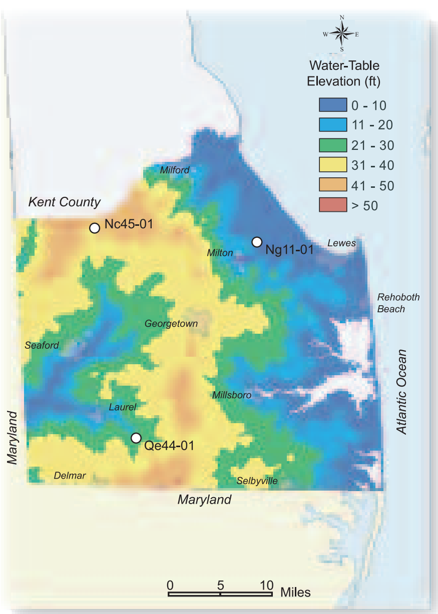
State of Delaware
DELAWARE GEOLOGICAL SURVEY
John H. Talley, State Geologist

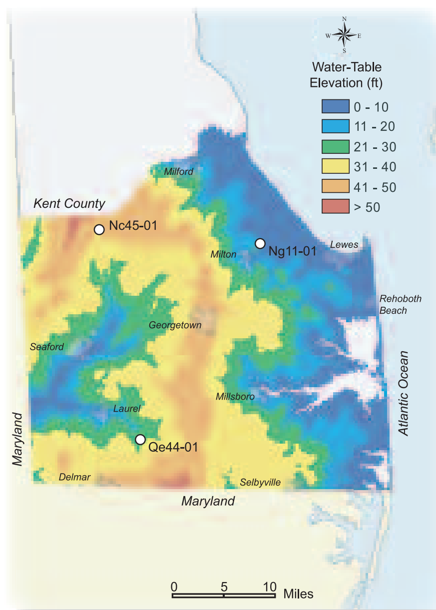
# REPORT OF INVESTIGATIONS NO. 73

# ANALYSIS AND SUMMARY OF WATER-TABLE MAPS FOR THE DELAWARE COASTAL PLAIN

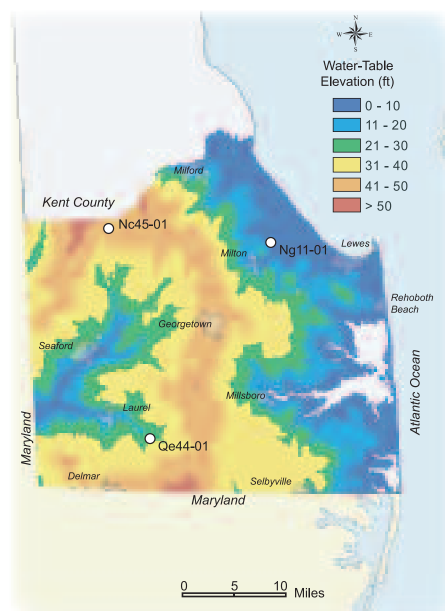
By
Matthew J. Martin[1] and A. Scott Andres[2]




Dry Conditions




Normal Conditions




Wet Conditions

University of Delaware
Newark, Delaware
2008

[1]Delta Development Group, Inc.
[2]Delaware Geological Survey

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# ANALYSIS AND SUMMARY OF WATER-TABLE MAPS FOR THE DELAWARE COASTAL PLAIN


## ABSTRACT

A multiple linear regression method was used to estimate water-table elevations under dry, normal, and wet conditions for the Coastal Plain of Delaware. The variables used in the regression are elevation of an initial water table and depth to the initial water table from land surface. The initial water table is computed from a local polynomial regression of elevations of surface-water features. Correlation coefficients from the multiple linear regression estimation account for more than 90 percent of the variability observed in ground-water level data. The estimated water table is presented in raster format as GIS-ready grids with 30-m horizontal (~98 ft) and 0.305-m (1 ft) vertical resolutions.

Water-table elevation and depth are key facets in many engineering, hydrogeologic, and environmental management and regulatory decisions. Depth to water is an important factor in risk assessments, site assessments, evaluation of permit compliance data, registration of pesticides, and determining acceptable pesticide application rates. Water-table elevations are used to compute ground-water flow directions and, along with information about aquifer properties (e.g., hydraulic conductivity and porosity), are used to compute ground-water flow velocities. Therefore, obtaining an accurate representation of the water table is also crucial to the success of many hydrologic modeling efforts.

Water-table elevations can also be estimated from simple linear regression on elevations of either land surface or initial water table. The goodness-of-fits of elevations estimated from these surfaces are similar to that of multiple linear regression. Visual analysis of the distributions of the differences between observed and estimated water elevations (residuals) shows that the multiple linear regression-derived surfaces better fit observations than do surfaces estimated by simple linear regression.


## INTRODUCTION

The water table is defined as the surface on which the water pressure in the pores of a porous medium is exactly atmospheric (Freeze and Cherry, 1979). In practice, the position of the water table is measured in wells constructed with openings along their lengths and penetrating just deep enough to encounter standing water. Water located at or beneath the water table is ground water. Given the climate and relatively permeable subsurface materials in Delaware, the water table often occurs at depths less than 10 ft below land surface (Andres and Martin, 2005; Martin and Andres, 2005a, b, c).

The first efforts to map the water-table for the state of Delaware were undertaken in the 1950s and were a cooperative effort between the United States Geological Survey (USGS), the Delaware Division of Highways, and the Delaware Geological Survey (DGS). Maps from this project were published as paper maps in the Hydrologic Atlas series at a scale of 1:24,000 and depicted the water table with contour lines at a 10-ft interval. These water-table maps have been widely used by both the public and private sectors (Andres and Martin, 2005). Despite the usefulness of these paper maps, more data are now available and recent advances in computer technology and the expanding use of Geographic Information Systems (GIS) have made it necessary to update water-table maps into a digital format.

The configuration of the water table is one of the major factors that controls regional ground-water flow patterns (Freeze and Witherspoon, 1967). Ground water moves slowly underground in the down-gradient direction and eventually discharges into streams, lakes, and oceans (Perlman, 2005). Because ground water is such an integral part of the water cycle, planners and developers often need to have a strategic plan when dealing with water resources. Excess pumping of wells over extended periods of time can result in lowering the water table leading to an increase in the cost of pumping from greater depths, depletion of the amount of water available for important wetland habitats, and salt-water intrusion into domestic water supplies (Dunne and Leopold, 1998). In addition, the practice of well drilling to extract ground water is dependent upon an understanding of the depth to the water table. Wells must be finished below the water table, and the depth of the water table determines the final specifications of the well.

Obtaining an accurate representation of the water table is also crucial to the success of many hydrologic modeling efforts (Williams and Williamson, 1989). Estimated water-table elevation can be used to specify heads in the surficial aquifer for a ground-water flow model, to estimate depths to areas of potential ground-water contamination, or to simulate recharge and discharge rates of the surficial aquifer (Sepulveda, 2003).

