IMPACTS OF LAND USE CHANGES ON RUNOFF GENERATION IN THE EAST BRANCH OF THE BRANDYWINE CREEK WATERSHED USING A GIS-BASED HYDROLOGIC MODEL

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ABSTRACT: *A distributed hydrologic modeling and Geographic Information System (GIS) approach is applied to assess land use change impact, upon surface runoff generation from 1992 to 2000, on the East Branch of the Brandywine Creek Watershed. This watershed is located within Chester County, Pennsylvania, and it covers an area of 316 square kilometers (km^2). This watershed has experienced an increase in its urban areas as well as loss of its forest cover areas. Due to this change in the land use practices, the hydrologic processes of the watershed have been affected by an increase in the amount of surface runoff water generated from precipitation. Runoff estimates were calculated through an application of the Soil and Water Assessment Tool (SWAT). The analysis of the model outputs indicated that subbasins within the study basin, facing urbanization, generate more surface runoff than subbasins with no significant land use changes. The application of the Spearman Rank Correlation Coefficient was used to measure the relationship between forest cover and the amount of surface runoff water generated within the watershed. The analysis concludes that there is a significant and positive rank correlation between these two variables. It can be concluded that as forest cover areas decrease as a result of urbanization, surface runoff generated will increase.*

Keywords*: Hydrology, Geographic Information Systems, Surface runoff, SWAT, Correlation*

INTRODUCTION

One of the recent interests in hydrologic modeling is the assessment of the effects of land use changes on water resources (Lui and De Smedt, 2005). Runoff water and its resulting impacts have become more important and have increased along with local economic development. As a watershed becomes more developed, it also becomes more hydrologically active with changing runoff components, streamflow and flood volume. The influence of land use on storm runoff generation is very complicated. Land use and soil cover have an effect on interception, surface retention, evapotranspiration, and resistance to overland flow (Olivera and Maidment, 1999). For example, urban land yields higher flood volumes, peak discharges and shorter concentration times than forest land. Increased runoff from urban areas results from impervious surfaces that prevent infiltration of water into soils. In contrast, less runoff is produced from undisturbed forest areas. A number of previous studies examine this relationship (Carlson, 2004).

The objective of this research was to evaluate the impacts of changes in land use on the generation of surface runoff for the East Branch of the Brandywine Creek Watershed using a GIS-based hydrologic model. This study identified and quantified land use changes in the watershed over an 8-year period and quantified the impacts of land use changes on surface runoff generation through the use of the SWAT hydrologic model. SWAT divides the watershed into subbasins that represent land use and soil type combinations called Hydrological Response Units (HRUs) (Arnold and Williams, 1995). HRUs are then interrogated on a daily time step basis to evaluate the impacts of different management conditions, in this case, land use trends. Modeling results show that as forest areas decrease, runoff increases. The reduction of watershed forest land is due to the changing trend of watershed land uses towards urbanization. This trend results in changes in the characteristics of the land surface of the watershed involved and therefore implies impacts on the hydrologic environment and hydrologic response of the watershed to precipitation. The significance of the relationship between two sets of values, forest cover and runoff generation was quantified using the

Spearman Rank Correlation Coefficient technique. There is a statistically significant rank correlation between the decrease in forest and increase in surface runoff generated.

STUDY AREA

The East Branch Brandywine Creek Watershed, located in Chester County in southeastern Pennsylvania, covers an area of 316 km^2 and its main stream channel has a length of 46 kilometers (Figure 1). It flows in a northwest – southeast direction with watershed elevations varying from 52 meters to 322 meters, with a relief of 270 meters. Average annual values for precipitation, streamflow, and evapotranspiration are 119, 56, and 66 centimeters, respectively (Sloto and Buxton, 2005). There are 17 municipalities of Chester County that are fully or partially within the watershed area. Heavy rains often create flood conditions in Downingtown and these occurrences on the East Branch of the Brandywine Creek Watershed are well studied (Slutzman and Smith, 2006). Population estimates for the watershed area indicate that the watershed has approximately 76,369 people as of 1998 with a density of 1.2 people per acre (1940 per km^2). In 2020, the projected population will be 103,111, an increase of 30% from the 1998 estimate (CCWRA, 2002).

