implementation

A conceptual model represents the current understanding of the hydrogeologic system. In simple terms, the conceptual flow model describes how the groundwater flow system of an area is believed to behave. In this study, the flow model simulates groundwater flow in multiple aquifers and confining beds, with seven model layers, from top to bottom, representing the Columbia, Frederica, Federalsburg, and Cheswold aquifers and intervening confining beds (Figure 2). The underlying Piney Point aquifer is not included in this model because it is separated from the Cheswold by a confining bed that limits the flow of water to the Piney Point (Leahy, 1976, 1979, 1982).

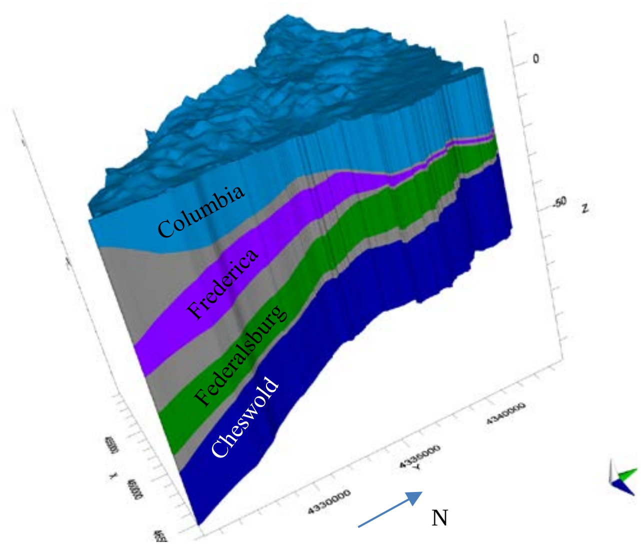


Figure 2. Three-dimensional grid diagram showing the hydrogeological units in the flow model area.

Layer configurations and geometries were derived from digital elevation models of aquifers that were produced by McLaughlin et al. (2014). Water enters the flow model as recharge and leaves the flow model through streams, tidal marshes, Delaware Bay, wells, and other artificial boundaries (discussed in a following paragraph).

The implementation of a numerical model is a process to translate the conceptual groundwater flow model into a mathematical formulation that can quantitatively describe the flow system. In this study, groundwater flow was simulated with MODFLOW-2005, a computer program that simulates three-dimensional groundwater flow through a porous medium using a numerical finite-difference method for solving the governing equations for steady (time invariant) and transient (time variable) flow. The pre-, post-processing of data input and output was completed using Visual Modflow Classic (Waterloo Hydrogeologic, Inc.) software.

Spatial and temporal discretization

The numerical model consists of seven layers representing four different aquifers and three intervening confining layers in the vertical direction. The thickness of each layer varies and is based on the study results of McLaughlin et al. (2014). In the horizontal direction, the study area is discretized into 288 rows and 222 columns of 75 m by 75 m computational cells.

Groundwater is part of a dynamic system. The amount of water that flows in and out of this area varies due to long-term and/or short-term changes of recharge, stream flow, and water use. In a steady-state model, the variability with time is simplified and all the parameters including recharge, pumping, and boundary conditions are held constant. As such, steady-state model results represent time-averaged conditions. In a transient flow model, recharge, pumping, and flow rates are allowed to vary with time, and resultant changes in groundwater conditions are computed in multiple stress periods. The pumping and boundary conditions vary between stress periods but are constant within each stress period. In this study, the transient flow model simulates hydrologic conditions over 20 years between January 1995 and December 2015, in which the total time is divided into 240 monthly stress periods. The choice of monthly stress periods reflects the fact that most water use is reported on a monthly basis.

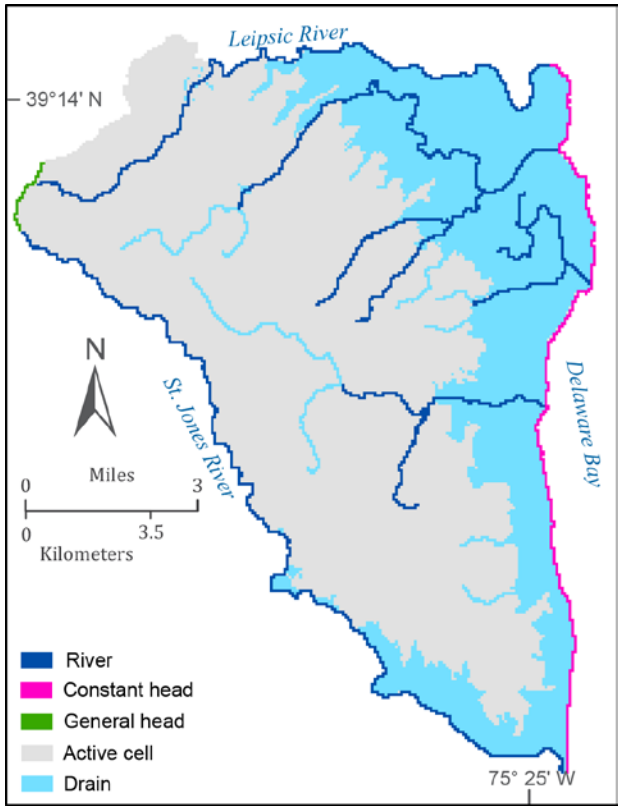


Figure 3. Model boundary conditions of top layer.

Boundary conditions and hydraulic properties

Boundary conditions in the flow model specify the locations and characteristics of groundwater flow into and out of the active areas of the model grid. Where possible, boundary conditions were selected to mimic the natural hydrologic boundaries within the study domain (Figure 3). No-flow boundaries were assigned to the bottom of the model (base of layer 7). In layer one, a no-flow boundary is assigned to the north-west corner coinciding with a drainage boundary where groundwater flow is assumed negligible. A no-flow boundary is also assigned along the perimeter of the model in layers 2-7, except part of layer 7, where a head-dependent-flux boundary (general head boundary) was assigned along the west and north boundary to simulate groundwater exchange between the Cheswold aquifer and areas outside of the model domain. The general head boundary elevations were assigned based on a contour map of the Cheswold aquifer groundwater level. Large streams are simulated using the river package (RIV) of MODFLOW-2005, in which the stages of streams are determined from a land-surface DEM, and the conductance that affects the flow exchange between groundwater and surface water is estimated through calibration. Larger ditches, ephemeral streams, tidal marshes, and wetlands were simulated using the drain package (DRN) of MODFLOW-2005. Similar to river cells, the elevations of drains are determined from a DEM, and conductance is estimated through calibration. This model formulation is reasonable for a long-term trend of a steady-state model and a monthly stress period in a transient model. Delaware Bay is represented as a constant head boundary in layer one with an elevation of zero.

