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

REPORT OF INVESTIGATIONS NO. 68

ESTIMATION OF THE WATER TABLE FOR THE INLAND BAYS WATERSHED, DELAWARE

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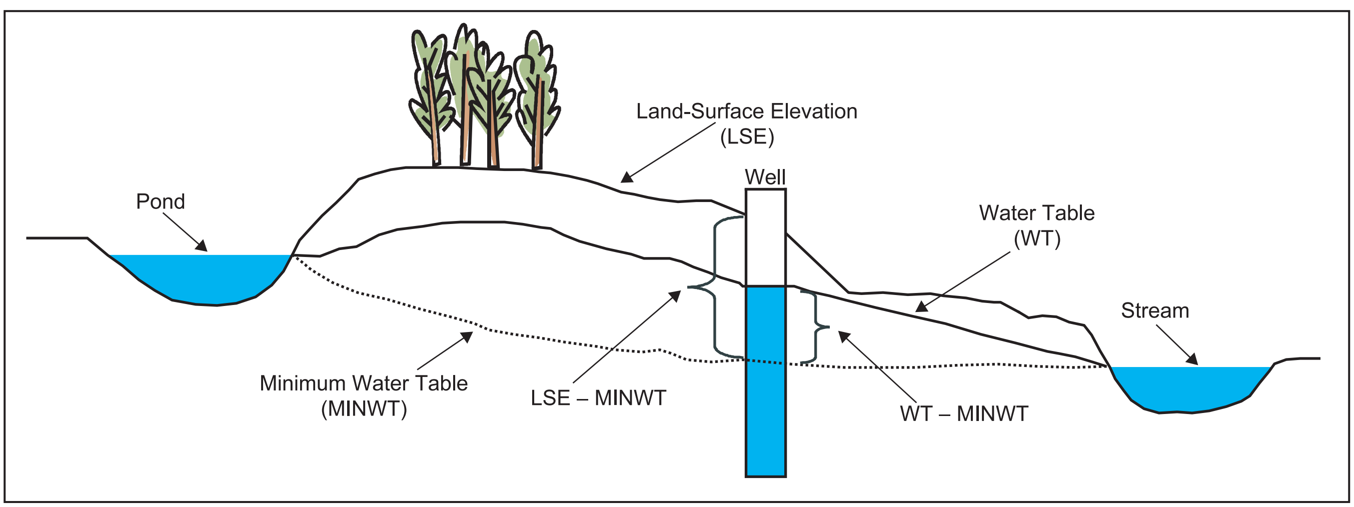

University of Delaware
Newark, Delaware
2005

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ABSTRACT

A geographic information system-based study was used to estimate the elevation of the water table in the Inland Bays watershed of Sussex County, Delaware, under dry, normal, and wet conditions. Evaluation of the results from multiple estimation methods indicates that a multiple linear regression method is the most viable tool to estimate the elevation of the regional water table for the Coastal Plain of Delaware. The variables used in the regression are elevation of a minimum water table and depth to the minimum water table from land surface. Minimum 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 output as a GIS-ready grid with 30-m (98.43 ft) horizontal and 0.305-m (1 ft) vertical resolutions.

Evaluation of long-term depth to water hydrographs (1963-2002) from two shallow observation wells in Sussex County, Delaware have defined time periods identified as characteristic of dry (5 to 25 percent exceedence), normal (40 to 60 percent exceedence), and wet (75 to 95 percent exceedence) water-level conditions. Ground-water level data measured in hundreds of wells during these periods are input data for estimation of the elevation of the water table during dry, normal, and wet conditions. These data show statistically significant relationships between land surface elevation and water-table elevation, land surface elevation and depth to water, and between the mean water levels of individual hydrogeomorphic regions and soil groups. Linear regressions using land surface elevation to estimate water-table elevation account for between 75 and 80 percent of the variability of the water-table elevation; however, except for the surficial confined hydrogeomorphic regions and hydric soil group, hydrogeomorphic regions and soil groups yield poorer correlations between land surface elevation and water-table elevation.

The estimated water table becomes progressively shallower as conditions change from dry to normal to wet. Multiple linear regression-estimated depth-to-water occurs less than 10 ft below land surface over 63, 79, and 86 percent under dry, normal, and wet conditions, respectively, in the Inland Bays watershed. Land areas with water less than 5 ft below land surface are 19, 30, and 49 percent under dry, normal, and wet conditions, respectively.

Water tables estimated by multiple linear regression are qualitatively similar to those of 1960s-period maps published by the U.S. Geological Survey. These maps represent the water table with discrete points and isoelevation lines with a 10-ft contour interval. Many assumptions and approximations are needed to convert from analog to digital format. Because the analog to digital conversion processes and choice of comparison algorithm significantly affect the resultant numerical values, there are no direct means to quantitatively compare them to gridded surfaces produced during this study.

INTRODUCTION

Ground water is "subsurface water that occurs beneath the water table in soils and geologic formations that are fully saturated" (Freeze and Cherry, 1979, p. 2). Freeze and Cherry (1979, p. 39) further define the water table as "the surface on which the fluid pressure in the pores of a porous medium is exactly atmospheric." In practice, the water table is measured in wells constructed with openings along their lengths and penetrating just deep enough to encounter standing water. Given the climate and relatively permeable subsurface materials of Delaware, the water table frequently occurs within 10 to 20 ft of land surface.

Depth to the water table is a key element in many engineering, hydrogeologic, and environmental management and regulatory decisions. Depth to the water table determines whether a site is suitable for a standard subsurface wastewater disposal system or will require an alternative design. Depth to the water table is an important consideration in risk assessments, site assessments, home and building construction, evaluation of permit compliance data, registration of pesticides, and determining acceptable pesticide application rates. Shallow depth to the water table has been the driving factor for construction of extensive ditch networks in almost every major watershed in Delaware. Water-table elevation maps derived from depth-to-water measurements are routinely used to predict ground-water flow directions.

The hydrologic characteristics of land are significantly influenced by depth to the water table. Under fair weather conditions, Coastal Plain stream surfaces represent the intersection of the water table with land surface. In areas where the ground is saturated because of shallow depth to water, there is little space for percolating rainwater or snowmelt to be stored and, as a result, overland runoff occurs much more frequently. Overland runoff is known to cause erosion and transport of contaminants from the land into streams.

Depth to the water table is a factor that influences the ecologic function of a landscape. For example, wetlands are found where the water table is at or near land surface for portions of the year. The duration of standing water or shallow depth to water conditions in large part prescribes the plant and animal communities that can live at that site.

Previous Water-Table Mapping and Modern Data Needs

In recognition of the importance of having ready access to depth to ground-water data, a statewide water-table mapping program was completed in the 1950s at a scale of 1:24,000 and published in the 1960s as a cooperative effort between the U. S. Geological Survey (USGS), the Delaware Division of Highways, and the Delaware Geological Survey (DGS). These paper maps show water-table elevation (WTE) contours at a 10-ft interval and were published in the Hydrologic Atlas

(HA) series of the USGS. The 34 HA maps that cover Delaware continue to be widely used by the public and private sectors. Hydrologic Atlas publications containing water-table elevation contours for the Inland Bays watershed are Adams and Boggess (1964), Boggess and Adams (1964, 1965), Boggess et al. (1964a, b), Adams, Boggess, and Coskery (1964), and Adams, Boggess, and Davis (1964).

In recent years, the increasing usage of geographic information systems (GIS) in environmental management and land-use decision making has led to several attempts to get the HA maps into suitable digital form. As a result of these efforts, there has been increasing recognition of the need to update the HA maps. The primary reasons to update the maps are:

(1) Very little of the original water-level or well data collected in the 1960s are available. As a result, accuracy and reproducibility cannot be evaluated. The topographic maps and spot elevation data used to estimate point location elevations for the water-table maps are of low resolution and accuracy compared to new topographic maps. The land surface elevation (LSE) control for many of the HA maps was based on a 1950s vintage 1:62,500-scale elevation model that generated 20 ft contours (e.g., U. S. Geological Survey, 1954). Ten-foot LSE contours were interpolated without additional elevation data to produce the 1:24,000-scale contour maps (W.S. Schenck, oral commun., 2004). As a result, accuracy of elevation contours, typically given as one-half the contour interval, is between 5 and 10 feet rather than 5 feet.

(2) The HA maps used a single depth to water (DTW) model to estimate WTE for the entire state (e.g., Boggess and Adams, 1964). The DTW model was determined from averaged monthly DTW measurements made in 13 wells located throughout the state over a relatively short, 11-year period record. The model was fit manually using the interpolated topographic contours. One symptom of problems with the HA maps is that detailed comparisons of WTE point data from the HA maps with the 1992 topographic maps have found some estimated WTEs greater than LSEs in areas near surface water features. The statewide averaging process also does not account for intra-state variability in water conditions.

(3) Maps constructed from higher resolution LSE data and digital elevation models, and GIS software-based numerical estimation procedures can reduce the subjectivity of the estimation procedure. These tools also can be used to produce estimates of dry and wet climate WTEs.

Purpose and Scope

This report documents the methods and results of a pilot project done to map the water table in the Inland Bays watershed (Fig. 1). The goals of the project were to establish appropriate methodologies and procedures for producing new water-table maps for dry, normal, and wet conditions; make a qualitative comparison with pre-existing water-table maps; determine if the method can be used to map the entire state in a cost effective and timely way; and make the resultant maps available for use. A key constraint for this effort was that it relied on existing data. Available funding was not sufficient to construct new wells or to support collection of additional water-level measurements.

Map products generated by this work will be used in support of a number of public environmental programs and private site reviews that need to assess hydrologic conditions. While the map products are an important part of the assessment process, they depict estimates of the water-table configuration. As a result, the map products are not intended to replace on-site data collection efforts.

Figure 1. Location map of study area and surrounding region.

The Inland Bays watershed was chosen by the DGS and the Delaware Department of Natural Rescources and

Environmental Control (DNREC) Water Supply Section (WSS) because there are a significant amount of existing data that were collected during previous ground-water studies, and the watershed is identified as a high priority area for a number of regulatory and environmental restoration efforts that can use the resultant information.

Acknowledgments

This project was funded by the DNREC through grants from the U.S. Environmental Protection Agency Ground-Water Protection and Source Water Protection programs. Cheryl A. Duffy, Scott V. Lynch, Tamika K. Odrick, and Evan M. Costas assisted with early phases of the project. Ronald E. Graeber, John T. Barndt, Blair Venables, Joshua W. Kasper, and Scott A. Strohmeier of the DNREC made monitoring data from numerous wastewater disposal facilities available. Stacey E. Chirnside of the University of Delaware, Department of Bioresources Engineering is thanked for providing access to ground-water research data. Thomas E. McKenna, John T. Barndt, and Mark R. Nardi critically reviewed the manuscript.

METHODS

This project has three main components: data compilation, statistical evaluation and model development, and WTE estimation. Water-level and well data are stored and extracted from the DGS's in-house Oracle-based data system. Spatial data management and processing and WTE estimation were done with desktop and workstation components of ArcGIS v8.3 (ESRI, 2002) and Surfer v8 (Golden Software, 2002) software. Horizontal coordinates of data are in Universal Transverse Mercator projection, North American Datum of 1983 (UTM-83). Elevations are reported as North American Vertical Datum of 1988 (NAVD-88). Statistics were computed with functions and procedures contained in Oracle, ArcMap, and Microsoft Excel.

Data Sources, Compilation, and Processing

LSE data used in this project were obtained from a 30-m digital elevation model (DEM) developed by John Mackenzie (University of Delaware's UD Spatial Analysis Laboratory, (www.udel.edu/FREC/spatlab/), and from 1992 USGS 1:24,000-scale topographic maps. Locations of surface water features are from the 1992 U.S. Geological Survey (USGS) 1:24,000 hydrography digital line graph (DLG) dataset obtained from UD DataMIL (www.datamil.udel.edu). These data are stored in an ArcGIS personal geodatabase.

DTW and well data were obtained from the files and electronic databases of the DGS, DNREC, USGS, and UD 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, and Tank Management Branch. Data are of two types: one type consisting of time-series DTW measurements from monitoring wells, the other type from single static DTW measurements reported by well drillers on well completion reports. Prior to analysis all DTW data were converted to depth relative to ground surface datum. DTW 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 DTW measurements from individual wells was evaluated by comparison to measurements in nearby wells and by converting DTW to water elevation. Because the elevation of the water table is above 0 ft under static conditions, water elevations less than 0 ft are generally considered to be inaccurate and were removed from the dataset.

Elevations of measurement points and ground surface were obtained from multiple sources. Elevations of most monitoring wells and associated ground surface measurement points were obtained from consultant and research reports. Elevation data are typically determined by surveying techniques and reported to the nearest 0.01 ft. Accuracy of these elevations are expected to be better than +/- 0.1 ft. Elevations of ground surface at some monitoring and all other wells were determined from visual interpretation of 1992-edition USGS 1:24,000-scale topographic maps (5-ft contour interval) or the 30-m DEM described previously. The resolution of elevation data determined from maps or DEM is 1 ft with an estimated accuracy of one-half the map contour interval or (+/- 2 to 3 ft).