METHODOLOGY

The tasks of this research included the development of a GIS-based application, normalization and comparison of land use data and use of the SWAT hydrologic model to estimate runoff regimes. In order to study the impact of land use change over time, ArcGIS software was used to assemble and prepare the map layers used by the SWAT model. ArcGIS was also used to quantify land use statistics in 1992 and 2000. SWAT was used to create two model runs based upon the two land use data sets. The Spearman Rank Correlation Coefficient technique was used to determine statistical significance between the two model runs.

Datasets used in this study included; land use, soils, topography, precipitation, streams and other base maps, and were acquired from a variety of sources. Topography, represented by 30 meter resolution Digital Elevation Models (DEMs) was acquired from the United States Geological Survey's (USGS's) National Elevation Dataset. The soils data is a vector map layer obtained from the Pennsylvania Spatial Data Access (PASDA) web site and developed by the U.S. Department of Agriculture (USDA), Natural Resources Conservation Service in 1994. The 1992 land use layer is a 30 meter resolution raster data set generated by the USGS in cooperation with U.S. Environmental Protection Agency (EPA). This data originated from historical U.S. land use and land cover data derived from 1970 and 1980 aerial photography. The 2000 land use data layer is a vector data set, created by the Delaware Valley Regional Planning Commission (DVRPC) in March 2004. This was derived from digital orthophotography from 2000 and digitized at a 1:2,400 scale (1 inch = 200 feet). The stream network is from the National Hydrologic Dataset, acquired from PASDA. It was created by USGS in cooperation with U.S. EPA, USDA Forest Service, and other governmental partners. Precipitation and weather data was provided by the SWAT software interface, which consists of weather information for

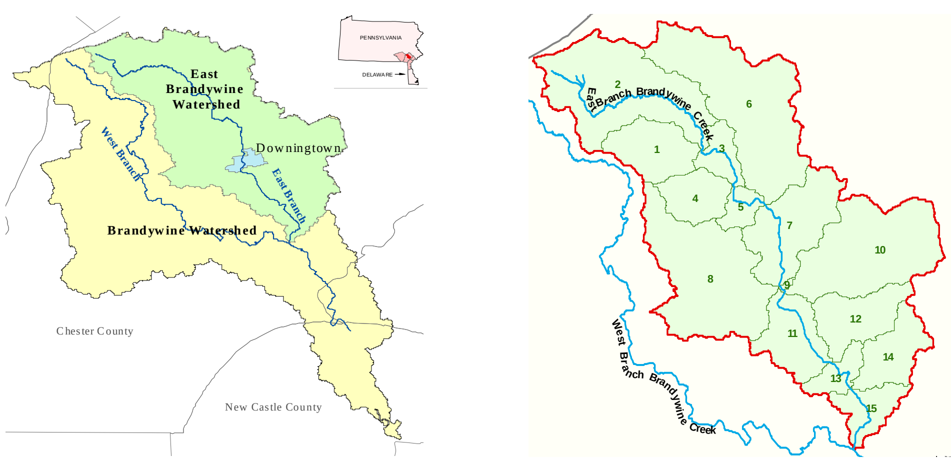

Figure 1. Location of the East Brandywine Watershed and SWAT-Generated Sub-watersheds.

1,041 stations around the U.S. While finer resolution data sets would be preferable, (at least at the resolution of the DVRPC 2000 land use) the 30 meter DEM and USGS land use are the available areal coverage.

SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. SWAT requires specific information about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed. Physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc, are directly modeled by SWAT (Gassman et al., 2007). Some of the benefits of using SWAT include; the ability to model watersheds with no monitoring data, quantification of the relative impact of alternative input data on hydrologic variables, and the use of readily available inputs offered by government agencies for modeling. SWAT is computationally efficient because the simulation of very large basins or a variety of management strategies can be readily performed. It also enables researches to study long-term impacts. The land phase of the hydrologic cycle, in SWAT, is based on the water balance equation. Each subwatershed is subdivided in HRUs in order to further classify watershed conditions. This subdivision of the watershed enables the model to reflect differences in evapotranspiration for various crops and soils. Land use is an important data input into this model process. Differences between the resolution of data sets is addressed by only including land use types that account for 20% or more, of the area in a HRU. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases accuracy and gives a much better physical description of the water balance (Neitsch et al., 2005).