Groundwater recharge is a hydrologic process where water moves downward from surface water to groundwater. In this model, only recharge from precipitation was simulated. In the steady-state model, the recharge is regionally uniform and temporally constant, and is assigned to layer one. In the transient-flow model, recharge amounts were determined from a climatic water-budget model. Monthly evapotranspiration (ET) and recharge (R) were calculated for the period 1995 through 2015 with a climatic water budget procedure using a spreadsheet model (Dilts, 2015). Input data for this model includes daily precipitation and temperature data collected by the National Weather Service and the Delaware Environmental Observing System (DEOS). Daily data were aggregated to a monthly mean for input to the spreadsheet model.

Initial hydraulic conductivity (K) and storage (S) values were obtained from previous work (Leahy, 1976, 1979, 1982; Andres, 2004) and unpublished data in the DGS internal database. For the Columbia aquifer, the value of horizontal hydraulic conductivity ranges between 50 to 250 ft/day (15 to 76m/d) based on aquifer tests in this region. Field test data are limited in the deep confined aquifers. A uniform value was assigned to confined aquifers and confining layers in the model, and the values were then adjusted through calibration. Vertical hydraulic conductivity was defined using a ratio of horizontal to vertical hydraulic conductivity; the ratio is set 10.0 for all the layers. The calibrated values are generally consistent with previously published values.

A hydraulic dredge sand and gravel open-pit mine and wash plant have been operating in the study area (Figure 1) since the early 1980s. Digitization of the pit outline on aerial orthophotographs shows the pit size grew from roughly 6 hectare (ha) in 1992, to 29 ha in 1997, 31 ha in 2002, 42 ha in 2007, and 49 ha in 2012. The dredge is capable of mining to depths of 60 ft (18 m), although the operating depth is sometimes limited by the presence of shallower clay and silt layers (Jeff Dawson, oral communication). All water used for production is pumped from, and returned to the pit. The operation has no off-site discharge of water. The pit intersects the water table and penetrates the Columbia aquifer. However, the impacts of the plant on the aquifer have never been studied in detail and, as a result, the sand pit was not simulated in this model. Bathymetric and water-level monitoring data from the pit are needed to further constrain the implementation of the pit in future modeling work.

Groundwater withdrawals

The major groundwater withdrawals from the Columbia aquifer in this area include the LPRW and dozens of irrigation wells. Acquiring reliable data on locations and use of irrigation wells is problematic. Good well construction and location data were available for wells in the LPRW, several industrial wells, and a small number of irrigation wells that have allocation permits. These wells were incorporated into the appropriate model grid cells based on location and depth. However, it is obvious from well permits and aerial photographic evidence of center-pivot irrigation systems that many more irrigation wells are present in the model area than have allocation permits. Available data do not allow the correlation of well permits and center pivot systems or to decide which wells are in

Table 2. Selected hydraulic properties of aquifers in the study area. Hydraulic properties of the confining units are those reported by Leahy (1976).

Aquifer	Calibrated K (ft/d)	Field test K mean/range (ft/d)	specific storage (m^{-1})	Specific yield
Columbia	102 , 138	70/ 0.42 – 490	0.00001	0.1
Frederica	16	85 / 41-160	0.00001	0.1
Federalsburg	16	4.1/ 3.6-4.6	0.00001	0.1
Cheswold	7 - ~24	5.3 /5.3	0.00001	0.1
Confining	0.08	NA	0.00001	0.1

operation and which are not. It is worth noting that well construction information present on irrigation well permits and completion reports show that all irrigation wells are pumping from the Columbia aquifer.

Considered the uncertainty of the irrigation wells information, two groups of scenarios were created based on how irrigation wells were simulated. In the first group, only 22 irrigation wells with differential global positioning system coordinates and recorded water use between 1996 and 2015 were simulated. Given the much larger number of irrigation systems in the area, this group of scenarios underestimates the amount of water used for irrigation. In the second group, it is assumed that each center pivot irrigation system identified in satellite images has one pumping well located to coincide with the center point of that system. A total of 72 proxy wells were created. Monthly and annual pumping rates for these wells were estimated from the results of a crop-water-demand model (e.g., KanSched, Rogers and Alam, 2006).

The monthly water use pumped from LPRW were recorded and reported to DNREC between 1996 and 2015. The City of Dover (2014) has indicated that they plan to increase the water pumped from the LPRW to roughly 4 million gallons per day to serve a planned expansion of the electrical generating station. The projected increased water use were also simulated in different model scenarios.

Calibration

Model calibration is an iterative process of adjusting the 3-D distribution or structure of aquifer properties, aquifer property values, or properties of boundary conditions to improve the match between simulation results and observations. The calibration of the numerical models in this study involved selecting and evaluating water levels measured in wells to be used as calibration targets and adjusting model parameters until an adequate match between observed and simulated hydraulic heads was obtained. Model parameters, including aquifer properties such as horizontal and vertical hydraulic conductivities, specific yields, and specific storage and boundary condition properties such as recharge and conductance, were adjusted either manually by “trial-and -error” or by using an automatic inverse method (PEST). In this study, water level data used for calibration were measured by the City of Dover, and by the DGS in LPRW monitoring wells and, by the DGS in one additional monitoring well that is part of the Department of Agriculture’s Pesticide Compliance Monitoring Network.

MODEL RESULTS AND APPLICATIONS

Steady-state model results

The steady-state model and results are used to test our understanding of the groundwater flow system under reported pumping conditions in the study area, identify gaps in input data, estimate model parameters such as hydraulic conductivity and

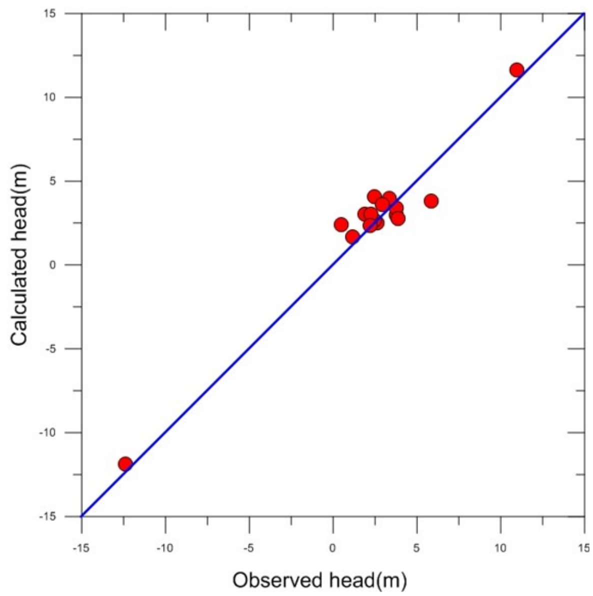


Figure 4. Steady state flow-model calibration result.

recharge, and provide the initial head field for transient flow simulations. Results of the estimated parameter values for each aquifer and confining layer are summarized in Table 2. It should be noted that only one well with adequate data is available for the Cheswold aquifer within the study domain.