In many areas throughout Delaware, the depth to the water table has a direct effect on how people utilize the land. For instance, based on depth to the water table, it can be determined whether or not a site is suitable for a standard subsurface wastewater-disposal system. Water-table depth is a key facet in many engineering, hydrogeologic, environmental management, and regulatory decisions. Depth to water is an important factor in risk assessments, site assessments, evaluation of permit compliance data, registration of pesticides and determining acceptable application rates. Shallow depth to ground water has been the principal motive for constructing the extensive ditch networks that can be found in many watersheds in Delaware. In many areas, the water table is also the top of the aquifer that provides water for potable, agricultural, commercial, and industrial uses. The thickness of this aquifer is one factor that controls the amount of water that is available to wells (Andres and Martin, 2005).

Depth to the water table is a prevailing factor in determining the ecological function of a landscape. For example, many wetlands are found where the water table is at or near land surface for portions of the year. The duration of standing water in large part prescribes the plant and animal communities that can live at that site. Under fair or "normal" weather conditions, the surfaces of Coastal Plain streams and ponds represent the intersection of the water table with land surface (Winter, 1999; Andres and Martin, 2005).

## Purpose and Scope

The purpose of this report is to provide both a brief review of the pilot project, the Inland Bays Watershed Water-Table Mapping Project, and a detailed summary and analysis of the results of mapping the water table for the Delaware Coastal Plain. The goals of the Delaware Coastal Plain project were to use the methodology and procedures established during the pilot project to map the water table for the remainder of Sussex County, as well as Kent County and New Castle County.

Appropriate methodologies and procedures for calculating the water table for the Coastal Plain of Delaware were established in the Inland Bays Watershed Water-Table Mapping Project. Water-table elevation maps were produced for dry, normal, and wet conditions using a variety of estimation methods, making qualitative comparisons between the different methods and pre-existing water-table maps, and determining which of the estimation methods could be used to map the Coastal Plain of Delaware in a cost-effective and timely manner. One crucial constraint in choosing a suitable estimation method for mapping the entire state was that it had to rely on existing data because available funding was not sufficient to construct new wells or to support collection of additional water-level measurements.

The Inland Bays watershed (Fig. 1) was selected as the pilot project by the Delaware Geological Survey and the Delaware Department of Natural Resources and Environmental Control (DNREC) Water Supply Section (WSS) because of the readily available pre-existing water-level data from previous hydrologic studies conducted in this region. In addition, the watershed was identified as a high priority area for a number of regulatory and environmental restoration efforts that can use the resultant information.

After creating and analyzing water-table maps for dry, normal, and wet conditions using various statistical estimators, it was determined that the method which produced the most desirable results was an algorithm based on a multiple linear regression (MLR) equation to estimate the water table. Water-table elevation and depth-to-water maps for the remainder of Sussex County, Kent County, and New Castle County were then produced using this algorithm (Martin and Andres, 2005a, b, c).

The map products created by this work are being utilized to support various public environmental programs and private site reviews that require hydrologic assessment. These map products will be an important tool in the assessment process; however, they depict estimates of water-table elevation and are, therefore, not intended to supplant on-site data collection efforts. The water-table maps will not be published paper maps; however, they are published as GIS-ready products and are available for download from the Delaware Geological Survey's website (http://www.udel.edu/dgs).

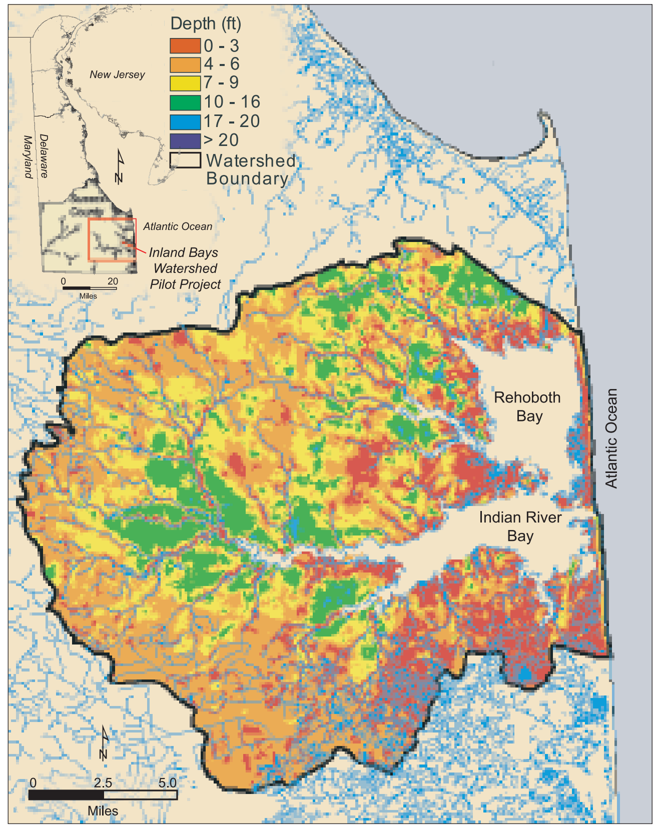


**Figure 1**. Depth to water under normal conditions for the Inland Bays watershed in Sussex County, Delaware.

## Acknowledgments

This work was funded by the DNREC through grants from the U.S. Environmental Protection Agency Ground-Water Protection and Source Water Protection Programs. Evan M. Costas, Cheryl A. Duffy, Bailey L. Dugan, Scott V. Lynch, and Tamika K. Odrick assisted with the work. Ronald Graeber, John Barndt, Blair Venables, Joshua Kasper, and Scott Strohmeier of the DNREC are thanked for making monitoring data from numerous wastewater disposal facilities available. Stacey Chirnside of the University of Delaware Department of Bioresources Engineering is thanked for providing access to ground-water data from several research projects. Thomas E. McKenna (DGS), John T. Barndt (DNREC), and Geoffrey C. Bohling (Kansas Geological Survey) critically reviewed the manuscript.

# METHODS

This work has three primary components: data compilation, statistical evaluation and model development, and estimation of the water-table elevation. Water level and well data were extracted from a DGS, Oracle-based database. Spatial data management and processing were done with desktop and workstation components of ArcGIS v9.0 (ESRI, 2003), ArcGIS v9.1 (ESRI, 2005) and Surfer v8 (Golden Software, 2002) software. Horizontal coordinates of all data are in meters, using the Universal Transverse Mercator projection and North American Datum of 1983 (NAD83). Elevations are reported relative to the North American Vertical Datum of 1988 (NAVD88). Statistics were computed with functions and procedures contained in Oracle, ArcGIS, and Microsoft Excel.

### Data Compilation and Statistical Evaluation

Land-surface elevation (LSE) data that were used throughout the estimation process are from a 30-m digital elevation model (DEM) created by John Mackenzie of the University of Delaware's Spatial Analysis Lab, and from USGS 1:24,000-scale topographic maps.