SWAT has become recognized as an effective tool to assess runoff and nonpoint source pollution problems for a range of scales and environmental conditions (Arnold and Fohrer, 2005). Over 250 articles have been published about the use and critique of the SWAT model. The model has been extensively used (42 published articles) for hydrologic assessment studies (Gassman et al., 2007). SWAT has been adopted by the EPA as part of the Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) applications and is being used to support Total Maximum Daily Load (TMDL) analysis (Saleh and Du, 2005; Borah et al., 2006). These studies show that the available DEM, land use and soils data can be used within SWAT to serve as surrogate model inputs when calibration data is not available. This paper reviews an approach to validate a SWAT analysis when a calibration cannot be performed.

In order to support the hypothesis that decreasing forest cover results in increasing runoff generation, a correlation between these variables is required. The Spearman Rank Correlation Coefficient is a nonparametric measure of the relationship between two sets of ordinal (ranked) values. Rank correlation provides a means of calculating the degree of correspondence between any two sets of rankings (Glantz, 2005). This statistical analysis was conducted through an analysis of the percent change in runoff and the percent change in forest cover.

RESULTS

Land use Patterns from 1992-2000 and SWAT-Generated Subbasins

Because the land use classification defined in both land use layers did not use the same classification system, a reclassification of the land use codes was conducted to make comparison of the two layers possible. SWAT uses a specific set of land use types which include Agricultural, Forest, Water, Commercial, Industrial and Residential classes. Reclassification results for the two data sets are presented in Table 1. A comparison of the re-classed land use categories for the two time periods clearly shows a strong reduction in Agricultural and Forest areas (-35%) and a large increase in residential area (290%).

The land use parameters for the watershed are next divided into local areal units. SWAT generates subbasins in the watershed in order to offer a finer area of classification for land use and soil types. SWAT classifies land use for each subbasin through reclassifying land use based upon a 20% minimum threshold. Fifteen subbasins (used to calculate runoff per unit) were delineated within the East Branch Watershed, ranging from 0.4 to 52 km^2. The average subbasin size is 21 km^2. Figure 2 represents the size and order of the subbasins within the East Branch Watershed.

Estimated SWAT Surface Runoff for 1992 and 2000 Land Use

SWAT was used to define the physical characteristics of the area of work such as size,

Table 1. Land Use Distribution within the Watershed Area in 1992 and 2000

Land Use	1992 Area (km^2)	1992 Area (%)	2000 Area (km^2)	2000 Area (%)
Agricultural	127.6	40.35	83.0	26.26
Forest	152.3	48.14	98.9	31.27
Water	3.2	1.02	4.9	1.56
Commercial	7.3	2.31	27.9	8.81
Industrial	1.0	0.31	4.1	1.28
Residential	24.9	7.87	97.4	30.81
	316	**100**	**316**	**100**

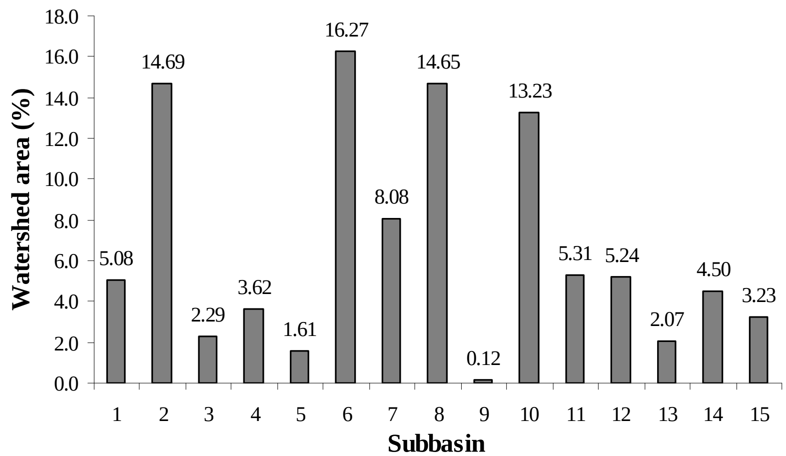

Figure 2. Subbasin distribution within the East Branch Brandywine Creek Watershed area.

boundaries, stream network, and dividing the watershed into subbasins. The delineation of subbasins in SWAT is based on an automatic procedure using DEM data. This tool carries out advanced GIS functions to aid in segmenting the watershed into several hydrologically connected subwatersheds for use in modeling with SWAT. From this, runoff and streamflow volumes were calculated for each subbasin in the watershed over a 12 year simulation. Table 2 documents the runoff volume by subbasin while Figure 3 displays the results graphically. These results from the SWAT model runs support the hypothesis that a decrease in forest cover results in an increase in runoff.

