Quantification of Urbanization in Experimental Watersheds

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Abstract

Although urbanization has a major impact on watershed hydrology, there have not been many studies to quantify how basic hydrological relationships are altered by the addition of impervious surface under controlled conditions. The USDA-ARS and U.S. EPA have jointly initiated a pilot program to study the impacts of simulated impervious surfaces on hydrology, sediment, and water quality in small experimental watersheds located at the North Appalachian Experimental Watershed, Coshocton, OH. This paper outlines the approach and rationale for using rainfall simulation, experimental watersheds subjected to natural precipitation and weather, and modeling for a multiyear project. Percent imperviousness is planned from 0% to 40% under two spatial arrangements of imperviousness - stream-channel-connected and stream-channel-disconnected imperviousness. The results from laboratory rainfall simulation will help guide the implementation of impervious surfaces in the watersheds. Preliminary evaluation of the Coshocton baseline runoff data shows that, during the time of constant land-use since 1975, annual runoff depths are similar and runoff regimes have been constant. Results from this study are applicable to the development of urban hydrology analyses, hydrology and water-quality models, design and testing of urban best-management practices, and environmental management.

Keywords: curve number, water quality, erosion, urban runoff, imperviousness

Introduction

Agricultural land is increasingly becoming urbanized due to residential and industrial development. These developments replace relatively pervious soils with impervious roofs, roads, streets, parking lots, driveways, etc. Rain falling on these impervious areas no longer infiltrates into the soil for later slow release to stream channels, but runs off quickly to adjacent pervious areas or to gutters and sewers, and eventually to stream channels. Furthermore, pesticide and nutrient use increase for lawns and landscaped areas, erosion increases, and other constituents are added to the developed watershed from deicers, leaked chemicals from vehicles on roads, etc., that under undisturbed conditions, would not be available for transport to the stream. The net effect of increasing imperviousness is to increase runoff volumes and peak-flow rates in stream channels, the

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frequency of downstream flooding, the likelihood of property damage and larger concentrations of sediment and chemical constituents, and generally to degrade aquatic ecosystems.

The U.S. EPA is interested in developing policy tools for watershed management that use market mechanisms and incentives to reduce ecological impacts and improve water quality in a cost effective manner. An example of such a mechanism is the trading of runoff-control responsibility within a watershed between those for whom it is expensive to abate with those for whom it is relatively cheap. To be ecologically effective, quantification of impervious-surface-caused runoff and efficacy of control efforts is crucial.

Many studies have been conducted using *available* stream-gauge and other data to quantify the effects of urbanization factors on runoff, sediment, water quality, and aquatic ecosystems (Schueler and Holland 2000, Shuster et al. 2003). However, results are only applicable to the generalized uncontrolled watershed conditions during the time of data collection. Research is lacking that isolates factors important to understand runoff generation and chemical transport under urbanized conditions. Investigations are needed to understand and quantify how runoff-forming and chemical-transport processes change during urbanization under controlled conditions. This will allow isolation of important factors to improve runoff and water-quality estimating procedures, provide results for science-based watershed management decisions, and to test innovative best-management practices (BMPs) that mitigate the hydrologic impacts of urbanization.

To address this issue, the U.S. EPA and the USDA-ARS jointly initiated a pilot project to investigate urbanization by utilizing experimental watersheds at the North Appalachian Experimental Watershed (NAEW) near Coshocton, Ohio. The purpose of this paper is to describe the approach being pursued and the rationale, and to present some preliminary background data on the hydrology of the experimental watersheds.

Project Objectives and Approach

Objectives for the urbanization project

The overall objective for the urbanization project is to explore and quantify the effects of land disturbances by urban development on watershed hydrology and water quality using a combination of rainfall simulation and experimental watersheds. Specific objectives are:

1. to conduct rainfall simulation experiments to evaluate general differences between connected and unconnected runoff paths to a stream channel;
2. to develop an understanding of changes in runoff-formation processes under controlled watershed conditions due to land alteration caused by urban development (i.e., increasing imperviousness);
3. to improve hydrologic modeling of urbanizing watersheds; and
4. to develop innovative urban best-management practices (BMPs) for controlling water and chemicals.