Three different landscape classification schemes were used to evaluate depth to ground-water data with respect to interpreted hydrologic functions such as infiltration and runoff. Digital format soils maps (Fig. 2) prepared by the U. S. Natural Resources Conservation Service were obtained from University of Delaware's Spatial Analysis Laboratory (www.udel.edu/FREC/spatlab/). Hydrogeomorphic regions (HGMR, Fig. 3) developed by the USGS (Hamilton et al., 1993) were obtained in digital format from Mark R. Nardi

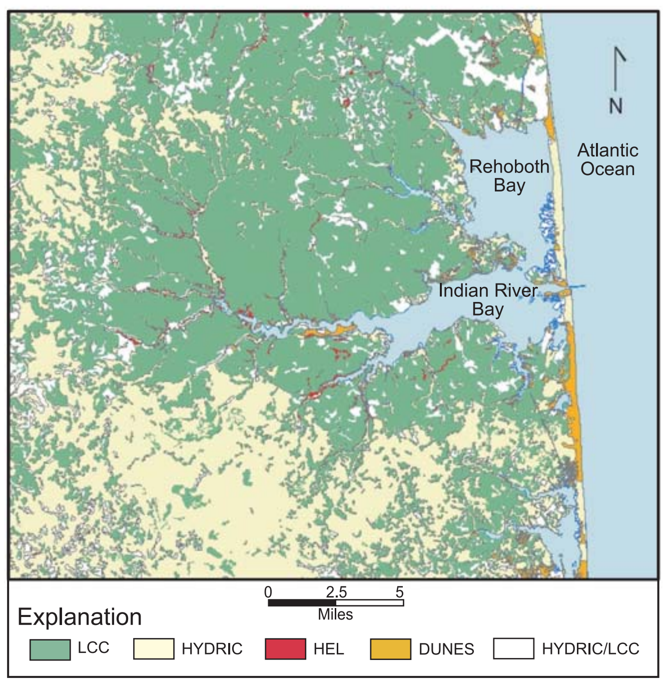


Figure 2. Map of soil groups in study area. Land capability class (LCC, i.e., well-drained), highly erodable land (HEL). The well-drained category includes land capability classes 1, 2, and 3. Data obtained from www.udel.edu/FREC/spatlab/.

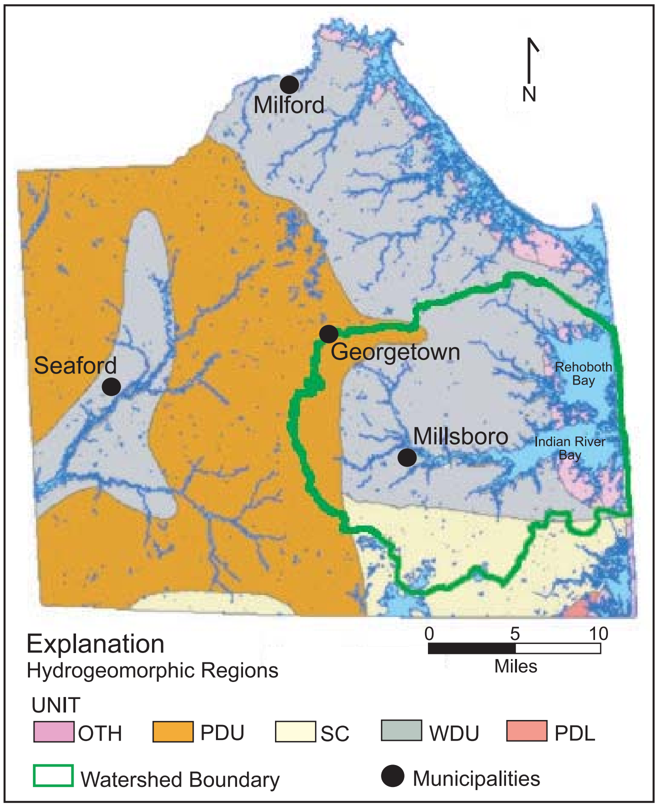


Figure 3. Map of hydrogeomorphic regions (HGMR) in Sussex County. Other (OTH), poorly drained uplands (PDU), surficial confined (SC), well drained uplands (WDU), and poorly drained lowlands (PDL). HGMR data provided by Mark R. Nardi (written commun., 2003).

(written commun., 2003). The last landscape classification scheme has two categories; one includes all areas north of Indian River (Fig. 1), and the other includes all areas south of Indian River. A line extending east-west from the head of the Indian River at Millsboro to the western edge of the study area completes the boundary between the two categories.

Determination of elevations of surface-water features

In the Coastal Plain of Delaware topographic relief is small and aquifers consist of unconsolidated granular material. 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).

Because of the correspondence of streams, ponds, and swamps to the water table, acquisition of elevations and maintaining the spatial configuration of these surface water features is an important part of modeling the water table. This was done with a multistep process using ArcMap v8.3 *Spatial Analyst* and *Geoprocessing* tools and is illustrated in Figure 4. DLG hydrographic line data were converted with Spatial Analyst into 30-m gridded raster datasets with each grid node set to a value of zero. The grid geometries were set to correspond to that of the 30-m land surface DEM. Two 30-m grids were created, one for bay and ocean shorelines and fringing tidal marshes, and one for freshwater streams. Two 90-m grids were created from DLG hydrographic polygons, one for freshwater ponds and swamps, and one for tidal marshes, bays, and the ocean.

For the grids representing freshwater features, the Spatial Analyst raster calculator was used to set the elevation of each hydrography grid node equal to the value of the corresponding land surface DEM. Modifications to the elevations of many features are described in this section and in the results section. The raster calculator was used to set elevations of nodes representing saltwater marshes to 1 ft, and to set the elevations of nodes representing the bay and ocean shorelines to 0 ft. These grids were then converted to point datasets and merged.

In areas of steep land slopes near streams the process of converting the hydrography DLG to a grid produced some nodes with anomalous elevations. This effect was minimized by using the *Buffer* and *Select by Location* tools to identify and remove points occurring more than 15 m from the original hydrography lines and polygons.

The final modifications made to the water feature elevation dataset were adjustments to elevations of groups of points representing individual ponds. The modifications were based on the assumptions that the points representing the surface of an individual pond should have the same elevation, and the surface elevation of an individual pond is

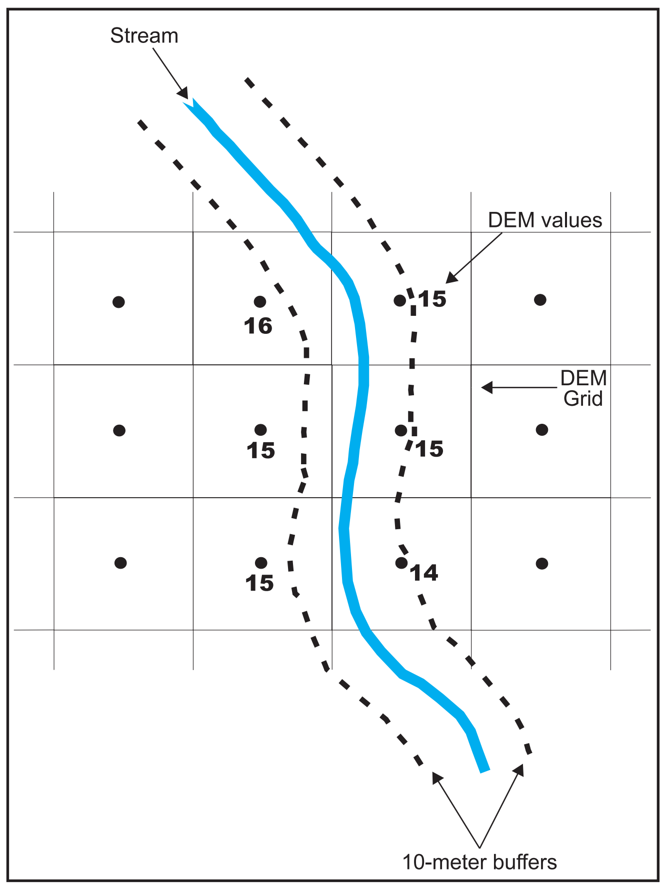


Figure 4. Illustration of process for obtaining elevations of surface water features. The land-surface elevations that are within the 10-meter buffer (10 meters on both sides of stream) are the values that were assigned to the stream feature. Digital elevation model (DEM). Elevation values are in ft.

equal to either the minimum elevation of all of the points representing the pond, or an elevation 1-ft less than the elevations of the surrounding dry land.

Statistical Evaluation of Data and Model Development

Identification of dry, normal, and wet conditions

In this study, dry, normal, and wet conditions were determined from time series DTW measurements. DTWs have been measured at roughly monthly intervals for more than 30 years in a number of observation wells in Delaware. Two shallow observation wells, Ng11-01 and Qe44-01, (Fig. 1) are screened within 10 ft of the water table and are the closest to the study area. 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 15th of each month for each month that a water level was measured. For some months that water levels were not measured, levels were interpolated from measurements made within 25 days of the 15th day of the unmeasured month (Fig. 5). Interpolation was done by on-screen digitizing using Grapher v4 (Golden Software, 2002). No estimates were made if a water-level observation was not made within 25 days of the 15th day of the unmeasured month. Years with less than 8 observations were also excluded from the dataset. Microsoft Excel was used to compute statistical measures of the water-level observations (e.g., percentiles) and identify the corresponding dates those water levels occurred.

Mean monthly stage-height data, which provide an indication of baseflow stage heights (Cushing et al., 1972), should also provide an indication of the range of groundwater elevations in streams. Unfortunately, a limited number of stage height data from water years 1974 through 1977 have been retained in digital format by the U.S. Geological Survey. As a result, there are a small number of data that correspond with the dry, normal, and wet condition periods.

Water levels and landscape attributes (Soils, HGMRs)

Relational database techniques were used to analyze and manage well, water level, and landscape attribute data. Structured Query Language (SQL) queries were constructed to create tables in Oracle containing well locations, LSEs, water-level observations, and computed statistics (mean, minimum, maximum, standard deviation, and number of observations) of observations made in the months and years of dry, normal, and wet conditions. On the bases of recent hydrogeologic studies in the area (Andres, 1986, 1987, 1991a, b, c, d; Andres and Howard, 1995; Andres and Keyser, 2001; Andres, Duffy, and Costas, 2003; Howard and Andres, 1998, 1999; Ramsey, 1999, 2003; Talley, 1988), data from wells deeper than 70 ft were excluded as they may represent deeper potentially confined aquifers. These resultant data were retrieved by SQL query in ARCMap, converted to point feature class format, and the landscape attributes of the wells (i.e., soils and HGMR) were identified using the *Select by Location* tool of ARCMap. The resulting data were then loaded and stored in Oracle tables for further analysis.

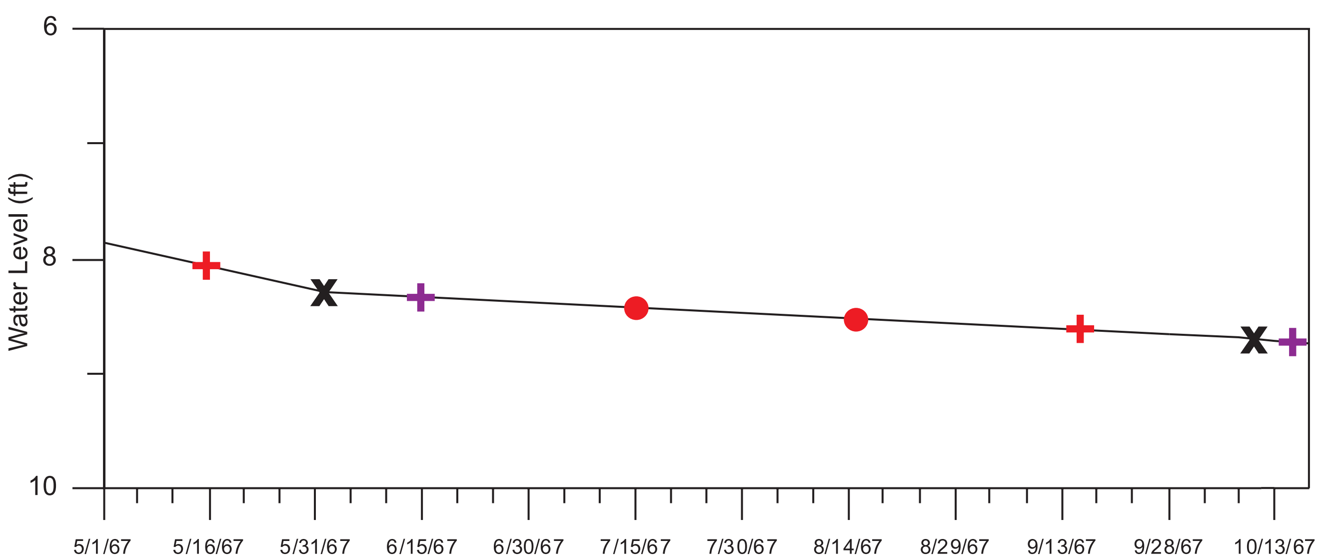


Figure 5. Illustration of the process for estimating monthly water levels. The black Xs on June 1 and October 10 represent actual days when water levels were measured. The red crosses on May 15 and September 15 symbolize water levels interpolated from measurements made within 25 days of the 15th day of the measured month. The purple crosses on June 15 and October 15th symbolize water levels interpolated on the 15th of the month that a water level was measured. No estimates were recorded for July 15 or August 15 (red circles) because no water-level measurement was made within 25 days of the 15th of either month.