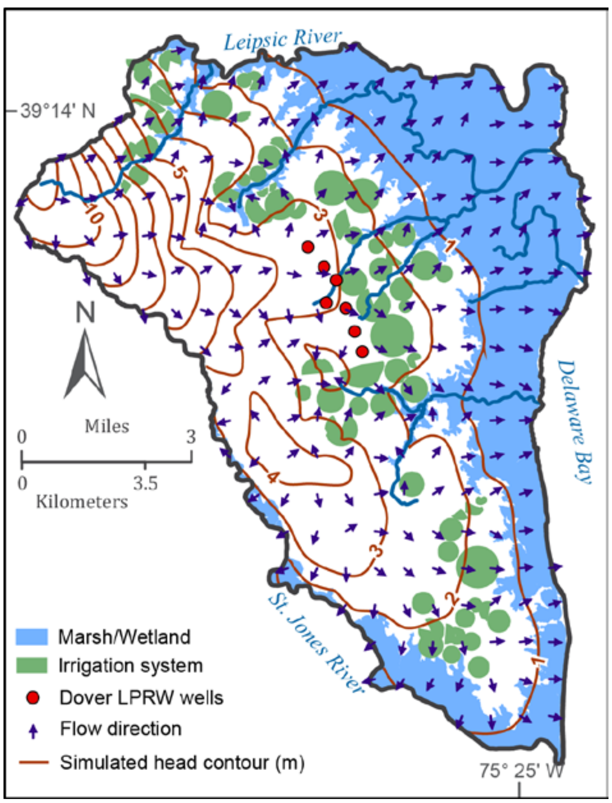


Figure 5. Steady-state flow-model simulated water-table elevation and flow directions.

The goodness-of-fit of model simulated heads to observed heads are represented by mean error, mean absolute error, standard deviation, and normalized root mean squares (NRMS) of model residuals (measured head minus simulated head). When these errors fall within an acceptable range, the model is considered to be calibrated; in this case a residual mean of 0.077m, an absolute residual mean of 0.836 m, a standard error of 0.253 m, and NRMS of 4.2 percent (Figure 4). The water-table contour map simulated by the calibrated model shows that groundwater flows laterally from areas of higher land-surface elevations to areas of lower elevations, discharging to streams, marshes/wetlands and Delaware Bay (Figure 5). Simulated groundwater elevations relative to the North American Vertical Datum of 1988 (NAVD88) range from above 10 m in the northwest highland areas to less than 1 m in the lowland/wetland/marsh areas to near to 0 m along river mouth and Delaware Bay.

Flow mass-budget analysis shows that, of the 75,800 m^3/day of groundwater recharge, approximately 64 percent discharges to wetlands/marshes, Delaware Bay, and other major rivers; 10 percent is pumped from the unconfined aquifer; 17 percent infiltrates to the underlying aquifers through the Frederica outcrop area, and 8 percent flows through the underlying confining layer to the deep confined aquifer (Figure 6).

Transient model results

Transient flow simulations calculate time-variant heads and flows in response to time-variant recharge and pumping. Figure 7 shows annual average recharge and estimated irrigation water use based on climatic water budget and crop water-demand models. Because steady-state results were calibrated based on historic average water levels instead of a snap shot of the flow system at a specific

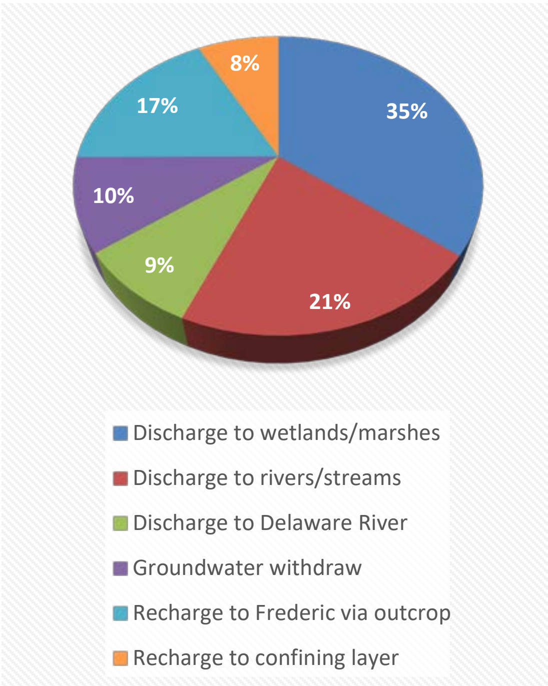


Figure 6. Steady-state model outflow budget analysis. The total outflow rate is 75780m3/day.

time, there is a training period in the beginning of the transient simulation when the model adapts to changing recharge and groundwater pumping. From 1996 through 2015, the average annual recharge in the study domain is approximate 154 mm, or about 13 percent of annual precipitation. The average irrigation rate is about 128 mm per year that in general follows a trend opposite that of precipitation. In a wet year (2003), only 32 mm of water were pumped for irrigation, while in a dry year (2008) 216 mm water was used for irrigation.

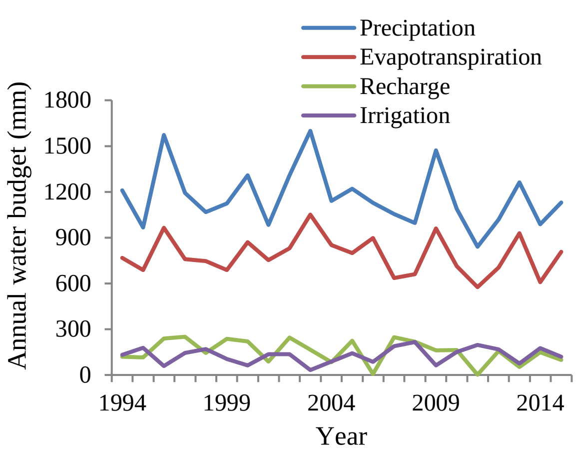


Figure 7. Climatic water budget in the study area between 1994 and 2015.

As described in the previous section, two different groups of pumping scenarios were proposed to simulate groundwater pumping by irrigation wells. However, the results discussed in this section only refer to the scenario case 2a (see details in the next section) in which LPRW wells and 22 irrigation wells with reported water-use data are simulated.