Approach

The approach to be used is empirical, exploratory, and statistical. Use of existing experimental watersheds having historical data is planned. This is because baseline data have been collected; except for additional parameters of interest for which there are no data. This also reduces the time to begin installation of imperviousness. Computer modeling will be used to extrapolate data beyond the experimental watersheds. Four experimental watersheds were selected as test beds to evaluate different levels of imperviousness over time.

Watersheds and Data

Description of watersheds

The four small experimental Coshocton watersheds chosen for study (Figure 1) are WS106, WS121, WS185, and WS192, and are located on a hilltop. Watershed areas for each are 0.63 ha for WS106, 0.57 ha for WS121, 2.99 ha for WS185, and 3.07 ha for WS192. Soils are primarily Rayne silt loams and Berks shaly silt loam. Slopes are typically of the order of 18-25%.

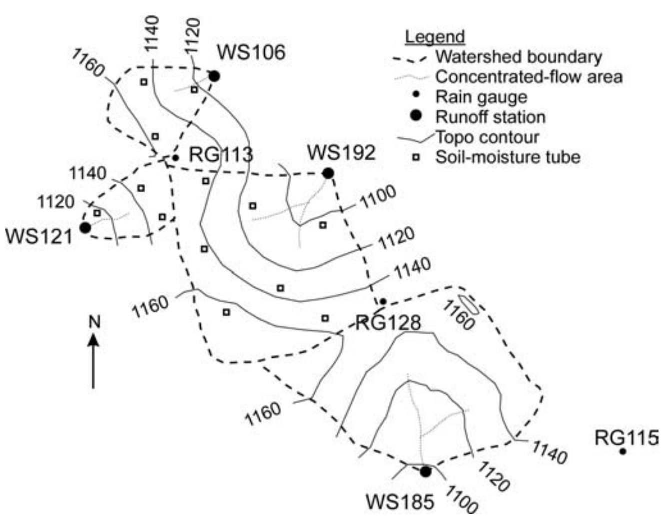

Figure 1. Experimental watersheds, soil-moisture tubes, and rain gauges at Coshocton, OH for the urbanization project.

Data available

Runoff records begin about 1940 at all sites; however, the record ended in 1972 at WS185, and in 1994 at WS192. Records for WS106 and WS121 continue to the present. Records prior to about 1975 were collected under a rotational cropping system and constant land-use records begin about 1975. Runoff data (breakpoint) were collected with H flumes.

Water quality data are available since about 1974 at the three sites with the longest records. Constituents measured include TOC, NO_3-N, NH_4-N, organic N, PO_4-P, K, SO_4, Ca, Mg, Na, Cl, Br, pH and sediment for varying record durations. Samples were obtained on a runoff-event basis by using a Coshocton wheel water sampler, which automatically samples the flow during runoff events.

Recording rain gauge RG113 is located the western part of the hilltop, and RG115 is located to the east (Figure 1). The rainfall record (breakpoint) begins in 1940 and continues to the present. Rain gauge 128 has a record from about 1942 to 1970. A 60+ year record of weather elements is also available at Coshocton.

The soil-moisture record began about 1975 at the three watersheds with long runoff records (Figure 1). Three sites in WS106 and WS121were measured through 1978, after which only one site was measured. Seven sites were measured in WS192 through 1978 and only at one site after this time. Frequency of measurement was every two weeks and then decreased to monthly measurements in the 1990s. Soil moisture was measured with a neutron probe in depth increments of 6 in to a depth of about 1 m, and gravimetrically in the top 7-9 in.

Detailed soil and topographic maps are available, and a first order soil survey is being conducted as well. Some soil physical characterization data are also available.

Land-use at the three sites with the longest records since 1975 was mostly hay meadow and pasture. The land-use since 1975 at WS185 has been no-till corn through 1986, and hay meadow since then. The period of record of most interest for the present study is from about 1975 to the present. This is because the land-use has been relatively constant and water quality data began at about this same time.