Water-Table Elevation Estimation

The water table is a continuous surface; however, observations of the surface exist at irregularly spaced locations. In this study, a regularly spaced grid of WTEs estimated from observational data was the model used to represent the water table. There are a wide variety of computer methods and software packages available to calculate grids. ARCMap and Surfer were used in this study to calculate grids, evaluate residuals, and check the accuracy of the computations. Each gridding method has its own set of benefits and problems with respect to time required for computation, input data requirements, and capabilities to represent local variations in the input data. Assessment of the various gridding methods was done by comparing estimated surfaces to land surface and to DTW measurement data.

Minimum water table

Sepulveda (2003) found that estimation of the WTE by regression could be improved by a multiple linear regression (MLR) procedure that uses a "minimum water table" (MINWT) in addition to LSE to estimate the WTE. The general form of the MLR equation is:

$$WTEi = \text{Beta1} * MINWT + \text{Beta2} * (LSE\text{-}MINWT)$$

where:

WTEi = estimated water table at point i

Beta1 = regression coefficient 1

MINWT = minimum water table elevation

Beta2 = regression coefficient 2

LSE = land surface elevation

(*LSE-MINWT*) = depth to the minimum water-table surface

MINWT (Fig. 6) is estimated by computing a gridded surface from elevations of surface water features (Sepulveda, 2003). The minimum and maximum elevations of the MINWT surface are 0 ft and LSEs, respectively. In this study, estimates of the MINWT surface were generated by inverse distance weighted, ordinary kriging, multiple, and localized polynomial regression (LPR) methods. LPR, which is a form of trend-surface analysis, was successfully used by Sepulveda (2003).

Table 1. Descriptive statistics of depth to water in ft below land surface (bls) in wells Ng11-01 and Qe44-01. Ng11-01 is located at latitude N38°49′55″, longitude W75°19′ 29″, land surface elevation 24 ft (NAVD 88) and is screened 16.1 to 19.1 ft bls. Qe44-01 is located at latitude N38°31′38″, longitude W75°26′03″, land surface elevation 49 ft (NAVD 88) and is screened 22 to 26 ft bls.

	Ng11-01	Qe44-01
No. Observations	475	468
Minimum	7.06	4.16
5th percentile	8.95	5.56
25th percentile	10.56	6.75
Median	11.63	7.81
Average	11.49	8.19
75th percentile	12.50	9.48
95th percentile	13.70	11.45
Maximum	14.55	12.35

Traditional estimators

Traditional estimation methods such as inverse distance weighting, triangulation, and kriging use the elevations of surface water features and ground-water elevation observations as input data to interpolate the elevation of the water table. For example, triangulation was used to manually draw water-table isoelevation lines on the HA maps. With the widespread use of computers in hydrologic studies, computational methods commonly represent surfaces as a rectilinear grid. Dunlap and Spinazola (1984) used kriging to estimate water-table altitudes in Kansas. Evaluations of how well the estimated surfaces represent the actual surface differ between methods and commonly include statistical measures of observed and predicted water levels (i.e., inverse distance weighted, triangulation), analysis of estimation errors (kriging), and visual and mathematical comparison of estimated surfaces to land surface. Interested readers are referred to Davis (1986), Journel (1987), or other textbooks on geostatistics.

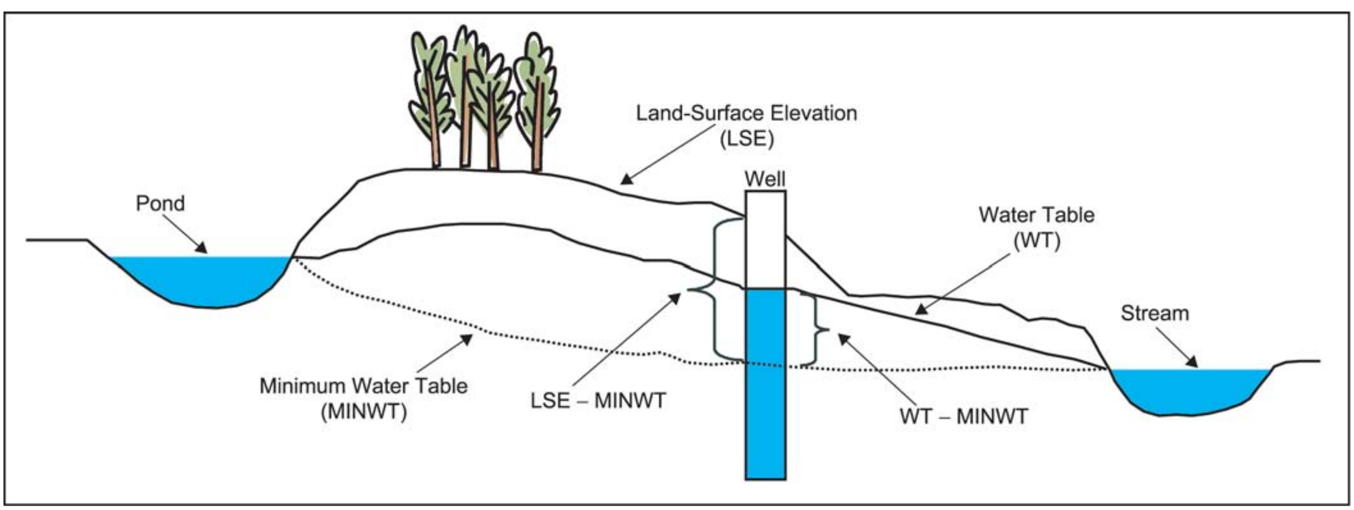


Figure 6. Illustration of the minimum water table.

RESULTS AND DISCUSSION

Statistical Evaluation of Ground-Water Levels

The relationships between long-term hydrographs and selected percentiles of water-level distributions for wells Ng11-01 and Qe44-01 are illustrated in Figures 7 and 8 and Table 1. After evaluating the results of this analysis, normal conditions are defined as the months with DTWs between the 40th and 60th percentiles in both wells, dry conditions (lowest water levels) occur in the months with DTWs below the 25th percentile (between the 25th and 5th) in both wells, and wet conditions (highest water levels) occur in the months with DTWs above the 75th percentile (between the 75th and 95th) in both wells. These percentiles 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. The 25th and 75th percentiles are also used as indicators of drier and wetter water-table conditions for the DGS's water conditions evaluations.

There are a small number of surface-water elevation data from water years 1974 through 1977 that were measured during dry, normal, and wet condition periods in Delaware Coastal Plain streams. Because these data show small differences (< 1 ft) in stream stage between wet and dry conditions, it is assumed that surface-water elevations are relatively consistent under all baseflow conditions.

Data from monitoring and observation wells

Observation wells having DTW measurements are not evenly distributed throughout the study area and are distributed differently for dry, normal, and wet conditions (Figs. 9A-C). Although the LSEs of observation points almost cover the range of LSEs in the study area (Figs. 10 through 12, Table 2), there are very few observation wells between LSEs of about 35 and 50 ft. DTW tends to decrease with increasing LSE (Fig. 10) reflecting the poorly drained and low relief characteristics of the land area near the western watershed boundary. The western portion of the study area also tends to have larger areas of lower recharge potential compared to the portion fringing Rehoboth and Indian River bays (Andres, 2003; Andres et al., 2002).

Correlation coefficients of regressions for WTE on LSE are statistically significant (Fig. 11) for dry, normal, and wet conditions (R^2 approximately 0.75) though the deviations from the regression lines are not evenly distributed over the entire range of LSEs. The high correlation coefficients indicate that in the absence of other data or estimators, LSE alone may be used as a reasonable predictor of WTE. The slopes of the regression lines predict that the WTE should be between 75 and 80 percent of the LSE.

The differences in DTW between dry and wet conditions are between 1 and 7 ft at approximately 90 percent of observation points. The magnitudes of differences tend to increase with increasing LSE (Fig. 12). Results of t-tests (alpha = 0.05, one tail, no assumption of equal sample variance) of the dry, normal, and wet groups indicated no difference between the means of wet and normal groups (t = 0.064, critical t = 1.65), but did find differences between the means of the wet and dry (t = -2.43, critical t = 1.65) and dry and normal groups (t = -2.96, critical t = 1.65). The lack of difference between the wet and normal groups is thought to be due to spatial clustering of observations rather than real similarities between wet and normal conditions throughout the study area.

In general, DTWs are greatest under dry conditions and

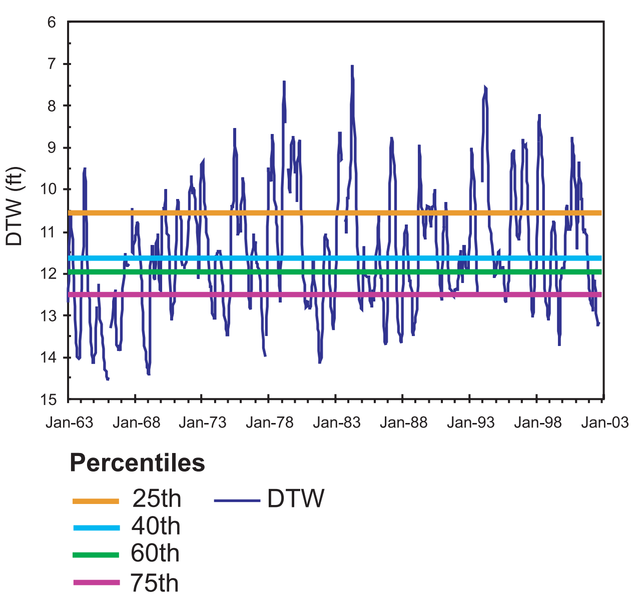


Figure 7. Hydrograph for well Ng11-01. Data points are estimated for the 15th of each month. Statistics derived from estimated data. Lines designated 25th, 40th, 60th, and 75th are percentiles of data distribution; depth to water (DTW).

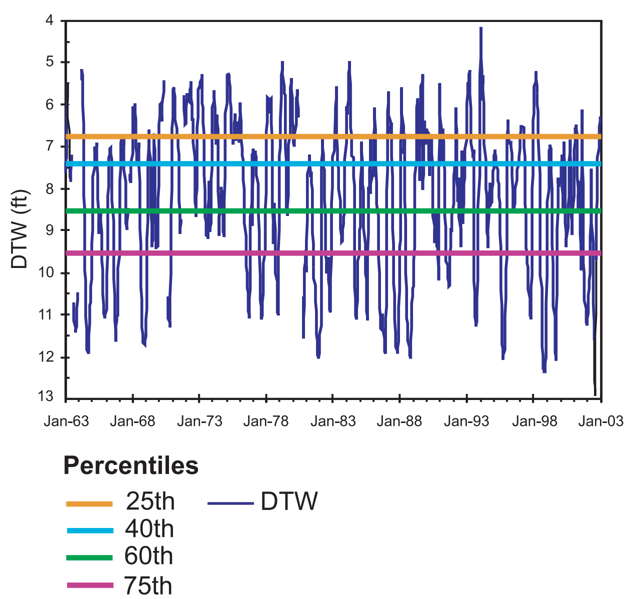


Figure 8. Hydrograph for well Qe44-01. Data points are estimated for the 15th of each month. Statistics derived from estimated data. Lines designated 25th, 40th, 60th, and 75th are percentiles of data distribution; depth to water (DTW).

are less under normal and wet conditions (Table 2). However, dry condition DTWs are less than wet condition water levels at a small percentage of points demonstrating that local differences in hydrologic conditions can affect DTW more than climatic conditions. Local differences in hydrologic conditions likely include wastewater disposal and ground-water pumping.