In both model runs, precipitation for each year modeled was kept constant; the average annual and total precipitation was the same for both Land Use 1992 and Land Use 2000. Figure 4 demonstrates that the surface runoff generated in the watershed with Land Use 2000 characteristics is higher than that produced with Land Use 1992.

Surface runoff generated in the watershed under characteristics of land use 2000, in general, is equivalent to 32.94% of rainfall water, while surface runoff under characteristics of land use 1992 is equivalent to 20.8%. This implies a surface runoff increase of 12.15%.

Influence of Forest Cover upon Surface Water Generation

Using the statistical technique of the Spearman Rank Correlation Coefficient, it was possible to measure the relationship between the reduction on forest areas and the increase in surface runoff. In order to rank the two variables, it was necessary to determine the change of the forest cover areas and the change of the surface runoff generated during the 8-year period analyzed. Table 3 presents

Table 2. Surface Runoff Volume Generated (m^3/s) for Land Use in 1992 and 2000

Subbasin	Area (km^2)	Land Use 1992	Land Use 2000
		Surface runoff (m^3/s)	Surface runoff (m^3/s)
1	16.1	0.085	0.080
2	46.5	0.267	0.273
3	7.3	0.031	0.030
4	11.4	0.073	0.150
5	5.1	0.023	0.054
6	51.4	0.270	0.443
7	25.6	0.127	0.272
8	46.3	0.257	0.459
9	0.4	0.007	0.007
10	41.8	0.327	0.551
11	16.1	0.067	0.129
12	46.5	0.067	0.175
13	6.5	0.033	0.039
14	14.2	0.089	0.193
15	10.2	0.075	0.119

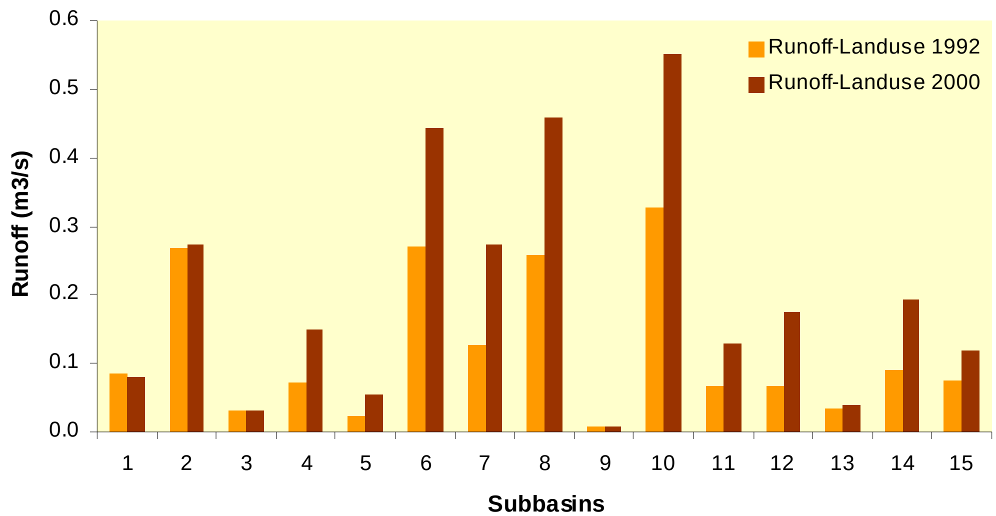

Figure 3. Surface runoff volume generated (m^3/s) for land use in 1992 and in 2000.

the change of forest cover area from 1992 to 2000, where *x* is the area change during this period, and the change of surface runoff generated from 1992 to 2000, where *y* is the surface runoff change during this period.

The variable, *x* was ranked from largest decrease in forest areas to smallest, and y was ranked from largest increase in surface runoff to smallest. Table 4 portrays the ranked values for each subbasin (r_x and r_y) and the differences between these values.