Observed groundwater levels in monitoring wells were compared with model simulated groundwater levels to evaluate how well the transient flow model simulated response of the aquifer to changing recharge and pumping in the unconfined aquifer. Water-level records from two wells in particular received additional scrutiny. Well Ie53-16 is located approximate 90 m away from an active irrigation well (Permit Number: 234476), which represents an area under strong influence of irrigation pumping. Well Ie32-02 is located 1.2 km northeast of the LPRW, where no irrigation wells exist within 1 km. Both wells were equipped with data loggers that recorded water levels on a 15-minute interval since July 2015. The statistics of historical manually measured water-level data from the two wells shows no apparent difference (Table 3). They have similar ranges (maximum – minimum) and similar standard deviations. The negative skewness of well Ie53-16 indicates some measurements are far below the

Table 3. Statistics of observed water level data from monitoring wells Ie53-16 and Ie32-02.

	Ie53-16	Ie32-02
Mean (m)	2.43	3.82
Median (m)	2.56	3.7
Standard Deviation (m)	0.63	0.84
Skewness	-0.77	0.36
Range (m)	3.40	3.36
Minimum (m)	0.24	2.31
Maximum (m)	3.64	5.67
Count	58	65

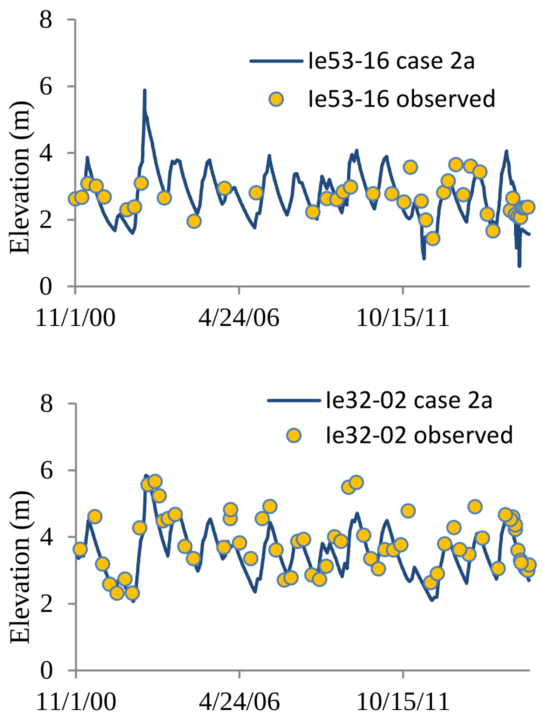


Figure 8. Simulated and observed groundwater levels in wells Ie53-16 and Ie32-02.

mean value, which likely represents pumping effects.

Manually measured and simulated heads follow similar trends over time indicating that the model is performing reasonably well (Figure 8). Assuming no bias or unknown errors in water level measurements, current pumping rates do not appreciably change flow conditions at well Ie53-16 in the long term. However, analysis of the daily mean water levels shows that pumping from an irrigation well located near well Ie53-16 has a significant impact on the range, mean, and standard deviation of water levels in the pumping season, in comparison to well Ie32-03 where there is no nearby pumping well (Figure 9). This difference illustrates the need to use high-frequency water-level observations in assessing pumping impacts in this area.

Figure 10 shows the simulated water level and flow directions for a wet year (2003) just before the pumping season (Figure 10a) and a dry year (2002) following the end of the pumping season (Figure 10b). Compared to the dry year, more water flows toward rivers/marshes/wetlands during the wet year. However, domain-wide flow directions are not appreciably impacted by pumping. The most noticeable changes in flow direction between wet and dry years occurred in the northwest portion of the model domain, near the no-flow boundary that represents a flow divide. With no water-level observation points in this area, it is not certain if the change in flow direction is an artifact of the model construction or a real phenomenon.

Projected pumping simulation scenarios

To assess the impacts of increasing pumping at City of Dover LPRW on the groundwater flow system, several scenarios were developed to compare with current conditions due to reported pumping (Table 4). *Case 1* represents the natural flow system without any pumping. Case 2 and case 3 represent the LPRW pumping along with different numbers of irrigation wells and pumping rates. Cases 2a, 2b,

Table 4. Description of projected pumping scenarios.

Scenarios		Irrigation wells water use (MG/Yr)	LPRW wells water use (MG/Yr)
Case 1	-	0	0
Case 2	a	Recorded data	74[1]
	b	Recorded data	630[2]
	c	Recorded data	1659[3]
Case 3	a	Estimated data	74[1]
	b	Estimated data	630[2]
	c	Estimated data	1659[3]

[1] Actual recorded water use data.
[2] Projected water use data based on 2015 allocation.
[3] Projected water use data based on potential doubling of energy generating capacity (see text).

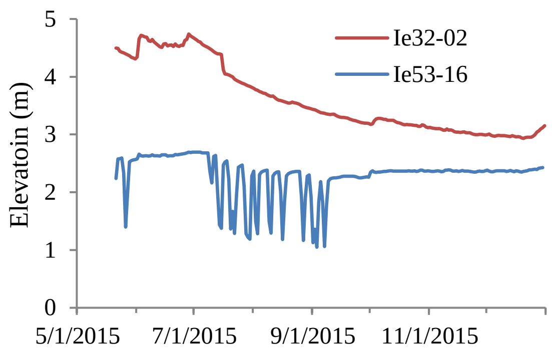


Figure 9. Measured daily mean groundwater levels in wells Ie53-16 and Ie32-02.

and 2c have 22 irrigation wells with recorded water-use data, and cases 3a, 3b, and-3c have 72 proxy irrigation wells located at the center of each center-pivot system with water use estimated from the irrigated area and modeled irrigation demand.

Prior to 2015, the reported amount of groundwater pumped by the LPRW is used in the simulation. In 2015, pumping rates vary and represent current and different projected water demands. Actual reported monthly pumping rates were used in scenario a (cases 2a and 3a); 2015 allocation rates were used in scenario b (cases 2b and 3b); and, projected increased allocation rates were used in scenario c (cases 2c and 3c). The projected allocation rates are those requested by the City of Dover to support operation of the expanded electric generating plant (City of Dover, 2014).

Reduced water-table elevation caused by increased pumping at the LPRW site (cases 2c and 3c) may result in potential economic, water quality, and environmental risks that are illustrated with the simulated heads at the end of September, 2015, representing the end of irrigation season.

