Hydrologic Response from a Developed Piedmont Watershed

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Abstract

Stormwater runoff has the ability to erode Earth's surface, causing channels to form along its path from impervious areas to streams, rivers, etc. Large channels, known as gullies, can be examined to determine the extent of the effects of stormwater. This type of investigation can provide insight into the implementation of appropriate stormwater management practices. Therefore, the objectives of this analysis are to (1) quantify total suspended solids loads received over time and (2) determine temporal probable peak flow for gullies located in a Piedmont watershed. These aims were addressed by first delineating three sub-watersheds boundaries and land uses in a Piedmont region of Newark, Delaware where erosion due to stormwater runoff has caused the formation of gullies. Next, this land use data, along with additional known and calculated parameters, was subjected to models used to predict the temporal pollutant load and flow data experienced within the gullies. Through the investigation in the accompanying paper, it was determined that (1) increases in predicted loading and flow are resultant of increases in the appearance of specific high nutrient- and/or high metal-containing land cover and (2) as functions of land use, graphical results depicting pollutant load and flow over time were found to exhibit the same shape.

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1. Introduction

During the urbanization of land over time, changes in watershed flow patterns occur. These changes include the degradation of stream banks as well as the formation of channels called gullies. Increases in impervious cover and decreases in sediment resultant of urbanization contribute to these adjustments (Bledsoe 2002). Though the implementation of streets, parking lots, and buildings as well as the reduction of forests and open spaces can contribute to flow pattern changes, water flow and channel generation and formation changes are not spontaneous. Water flowing through these developing areas must be present to cause these hydrologic adjustments. The primary sources for such water flows are storm events. Storms in the mid-Atlantic, Piedmont region of the United States produce approximately two inches of rainfall in a 24 hours period which results in the transport of over 600 gallons of rainwater to creeks, streams, and rivers through drainage systems and impervious runoff (Suffian). Because surface waters dynamically adjust to water flow, at such high volumes, nonpoint pollutant sources like these have the ability contribute to the aforementioned stream bank erosion and gully formation in watersheds (Tsihrintzis and Hamid 1997).

The formation of gullies, as well as the flow of stormwater through them, causes large amounts of sediment to be introduced into surrounding surface waters. As stormwater travels through eroded channels which characterize gullies, sediment is kicked up by and accumulated in the runoff. The sediment that exists within urbanized areas is often contaminated by nutrients and metals and thus pollutes the stream as it enters with the runoff (Water: Sediments).

In order to decrease both the erosion and pollution due to stormwater runoff, stormwater management practices and plans are implemented. However, "past sub-watershed alterations must be understood in order to set realistic expectations for future restoration" (Schueler 2007). Therefore, in order to design an appropriate method for stormwater management, it is important to first analyze the watershed hydrology response throughout the duration of the development of the area. The objectives of this analysis are to investigate the hydrologic response of a developed Piedmont watershed by (1) quantifying the total suspended solids loads received over time and (2) determining the temporal probable peak flow for three gullies located in the Christiana River watershed.

2. Research Methods

2.1 Site Description

The following analysis was conducted on three sub-watersheds delineated about the channels formed erosion due to stormwater runoff. Each of the gullies which provided sub-watershed boundaries are shown in Figure 1 and are located in the Christina River Watershed, a developed watershed in the Piedmont region of Newark, Delaware.

Figure 1. Photographs of gullies investigated throughout this report.

2.2 Sub-Watershed and Land Use Delineation

The sub-watersheds associated with each gully for the years 1937, 1954, 1961, 1968, and 1992 were delineated using ArcGIS and its ArcHydro component. Because the necessary GIS data layers (i.e. elevation and stream) for the years 1937, 1954, 1961, and 1968 do not exist, each sub-watershed for these years was delineated separately using elevation and stream data layers for the year 1992. In order to re-delineate the sub-watersheds after the installation of the sewer system in between 1970 and 1990, a storm sewer layer from 1992 was inputted in to the ArcHydro model in addition to elevation and stream data layers. Using this data and the outfall location of each eroded channel into White Clay Creek as the point of interest for each sub-watershed, the ArcHydro component of ArcGIS generated sub-watershed boundary layers.