Methods

The project calls for installation of increasing percentages (0% to 40%) of imperviousness on the experimental watersheds over time. However, challenges arise regarding the actual size, shape, materials, distribution of impervious elements on the watersheds, and representativeness of the impervious elements in terms of simulating of actual urban conditions, as well as the nature of land disturbance surrounding each impervious element. Initially, the urban condition to be approximated will be a residential neighborhood, without streets, and no house gutters. Because results from watershed studies depend upon the weather and the urbanization project will take at least five years to complete, rainfall simulation will be used to help guide the size and spacing of impervious elements to be placed on the watersheds.

Rainfall simulation

Warnemuende et al. (2003) describe the rainfall-simulator component of this research and present some initial results. The role of the simulator in the overall project is discussed below.

There are two primary spatial configurations that have been found to be important in urban watersheds - "connected" and "unconnected" impervious elements (Figure 2), also cited in the literature as "effective" and "ineffective" imperviousness. At the extremes, an element that is "connected" to the stream channel will shed water immediately to the channel. An "unconnected" element will shed water to pervious areas, allowing infiltration while traveling to the channel. The purpose of the initial rainfall simulations is to provide guidance on arrangement of impervious elements in the experimental watersheds (connected and unconnected).

The rainfall-simulator research activity addresses the impact of different levels and arrangements of impervious surface on runoff production and soil water dynamics at a spatial scale of the order of square meters. Experiments have initially been conducted using constant-intensity artificial rainfall applied to a 16-m^2 square soil bed (4 m x 4 m). This soil bed had a concave shape that simulates a concentrated-flow area in a watershed. The overland-flow and channel slopes in the soil bed were set to small slopes, and data were collected at the lower edge of the box. Runoff hydrograph data were collected and erosion samples obtained. Results suggested that travel times were too short and treatment differences were not detectable.

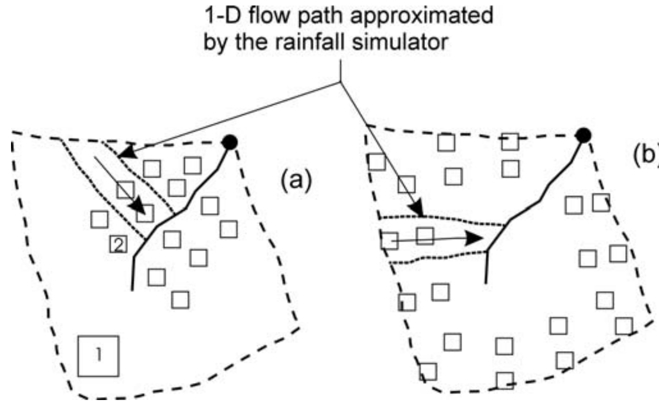

Figure 2. Spatial arrangement of impervious elements on the experimental watersheds for: (a) elements "connected" to the stream channel, and (b) elements "unconnected" to the stream channel.

As an alternative, a 1-dimensional approach approximates a 1-dimensional strip of watershed (Figure 2) by a uniformly sloped, rectangular surface on which impervious elements are installed and artificial rainfall applied. Runoff and sediment are collected at the bottom edge of the plot.

Preliminary plans call for the use of one rainfall simulation (~25 mm hr^{-1}), for zero and 100 percent impervious cover; and one run for each of two different arrangements of 5, 10, 25, and 40 percent impervious cover. The 100 percent impervious cover is a precipitation calibration run to confirm rainfall intensity and to develop corrections as necessary. All simulations are performed with a triple layer of screen between the simulator and soil surface to moderate rain-drop impact and to minimize erosion of the bare soil surface. Impervious elements will be installed and a rainfall-simulation run conducted for different imperviousness configurations.

The data will be analyzed to evaluate the effectiveness of unconnected impervious elements as a potential best-management practice (BMP) for practical landscaping and construction, for evaluating the utility of rainfall simulation for urbanization objectives, and for guiding the field watershed experiments of this project. Furthermore, the rainfall simulator will be used as a screening tool for a variety of BMPs such as vegetated areas, pavers, etc.

Watershed studies

Watershed studies require many years to conduct because of varying weather. In the present study, sufficient data must be collected for an adequately-sized data set for each level of imperviousness.

Impervious elements will be installed on four watersheds as described below, and the percent imperviousness will be increased through the years as sufficient data are collected. Initially, 5% imperviousness is planned. By the end of the multi-year project, total imperviousness will have been increased to 40%.