*Depth-to-water data*

Depth-to-water (DTW) and well data were acquired from the files and electronic databases of the DGS, DNREC, USGS, and the University of Delaware Department of Bioresources Engineering. DNREC data were extracted from the files and electronic databases of the Site Investigation and Restoration Branch, Water Supply Section, Ground-Water Discharges Section, Spray Irrigation Program, and Tank Management Branch of the DNREC. Additional monitoring-well and water-level data were obtained for New Castle County from the USGS (1996). The data gathered were of two types: one type consisting of time-series depth-to-water measurements from monitoring wells, the other type from single static depth-to-water measurements reported by well drillers on well completion reports. Prior to analysis, all depth-to-water data were converted to depth relative to ground-surface datum. Depth-to-water data from monitoring wells typically are reported to the nearest 0.01 ft; data from well completion reports usually are reported to the nearest foot. The accuracy of measurements from individual wells was evaluated by comparison to measurements in nearby wells and by converting depth-to-water to water-table elevation. Because the elevation of the water table is above 0 ft under static conditions, water elevations less than 0 ft and greater than LSE are generally considered to be non-representative of local conditions or inaccurate and were removed from the dataset.

Depth-to-water and well data were managed and analyzed in a relational database format. Structured Query Language (SQL) queries were assembled to create tables in Oracle that contained well locations, land surface elevations, water-level observations, and computed statistics (mean, minimum, maximum, standard deviation, and number of observations) of observations made in the months and years of normal, dry, and wet conditions. Each of Delaware's counties (Sussex, Kent and New Castle) had its own well-information dataset.

*Surface-water features*

In the Coastal Plain of Delaware, topographic relief is small and aquifers consist of unconsolidated sediments. In this type of hydrogeologic setting, the surfaces of streams, ponds, and swamps can be assumed to be the water table under fair weather conditions (Freeze and Cherry, 1979). This assumption also was used in the production of the 1960s hydrologic atlases and other regional evaluations of the water table in Delaware (Johnston, 1973, 1976).

Streams, ponds, and swamps have a direct correspondence to the water table; therefore, acquiring the elevations and maintaining the spatial configuration of these surface-water features is an important part of modeling the water table. Locations of surface-water features are from the 1992 USGS 1:24,000 hydrography digital line graph (DLG) dataset obtained from DataMIL (datamil.delaware.gov). These data are stored in an ArcGIS personal geodatabase. DLG hydrographic data were converted into 30-m gridded raster datasets with each grid node set to a value of zero. The grid geometries were set to correspond to the 30-m land surface DEM. Two 30-m grids were created: one for shorelines and fringing tidal marshes, and one for fresh-water streams. Two 90-m grids were created from DLG hydrographic polygons: one for fresh-water ponds and swamps, and one for tidal marshes and the ocean (Andres and Martin, 2005) For the grids representing fresh-water features, the elevation of each grid node was set equal to the elevation from the corresponding land-surface DEM. The raster calculator was also used to set elevations of nodes representing salt-water marshes to 1 ft, and to set the elevations of nodes representing the shorelines to 0 ft. These grids were converted to point datasets and merged (Andres and Martin, 2005).

Surface-water feature point data were modified to reduce noise in the dataset. Areas of steep land slope near streams produced some data points with anomalous elevation values. The number of these anomalous values was minimized by removing points occurring more than 15 m from surface-water features.

### Model Development

*Hydrologic conditions*

For this work, dry, normal, and wet conditions were determined from time-series measurements of depth-to-water. Depth-to-water measurements have been collected at approximately monthly intervals for more than 30 years in a number of observation wells located throughout the state. A set of observation wells was chosen for each county to define the hydrologic conditions for that particular area (Table 1). A multi-step procedure was used to identify dry, normal, and wet conditions from observations made in those wells.

Ideally, comparison of long-term water-level observations made at different locations should use data measured on the same days and at regular intervals (e.g., monthly measurements should be made on the same day of the month in the wells being compared). To correct for the fact that this did not occur, the observed water levels were used to interpolate water levels on the 15$^{TH}$ of each month for each month that a water level was measured. For some months when water levels were not measured, levels were interpolated from measurements made within 25 days of the 15$^{TH}$ day of the unmeasured month. Interpolation was done by on-screen digitizing of hydrographs. No estimates were made if water levels were not observed within 25 days of the 15$^{TH}$ day of the unmeasured month

Statistical measures of the water-level observations were computed and the corresponding dates that those water levels occurred were identified. From these statistics (Table 1), dry,

**Table 1**. Long-period observation wells used for each county. Values are depth to water measured in feet below land surface.

| | | WET | | NORMAL | | DRY | |
|---|---|---|---|---|---|---|---|
| **County** | **Well** | **5th Percentile** | **25th Percentile** | **40th Percentile** | **60th Percentile** | **75th Percentile** | **95th Percentile** |
| Sussex | Qe44-01 | 5.56 | 6.76 | 7.42 | 8.54 | 9.52 | 11.54 |
| Sussex | Ng11-01 | 8.97 | 10.56 | 11.22 | 11.96 | 12.50 | 13.70 |
| Sussex | Nc45-01 | 10.52 | 11.78 | 12.27 | 12.77 | 13.10 | 13.87 |
| Kent | Mc51-01 | 8.22 | 10.55 | 11.54 | 12.82 | 13.62 | 14.94 |
| Kent | Md22-01 | 2.24 | 3.55 | 4.51 | 5.96 | 7.46 | 9.80 |
| New Castle/Kent | Jd42-03 | 4.49 | 5.44 | 6.19 | 7.29 | 7.94 | 9.17 |
| New Castle | Hb14-01 | 3.29 | 5.59 | 6.66 | 8.03 | 8.89 | 10.28 |
| New Castle | Db24-10 | 6.84 | 10.05 | 11.58 | 13.43 | 14.35 | 15.96 |

normal, and wet hydrologic conditions were defined. Normal conditions were defined as the months with DTW levels falling between the 40TH and 60TH percentiles (Fig. 2) in the wells that were compared. Dry conditions (lowest water levels) were defined as months where the DTW levels fell between the 75TH and 95TH percentiles (Fig. 2) and wet conditions (highest water levels) were defined as months where the DTW levels fell between the 5TH and 25TH percentiles (Fig. 2). These percentile values were chosen as a balance between having an adequate number of dates to identify wells for estimating the water table and minimizing the differences in water levels within a particular group compared to differences between dry, normal, and wet groups. Extreme values (< 5TH and > 95TH percentiles) were excluded from the analysis.