These sub-watershed perimeter layers provided the boundary to which the land use classification for the years 1937, 1954, 1961, 1968, and 1992 was applied. Aerial photographs from each of the aforementioned years were downloaded from the Delaware DataMIL, an online source for GIS data layers for the state of Delaware. Land use delineation was completed by analyzing the aerial photographs for visual signs indicating types of land cover. Shapefiles characterizing these land covers (i.e. forest, agriculture, open space, parking lots, industrial, and roof) were generated for each sub-watershed and year. The geometry tool available in ArcGIS was used to calculate the area corresponding to each land cover layer. Lastly, the distance tool and topographic map for 1992 were employed to calculate the lengths and slopes for sheet, shallow concentration, and channel flow associated with each gully.

2.3 Modeling Temporal Total Suspended Solids Pollutant Load

Total Suspended Solids (TSS) pollutant load estimates were generated for the aforementioned years in addition to a pre-1492 (i.e. all forested) condition. As presented later in this report, these resultant loads were obtained by using the Simplified Method of determining pollutant loads as proposed by Tom Schueler in his *Urban Stormwater Retrofit Manual*. The TSS load for each gully and year was estimated by combining annual precipitation data (41 inches in Northern Delaware) and the corresponding land use characterizations and areas in Schueler's model.

2.4 Modeling Temporal Flow

TR-55, a small watershed hydrologic modeling system, was utilized in the analysis of the temporal flow experienced by each gully. As in the modeling of the TSS pollutant loads, flows associated with each gully were estimated for pre-1492 conditions, 1937, 1954, 1961, 1968, and 1992. Within TR-55, land use characterization and land use area data are combined with time of concentration data to produce predicted flows. TR-55 calculates time of concentration data internally but requires the input of sheet, shallow concentration, and channel flow lengths and slopes.

3. Results and Discussion

3.1 Sub-Watershed and Land Use Delineation

The following figure illustrates the results of the sub-watershed delineation described in the Methods section above. Sub-watershed delineations for the years 1937, 1954, 1961, and 1992 are shown. Delineations for the year 1968 were omitted because they are identical to that of 1961.

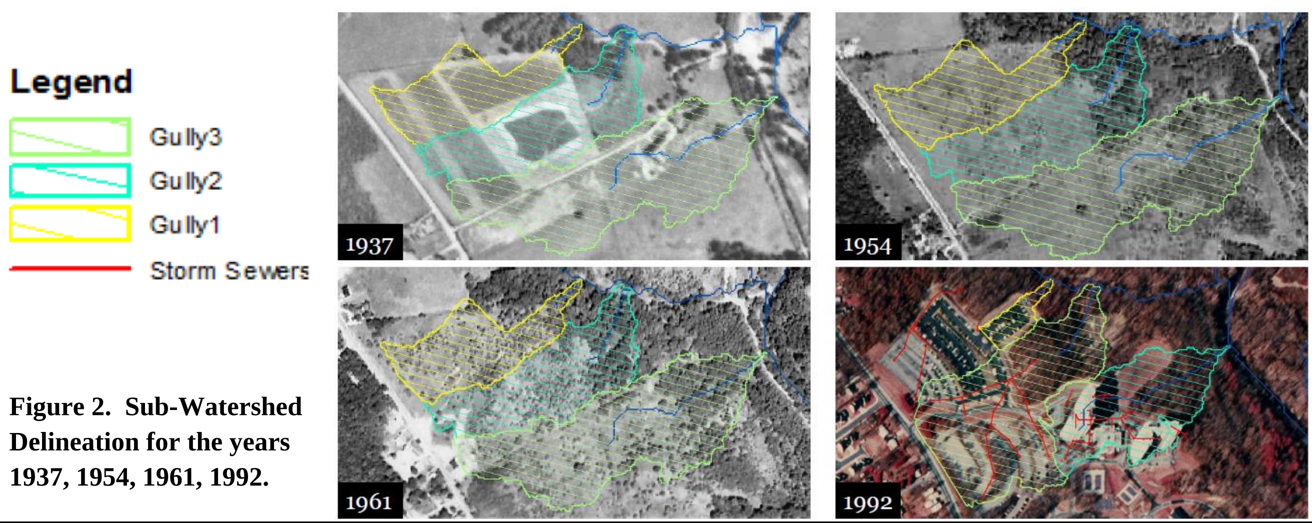

Figure 2. Sub-Watershed Delineation for the years 1937, 1954, 1961, 1992.

Tabulated below are the results of the mathematical analysis performed in ArcGIS to provide the data necessary for modeling temporal TSS loading and flow.

Table 1. Land use type and area by year and gully.