Using the four watersheds, there will be two treatments, based on preliminary rainfall simulator analysis (simulator tests are ongoing). One treatment will consist of impervious elements placed at the periphery of one of the 0.6- and 3-ha watersheds (unconnected; Figure 2b). The other treatment will consist of watershed impervious elements placed closer to the concentrated flow areas on the other 0.6- and 3-ha areas (connected; Figure 2a). On the smaller watersheds the watershed impervious elements will be smaller than realistic in order to attain 40% imperviousness. The larger watersheds will enable the watershed elements to be more realistic in size. The use of small and large watersheds will also allow a measure of scale of imperviousness and natural spatial variability in watershed response to precipitation to be addressed. Along with rainfall simulator trials, the size of the impervious elements will be determined by consulting a landscape architect, and by using digitized topographic maps and GIS to determine "reasonable" sizes for the impervious elements.

The 3-ha sites have not been consistently monitored over recent years. That is, one watershed has a recent record, while the other has not been measured for many years. This may require the installation of impervious elements later in the project. One approach to monitoring is to have the different percentage imperviousness treatment levels within the same year. This would allow the evaluation of the watershed treatments under a wider variety of precipitation inputs.

The aggregate of impervious elements will simulate a residential neighborhood. Each element will be made of landfill liner that will be in gable-roof form suspended about 1 m above the ground. Water will not be allowed to flow under the impervious element. To simulate disturbance due to excavation for foundations, a moldboard plow will be used to disturb the area surrounding each impervious element (a residential lot) and then disked. It has been shown that land disturbance increases runoff due to destruction of soil structure. Turf will be installed around each impervious element to simulate the turf that would be installed by a homeowner. Turf will be maintained by application of pesticides and nutrients, and by mowing. In each of the following years the percent imperviousness will be increased the same amount on the watersheds.

Infiltrometer measurements are planned using the truck-mounted NAEW infiltrometer. Infiltrometer measurements will be taken in areas scheduled for impervious-element installation. This will quantify both the potential loss of infiltration after the area becomes impervious and determine the extent of perviousness for sod or seeded lawns under different antecedent soil water conditions.

Soil-water potential and water-content measurements will be made across the watershed to quantify changes in soil-water regimes under varying precipitation events and weather conditions.

Methods of analysis

Data collected will be runoff hydrographs and a variety of water-quality constituents. Data collected under imperviousness will be compared with historic NAEW data. Baseline data will be analyzed to determine differences between the watersheds, and the degree to which they respond similarly (preliminary results in "Baseline Runoff Data" section).

Data analysis for each level of imperviousness will include an evaluation of curve number, runoff rate increase, runoff volume increase, soil moisture changes, water quality changes, etc. Nutrient, sediment, and major ion concentrations will be determined. If enough funding is available, pesticide concentrations will be determined as well.

The initial approach to analyzing the data will involve plotting a measure of percent imperviousness on the abscissa against a response variable on the ordinate (Figure 3). A response variable is the ratio of a variable to its pretreatment average or median value (or another representative pretreatment value). For example, the ratio of the average or median total runoff under a given percent imperviousness to the corresponding pretreatment value will be computed and plotted against percent imperviousness. Response variables to be initially investigated include peak runoff, total runoff volume, unit-hydrograph parameters, chemical constituent and sediment concentrations and loads, etc. In addition, duration curves of runoff, concentrations, and loads, and NRCS curve numbers will be compared among treatments. The method of analysis may be changed after preliminary exploratory analysis of the data.

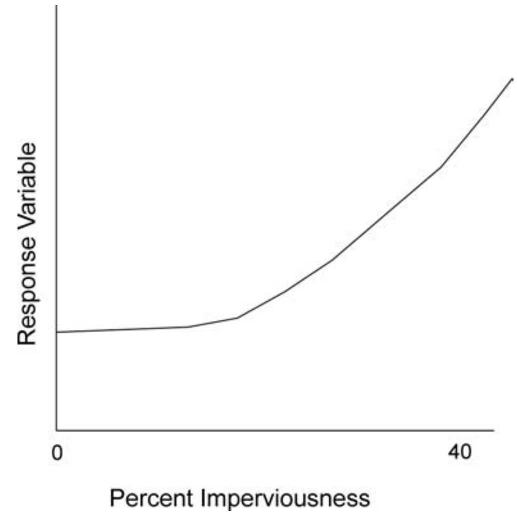

Figure 3. Initial analysis of the urbanization data using a response variable.