*Multiple linear regression and the initial water table*

Sepulveda (2003) reported that estimation of the water-table elevation by linear regression (LR) on LSE could be improved by a multiple linear regression (MLR) procedure

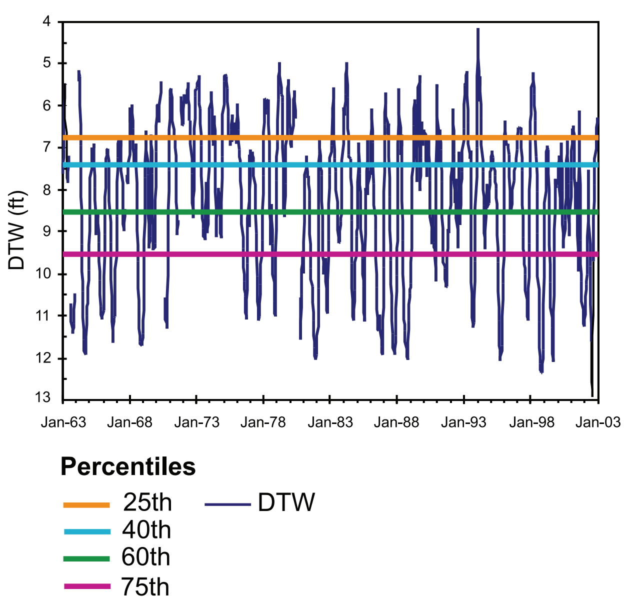


**Figure 2**. Hydrograph for well Qe44-01 showing monthly depth to water (DTW) below the land surface. Data points are estimated for the 15th of each month. Statistics derived from estimated data. Lines represent 25TH, 40TH, 60TH, and 75TH percentiles of data distribution.

that used a "minimum water table" along with land surface elevation to estimate the water-table elevation. A key assumption used in many water-table estimation projects is that streams, ponds, and swamps represent the intersection of the water table with land surface (Winter, 1999) (Fig. 3). Thus, the land-surface DEM was used to assign elevations to the surface-water features.

The minimum water table was then estimated by computing a grid from the elevations of surface-water features (Sepulveda, 2003). In this process, the minimum and maximum elevations of the minimum water table are 0 ft (e.g., tidal-water elevation) and land-surface elevation, respectively. For clarity, Sepulveda's term "minimum water table" is replaced by "initial water table" (INITWT) for application to Delaware. For Sussex County and Kent County, estimates of the INITWT were created by a 5th-order local polynomial regression method. A kriging algorithm was used to calculate the INITWT for New Castle County. Three separate initial water-table grids were created for Sussex, three for Kent, and two for New Castle Counties.

The second variable in the MLR equation is a depth to the initial water table, which was calculated by subtracting the initial water-table elevation from the land surface elevation DEM. Thus, the general form of the multiple linear regression equation is:

$$\text{Est WTi} = \beta_1 * \text{INITWTi} + \beta_2 * (\text{LSEi-INITWTi}) \quad (1)$$

where:

Est WTi = estimated water-table elevation at point i
$\beta_1$ = regression coefficient 1
INITWTi = initial water-table at point i
$\beta_2$ = regression coefficient 2
LSEi = land-surface elevation at point i
(LSEi-INITWTi) = depth to the initial water table at point i

The regression coefficients, $\beta_1$ and $\beta_2$, were calculated from the depth-to-water and well datasets. INITWT and depth to INITWT were converted into point feature class format in ArcGIS and then exported into Microsoft Excel for the regression analysis. The dry, normal, and wet well datasets for each county produce their own unique sets of regression coefficients. The effectiveness of MLR was compared to simple LRs on LSE and the INITWT by comparing

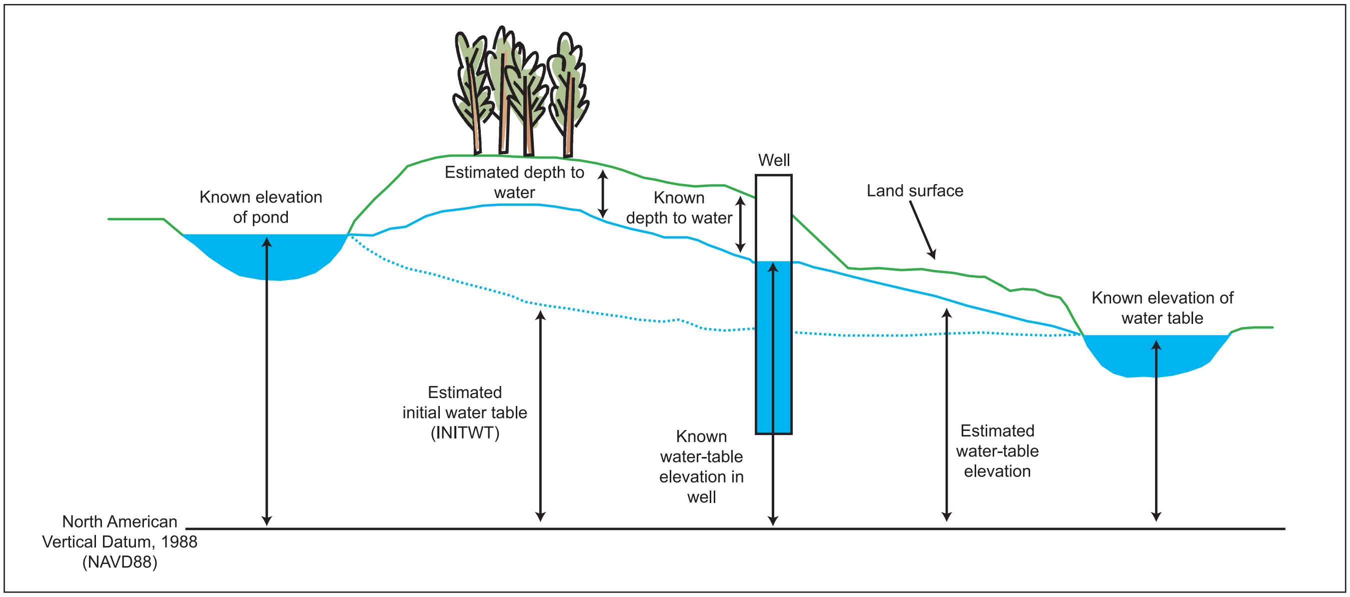


**Figure 3**. Illustration showing the initial water table including graphical representation of water-table terms and vertical datums. Illustration modified from Sepulveda (2003).

statistical measures of observed and predicted WTEs.

### Estimation of Water-Table Elevation

The elevation of the water table is the distance of the water-table surface from a vertical datum, in this case the NAVD88, which is approximately sea level. The two variables (the initial water table and the depth to the initial water table) and the two coefficients (coefficient $\beta_1$ and coefficient $\beta_2$) were computed and applied to the multiple linear regression equation. The resultant water-table elevation maps for each county are continuous surfaces; however, observations of the surface exist at irregularly spaced locations. The multiple linear regression equation interpolates water-table elevations between these surface observations to produce the continuous surface. The water-table elevation grids are in the form of GIS grids with 30-m horizontal and 1-ft vertical resolution.