Data from well completion reports

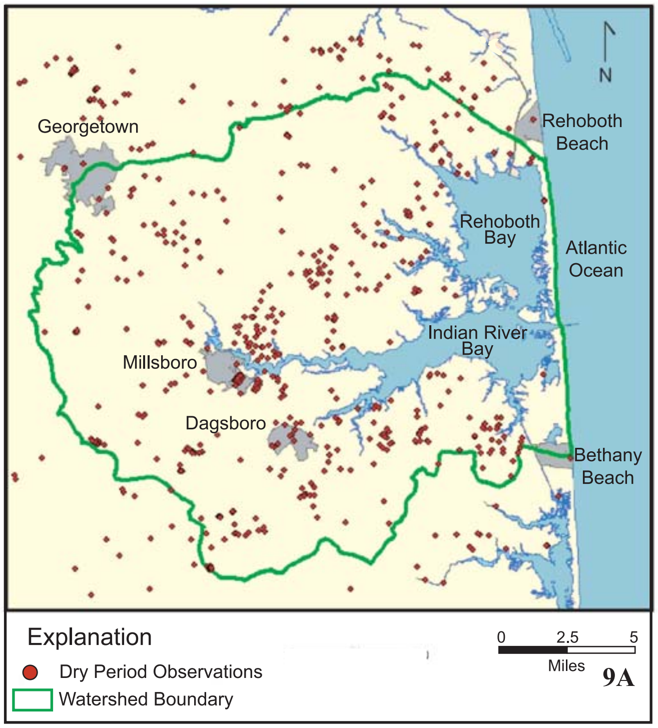
DTW measurements from well completion reports supplement the measurements from observation wells. Similar to the observation well dataset, locations of these measurements are not spread evenly across the study area (Figs. 9A-C). Checks on the data found many likely errors, which in almost all cases consist of computed water elevations that are less than 0 ft. These negative elevations are not spatially clustered indicating that either the DTW measurements or the well locations are in error. These observations were removed from the dataset.

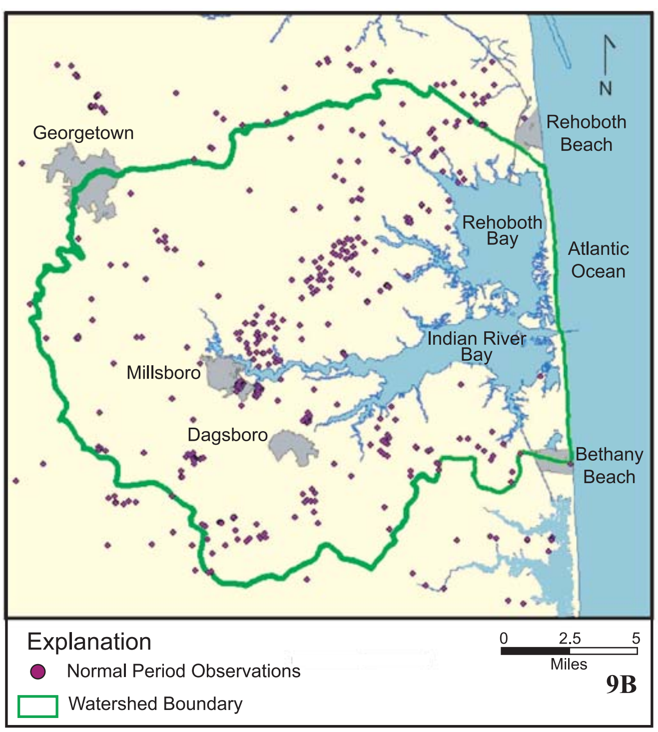
T-tests (alpha = 0.05, two tail, no assumption of equal sample variance) of the well completion report data compared to data obtained from observation wells show no differences for the wet (t = -0.045, critical t = 1.98) and normal (t = 0.14, critical t = 1.98) data but do show a difference for the dry data (t = -2.08, critical t = 1.96). Analysis of the dry-period data indicates that the difference is due to lower LSEs in the well completion report dataset compared to the observation well dataset.

Water levels from all wells and soil type, hydrogeomorphic region, and watershed position

The relationships between DTW and soil type, HGMR, and position relative to Indian River were evaluated using the merged data from the well completion report and observation well datasets. Comparisons of mean DTW between HGMRs (Table 3) show significant differences between well-drained uplands (WDU) and the poorly drained uplands (PDU) and surficial confined (SC) groups, but not between the PDU and SC groups. Similar comparisons between soil groups (Table 3) show differences in DTW between hydric and land capability class groups, the only groups with enough measurements to make comparisons meaningful.

Although there are significant differences between mean depths to water, data groupings by soil type and HGMR generally yield poorer linear regression correlation coefficients





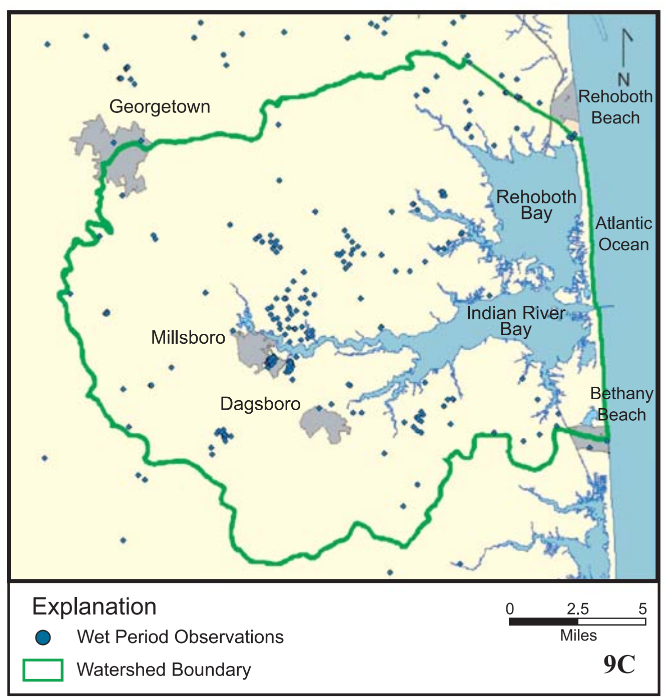


Figure 9. Map of ground-water level data points. A. Dry period data points. B. Normal period data points. C. Wet period data points.

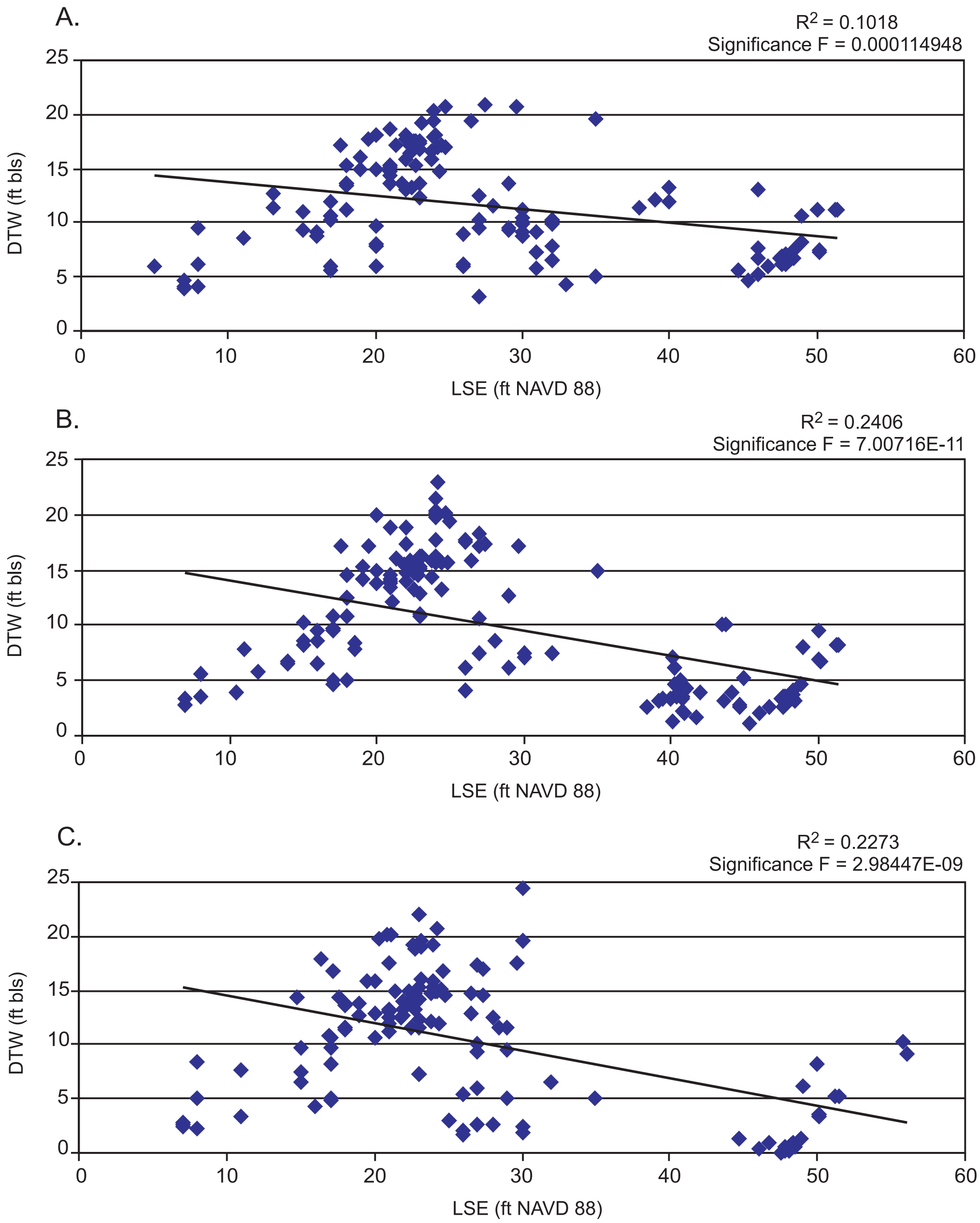


Figure 10. Plots of depth to water table (DTW) versus land-surface elevation (LSE). Best-fit linear regression line shown plotted on each plot. A. Dry conditions. B. Normal conditions. C. Wet conditions. Correlation coefficients (R^2) shown on each plot are statistically significant at the critical F-values shown indicating that depth to water decreases with increasing LSE.

Table 2. Descriptive statistics for water levels measured in observation wells under dry, normal, and wet conditions. Water levels reported as depth to water in feet below land surface.

	Dry	Normal	Wet	Dry-Wet	Dry-Normal	Wet-Normal
No. Observations	639	479	301	139	141	157
Minimum	0.00	0.00	-0.45	-0.02	-5.85	-0.83
5th percentile	3.00	2.00	0.43	0.62	-0.65	-0.25
25th percentile	6.00	4.00	3.97	1.91	0.79	0.68
Median	8.27	8.00	9.00	2.68	1.40	1.14
Average	9.87	9.19	9.11	3.35	1.60	1.55
75th percentile	13.17	13.00	14.00	4.45	2.92	2.25
95th percentile	20.64	19.00	19.25	6.74	4.11	3.56
Maximum	27.00	33.00	25.35	14.50	6.16	9.90

between WTE and LSE than correlation coefficients computed for the entire dataset (Fig. 11). This is likely due to the smaller ranges of WTE and LSE in the subsets compared to the entire dataset. Linear regression correlation coefficients for WTE and LSE for the entire dataset and for groupings of points by position relative to the Indian River are of similar magnitude (R^2 = 0.75 to 0.8).

Multiple Linear Regression with Minimum Water Table

The minimum water table (MINWT) (Sepulveda, 2003) is used in a multiple linear regression (MLR) process to compute elevation of the water table. The elevation of the MINWT is estimated from elevations of surface water features. Several different gridding algorithms were evaluated for estimating the MINWT: inverse distance weighted (IDW), ordinary kriging (OK), and localized polynomial regression (LPR). The same rectangular grid extent (1129 rows, 1177 columns, 30-m spacing) and origin (461409 East, 4290507 North) were used for all computations. The grid extends beyond the irregular study area boundary and allows the MINWT elevations to be estimated along the study area boundary. This approach is used because ground-water level data are not sufficient to determine the elevation of the water table along the study area boundary.