A lowered water-table elevation can lead to degradation of groundwater quality due to saltwater intrusion. Saltwater is denser than freshwater and exerts a constant pressure toward freshwater zones. The Ghyben-Herzberg equation (De Wiest, 1965) describes the relationship between the water table

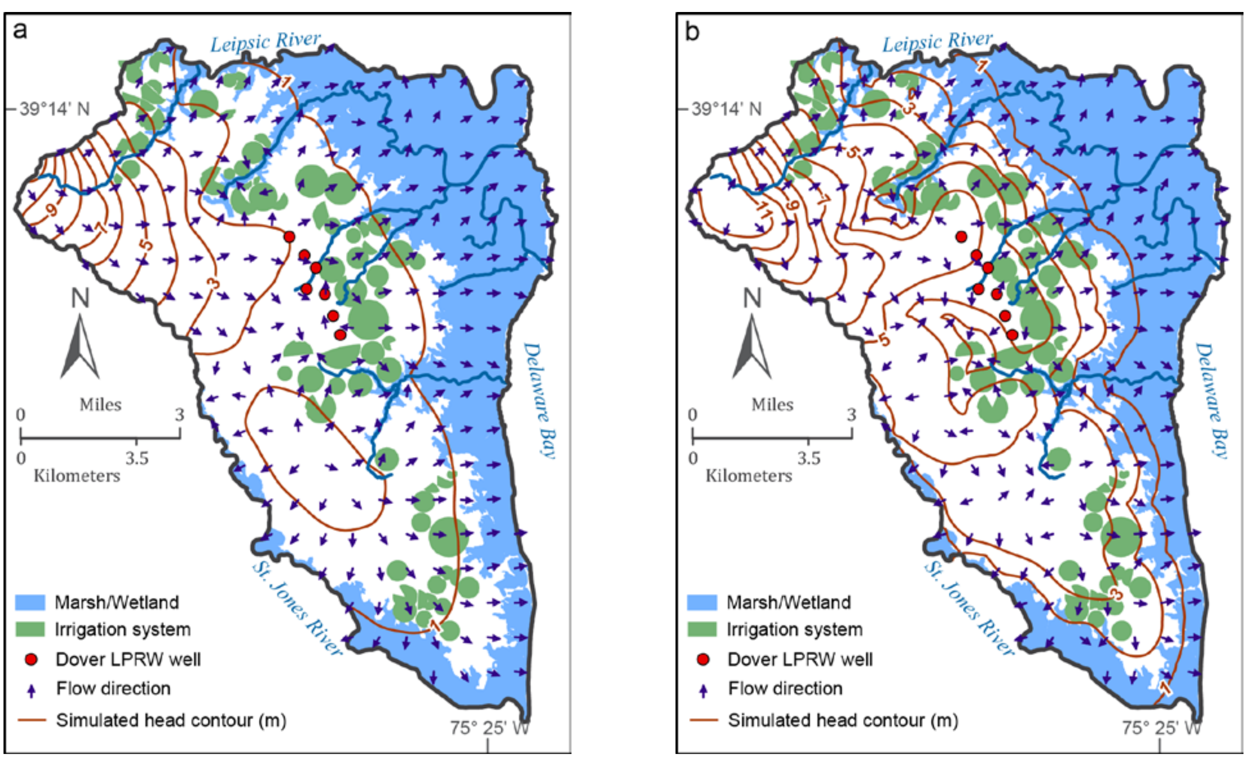


Figure 10. Simulated groundwater flow directions for case 2a. a: 9/30/2002, in a dry year; b: 5/31/2003, in a wet year.

Table 5. Cropland areas that are impacted due to water table reduction for different scenarios.

water table elevation	Case 2a hectare (percentage)	Case 2b hectare (percentage)	Case 2c hectare (percentage)	Case 3a hectare (percentage)	Case 3b hectare (percentage)	Case 3c hectare (percentage)
< 0.5 m	11 (0.2%)	11 (0.2%)	444 (8%)	14 (0.2%)	15 (0.2%)	575 (10.4%)
< 1.0 m	109 (2%)	128 (2.3%)	1020 (18.4%)	356 (6.5%)	473 (8.5%)	1563 (28.2%)

elevation above a sea level datum (SLD) and saltwater/freshwater interface:

$$z = \frac{\rho_f}{\rho_s - \rho_f} h$$

Where z is the depth of the saltwater/freshwater interface below SLD, h is the water table elevation above SLD, ρ_f is the freshwater density, and ρ_s is the saltwater density.

As long as freshwater levels in the aquifer are above sea level, the pressure from the freshwater limits the inland movement of saltwater. In the projected scenarios, the water level in the irrigation well could be as low as three meters below NAVD88 for case 2c (Figure 11a). Even 300 feet away from the pumping well, water levels are lower than NAVD88 for an extended period during the pumping season (Figure 11b). The saltwater/freshwater interface moves landward in response to the decline of the water table. Due to uncertainty in simulated heads we take a conservative view and define an elevated risk of saltwater intrusion in the areas where the water-table elevation is less than 1.0 m (Figure 12). Compared to case 2a and case 3a, the areas of elevated risk only slightly increase near the LPRW for case 2b and 3b; but for case 2c and 3c, the impacted areas are significantly increased (Table 5). For example, of the total 5,534 ha of cropland in the study domain, the areas where the water table elevation is less than 1.0 m are increased from 2 percent for case 2a to 2.3 percent and 18 percent for case 2b and 2c, respectively.

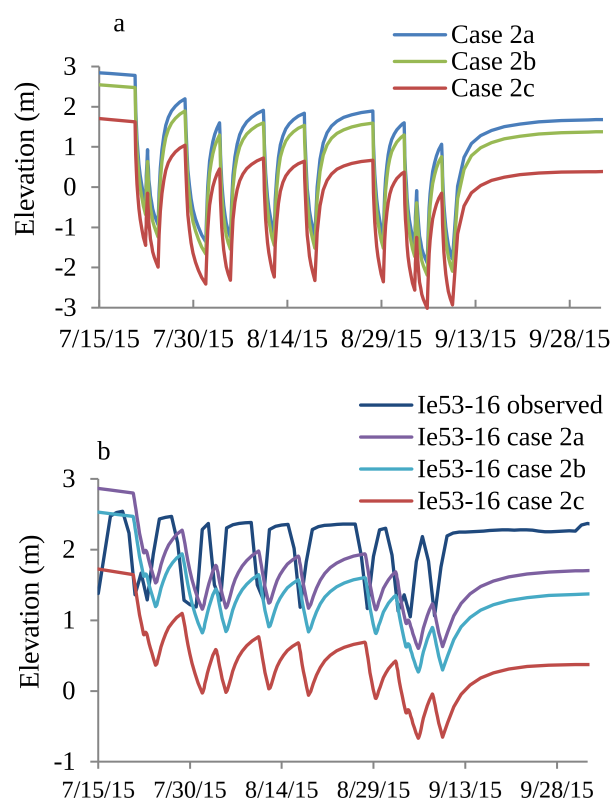


Figure 11. Simulated groundwater levels for a pumping well (a) and an observation well (b) under different pumping scenarios.