The Rank Correlation Coefficient between forest cover and surface runoff is 0.686, with 15 degrees of freedom (the number of pairs of rankings). Assuming a significance level of 0.05, the critical

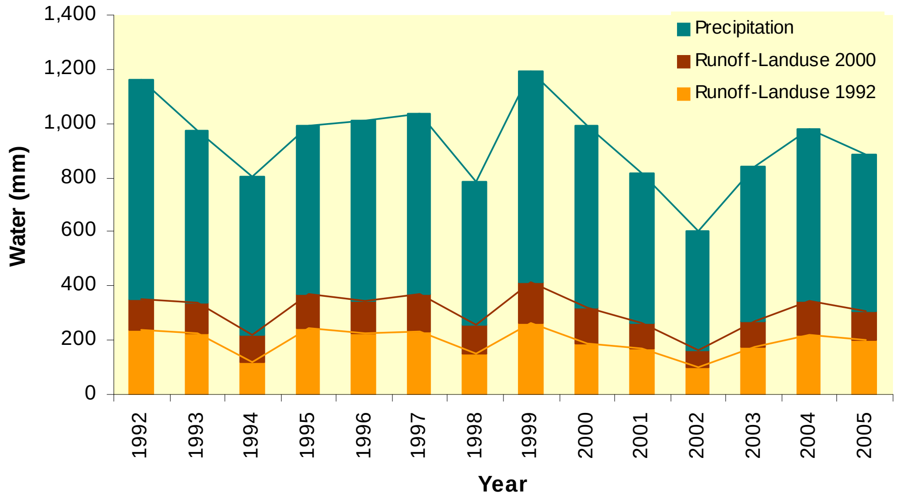

Figure 4. Surface runoff generated by year in the watershed, 1992 – 2005.

Table 3. Forest Cover Area Change and Surface Runoff Generated Change from 1992 to 2000

Subbasin	Forest Cover Area (km²)			Surface Runoff (mm H_2O)		
	1992	2000	*x* 2000-1992	1992	2000	*y* 2000-1992
1	8.4	9.2	0.28	166.82	158.07	-8.75
2	20.2	19.3	-0.33	181.36	184.96	3.60
3	4.8	5.0	0.07	136.93	131.49	-5.44
4	3.8	0.0	-1.48	201.38	414.72	213.34
5	3.3	2.3	-0.39	141.25	332.54	191.29
6	26.5	19.6	-2.66	165.32	271.38	106.06
7	15.2	11.3	-1.52	156.57	335.43	178.85
8	22.7	14.8	-3.04	174.85	312.38	137.54
9	0.0	0.0	0.00	531.23	531.24	0.00
10	19.9	11.0	-3.46	246.82	415.16	168.34
11	12.1	10.6	-0.58	125.67	242.52	116.85
12	11.8	7.3	-1.72	128.27	332.59	204.32
13	3.6	2.8	-0.32	160.34	190.28	29.94
14	9.2	4.4	-1.85	198.27	426.80	228.54
15	5.5	2.7	-1.08	231.96	368.26	136.31

value of r_s for a one-tailed test is 0.441. For this correlation, the alternative hypothesis is likely to be directional: that there is a positive correlation between the two variables. The calculated value of r_s is positive and greater than the critical value for a one-tailed test:

$$(H_1 : \rho_s > 0)$$

at the chosen significance level of 0.05 (Ebdon, 1977). The null hypothesis:

$$(H_0 : \rho_s = 0)$$

can therefore be rejected and the conclusion is that there is a significant rank correlation between the reduction of forest area and the increment of surface runoff in the East Branch of the Brandywine Creek Watershed at the 0.05 level. Considering that land

Table 4. Spearman Rank Correlation Coefficient Calculation

Subbasin	Forest	Surface Runoff	Ranked Values		Rank Differences	
	x	y	r_x	r_y	d	d^2
1	0.28	-8.75	15	15	0	0
2	-0.33	3.60	11	12	1	1
3	0.07	-5.44	14	14	0	0
4	-1.48	213.34	7	2	-5	25
5	-0.39	191.29	10	4	-6	36
6	-2.66	106.06	3	10	7	49
7	-1.52	178.85	6	5	-1	1
8	-3.04	137.54	2	7	5	25
9	0.00	0.00	13	13	0	0
10	-3.46	168.34	1	6	5	25
11	-0.58	116.85	9	9	0	0
12	-1.72	204.32	5	3	-2	4
13	-0.32	29.94	12	11	-1	1
14	-1.85	228.54	4	1	-3	9
15	-1.08	136.31	8	8	0	0
	$\sum d^2 =$	176			$n =$	15

use was the only independent variable in the simulation of the hydrological model, it is evident that these runoff increments are, due, at least in part, to the shift of land use. This tendency to decrease the forest cover is an important factor incrementing the vulnerability of the watershed to response to weather changes through time, especially responding to the effects of rainfall water.