Year	Gully I.D.	Land Use Area (Acres)						
		Forest	Agriculture	Open Space	Industrial	Parking Lots	Roofs	Total
1937	Gully 1	0.2058	5.0575	0.0000	0.0000	0.0000	0.0000	5.2633
	Gully 2	0.8231	6.5307	0.0000	0.0000	0.0000	0.0000	7.3538
	Gully 3	0.0000	11.7167	0.3783	0.0000	0.0000	0.1475	12.2426
1954	Gully 1	5.2633	0.0000	0.0000	0.0000	0.0000	0.0000	5.2633
	Gully 2	2.3208	5.0330	0.0000	0.0000	0.0000	0.0000	7.3538
	Gully 3	0.0000	4.7457	0.6276	0.0000	0.0000	6.8693	12.2426
1961	Gully 1	1.9079	0.0000	3.3554	0.0000	0.0000	0.0000	5.2633
	Gully 2	2.8943	0.0000	4.4595	0.0000	0.0000	0.0000	7.3538
	Gully 3	4.0493	0.0000	8.1933	0.0000	0.0000	0.0000	12.2426
1968	Gully 1	1.9079	0.0000	3.3554	0.0000	0.0000	0.0000	5.2633
	Gully 2	2.8943	0.0000	4.4595	0.0000	0.0000	0.0000	7.3538
	Gully 3	4.0493	0.0000	8.1933	0.0000	0.0000	0.0000	12.2426
1992	Gully 1	0.3259	0.0000	0.0833	0.0000	0.6766	0.0000	1.0858
	Gully 2	4.3930	0.0000	2.3300	0.6548	5.6903	0.0000	13.0682
	Gully 3	3.1643	0.0000	3.1643	0.0000	1.1841	0.7946	8.3073

Table 2. Length and slope data for each gully.

Gully I.D.	Length (ft)			Slope (ft/ft)		
	Shallow Concentrated	Sheet	Channel	Shallow Concentrated	Sheet	Channel
Gully 1	49.2150	100.0000	65.6200	0.0667	0.0000	0.0500
Gully 2	246.0750	835.0850	229.6700	0.0533	0.0589	0.0571
Gully 3	194.2352	475.7450	544.3179	0.2534	0.0690	0.1206

3.2 Temporal Total Suspended Solids Pollutant Loads

The results predicted by the Schueler's Simplified Method for determining the TSS load experienced by the gullies over time are presented in Figure 3 on the following page. Each graph represents the expected TSS loading rates normalized by area in acres for each gully studied.