The literature has many examples of the use of percent imperviousness as a measure of urbanization. This is because *available* data were analyzed. However, percent imperviousness in not necessarily the best measure of imperviousness to use. This is because of the infinite combinations of width of impervious element, spacing between them, and position with respect to the stream channel. In the present study, other measures of imperviousness can be investigated in both the rainfall simulator and watershed studies because of the controlled nature of the study.

Watershed models (e.g., TR-20/55; HSPF; SWMM) for urban areas will be reviewed and one or more selected for further study. Using data collected from project experiments and other data sources, the model(s) will be verified. Model components will be modified as needed to improve modeling. The advantages, disadvantages, and limitations of event-based and continuous simulation approaches using different models for a runoff-credit-trading system will be explored. This will include evaluating the importance of connectedness of impervious areas to the stream channel, use of design storms, use of weather and precipitation generators, and utility of flow-duration curves. It is also of practical interest that effectiveness and performance measures for BMPs be assessed.

Best Management Practices (BMPs)

BMPs for controlling water, sediment, and chemicals will be developed and evaluated. This includes evaluation of the spatial arrangement of impervious elements in a watershed, impervious pavers, vegetative control of water and chemicals, and other innovative BMPs that will be developed as data collection proceeds. A rainfall simulator will be used to conduct some of these studies, including indoor and outdoor simulators.

At the end of monitoring when all watersheds are at the maximum percent imperviousness, additional monitoring will allow for evaluation of BMPs and investigation of other factors involved in urbanization. Examples include installing a road with runoff ditches in the watersheds; gutters to cause flow to bypass pervious areas for the unconnected treatment, forcing flow directly to the stream channel; use of porous pavers; and installing "green roofs" on the impervious elements to store water for later slow release.

Baseline Runoff Data

Baseline annual runoff data were examined on three of the experimental watersheds for consistency and for potential changing hydrologic conditions. The data for WS106, WS121, and WS192 since 1975 (the start of constant land-use) were plotted against one another (Figures 4 and 5). The data show generally good agreement between WS106 and WS121, and WS106 and WS192. The annual runoff comparison between WS121 and WS192 agree well also (not shown) as inferred from Figures 4 and 5. Average annual runoff for the available record from 1975 through 2002 for WS106 is 4.96 cm, WS121 is 5.83 cm, and WS192 is 6.42 cm (through 1994). The corresponding average annual precipitation from RG113 is 95.15 cm. On an annual basis, 5.2% of the precipitation runs off at WS106, 6.1% at WS121, and 10.5% at WS 192. It is apparent that runoff occurs only during heavy snowmelt and rainfall events. Differences in runoff due to urbanization should be apparent as imperviousness increases during the experiment.

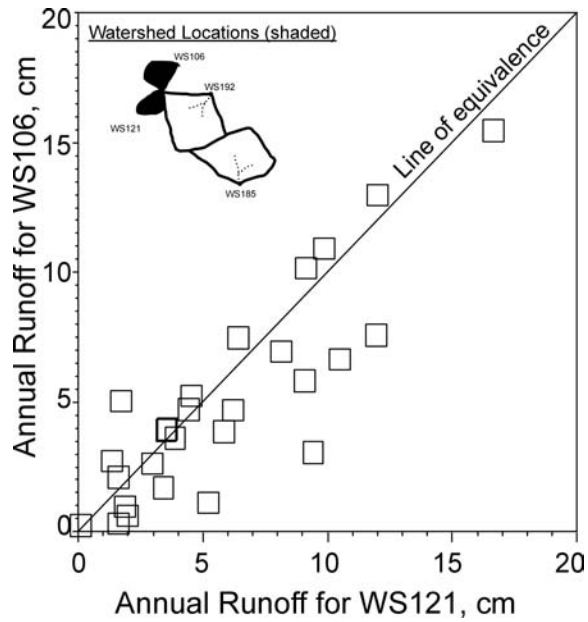

Figure 4. Annual runoff comparison between WS106 and WS121.