CONCLUSION

The East Branch of the Brandywine Creek Watershed has undergone an urbanization process during the 8-year period observed in this study. Eleven of its fifteen model-generated subbasins have experienced significant increases in urban areas. Watershed land uses changed from forest (52.81%) and agricultural (43.89%) uses to mainly residential (33.36%) which increased about 300% over the study time period. This urbanization tendency in the watershed entails significant increases in the production of surface runoff. This has risen about 12.15%, from a surface runoff equivalent to 20.8% of rainfall-water under Land Use 1992 characteristics to a surface runoff equivalent to 32.94% of-rainfall water under Land Use 2000 characteristics. The result of the watershed land uses changes on the generation of surface runoff was tested through the application of the Spearman Rank Correlation Coefficient. The relationship between the forest cover areas and the surface runoff generated in the watershed resulted in a significant and positive rank correlation between these two variables. Thus, as forest cover areas decrease, surface runoff will increase.

REFERENCES

Arnold, J.G. and Fohrer, N. 2005. SWAT2000: Current Capabilities and Research Opportunities in Applied Watershed Modeling. *Hydrologic Processes* 19(3):563-572.

Arnold, J.G. and Williams, J. 1995. SWRRB - A Watershed Scale Model for Soil and Water Resources Management. In: *Computer Models of Watershed Hydrology*, ed. Water Resources Publications. 847-908pp.

Borah, D.K., Yagow, G., Saleh, A., Barnes, P.L., Rosenthal, W., Krug, E.C., and Hauck, L.M. 2006. Sediment and Nutrient Modeling for TMDL Development and Implementation. *Transactions of the ASABE* 49(4):967-986.

Carlson, T. 2004, August. Analysis and Prediction of Surface Runoff in an Urbanizing Watershed Using Satellite Imagery. *Journal of the American Water Resources Association (JAWRA)* 1087-1097pp.

CCWRA (Chester County Water Resources Authority). 2002, December. *Brandywine Creek, Watershed Action Plan*, ed. Chester, PA.

Ebdon, D. 1985. *Statistics in Geography*, ed. Blackwell Publishers

Gassman, P.W., Reyes, M.R., Green, C.H., and Arnold, J.G. 2007. The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions. Invited Review Series. *Transactions of the ASABE* 50(4):1211-1250

Glantz, S. 2005. *Primer of Biostatistics*, ed. McGraw Hill.

Liu, Y., and De Smedt, F. 2005, January. Assessing Land Use Impacts on Flood Processes in Complex Terrain by Using GIS and Modeling Approach. *Journal of Environmental Modeling and Assessment* 9(4):227-235.

Neitsch, S., Arnold, J., Kiniry, J., and Williams, J. 2005. *Soil and Water Assessment Tool (SWAT) Theoretical Documentation Version 2005*, ed. Agricultural Research Service and Texas A&M University.

Olivera, F. and Maidment, D. 1999. Geographic Information Systems (GIS)-Based Spatially Distributed Model for Runoff Routing. *Water Resources Research* 35(4):1155-1164.

Saleh, A. and Du, B. 2004. Evaluation of SWAT and HSPF within BASINS Program for the Upper North Bosque River Watershed in Central Texas. *Transactions of the ASAE* 47(4):1039-1049.

Sloto, R. and Buxton, D.E. 2005. *Water Budgets for Selected Watersheds in the Delaware River Basin, Eastern Pennsylvania and Western New Jersey.* Scientific Investigations Report 2005-5113, U.S. Geological Survey. Reston, Virginia: 2005.

Slutzman, J. and Smith, J. 2006, September/October. Effects of Flood Control Structures on Flood Response for Hurricane Floyd in the Brandywine Creek Watershed, Pennsylvania. *Journal of Hydrologic Engineering*, 11(5):432-441.