Decreased water levels also can impact operational costs and well yields. Extra operating costs may occur when water has to be pumped from greater depths. In an unconfined aquifer, pumping reduces the saturated thickness of the aquifer, and given the dependency of well yield on hydraulic conductivity and saturated thickness of the aquifer, declines in

Table 6. Irrigation systems that are impacted due to reduction of thickness of saturated aquifer for different scenarios.

Thickness of saturated aquifer	Case 2a hectare (percentage)	Case 2b hectare (percentage)	Case 2c hectare (percentage)	Case 3a hectare (percentage)	Case 3b hectare (percentage)	Case 3c hectare (percentage)
<6m	17 (0.80%)	17 (0.80%)	17 (0.80%)	28 (1.27%)	28 (1.27%)	28 (1.27%)
<14m	978 (45.1%)	1015 (46.8%)	1174 (54.1%)	1033 (47.6%)	1100 (50.7%)	1230 (56.7%)

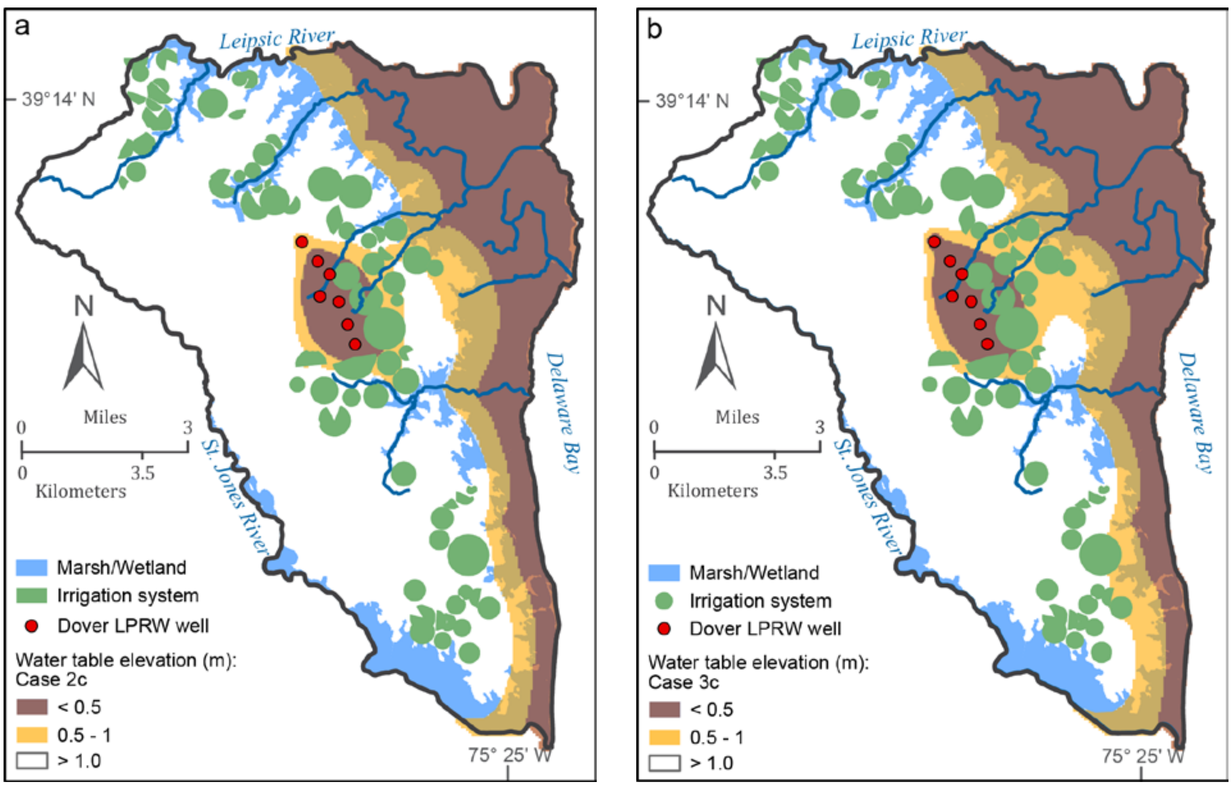
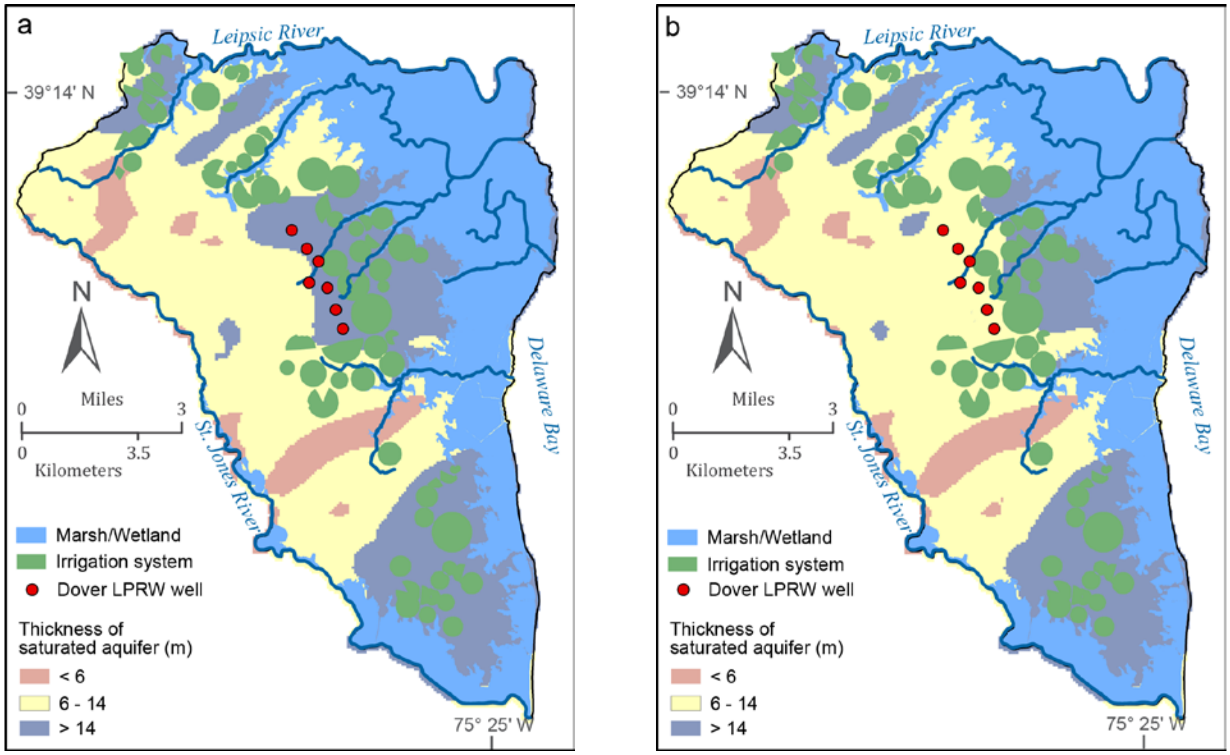