The water-table grids were completed as a series of sub-grids that were subsequently merged into single county-wide grids. For example, a water-table DEM for normal conditions for eastern Sussex County was merged with a water-table DEM for normal conditions for western Sussex County.

There are several different methods that can be used to mosaic raster datasets, and because the grids overlapped in some areas, a weighted average algorithm was used followed by a filtering step. The weight-based algorithm is dependent on the distance from the pixel to the edge within the overlapping area. As an example of a filter, the different sections of Sussex County were separated based upon hydrography, so the merged Sussex County WTE grids were put through a 3x3 Gaussian low-pass filter that removes higher frequency variations in grid values and smooths the artifacts along the seams.

Merging the county DEMs into a statewide grid was explored; however, the large size of the resultant grid severely taxes the performance of even high-end PC workstations. In addition, the merge process resulted in unwanted grid artifacts because the DEMs are regular grids and the county boundaries are in part formed by meandering streams. These artifacts are a problem because when the statewide grid is cut into county grids, there are no-value nodes located in the interior of the resultant county grids. To work around these issues, the grids are completed by county and include an overlap of 200 m into the adjacent county. If a user needs a simple map covering more than one county for display purposes, then the county grids are adequate. Any analytical work (i.e., slope and aspect, hillshade, etc.) that requires a seamless grid across county boundaries will require the user to merge the grids and develop the appropriate smoothing procedures most suited to the location and scale of investigation.

### Potential Improvements to Water-Table DEM from LIDAR-Derived DEM

DEMs of land surface produced from aircraft-borne LIDAR (Light Detection And Ranging) data offer the potential for increasing the horizontal and vertical resolutions of the elevations of surface-water features and water-table DEMs. Compared to the 30-m horizontal and 1-ft vertical resolution DEMs derived from 1:24,000 DLG data, experimental DEMs produced from LIDAR data collected by aircraft-borne sensors in the past few years typically result in DEMs with 2-m horizontal and approximately 0.328-ft vertical resolutions.

A simple experiment was conducted with experimental LIDAR-derived DEMs produced by the USGS for two randomly selected small watersheds located in Sussex County. In the same way that the elevations of surface-water features were determined from existing DLG hydrography data (USGS, 1992) and 30-m DEMs (Mackenzie, 1999), LIDAR-derived DEMs and the USGS (1992) hydrography DLG data were used to determine elevations of surface-water features. The resulting point elevation data were visually compared to the LIDAR-derived DEM to determine if the DLG-derived points were aligned with the local elevation minima on the LIDAR-derived DEM.

**Table 2.** Grid dimensions and numbers of ground-water points used to estimate water-table elevation and depth to water table. Surface water points were used to estimate the initial water table. Ground-water points were used in the multiple linear regression estimation procedure.

| **Geographical Area** | **Grid Dimensions** | | **Number of Ground-Water Points** | | | **Number of Surface-Water Points** |
|---|---|---|---|---|---|---|
| | Rows | Columns | Dry | Normal | Wet | |
| Eastern Sussex County | 1148 | 1154 | 542 | 475 | 303 | 145,013 |
| Western Sussex County | 1113 | 924 | 198 | 164 | 366 | 171,416 |
| Northern Sussex County | 939 | 2000 | 271 | 481 | 362 | 99,356 |
| Sussex County | 1891 | 1950 | n/a | n/a | n/a | n/a |
| Kent County | 1994 | 1298 | 871 | 732 | 573 | 855,111 |
| New Castle County | 2039 | 1048 | 236 | 421 | 155 | 137,810 |

## RESULTS AND DISCUSSION

Water-table elevations were estimated as a series of overlapping grids (Table 2). For each grid area, a set of long-term observation wells was used to define dry, normal, and wet periods (Table 1). This enabled collection of water-level observations made in additional wells during those periods. Separate INITWT and MLR estimations (Tables 3 and 4) were run for each grid area.

Two interesting observations can be made regarding the coefficients of the MLR equations and of the coefficient for the regression on INITWT. First, $\beta_1$ values (weighting factor for INITWT), except for one grid, are slightly less than 1. In Sepulveda's analysis of the water-table elevation in Florida (Sepulveda, 2003), the regression coefficients of the initial water table were all ≥ 1 in all but one of his study groups. This indicates that the data (i.e., elevations of surface-water features) and methods (polynomial surface fit) used to estimate the INITWT in Delaware slightly overestimate observed water-table elevation (WTE) rather than underestimate WTE as in Florida. Spatially, the INITWT elevations, regardless of hydrologic condition, are less than the estimated WTEs in low-lying areas along the shorelines and around the streams and bays. In addition, INITWT elevations for eastern Sussex County are less than the estimated WTEs in all areas under wet conditions. These conditions also can be partially due to artifacts from estimating elevations of surface-water features from DLGs and DEMs. Second, the magnitude of $\beta_2$ (weighting factor for depth to INITWT) is largest in New Castle County, and lowest in Sussex County. This is likely due to deeper incision of streams and greater topographic relief in New Castle and Kent counties, and resultant greater depth to the INITWT.

Simple linear regressions were performed with the normal condition water-level data on both LSE and the INITWT for statistical comparison to the multiple linear regression method (Tables 3 and 4). The coefficients of determination ($R^2$), which show the proportions of sample variances accounted for by the regression equations, are very similar between the MLR and both LR models. Root mean square error (RMS), a statistical measure of the magnitude of the total estimation error, were also calculated for the MLR and both LR methods. The RMS value for the MLR method is smaller than the RMS values produced from the LSE LR and the INITWT LR analyses. These statistical measures indicate that the MLR method is a slightly more accurate predictor of water-table elevation than a simple LR on LSE or INITWT. It is important to note that a statewide analysis by simple LR on LSE fairly accurately predicts the normal WTE, and that WTE is approximately 80 percent of LSE (Table 4).

A second way of assessing the goodness of fit between the different estimation methods is to evaluate the individual residuals, or observed minus predicted WTE values. In general, differences between the $2^{\nu\delta}$ and $3^{\rho\delta}$ quartiles and $5^{\tau\eta}$ and $95^{\tau\eta}$ percentiles of residuals from the MLR method are less than similar differences from both of the LR methods. This indicates that the MLR method better estimates 90 percent of water-level observations than do the LR methods. However, the MLR method did produce a higher range (maximum-minimum) of residuals in Kent County and New Castle County than did the LSE LR; this is likely a result of increasing LSE values and ranges in these two counties.

On closer inspection, many of the largest residuals are located near areas of steepest topography, and some are located near bodies of tidal surface water. In the cases of steep topography, errors in coordinates of measurement location can result in significant changes in LSE and observed WTE. In cases of measurements made in northern New Castle County, where topographic contours have 10 ft intervals, an error in horizontal position of just 60 m can easily result in a change in LSE and of the observed WTE of 10 to 20 ft. Larger residuals associated with measurement points located near bodies of tidal surface water indicate that those measurement points may not be indicative of WTE of the water-table aquifer. It is also possible that some of the large residuals are artifacts from estimating the elevations of surface-water features from DLGs and DEMs.