In addition to the topics covered in the methods section several other steps were required to compute MINWT. Comparison of the results of initial estimates of the MINWT to land surface identified many areas (approximately 20 percent of the grid) where the MINWT was at or above land surface. As a result, estimation of the MINWT was done by an iterative process consisting of gridding, evaluation of results, modifica-

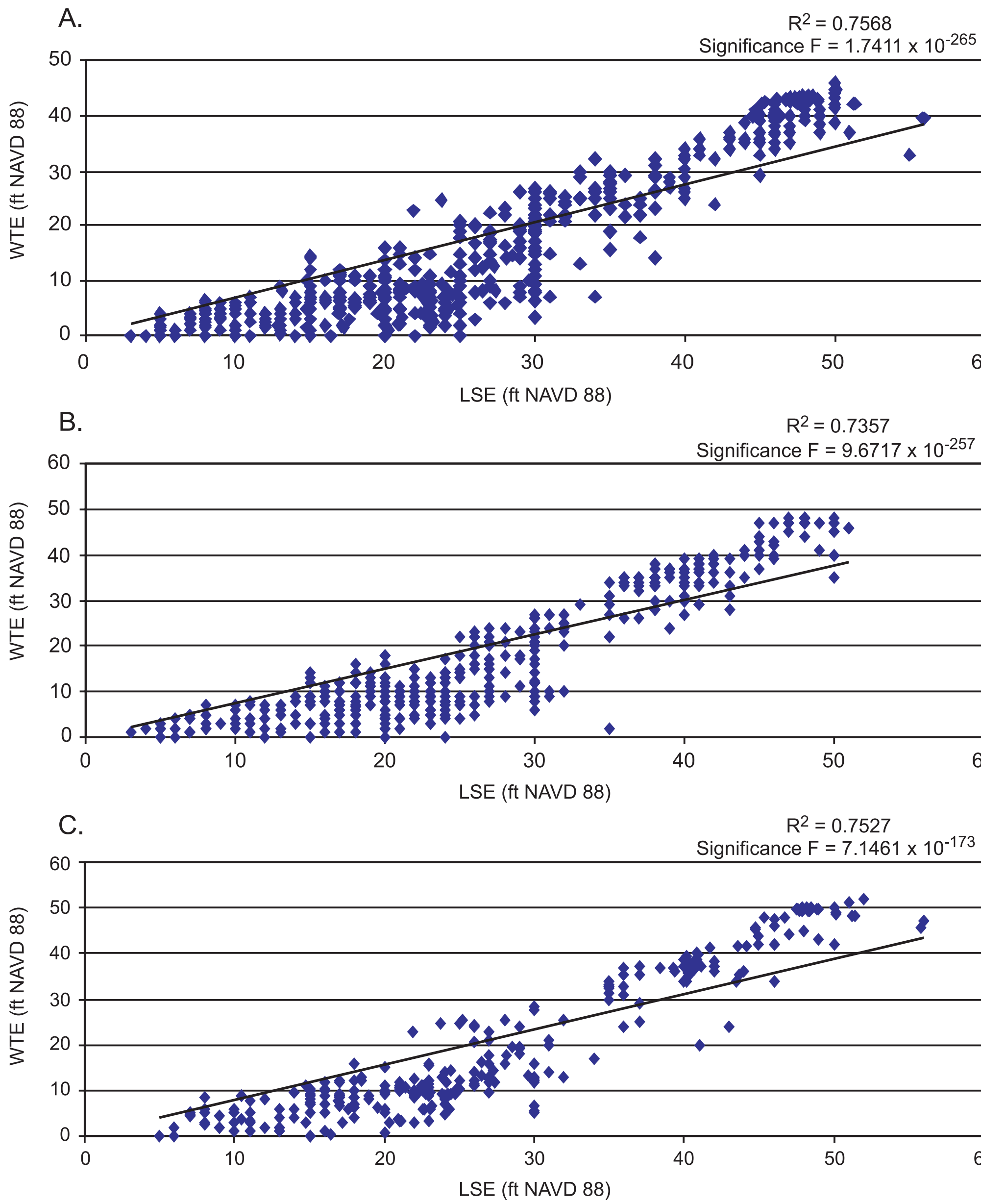


Figure 11. Plots of water-table elevation (WTE) versus land-surface elevation (LSE). A. Dry conditions. B. Normal conditions. C. Wet conditions. Correlation coefficients (R^2) shown on each plot are statistically significant at the critical F-values shown. See text for additional discussion.

Table 3. Multiple linear regression coefficients used to estimate water-table elevation (WTE). Root mean squared (RMS). Soil groups: hydric (HYD), highly erodable (HEL), hydric/well-drained (HYD/LCC), well drained (LCC). Hydrogeomorphic regions: other (OTH), poorly-drained upland (PDU), surficial confined (SC), well-drained upland (WDU).Multiple linear regression coefficients used to estimate water-table elevation (WTE). Root mean squared (RMS). Soil groups: hydric (HYD), highly erodable (HEL), hydric/well-drained (HYD/LCC), well drained (LCC). Hydrogeomorphic regions: other (OTH), poorly-drained upland (PDU), surficial confined (SC), well-drained upland (WDU).

DRY

	HYD	HEL	HYD/LCC	LCC	OTH	PDU	SC	WDU	North	South	All
No. Observations	81	19	22	416	27	79	66	362	324	218	542
MIN LSE	5.00	5.00	7.00	3.00	5.00	41.00	3.00	5.00	4.00	3.00	3.00
AVG LSE	35.05	21.13	17.50	25.57	10.07	47.40	24.81	23.56	29.01	22.42	26.36
MAX LSE	49.00	39.00	50.00	56.04	19.00	56.04	45.00	55.00	56.04	50.00	56.04
MIN DTW	2.94	3.00	2.57	-1.00	2.00	3.07	2.00	-1.00	1.00	-1.00	-1.00
5th percentile	4.00	4.07	3.05	4.00	2.93	4.63	3.00	4.51	4.13	3.00	4.00
25th percentile	6.00	6.69	4.00	7.18	5.00	6.00	4.35	8.00	6.94	6.00	6.55
Median	7.00	10.00	4.68	10.19	6.00	6.76	7.00	11.54	10.00	9.05	9.76
Mean	7.85	11.14	5.59	11.44	7.41	7.52	7.74	12.11	11.14	9.82	10.61
75th percentile	9.00	15.00	6.50	15.22	9.29	8.12	8.80	16.00	15.00	13.64	14.27
95th percentile	13.00	18.58	12.75	21.57	14.00	12.11	18.25	21.90	22.00	18.00	20.96
MAX DTW	16.00	23.80	13.08	27.00	15.00	16.47	24.00	27.00	27.00	24.00	27.00

NORMAL

	HYD	HEL	HYD/LCC	LCC	OTH	PDU	SC	WDU	North	South	All
No. Observations	100	9	225	299	13	57	97	303	248	227	475
MIN LSE	5.00	8.00	7.00	4.00	3.00	40.00	6.00	6.00	3.00	4.00	3.00
AVG LSE	35.55	22.56	34.00	24.58	9.38	46.70	33.84	22.54	27.49	26.96	27.24
MAX LSE	50.00	39.00	46.00	50.00	21.00	51.00	45.00	50.00	51.00	50.00	51.00
MIN DTW	1.00	3.00	1.00	2.00	2.00	1.00	1.00	3.00	1.00	1.00	1.00
5th percentile	2.00	4.20	2.00	4.00	2.60	2.00	2.00	4.10	2.00	3.00	3.00
25th percentile	3.00	6.00	3.00	7.00	4.00	3.00	4.00	8.00	66.00	4.00	5.00
Median	4.00	7.00	3.00	11.00	6.00	3.00	4.00	12.00	10.00	6.00	8.00
Mean	4.71	10.11	4.48	11.35	6.62	4.25	4.99	12.04	10.81	7.96	9.45
75th percentile	5.00	14.00	5.00	15.00	9.00	5.00	6.00	16.00	15.00	12.00	13.00
95th percentile	10.00	19.20	11.60	20.00	12.40	8.40	10.00	20.00	21.00	17.00	20.00
MAX DTW	18.00	22.00	13.00	33.00	13.00	15.00	13.00	33.00	33.00	20.00	33.00

WET

	HYD	HEL	HYD/LCC	LCC	OTH	PDU	SC	WDU	North	South	All
No. Observations	46	7	18	229	16	41	32	213	176	127	303
MIN LSE	6.00	8.00	7.00	6.00	5.00	40.00	9.00	6.00	6.00	5.00	5.00
AVG LSE	39.61	16.77	31.95	24.78	11.50	47.92	37.43	22.73	25.03	25.03	27.09
MAX LSE	50.00	26.00	52.00	56.04	16.00	56.04	44.14	50.00	56.04	49.00	56.04
MIN DTW	-2.11	-0.35	-0.45	-1.00	2.56	-2.11	-0.45	-1.00	-2.11	-1.00	-2.11
5th percentile	-1.55	0.44	-0.09	1.75	2.60	-1.57	0.54	0.92	0.00	0.80	0.23
25th percentile	0.51	7.12	0.26	5.05	2.74	0.25	1.27	5.00	2.78	3.58	3.04
Median	2.93	12.00	0.72	11.27	3.28	3.47	3.43	11.00	8.00	9.42	8.41
Mean	3.09	10.44	1.44	10.38	3.90	6.61	5.59	9.93	8.62	8.81	8.70
75th percentile	5.09	13.81	1.25	114.72	4.99	11.53	8.72	14.02	14.00	13.77	13.91
95th percentile	9.53	18.19	8.07	19.28	6.03	19.56	15.63	19.26	19.57	16.68	19.04
MAX DTW	12.00	219.56	8.48	25.35	7.69	24.45	17.44	25.35	25.35	19.28	25.35

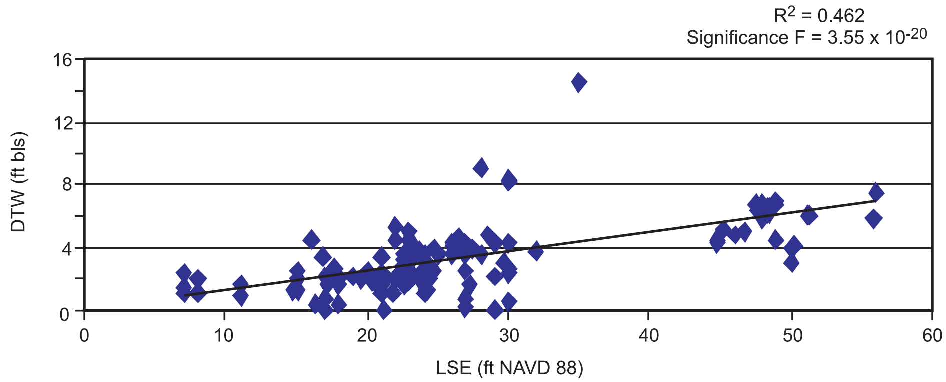


Figure 12. Plots of difference in depth to water table (DTW) between dry and wet conditions and land-surface elevation. Correlation coefficient (R^2) is statistically significant at the F-value shown.

tion of the input dataset, and re-gridding to minimize the area where the MINWT was at or above land surface.

OK used a semi-variogram model derived from ground-water level data and is described in a later section (*Water-Table Elevation Estimated from All Data by Ordinary Kriging*). LPR- and OK-MINWT grids had much fewer cells with elevations above land surface than IDW. The surface generated by LPR (Fig. 13) tends to be much smoother (i.e., smaller changes in elevation over short distances) than the OK generated surface. This is discussed in more detail in a following section (*Comparisons of Grids Estimated by Different Methods*).

Visual comparison of the estimated MINWT, land surface DEM, DLG hydrography data, and 1:24,000-scale digital raster graphic (DRG) topographic maps indicated that some of the areas with the estimated MINWT greater than LSE are associated with swamps, which is to be expected; however, many of the areas where the estimated MINWT is greater than LSE are associated with drainage ditches. Further evaluation of DEM and hydrography DLG data revealed that the DEM-determined elevations of ditch features were frequently equal to the elevations of the surrounding land. Considering that streams are at the lowest points in the landscape under baseflow conditions and that ditches are always excavated, modification of the elevations of these features is reasonable. Mackenzie (1999) reduced the elevations of surface water features when using the DEM for a watershed analysis study. The modifications that produced a MINWT that did not equal or exceed land surface consisted of reducing elevations by 3 ft for features at elevations greater than 32 ft, reducing elevations by 2 ft for elevations between 22 and 32 ft, and reducing elevations by 1 ft for elevations between 2 and 22 ft. The final step was to set the elevation of the MINWT equal to land surface in the remaining areas (< 0.5 percent of the grid area) where the elevation of the MINWT surface was greater than land surface.

Table 4. Multiple linear regression coefficients used to estimate water-table elevation (WTE). Root mean squared (RMS). Soil groups: hydric (HYD), highly erodable (HEL), hydric/well-drained (HYD/LCC), well drained (LCC). Hydrogeomorphic regions: other (OTH), poorly-drained upland (PDU), surficial confined (SC), well-drained upland (WDU).