Figure 12. Model-predicted zones for high risk of saltwater intrusion. a: case 2c; b: case 3c.

well yield can occur when saturated thickness is significantly reduced. The amount of reduction in yield is dependent on a complex function of well hydraulics and aquifer hydraulic conductivity that is empirically determined by in-field testing. Hecox et al. (2002) described the relationship between minimum saturated thickness and well yield based on Cooper-Jacob equation. For example, given a hydraulic conductivity value of 30 m/day and specific yield of 0.1 in the model domain, the thickness of the saturated aquifer needs to be approximately 6 m (approximately 20 feet) to support a pumping rate of 75 gallons per minute (GPM) for the duration of the growing season, and 14 m (approximately 45 feet) to support a pumping rate of 500 GPM for one day. Both are common pumping scenarios for the larger irrigation systems in the study area. For both pumping scenarios, the areas where the thickness is less than 6 m do not change significantly and are located in areas where



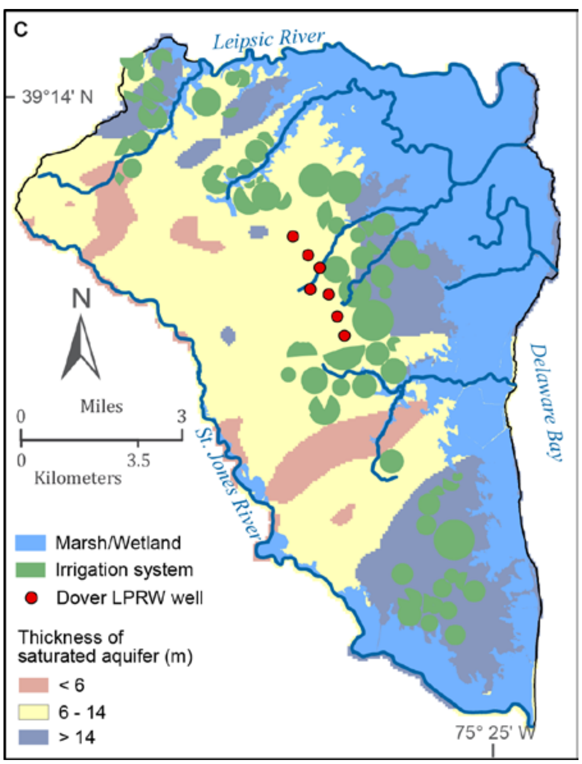


Figure 13. Model-predicted thickness of saturated Columbia aquifer. a. case 1, b. case 2c, c. case 3c.

the Columbia aquifer is thin. However, for cases 2c and 3c, the areas where the aquifer is capable of supporting 500 GPM over a 24- to 72- hour period are reduced (Figure 13). For example, of the total 2,169 ha of cropland equipped with center-pivot systems, the areas where the thickness of the saturated aquifer is less than 14 m increased from 45.1 percent for case 2a to 46.8 percent for case 2b, and 54.1 percent for case 2c (Table 6).

Pumping also altered the groundwater flow directions and in doing so reduced the amount of water that flowed to streams and marshes/wetlands, by capturing groundwater before it reached streams and also by inducing flow of water from streams into the aquifer. The change in flow directions is clearly observed in the area east of the LPRW and adjacent to the saltmarsh (Figure 14). Monthly base flow (groundwater discharge to streams) was significantly reduced in case 2c as compared to case 1 (Figure 15). In case 2c, monthly base flow was reduced by approximately 10 percent between 2000 and 2015. In general, the greatest decrease in groundwater discharge to streams occurred in October at the end of the irrigation season. For example, in a dry year (2011), the base flow in October was 27.7 percent less than the base flow in the case 1 (no pumping). It is not certain what the impacts of reducing recharge to streams and marshes/wetlands on the local eco-system will be. Assessment of these impacts is beyond the scope of this study.

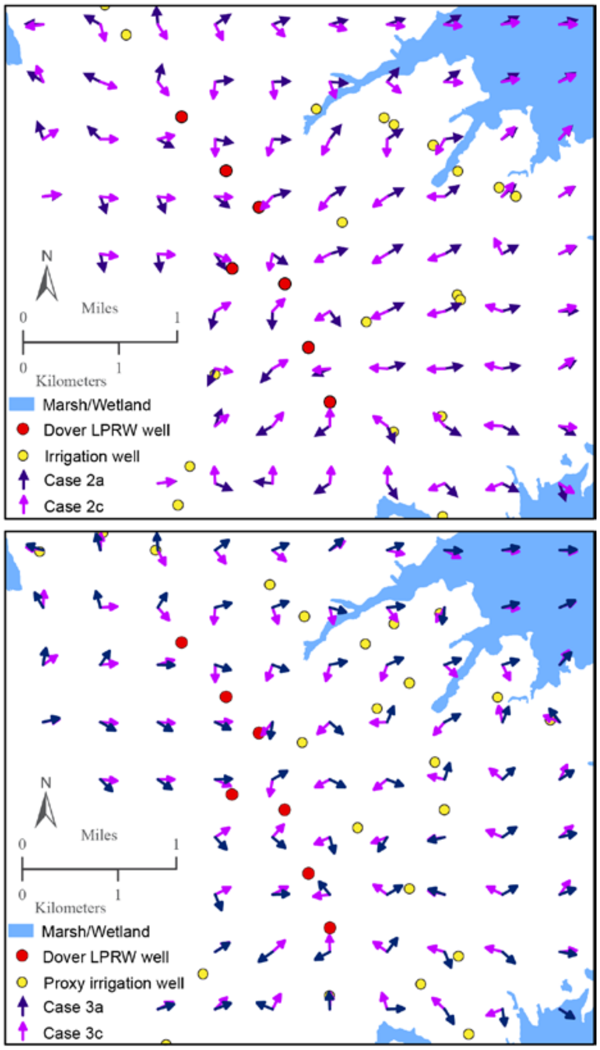


Figure 14. Changes in model-predicted flow directions for different pumping scenarios.