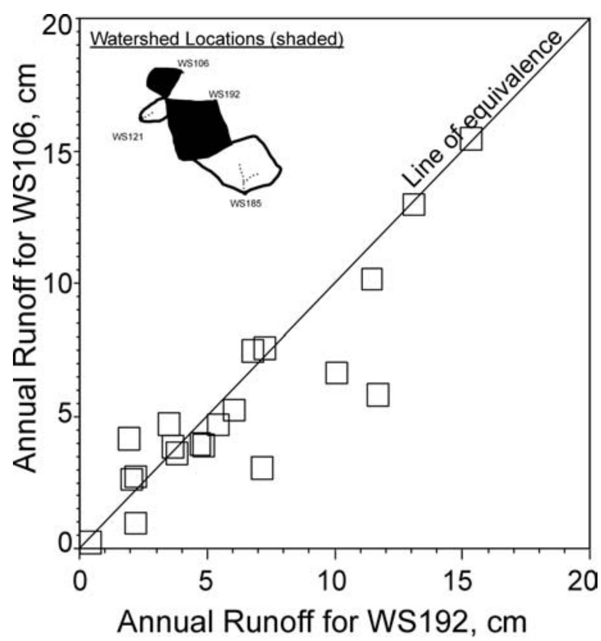

Figure 5. Annual runoff comparison between WS106 and WS192.

The plot of monthly total runoff at WS106 and WS121 (Figure 6) is typical of similar comparisons between the other watersheds (graphs not shown). Monthly runoff shows more scatter than the similar annual-runoff comparisons (Figure 4). Differences are attributed to different slope aspects among these two watersheds (Figure 1); differences in monthly snow accumulation and subsequent delayed snowmelt runoff; and physical characteristics affecting runoff generation in the watersheds though particularly for small storm events.

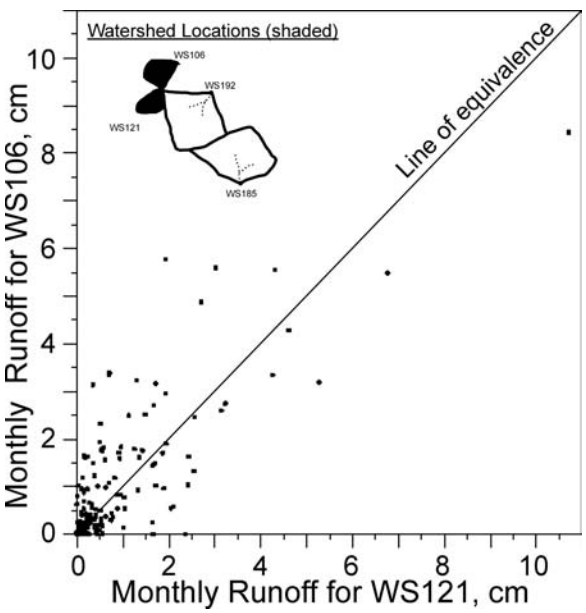

Figure 6. Monthly runoff comparison between WS106 and WS121.

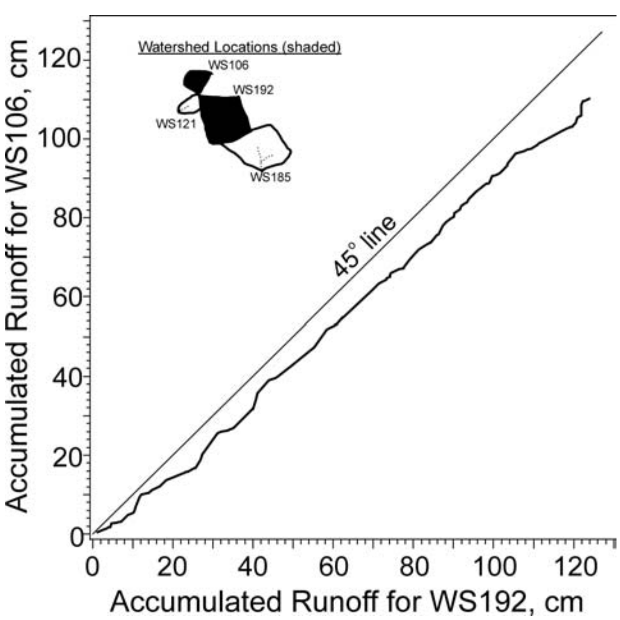

Figure 7. Double-mass plot of monthly runoff between WS106 and WS192.