**Table 3.** Coefficients for MLR and LR used to calculate the water-table elevation for each county and/or county section. The first regression coefficient ($\beta_1$) is multiplied by the initial water table (INITWT). The second regression coefficient ($\beta_2$) is multiplied by the regressor (LSE-MINWT).

| Geographical Area | Hydrologic Condition | Multiple Linear Regression (MLR) | | Linear Regression (LR) on Land Surface Elevation | Linear Regression (LR) on Initial Water Table |
|---|---|---|---|---|---|
| | | $\beta_1$ | $\beta_2$ | $\beta_1$ | $\beta_1$ |
| **Eastern Sussex County** | Dry | 0.877506631 | 0.12554345 | 0.751150361 | 0.988764472 |
| | Normal | 0.9699881172 | 0.088476033 | | |
| | Wet | 1.006785916 | 0.168404688 | | |
| **Western Sussex County** | Dry | 0.858130822 | 0.122880434 | 0.80066841 | 0.94186578 |
| | Normal | 0.91264406 | 0.181543616 | | |
| | Wet | 0.924212273 | 0.322277435 | | |
| **Northern Sussex County** | Dry | 0.90412195 | 0.07349541 | 0.805909385 | 0.971053201 |
| | Normal | 0.937692269 | 0.182960272 | | |
| | Wet | 0.95812644 | 0.173098472 | | |
| **Kent County** | Dry | 0.911533989 | 0.243368713 | 0.8316430423 | 0.9691432173 |
| | Normal | 0.917271343 | 0.345362728 | | |
| | Wet | 0.936363101 | 0.349072396 | | |
| **New Castle County** | Dry | 0.910601575 | 0.328110368 | 0.78751886 | 0.990205739 |
| | Normal | 0.917881257 | 0.34105439 | | |
| | Wet | 0.950049978 | 0.460788642 | | |
| **Statewide** | Normal | 0.924980515 | 0.279647265 | 0.803279 | 0.976699 |

### Sussex County Water-Table Elevation

Creating the water-table elevation maps for Sussex County, Delaware, was a multi-step process that involved dividing the county into three separate geographic sections (east, west, and north). In large part, the geographic sections of Sussex County were delineated based on watershed boundaries and DLG lines representing hydrography (e.g., streams) in the area. Each geographic region of Sussex County has its own unique well data set, and thus its own unique set of regression coefficients for dry, normal, and wet conditions. Water-table elevation grids for each hydrologic condition were created for eastern, western, and northern Sussex County and were then merged to create a unified, county-wide water-table elevation grid for dry (Fig. 4A), normal (Fig. 4B), and wet (Fig. 4C) conditions (Martin and Andres, 2005a).

Hydrologic conditions for the area identified as eastern Sussex County were determined by comparing the long-term water-level measurements in monitoring wells Ng11-01 and Qe44-01. The observation well dataset used to compute the regression coefficients in this area included water-levels from 1,320 wells (Table 2). Locations of these measurements are not spread evenly across the study area.

Long-term water-level measurements from monitoring wells Nc45-01 and Qe44-01 were compared in order to define the time periods for dry, normal, and wet conditions for western Sussex County. The water-level observation datasets for this area included data from 728 water-level observation points (Table 2) that were unevenly distributed across the study area.

Dry, normal, and wet conditions for the area defined as northern Sussex County were determined from the comparison of long-term water-level measurements in monitoring wells Nc45-01 and Ng11-01. A total of 1,114 wells was included in the water-level observation data set (Table 2).

In all three areas, MLR equations and weighing factors (Table 3) were used to calculate water-table elevation grids. The final water-table elevation maps for Sussex County had elevations ranging from 0 to 66 ft. Because land-surface elevation was a component of the multiple linear regression, the water-table elevation maps resemble the land surface elevation DEM maps. Water-table elevations, in general, increase with increasing land surface elevations. This is true for Kent and New Castle counties as well.

**Table 4.** Statistical comparison of residuals from water-table elevation (WTE) estimation residuals for normal conditions. Residuals were calculated using multiple linear regression (MLR), linear regression on land surface elevation (LSE), and linear regression on the initial water table (INITWT).

| Area | Min | 5th | 25th | 50th | 75th | 95th | Max | Range | $R^2$ | RMS |
|---|---|---|---|---|---|---|---|---|---|---|
| **Multiple Linear Regression** | | | | | | | | | | |
| Eastern Sussex | -14.82 | -8.28 | -2.84 | 0.38 | 2.25 | 4.99 | 9.61 | 24.43 | 0.96931 | 16.91 |
| Western Sussex | -9.24 | -6.65 | -2.15 | -0.28 | 1.88 | 3.74 | 11.56 | 20.80 | 0.9886 | 10.94 |
| Northern Sussex | -18.80 | -7.25 | -2.61 | -0.17 | 2.32 | 5.35 | 13.71 | 32.51 | 0.98811 | 16.37 |
| Kent | -37.79 | -9.36 | -3.37 | -0.13 | 2.59 | 6.05 | 25.19 | 62.98 | 0.9843 | 27.05 |
| New Castle | -53.71 | -17.67 | -5.04 | -0.68 | 2.99 | 14.33 | 42.63 | 96.34 | 0.9680 | 96.64 |
| **Linear Regression on Land-Surface Elevation** | | | | | | | | | | |
| Eastern Sussex | -24.29 | -12.68 | -7.27 | -2.27 | 3.71 | 10.19 | 13.20 | 37.49 | 0.90134 | 54.25 |
| Western Sussex | -12.81 | -9.81 | -3.22 | 0.37 | 2.02 | 4.76 | 8.57 | 21.38 | 0.97857 | 20.44 |
| Northern Sussex | -21.21 | -11.93 | -5.10 | 0.22 | 3.51 | 6.51 | 9.65 | 30.86 | 0.97374 | 36.08 |
| Kent | -41.57 | -8.52 | -4.76 | -0.69 | 2.76 | 9.47 | 12.49 | 54.06 | 0.97579 | 41.66 |
| New Castle | -63.08 | -17.67 | -7.99 | -0.88 | 6.91 | 14.33 | 24.50 | 87.58 | 0.95076 | 148.51 |
| **Linear Regression on Initial Water-Table Elevation** | | | | | | | | | | |
| Eastern Sussex | -14.83 | -8.28 | -2.69 | 1.02 | 3.01 | 4.99 | 11.01 | 25.84 | 0.96821 | 17.48 |
| Western Sussex | -8.67 | -6.14 | -2.31 | -0.29 | 2.40 | 4.38 | 14.34 | 23.01 | 0.98775 | 11.68 |
| Northern Sussex | -19.53 | -7.10 | -2.29 | 0.09 | 2.62 | 6.37 | 16.82 | 36.35 | 0.9869 | 18.00 |
| Kent | -34.73 | -12.46 | -3.01 | 0.15 | 3.30 | 7.26 | 35.48 | 70.21 | 0.97981 | 34.74 |
| New Castle | -45.55 | -24.13 | -4.54 | -0.57 | 4.69 | 12.50 | 59.21 | 104.76 | 0.95847 | 125.25 |