Examination of changes in vertical flow volumes from layer 1 (Columbia) to deeper aquifers was examined in greater detail for scenarios 2a and 2c to determine how increased pumping from layer 1 impacts the downward transfer of water. Changes in vertical flow could potentially impact heads and water availability in the deeper aquifers. However, the vertical flow is complicated due to the geologic heterogeneity and connectivity to surface-water features. We found that, as the pumping rates are increased, the downward flow is reduced in the LPRW area, but increased outside the LPRW impacted area, even though the change is relatively very small (1.2 percent). The model also predicts that the vertical flow to the Cheswold aquifer is reduced approximately 1.1 percent due to increased pumping in the Columbia aquifer. Generally speaking, we consider these differences to be insignificant given the uncertainties of hydraulic variables used in the model, the limited spatial extent of the model domain, and the simplified general-head boundary conditions used in the deeper aquifers. In order to properly evaluate the impact of increased water use in the Columbia aquifer on flow to deeper aquifers, the model domain should be expanded to the west to directly simulate the effects of pumping wells in the City of Dover and to minimize the effects of the general head boundaries in the area of the LPRW.

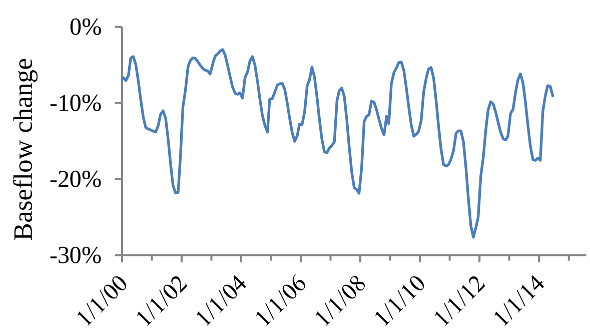


Figure 15. Model-predicted changes in base flow for case 2c.

MODEL LIMITATIONS

As is the case for all models, the accuracy and usefulness of the results hinge on appropriate conceptual models of subsurface geology, groundwater flow system, hydraulics, and boundary conditions. In this study, several specific issues and assumptions likely limit the ability of the model to precisely simulate heads and flow.

(1) Only a small portion of irrigation wells have complete location, construction, and pumping rate data. The number and distribution of monitoring wells are also limited, which may bias calibration and results in specific areas. Streamflow data are almost entirely absent. Most streams are too small, have intermittent flow, or are tidal making acquisition of accurate measurements extremely difficult and expensive. Because of limited hydraulics data, the model used a small number of K zones and adjusted the K values through calibration. This implementation, however, does not incorporate known spatial heterogeneity in the aquifers. The parameterization of no-flow and general-head boundaries used to simulate flow through the model perimeter into and out of the Frederica, Federalsburg and Cheswold aquifers is based on very few data. We assume that those boundaries are far enough from the LPRW to have minimum impacts on the unconfined aquifer at the LPRW.

(2) The transient-flow model uses monthly stress periods, in which recharge and pumping are averaged on a monthly time step. This stress-period implementation does not account for short period events such as tides and storms, and weekly or daily pumping cycles that can have significant short-duration impacts on flow and salinity in close proximity to the streams or pumping wells. However, this stress-period implementation does not adversely impact overall model performance over multiple decades of simulation.

SUMMARY AND FUTURE WORK

Model results show that pumping by the City of Dover and pumping for irrigation have a significant impact on groundwater elevations and flow directions in the Columbia aquifer within the study area. The magnitude of the impact varies with modeled pumping rates, with larger pumping rates causing greater drawdown and larger areas where flow directions change more than 90 degrees.

Impacts of current and projected water use result in two main concerns. Areas associated with water-table elevations near or below sea level and located in proximity to saline tidal creeks and marshes are at risk for intrusion of saline water. Areas where pumping significantly reduces the thickness of saturated the aquifer are at risk for reduced well yields due to decreased aquifer transmissivity and increased pumping costs due to lower dynamic heads in the wells. For both concerns, the risks are greatest during the irrigation season when pumping rates are greatest and lowest when irrigation is not occurring.

Water-use data are incomplete and a source of uncertainty. Data are not available to link many irrigation systems to a specific well or wells. Water use is not reported for many irrigation systems. Where irrigation water use is measured it is usually determined by time of operation and estimated flow rates. Unreported irrigation water use can be reasonably estimated by using cropland area and plant-water-demand models.

The sand and gravel pit is reported to penetrate the entire thickness of the Columbia aquifer and may have a significant impact on local hydrogeology. Future work will incorporate data from the water-level recorder along with climatic models of evaporation from the pit. A bathymetric survey of the pit is needed to further constrain the implementation of the pit in groundwater flow models.

REFERENCES CITED

Andres, A.S., 2004, Results of the groundwater recharge potential mapping project: Delaware

Geological Survey Report of Investigations No. 66.

City of Dover, 2014, Letter to Department of Natural Resources and Environmental Control.

De Wiest, R. J.M., 1965. Geohydrology, New York. John Willey & Sons, 366 pp

Dilts, T., 2015, Climatic Water Deficit Excel Spreadsheet: https://naes.unr.edu/weisberg/old_site/downloads/

Hecox, G. R., Macfarlane, P. A., and Wilson, B. B., 2002, Calculation of yield for High Plains wells: Relationship between saturated thickness and well yield: Kansas Geological Survey Open File Report 2002-25C.

Leahy, P.P, 1976, Hydraulic Characteristics of the Piney Point Aquifer and Overlying Confining Bed near Dover, Delaware: Delaware Geological Survey Report of Investigations No. 26.

Leahy, P.P, 1979, Digital Model of the Piney Point Aquifer in Kent County, Delaware: Delaware Geological Survey Report of Investigations No. 29.

Leahy, P.P, 1982, Ground-Water Resources of the Piney Point and Cheswold Aquifers in Central Delaware as Determined by a Flow Model: Delaware Geological Survey Bulletin No. 16.

Mclaughlin, P.P., Tomlinson, J.L., and Lawson, A.K., 2014, Aquifers and groundwater withdrawals, Kent and Sussex Counties, Delaware, unpublished report submitted to Delaware Department of Natural Resources and Environmental Control.

Ramsey, K.W., 2007, Geologic map of Kent County, Delaware: Delaware Geological Survey Geologic Map No. 14,

Rogers, R.H. and Alam, M., 2006, KanSched2 An ET-Based Irrigation Scheduling Tool, Biological and Agricultural Engineering K-State Research and Extension.

University of Delaware Agricultural Experiment Station, 2012, Irrigation system.