	Group	Number of Wells	Beta 1	Beta 2	RMS Error (ft)	Range of Differences (ft)	R^2
OK - MLR	Dry	542	0.8775	0.1254	4.416	-15, 15	0.8957
	Normal	475	0.9700	0.0882	4.078	-14, 10	0.9187
	Wet	303	1.0065	0.1688	4.128	-16, 14	0.9284
LPR - MLR	Dry	542	0.8775	0.1254	4.416	-7, 15	0.8957
	Normal	475	0.9697	0.0880	4.112	-15, 10	0.9176
	Wet	303	1.0066	0.1682	4.126	-16, 14	0.9286
Soil Group under normal conditions	HYD	100	1.0299	0.0590	2.424	-10, 4	0.9694
	HEL	9	0.8972	0.1674	2.241	-3, 3	0.9625
	HYD/LCC	25	0.9487	0.5603	3.689	-10, 3	0.9299
	LCC	299	0.8848	0.1509	3.970	-13, 4	0.8606
	DUNES	5	0.1176	0.3575	1.555	-2, 2	0.1758
HGMR under normal conditions	OTH	13	0.0893	0.4717	2.933	-4, 7	0.4470
	PDU	57	1.0159	0.1959	2.941	-8, 4	0.5921
	SC	97	0.9748	0.3356	2.808	-10, 5	0.9296
	WDU	303	0.7753	0.1913	3.822	-12, 11	0.7326

The process used to determine elevations of surface water features also introduced digital anomalies that could not be corrected within the scope of this study. Elevations of non-tidal streams should decrease uniformly from headwater to mouth. However, topographic relief and the 30-m spacing of the DEM cause elevations of the DEM along some stream segments to increase slightly in a downstream direction. GIS software utilities can correct for this noise if hydrography data allow the streams to be represented as networks. The work to produce these data is part of the National Hydrography Dataset program (U.S. Geological Survey, http://nhd.usgs.gov) that is in progress for the study area. The effect of this problem is limited to small areas of the grid (less than 1 percent) in the immediate vicinity of a small number of stream segments. The problem can be corrected when the National Hydrography Dataset work for this area is complete.

Correlation coefficients (Table 4, Fig. 11) for OK-MLR and LPR-MLR with the entire dataset and the regions north and south of Indian River are better than those for linear regressions between WTEs and LSEs alone (Fig. 11). Root mean square errors from the MLR predictions range from about 4.1 to 4.4 ft (Table 4), which is approximately 7 percent of the total range of observed elevations. Maximum absolute deviations (observed-predicted) range from -16 to 15 ft. It is important to note that many of the deviations of greater magnitude are associated with wells located on spray irrigation facilities and sites with active pump and treat ground-water remediation systems and may reflect the operation of those facilities.

Except for the surficial confined HGMR, MLR correlation coefficients associated with HGMR classifications are much smaller than those determined from soil groups. Correlation coefficients for all soil groups except land capability class are slightly larger than those for the entire dataset. Because maximum absolute deviations (observed - predicted) in the individual soil groups are smaller than those for the entire dataset, water tables estimated by MLR by soil group appear to fit the observed data better than surfaces derived from MLR for the entire dataset.

The water table for dry (Fig. 14), normal (Fig. 15), and wet (Fig. 16) conditions estimated with the LPR-MLR equations (Table 4 and Fig. 17) bear some gross similarities to the water-table equipotential lines from the HA series maps (Figs. 14 through 16). This is to be expected as the equipotential lines on the HA maps are in part derived from topography (Boggess et al, 1964a). In a qualitative sense, key differences are the areas in the western portion of the study area where the LPR-MLR estimated surfaces have elevations above 50 ft, and the smoother character of the LPR-MLR estimated surfaces around surface water features.

Summary statistics for MLR estimated depths to water and differences between dry, normal, and wet water tables (Table 5) show that the difference between mean and median depths to water between wet and dry water tables is relatively small (less than 3 percent of the range of water elevations). Differences between wet and dry surfaces are less than 5 ft for 90 percent of the Inland Bays watershed.

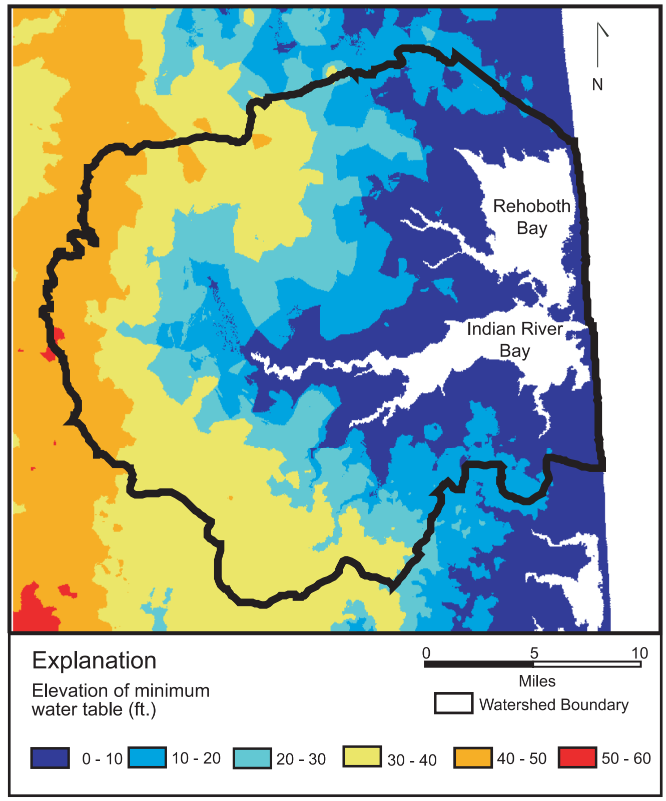


Figure 13. Map of minimum water table. Surface generated by localized quintic polynomial regression in ArcMap Geostatistical Analyst.

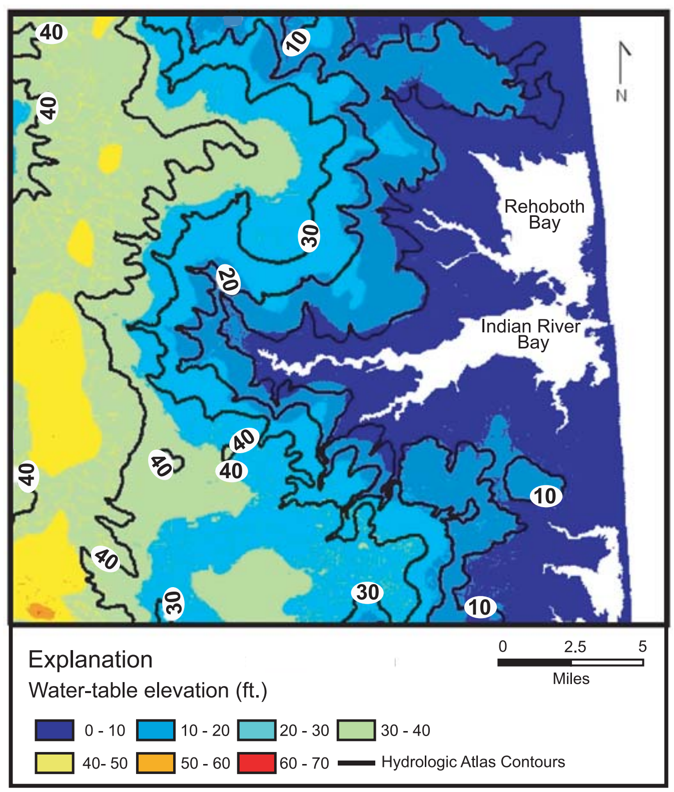


Figure 14. Water-table elevations under dry conditions estimated by multiple linear regression. Water-table contours are from the Hydrologic Atlas Series maps.

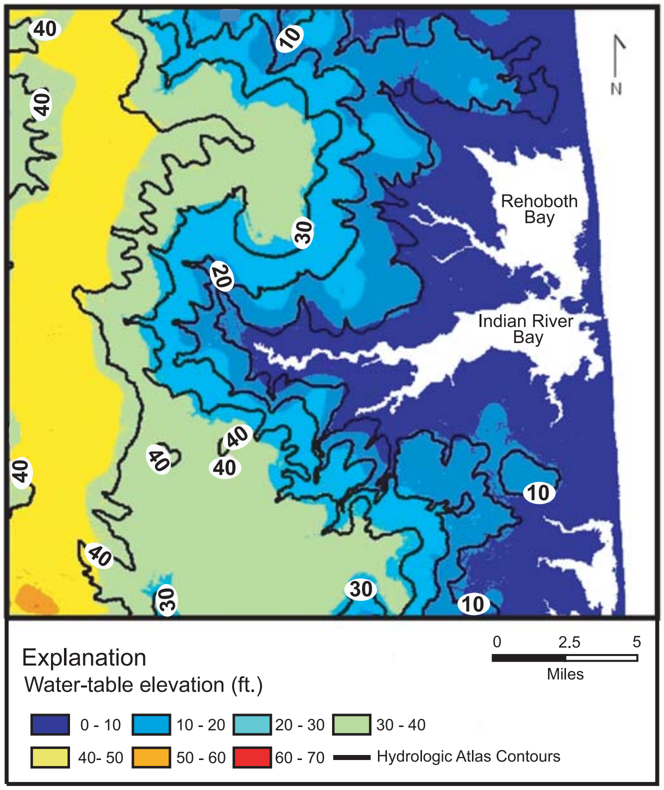


Figure 15. Water-table elevations under normal conditions estimated by multiple linear regression. Water-table contours are from the Hydrologic Atlas Series maps.

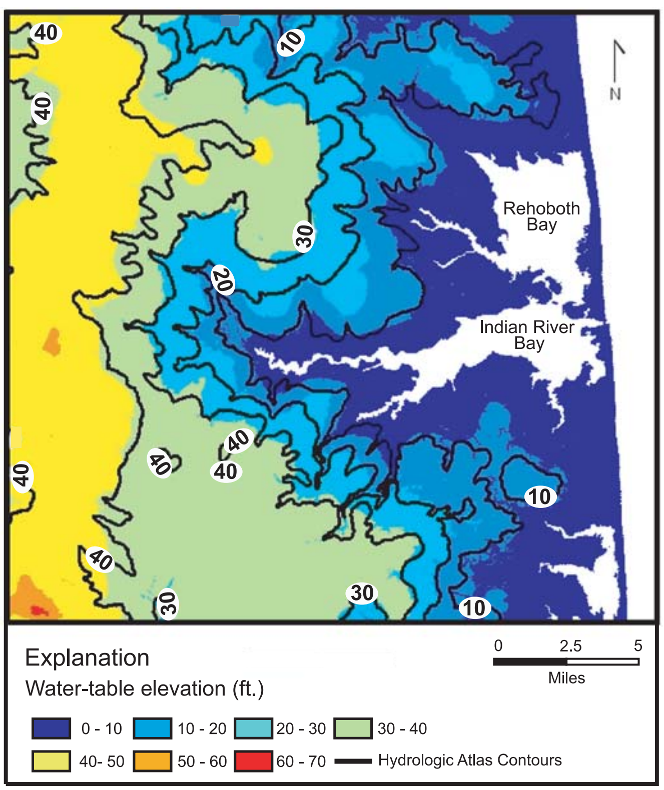


Figure 16. Water-table elevations under wet conditions estimated by multiple linear regression. Water-table contours are from the Hydrologic Atlas Series maps.

Nearly 2.5 times as much area has DTW less than 5 ft under wet conditions than under dry conditions. Shallow DTW is an important consideration in evaluating the feasibility of sites for wastewater disposal. Along with soil maps, estimated DTW maps can be used to quickly identify the areas where the suitability of standard on-site wastewater disposal systems would be questionable.

Estimation of WTE on a watershed scale by MLR is a viable option for doing similar work in other areas of the Coastal Plain of Delaware for two primary reasons. First, the correspondence between elevations of surface water and ground water is confirmed by the correlation of observed and predicted ground-water levels. Second, the MLR method can be done with existing data and does not require acquisition of closely spaced ground-water level observations over the estimation region. Issues related to irregular representation of the water table near some surface water features affect small portions of the grid and can be corrected when National Hydrography Dataset results become available.

Water-Table Elevation Estimated from All Data by Ordinary Kriging

The WTEs under dry (Fig. 18), normal (Fig. 19), and wet (Fig. 20) conditions were estimated by OK using a spherical semi-variogram model (length = 1500 m, nugget = 5, partial sill = 40, 16 nearest neighbors, 4 neighbors per quadrant) derived from an experimental semi-variogram of ground-water level observations made during dry conditions (Fig. 21). The semi-variogram from the dry conditions dataset was used because it contains the largest number of observations, and the observation locations have the broadest spatial distribution. The OK method produced much smaller areas where the estimated water table exceeded land surface and more closely reproduced surface water features in comparison to surfaces computed by IDW methods.

The water table estimated by OK is generally similar to the surface depicted by equipotential lines on the HA maps. In a qualitative sense, key differences between the OK estimated and HA map water tables are the areas in the southwestern portion of the study area where the OK estimated WTE is above 50 ft, and the more detailed (i.e., less smooth) character of the new estimated surfaces.

Percentages of land areas having similar estimated DTWs are very similar between dry, normal, and wet conditions (Table 5) with more than 80 percent of the area having no difference in DTW between wet and dry conditions. Mean and median DTWs are also very similar between dry, normal, and wet conditions. The similarities are likely due to the facts that the elevations of surface water features are the same for dry, normal, and wet conditions, and these features are the only data used by the OK estimation process in areas of few ground-water level observations.