### Kent County Water-Table Elevation

Initially, the process for calculating the water-table elevation maps for Kent County was going to be consistent with that for Sussex County. Long-term water-level measurements from monitoring wells Mc51-01, Md22-01, and Jd42-03 were compared in order to define the time periods for dry, normal, and wet hydrologic conditions. Kent County was divided into three geographical sections (south, central, and north) based on watershed boundaries and hydrography. However, the water-level observation point data sets for central and northern Kent County were not adequate calculate accurate water-table elevation grids. The regression analysis produced poor $R^2$ values for each condition due to an insufficient number of water-level observation points. Therefore, the water-level points were incorporated together to form a single data set and the water table was estimated for the entire county as a whole entity. As a result, the initial water-table grids for southern, central, and northern Kent County were also merged together to form a unified Kent County initial water-table grid. The water-level observation point data set for Kent County consisted of 2,176 wells (Table 2). The regression analysis performed on these data sets yielded the regression equations (Table 3) for each hydrologic condition and the resulting water-table elevation grids for dry (Fig. 5A), normal (Fig. 5B), and wet (Fig. 5C) conditions in Kent County (Martin and Andres, 2005b).

### New Castle County Water-Table Elevation

Calculating the water-table elevation maps for New Castle County also involved applying the same concepts that were established in Sussex County by dividing New Castle County into two separate sections (north and south) with the C&D Canal acting as the hydrologic boundary. Long-term water-level measurements from monitoring wells Jd42-03, Hb14-01, and Db24-10 were compared in order to define the time periods for dry, normal, and wet conditions. However, as was the case in Kent County, the regression analysis performed on the water-level point data sets for these areas failed to produce useable correlation coefficients; therefore, the water-level points for the north and south sections were joined to produce a single data set for the entire county. INITWT grids for New Castle County were created with an ordinary kriging algorithm because grid elevations computed by local polynomial regression were too high at low LSE and too low at high LSE. It is likely that local polynomial regression could not adequately reproduce the greater relief of land surface and the water table in New Castle County. The INITWT grids for southern, and northern New Castle County were also merged together to form a unified New Castle County INITWT grid. The water-level point data set for New Castle County contained an uneven distribution of 812 wells (Table 2). The regression analysis performed on these wells produced the regression equations (Table 3) that were used to create the water-table elevation maps for dry (Fig. 6A), normal (Fig. 6B), and wet (Fig. 6C) conditions in the Coastal Plain of New Castle County (Martin and Andres, 2005c). When using the water-table elevation and subsequent depth-to-water maps for New Castle County it is important to note that the Piedmont region of Delaware was excluded from this work due to the sparse availability and inaccuracy of water-level data for this area.

### Depth to Water

The water-table DEMs for dry, normal, and wet conditions for Sussex (Figs. 7A, B, and C), Kent (Figs. 8A, B, and C), and New Castle (Figs. 9A, B, and C) counties were

**Table 5.** Comparisons of depth to water (ΔΤΩ) and percentage of land area.

| | | Depth to Water( DTW) in feet below land surface | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Geographical Area** | **Hydrologic Condition** | **0** | **<2** | **<5** | **<10** | **<25** | **<50** | **Mean DTW (ft)** |
| **Statewide** | Dry | 1.4% | 4.3% | 17.5% | 58.9% | 97.8% | 99.8% | 9.4 |
| | Normal | 1.7% | 5.3% | 21.2% | 70.5% | 97.9% | 99.8% | 8.4 |
| | Wet | 2.0% | 6.7% | 28.5% | 79.1% | 98.9% | 99.9% | 7.1 |
| **Sussex County** | Dry | 0.8% | 3.9% | 16.3% | 66.0% | 99.9% | 99.9% | 8.3 |
| | Normal | 1.6% | 5.9% | 28.5% | 84.5% | 99.9% | 99.9% | 6.4 |
| | Wet | 1.9% | 8.5% | 40.6% | 89.8% | 99.9% | 99.9% | 5.4 |
| **Kent County** | Dry | 2.9% | 6.8% | 23.3% | 71.3% | 99.9% | 99.9% | 7.7 |
| | Normal | 2.9% | 9.4% | 25.2% | 80.6% | 99.9% | 99.9% | 6.9 |
| | Wet | 3.0% | 11.2% | 27.6% | 85.7% | 99.9% | 99.9% | 6.2 |
| **New Castle County** | Dry | 0.5% | 3.3% | 15.6% | 42.9% | 88.4% | 98.6% | 13.5 |
| | Normal | 0.5% | 3.3% | 15.8% | 44.5% | 89.1% | 98.7% | 13.2 |
| | Wet | 0.8% | 5.0% | 24.6% | 60.1% | 94.6% | 99.3% | 10.1 |

subtracted from the land surface DEM to produce depth-to-water grids. When comparing depth to water to the percentage of land area (Table 5) it becomes apparent that a significant portion of the Coastal Plain of Delaware can be classified as having a shallow water table. Under normal conditions, 71 percent of the land area has a depth to water of less than 10 ft and 21 percent of the land area has a depth to water of less than 5 ft, with these percentages being significantly higher in Sussex and Kent counties.

When dealing with depths to water of less than 10 ft there will likely be significant environmental issues with larger wastewater disposal facilities such as rapid infiltration basins and community disposal systems (USEPA, 1999, 2003). When dealing with depths to water of less than 5 ft, sites become high risk for individual standard domestic subsurface wastewater disposal systems (DNREC, 2005) and for any excavations, building foundations, and basements.

### Comparison of Existing DLG Hydrography to LIDAR-Derived DEM

Utilizing existing DEMs, DLGs, water level data, and GIS tools to estimate the water-table elevation was cost efficient and effective; however, the potential still exists for greater precision and accuracy through the use of LIDAR-derived DEMs of land surface and elevations of surface-water features. It is not unreasonable to expect that water-table grid resolutions could be increased to the 2-m horizontal and 0.328-ft levels of the LIDAR-derived DEMs. However, improvements to the water-table DEMs from LIDAR DEMs will require significant additional efforts as visual comparison indicate that there are inaccuracies in the DLG locations of surface-water features. There also are data processing artifacts that result from the procedures used to estimate elevations of surface features from land surface DEMs.