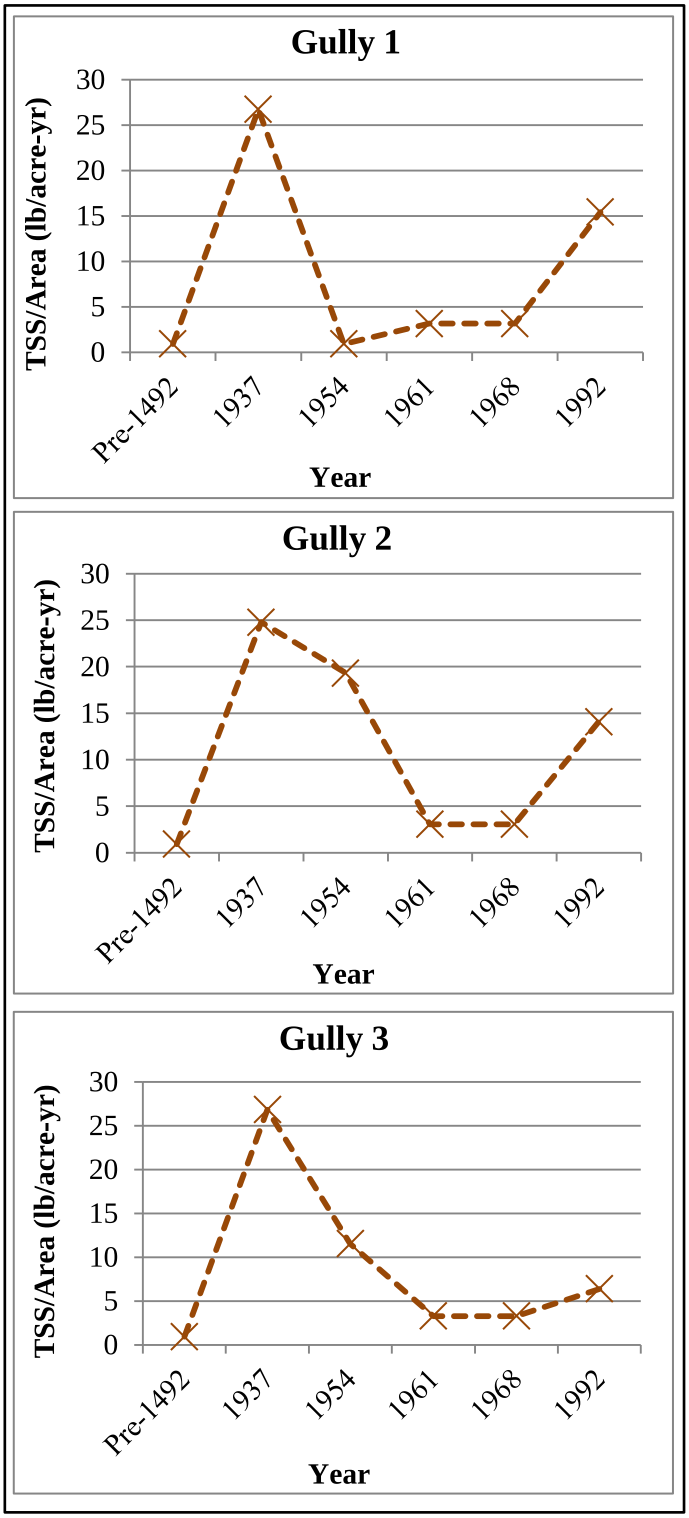

Figure 3. Temporal total solids loading rates experienced by each gully.

As seen in Figure 3 to the left, the TSS loading rates that each of the gullies experienced throughout the duration of the colonization and eventual urbanization that occurred within the watersheds are similar. The shape of each graph, and thus, the pattern of TSS loading over time are common to each of the three graphs in Figure 3. The peak in TSS loading that appears on each graph in the year 1937 correlates to the rise in the farming society and increase in agricultural lands in each of the sub-watersheds.

The rising TSS loading levels predicted for each gully in 1992 illustrate the effects of urbanization on a Piedmont watershed. The increase expected for this pollutant within each gully can be attributed to the erection of several University of Delaware housing facilities and placement of parking lots in the area between 1970 and 1990. The region that was characterized by low nutrient- and metal-containing land cover such as open space and forested land in the years 1954, 1961, and 1968 was developed in later years to be classified primarily as parking lot and roof land covers. Inherent in the Simplified Method is the high concentrations of metals in land uses such as parking lots and roofs.

3.3 Temporal Flow

The results predicted by the TR-55 hydrologic modeling system for determining the peak flow values experienced by the gullies over time are presented in Figure 4 and analyzed on the following page. Each graph represents the expected peak flow values normalized by area in acres for each gully studied.

The graphical analysis of the temporal peak flow values for each of the three gullies shown in the figure to the right exhibits patterns similar to those observed in the presentation of the TSS loading rates on analyzed on the previous page. Like the graphs depicting the TSS pollutant load, the peak flow values for the 2-, 10-, and 100-year storm flow experience a spike in the year 1937.

Also like the predicted TSS loading rate data, the curves on each graph begins to increase again in 1992. Because, like TSS loading rates, peak flow values are a function of land use and increase with increases in impervious surfaces (i.e., parking lots, roofs), the observed rise in peak flow in 1992 is expected. Unlike the graphical analysis of the TSS loading rates, however, the spike in peak flow values in 1992 are greater than those in 1937 with respect to all three storm flows and all three gullies.