Comparisons of Grids Estimated by Different Methods

MINWTs computed by LPR are much smoother than those estimated by OK because OK uses observed WTEs (e.g., surface water features and ground-water levels) as the elevation of the estimated water table at locations where observations and grid cells are coincident (Davis, 1986; Journel, 1987), whereas LPR uses a polynomial function to estimate the surface. As a result, in areas with densely spaced observations, surfaces estimated by OK would be expected to more closely represent actual surfaces than surfaces represented by methods that smooth the data, such as LPR. It is no surprise then that even though correlation coefficients from LPR-MLR and OK-MLR are similar (Table 4), there are visually noticeable differences between grids generated by LPR-MLR, OK-MLR, and OK.

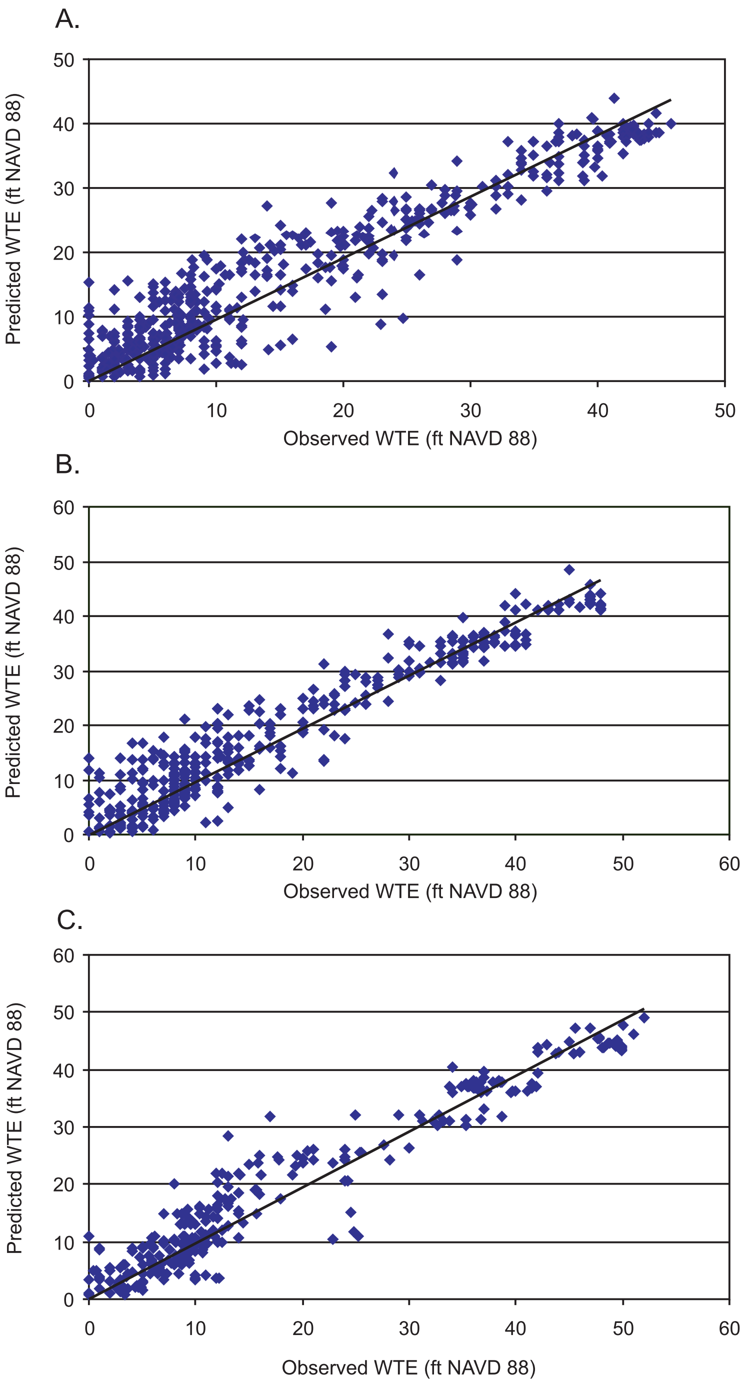


Figure 17. Plots of estimated and observed water levels at observation points and regression lines. Water-table elevation (WTE), in ft. A. Dry conditions. B. Normal conditions. C. Wet conditions.

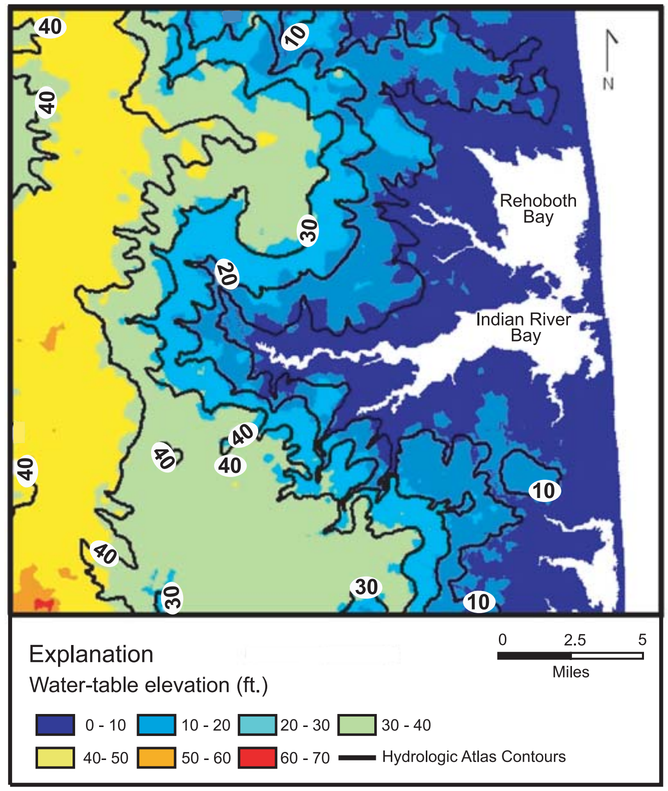


Figure 18. Water-table elevations under dry conditions estimated by ordinary kriging. Water-table contours are from the Hydrologic Atlas Series maps.

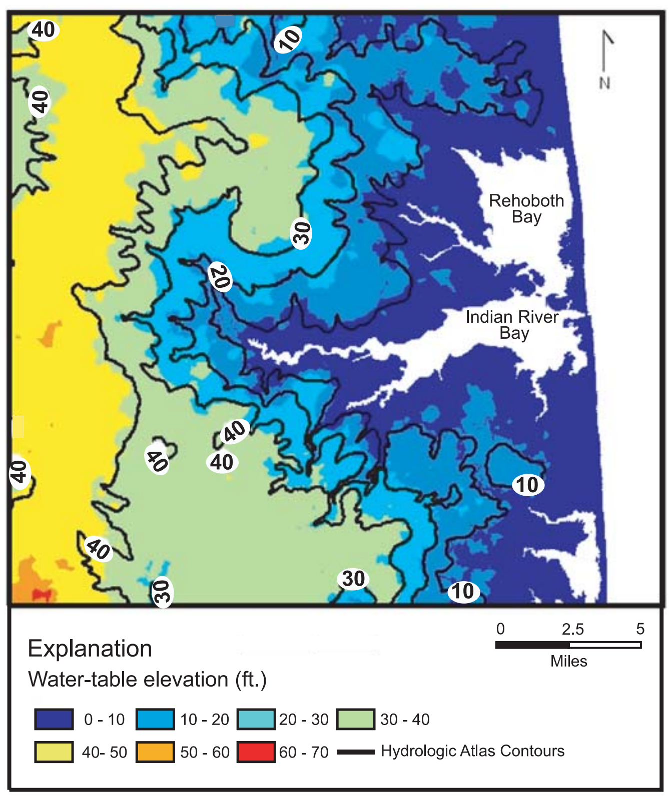


Figure 19. Water-table elevations under normal conditions estimated by ordinary kriging. Water-table contours are from the Hydrologic Atlas Series maps.

Table 5. Relationships between land areas and calculated water-table depths. These data compare gridding methods and grid areas. Grid values (0, <2, <5, etc.) are depth to water in feet below land surface.

LPR-MLR Grids								
	0	<2	<5	<10	<25	<50	Mean	Median
Entire Grid								
Dry	1	4	20	65	99	100	8.3	8
Normal	1	6	35	82	99	100	6.4	4
Wet	2	11	55	87	99	100	5.0	4
Wet-Dry (elevation)	13	28	64	100	100	100	3.2	3
Inland Bays								
Dry	1	4	19	63	99	100	8.3	8
Normal	1	6	30	79	99	100	6.7	6
Wet	1	9	49	86	99	100	5.4	5
Wet-Dry (elevation)	14	31	74	100	100	100	2.9	3

Kriging Grids								
	0	<2	<5	<10	<25	<50	Mean	Median
Entire Grid								
Dry	3	9	50	81	99	100	6.0	5
Normal	3	9	51	82	99	100	5.9	4
Wet	3	10	51	83	99	100	5.8	4
Wet-Dry (elevation)	86	93	98	99	100	100	0.2	0
Inland Bays								
Dry	2	8	43	77	99	100	6.6	5
Normal	2	8	43	78	99	100	6.5	5
Wet	3	8	45	79	99	100	6.3	5
Wet-Dry (elevation)	82	91	97	99	100	100	0.3	0

Review of the statistics (Tables 5 and 6) of the surfaces estimated by LPR-MLR and OK show that the surfaces estimated by LPR-MLR for normal and wet conditions show slightly lesser DTW than OK estimated surfaces and greater depths for dry conditions. In terms of land area, the differences are small with elevations of almost 90 percent of the OK and LPR-MLR grids being within 2 ft of each other. In general, the elevations of the surfaces estimated by LPR-MLR are greater than that of the OK estimated surface (Fig. 22) in areas of the land capability class (i.e., well drained) soil group (Fig. 2). The elevation of the OK estimated surface is generally greater than the MLR surface in areas of the hydric soil group.

Areas of greatest differences between LPR-MLR and OK water tables are located in three types of areas: (1) coincident with some clusters of water-level observation points (Fig. 22); (2) associated with areas of greater local topographic relief between streams and uplands (Fig. 22); and (3) located more than 1500 m (i.e., greater than length of semivariogram) from water-level data points. Comparison of MINWT profiles generated by LPR and OK and water-table profiles generated by OK, OK-MLR, and LPR-MLR in an area with many water-level observation points (Fig. 23) shows that the OK-MINWT and OK-MLR profiles have much sharper peaks and valleys than the OK, LPR-MINWT, and LPR-MLR profiles. Given that the WTE estimates have no dependence on hydraulic properties of the aquifer, changes of more than 2-ft in WTE over short distances (i.e., steep gradient) in the OK-MINWT and OK-MLR surfaces (Fig. 23) are an artifact of the estimation process and are not reasonable. It is likely that some of the differences between LPR-MLR and OK estimated surfaces (Fig. 22) not associated with cases (2) or (3) are the result of errors in the ground-water level dataset or are the result of local wastewater disposal at spray irrigation facilities or high-capacity pumping. We consider the watershed water tables generated by LPR-MLR to be better than surfaces generated by OK and OK-MLR that reflect erroneous data and artifacts of operations of spray irrigation facilities and high-capacity wells.

CONCLUSIONS

Evaluation of long-term depth to water hydrographs (1963-2002) from two shallow observation wells near the study area have defined time periods identified as dry (5 to 25 percent exceedence), normal (40 to 60 percent exceedence), and wet (75 to 95 percent exceedence) water-level conditions. Ground-water level data measured in hundreds of wells during these periods show statistically significant relationships between land-surface elevation (LSE) and

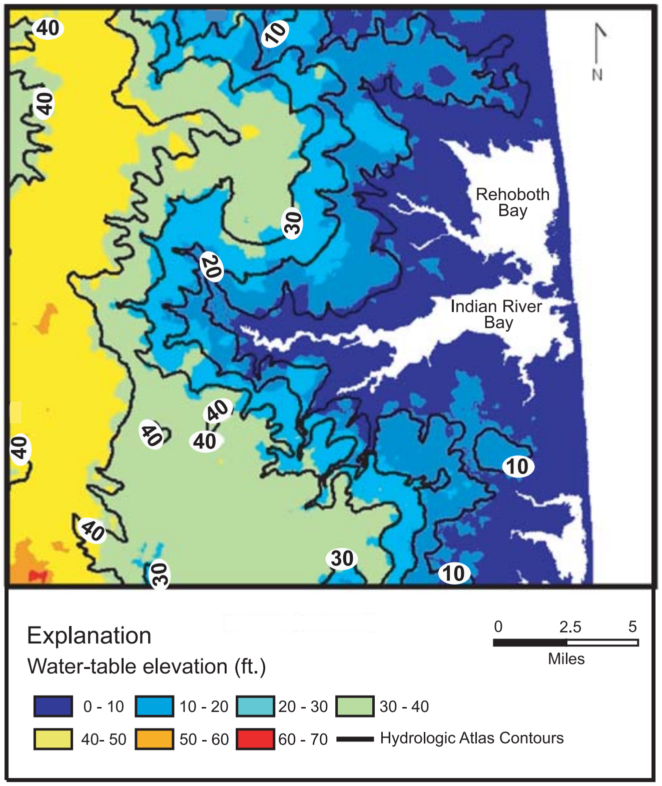


Figure 20. Water-table elevations under wet conditions estimated by ordinary kriging. Water-table contours are from the Hydrologic Atlas Series maps.