Locational inaccuracies in the 1:24,000 hydrography DLGs were evident where DLG locations of surface-water features did not align with the local minimum land surface elevations on the 30-m DEMs; data processing artifacts are evident where the elevations of stream features do not decrease in the downstream direction (Andres and Martin, 2005). These issues become even more apparent when comparing the 1:24,000 hydrography DLGs with LIDAR-derived DEMS (Fig. 10). Reducing the effects of these problems will require work to locate the streams within the areas of local topographic minima and to mitigate any other artifacts in the LIDAR DEMs that result from bridges, culverts, channel obstructions, and/or data processing problems.

## CONCLUSIONS

Water-table depth is a key facet in many engineering, hydrogeologic, and environmental management and regulatory decisions. Depth to water is an important factor in risk assessments, site assessments, evaluation of permit compliance data, and registration of pesticides and determining acceptable application rates. Obtaining an accurate representation of the water table is also crucial to the success of many hydrologic modeling efforts.

An extensive cooperative effort to produce readily available water-table elevation maps for the state of Delaware was undertaken in the 1950s. However, despite the usefulness of these paper contour maps, contemporary advances in computer technology and the expanding utilization of GIS has made it necessary to update these maps and has brought about the demand to have them published in a suitable digital format.

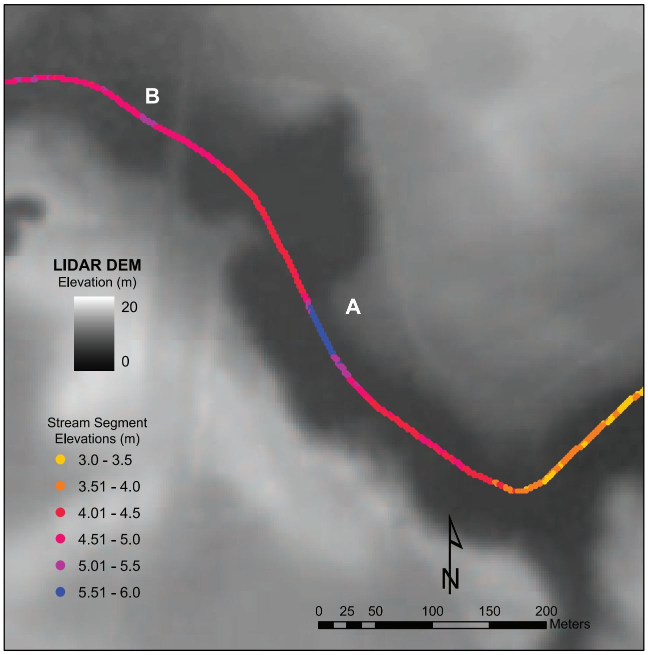


**Figure 10**. Illustration showing stream segment elevation artifacts caused by misalignment of 1:24,000 hydrography DLG with LIDAR DEM and road crossings.

Mapping the water-table elevation of the Delaware Coastal Plain was accomplished by using pre-existing data such as long-term hydrographs to determine dry, normal, and wet hydrologic conditions, a 30-m DEM to assign elevations to surface-water features, and well completion reports used to obtain static water levels of shallow domestic wells to produce the regression coefficients that were inserted into the multiple linear regression equation. The resultant products are GIS ready grids with a horizontal spacing of 30 m and a vertical resolution of 1 ft.

Existing DEMs, DLGs, water-level data, and GIS tools provided a cost efficient and relatively accurate means to estimate the water-table elevation; however newer technology offers potential for greater precision and accuracy. LIDAR measured DEMS offer the potential for increasing the horizontal and vertical resolutions of the water-table grids. Use of LIDAR DEM data to estimate higher resolution grids of water-table elevation will require more accurate locational data for surface-water features as well as more powerful and efficient computers and software.

## REFERENCES CITED

Andres, A. S., and Martin, M. J., 2005, Estimation of the water table for the Inland Bays watershed, Delaware: Delaware Geological Survey Report of Investigations No. 68, 20p.

Delaware Department of Natural Resources and Environmental Control (DNREC), 2005, Regulations governing the design, installation and operation of on-site wastewater treatment and disposal systems: DNREC Document No. 40-08-05/04/07/01, 75p.

Dunne, T., and Leopold, L. B., 1998, Water in environmental planning: New York, New York, W. H. Freeman and Company, 818 p.

ESRI, Inc., 2003, ARCGIS software v. 9.0: Redlands, California.

____ 2005, ARCGIS software v. 9.1: Redlands, California.

Freeze, A. R., and Cherry, J. A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice Hall, Inc., 604 p.

Freeze, A. R., and Witherspoon, P. A., 1967, Theoretical analysis of regional ground-water flow: Water Resources Research, vol. 3, p. 623-634.

Johnston, R.H., 1973, Hydrology of the Columbia (Pleistocene) deposits of Delaware: An appraisal of a regional water-table aquifer: Delaware Geological Survey Bulletin No. 14, 78p.

____ 1976, Relation of ground water to surface water in four small basins of the Delaware coastal plain: Delaware Geological Survey Report of Investigations No. 24, 56p.

Golden Software, Inc., 2002, Surfer software v. 8, Golden, Colorado.

Mackenzie, J., 1999, Watershed delineation project, alpha data release: www.udel.edu/FREC/spatlab/basins.

Martin, M. J., and Andres, A. S., 2005a, Digital water-table data for Sussex County, Delaware: Delaware Geological Survey Digital Product 05-01, ESRI grid format.

____ 2005b, Digital water-table data for Kent County, Delaware: Delaware Geological Survey Digital Product 05-01, ESRI grid format.

____ 2005c, Digital water-table data for New Castle County, Delaware: Delaware Geological Survey Digital Product 05-01, ESRI grid format.

Perlman, H., 2005, Earth's water: Ground water, United States Geological Survey, United States Department of the Interior, http://ga.water.usgs.gov/edu/earthgw.html.

Sepulveda, N., 2003, A statistical estimator of the spatial distribution of the water-table altitude: Ground Water, vol. 41, p. 66-71.

U.S. Environmental Protection Agency, 1999, The Class V underground injection control study, large-capacity septic systems: U.S. Environmental Protection Agency, EPA/816-R-99-014e, 120p.

____ 2003, Rapid infiltration land treatment, U.S. Environmental Protection Agency wastewater technology fact sheet: EPA 832-F-03-025, 6p.

U.S. Geological Survey 1992, Hydrography digital line graph for Delaware: U.S. Geological Survey.

____ 1996, Water-level data for the industrial area northwest of Delaware City, Delaware, 1993-94, USGS Open File Report 96-125: U.S. Environmental Protection Agency, Towson, Maryland, 23 p.

Williams, T. A., and Williamson, A. K., 1989, Estimating water-table altitudes for regional ground-water flow modeling, U.S. Gulf Coast: Ground Water, vol. 27, p. 333-340.

Winter, T. C., 1999, Relation of streams, lakes, and wetlands to groundwater flow systems: Hydrogeology Journal vol. 7, no. 1, p. 28-45.

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