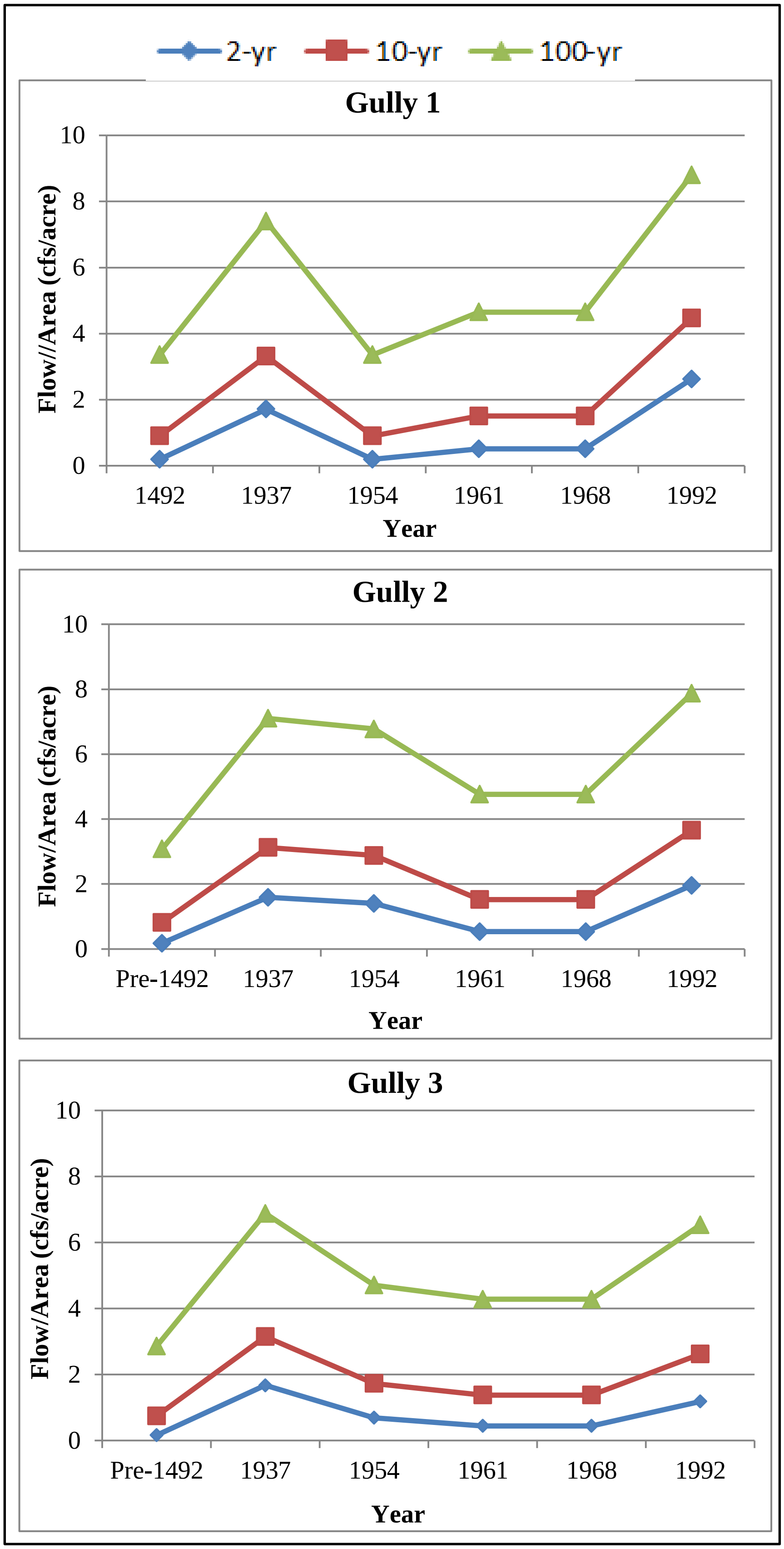

Figure 4. Temporal peak flow values experienced by each gully.

4. Conclusions

After conducting the methods and analyzing the resulting model data as described and presented above, several conclusions about the hydrologic response of a Piedmont watershed can be asserted. First, the comparatively high values for both TSS pollutant loads and peak flow values expected to have been experienced by each sub-watershed in the year 1973 suggest that the formation of each gully began during the time period in which agriculture dominated society and has continued since. Secondly, the correlation between the two sets of graphs in Figures 3 and 4 imply that both TSS pollutant loading rates and are functions of primarily land use. Land uses such as parking lots and roofs, which according to Schueler's Simplified Method contribute more metal contaminants and according to the TR-55 Hydrologic Model increase impervious surfaces, have the greatest effect on both TSS pollutant loads and peak flow values. As exemplified and mentioned in the comparison of Figures 3 and 4 in Section 3.3 of this paper, however, it can be concluded that predicted flow values are impacted by urbanization to a greater extent than TSS pollutant loads. The results and conclusions reaches through this investigation will provide insight into the implementation of appropriate stormwater management practices in the future.

Acknowledgements

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References

Bledsoe, B., 2002. Stream Erosion Potential and Stormwater Management Strategies. Journal of Water Resources Planning and Management (128): 451-455.

Schueler, T., D. Hirschman, M. Novotney, and J. Zielinski, 2007. Urban Stormwater Retrofit Practices. Center for Watershed Protection.

Suffian, F. Storm Water Runoff. U.S. EPA.

Tsihrintzia, V. and R. Hamid, 1997. Modeling and Management of Urban Stormwater Runoff Quality: A Review. Water Resources Management (11): 137-164.

Water: Sediments, 2012. U.S. EPA.