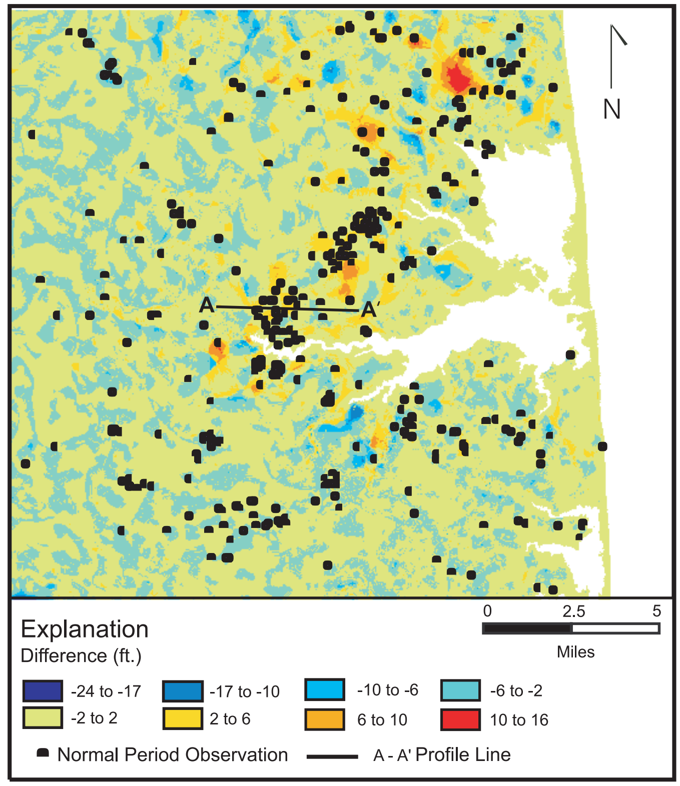


Figure 22. Map of differences between multiple linear regression and ordinary kriging estimated water tables under normal conditions. Profile line A-A′ illustrated in Figure 23.

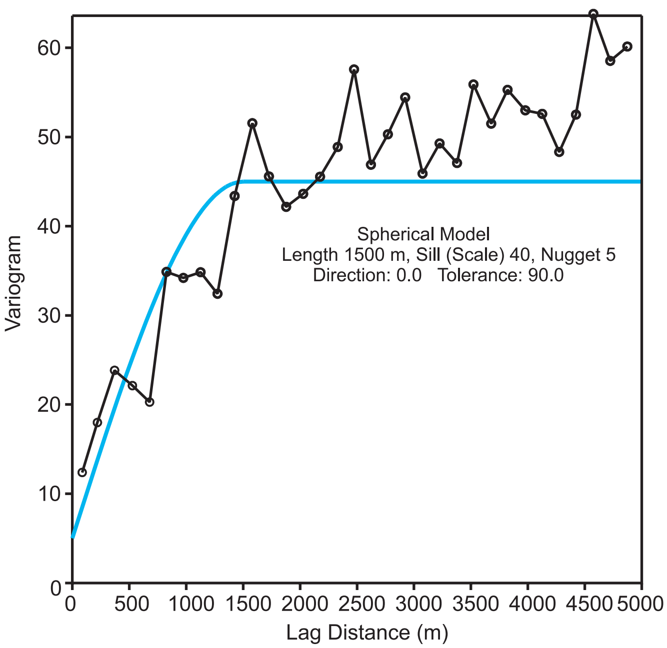


Figure 21. Experimental semi-variogram used for kriging. This semi-variogram is a spherical model (blue line), used in ordinary kriging estimates of the minimum water table and water table.

water-table elevation (WTE), LSE and depth to water (DTW), and between the means of individual hydrogeomorphic regions (HGMR) and soil groups. Linear regressions using LSE to estimate WTE account for between 75 and 80 percent of the variability of the WTE; however, except for the surficial confined HGMR and hydric soil group, HGMR and soil groups yield poorer correlations between LSE and WTE.

Surface-water features such as streams, ponds, marshes, and swamps represent the intersection of the water table with land surface. Elevations of surface water features determined from 30-m digital elevation models (DEMs) are key input for estimation of the water table. Evaluations of elevations determined by this process indicate that the DEM-based elevations of surface-water features do not appropriately portray the incised nature of the area's ditches and streams, and have been systematically reduced by amounts ranging from 1 to 3 ft. DEMs with resolutions of 10 m or higher should better capture the incised nature of ditches and streams, but will require greater storage and processing resources. Further, the DEM-based elevations of some segments of surface water features do not decrease in a downstream direction. This latter issue can be resolved when the National Hydrography Dataset for this area becomes available.

When a second variable is added to the water-table estimation process, the minimum water table (MINWT) (Sepulveda, 2003), the resultant estimates of WTE are more closely correlated with observed water-table elevations than estimates derived only from LSE. The multiple linear regression (MLR) estimates account for more than 90 percent of the variability of the WTE. The MLR estimation process uses MINWT, which is estimated from the elevations of surface water features, and depth to the MINWT as the regression coefficients. Because the MLR model does not require input data to be spatially distributed throughout the estimation region, it is a viable tool to estimate the regional-

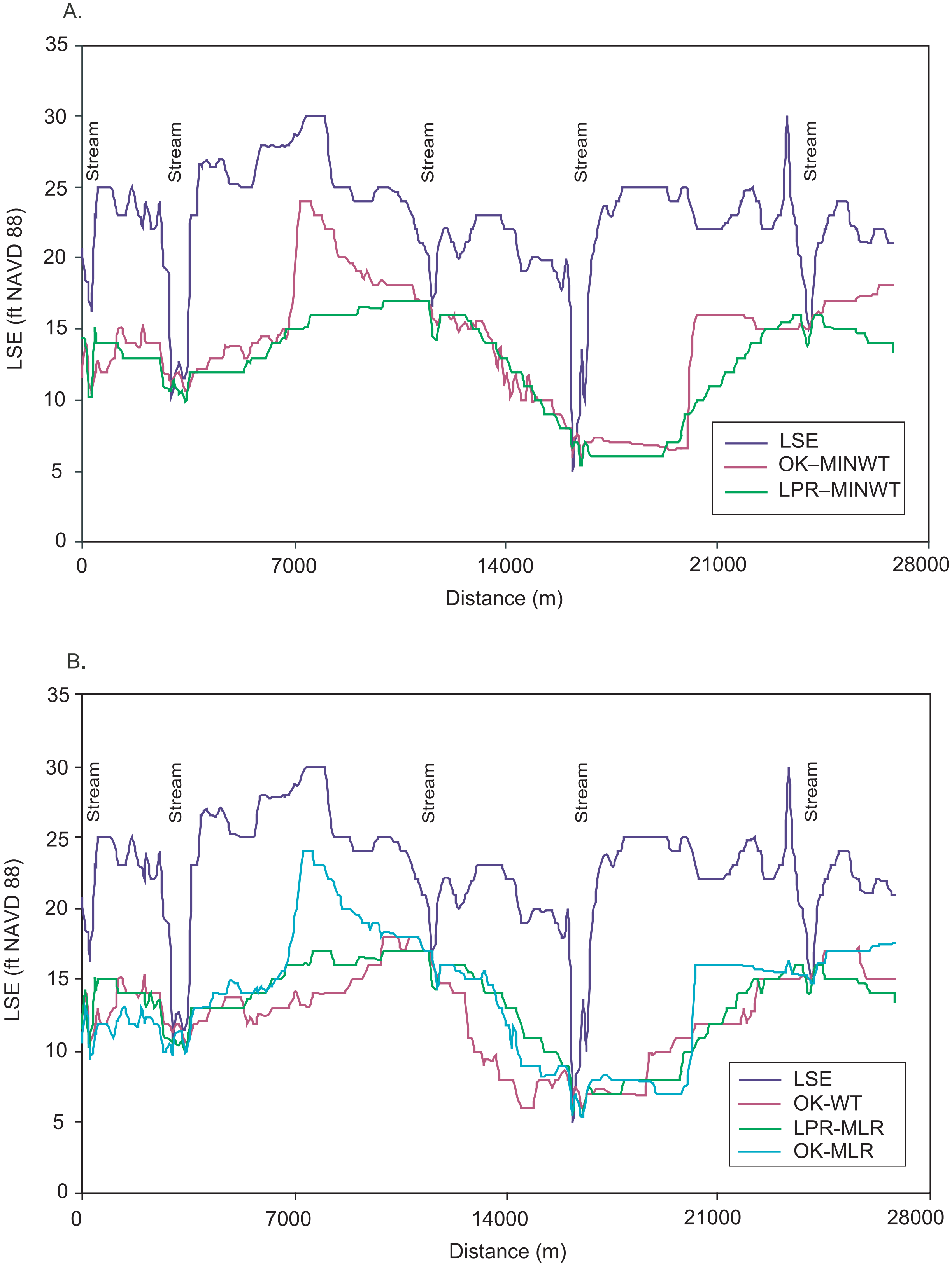


Figure 23. Land-surface elevation (LSE) and water-table elevation (WTE) profiles. Locations of profile line and ground-water level measurements are shown in Fig. 22. A. LSE, minimum water table (MINWT) profiles computed by ordinary kriging (OK-MINWT) and localized polynomial regression (LPR-MINWT) from elevations of surface water features. Sharp breaks in slope of the OK-MINWT profile at distances of approximately 7,000 and 21,000 m indicate locations where OK is not an appropriate algorithm. B. LSE and WTE profiles computed by OK, and combinations of multiple linear regression (MLR) with LPR (LPR-MLR) and OK (OK-MLR). Because there are many ground-water level observations in this area, the sharp breaks in slope seen in Fig. 23A are not present; however, the sharp breaks would remain in the absence of ground-water level data.

Table 6. Differences between multiple linear regression and kriging grids expressed as percentage of land area. Difference values are expressed as feet.

			Difference Values											
			<-10	<-5	<-3	<-1	0	<1	<3	<5	<10	>10	Median	Mean
MLR-OK Grids	Entire Grid	Dry	<1	11	37	61	14	85	95	99	100	<1	-3	-2.3
		Normal	<1	1	5	26	26	76	94	98	100	<1	-1	-0.5
		Wet	<1	<1	2	9	24	45	86	97	100	<1	1	0.8
	Inland Bays	Dry	<1	7	29	54	16	80	93	98	100	<1	-2	-1.7
		Normal	<1	1	5	24	26	72	92	97	100	<1	0	-0.3
		Wet	<1	1	2	9	24	44	83	96	100	<1	1	0.9
LPR-MLR and MLR-Kriging	Entire Grid	Dry	<1	1	3	16	37	70	93	98	100	<1	0	-0.05
		Normal	<1	1	4	18	33	69	95	99	100	<1	0	-0.2
		Wet	<1	1	4	18	33	73	96	99	100	<1	0	-0.3
	Inland Bays	Dry	<1	1	3	16	36	70	93	98	100	<1	0	-0.04
		Normal	<1	1	5	18	32	68	94	98	100	<1	0	-0.2
		Wet	<1	1	5	19	32	72	95	98	100	<1	0	-0.2

scale, water-table elevation for the Coastal Plain of Delaware.

The water table becomes progressively shallower as conditions change from dry to normal to wet. MLR estimated depth to water occurs less than 10 ft below land surface over 63, 79, and 86 percent under dry, normal, and wet conditions, respectively, in the Inland Bays watershed. Land areas with less than 5 ft to water are 19, 30, and 49 percent under dry, normal, and wet conditions, respectively.

Inadequate spatial distribution of water-level data and likely errors with data point locations, water-level measurements, and data management generally makes inverse distance weighted, kriging, and other single-variable estimation methods less desirable for estimating the regional water-table surface. These methods will provide reasonable estimates of the water-table surface if there is an adequate spatial distribution of error free water-level measurements.

Water tables estimated by MLR are qualitatively similar to those of the 1960s vintage Hydrologic Atlas maps. Because the older maps represent the water table as isoelevation lines with a 10-ft contour interval and MLR produces a gridded surface with 30 m horizontal and 1 ft vertical resolution, there are no direct means to quantitatively compare the two types of maps.

Map products generated by this work will be used in support of a number of public environmental programs, private site reviews, and construction projects that need to assess hydrologic conditions. While the map products are an important part of the assessment process, they depict estimates of the water-table configuration. As a result, the map products are not intended to replace on-site data collection efforts.

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