The double-mass curve of monthly runoff for WS106 and WS192 (Figure 7) since 1975 show a general constant slope (nearly a 45^{o} line). This also confirms the good agreement between annual totals at these two sites in Figure 5. This is because the accumulated annual totals will plot on the monthly double-mass-curve graph. and nearly a 45 ^{o} line (Figure 8).

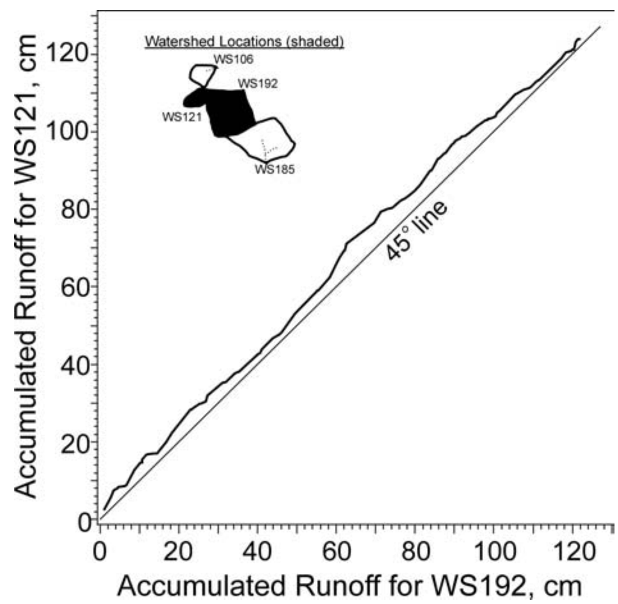

Figure 8. Double-mass plot of monthly runoff between WS121 and WS192.

The double-mass plot between WS 121 and WS192 shows similar constant slope. This graph also shows that annual totals agree well. A similar plot for WS106 and WS121 shows a similar linear trend. The constant slopes at all sites show that there are no major changes that have occurred during this period of record to affect hydrology.

Summary

This paper outlines the approach and rationale for a project investigating the effects of increasing urbanization (0% to 40%) on runoff, sediment, and water quality by using artificial rainfall simulation, modeling, and experimental watersheds. The project was jointly initiated by the U.S. EPA and the ARS at the North

Appalachian Experimental Watershed at Coshocton, OH. Rainfall simulation initially will help guide placement of impervious elements on the watersheds as percentage imperviousness increases. Two spatial arrangements of imperviousness will be explored - impervious elements connected to the stream channel and elements unconnected, wherein water flows over pervious areas en route to stream channels. The Coshocton watershed study will increase general understanding of runoff-production processes under urbanizing conditions, and will document the effects of land disturbances due to urbanization on hydrology and water quality under natural precipitation and weather. Modeling efforts will aid in the extrapolation of experimental watershed results to ungaged areas. Rainfall simulation and experimental watershed studies will also be used to investigate potential best-management practices.

During this project, urbanization on the experimental watersheds will be approximated by installing impervious surfaces on the surface of the watersheds. A small area surrounding each impervious element will be disturbed to simulate excavations during construction. This will simulate an increase in runoff production on pervious areas as would occur during construction in a residential development. A lawn will be installed and maintained on the disturbed area and will receive nutrient and pesticide inputs.

The experimental watersheds have long records (since 1975) of runoff, precipitation, and water quality under constant land-use, providing baseline conditions with which to compare urbanizing effects. Preliminary exploration of the baseline runoff data revealed that the three watersheds, for which there are runoff records, behaved similarly. Annual runoff totals agree well, and no apparent changes are occurring in runoff regime during the baseline period.

The data and results of this project will be used for improved modeling, BMP development and evaluation, and as data bases for a national tradable runoff credits program. Users of results from this project include U.S. EPA, ARS, and university scientists, environmental regulators, engineers, hydrologists, landscape architects, and governmental officials involved in establishing guidelines for minimizing the impacts of urbanization.

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