Lag time characteristics for small watersheds in the U.S.

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Abstract

Lag time, defined as the time from the centroid of rainfall excess to the centroid of direct runoff, was evaluated for over 50,000 rainfall-runoff events in 168 small watersheds in the United States ranging from 0.243 to 3490 acres. In most watersheds a stable value of lag time was observed for the larger storms, with peak flow the variable that best showed this tendency. The watersheds were divided into groups to explain the variation of lag time between watersheds. The groups that had a significant effect in the regression equation were geographical regions, watershed management practices, and the stability of the lag time value for the bigger storms. Separation of watersheds by land use and hydrologic behavior did not significantly improve the regression analyses. When only watersheds with stable behavior were used (N=78), no group significantly improved the regression equation, $t_{lag} = 0.0051 \times width^{0.594} \times slope^{-0.150} \times S_{nat}^{0.313}$, which exhibited R^2=58%.

Introduction

Public investment in surface drainage improvements in developing urban areas involves an annual capital investment on the order of a few billion of dollars (Pilgrim and Cordery, 1993). The average annual expenditure for works in small rural drainage basins amounts to 46 percent of the total expenditure on structures and works, making

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flood estimation for these small drainage basins of great importance in terms of national expenditure.

In design flood estimation, characteristic response times are required for the determination of hydrograph parameters and critical duration of flood producing rainfall (Ward et al., 1980). A given volume of water may or may not represent a flood hazard, as the hazard will depend on the time distribution of the flood runoff. Almost all hydrologic analysis of rainfall and runoff usually require the value of at least one time parameter as input (McCuen, 1989).

Most hydrologic models require a watershed characteristic that reflects the timing of runoff. One of the most widely used methods for estimating floods on small drainage basins is the U.S. Soil Conservation Service (SCS) method. The SCS method uses lag time, defined as the time difference between the centroid of the effective rainfall and the peak of direct runoff.

There is some inconsistency in the definition of lag time, and this leads to difficulty in analyzing the results from the different models that use it. Singh (1988) gathered nine different definitions for lag time. Still another constraint in the applicability of the time parameters is the lack of diversity of data (McCuen et al., 1984), since most empirical equations were developed for urbanized areas, rather than for rural areas (Miller et al., 1995).

The accuracy of the design flood estimate is directly related to the accuracy with which an estimate of the watershed response time is made (Singh, 1988). Errors on the order of 75% in the estimation of the peak discharge can be attributed to errors in the estimated value of the time parameter (McCuen, 1989; Singh, 1988). Little is known about the accuracy of estimates of response times on ungaged watersheds. For a specified recurrence interval, a first approximation of the design flood estimate is inversely proportional to the response time (Singh, 1988). In performing hydrologic computations of runoff, a particular synthetic unit hydrograph is often selected, and as such, a particular time parameter consistent with the unit hydrograph theory adopted. However, if a unit hydrograph method is chosen and the selected time parameter is inconsistent with it, unknowingly significant errors may be introduced in runoff computations (Miller et al., 1995).

Lag time is affected by watershed and rainstorm parameters. The physiographic parameters that affect lag time are areal extent, form, slope, surface topographic characteristics, vegetation, and land use. The rainfall characteristics are intensity in time and space, rainfall duration, and direction of runoff. There are still other factors that affect lag time, like the antecedent moisture conditions, infiltration characteristics, wind velocity, and weather condition (Singh, 1988).

Lag time used in this study was defined as the time from the centroid of rainfall excess to the centroid of direct runoff. This definition has been accepted as being the most stable measure of lag time (Schultz and Lopez, 1974).

Methodology

Lag time values were evaluated from rainfall-runoff data in over 50,000 events from 168 small watersheds in the United States. The watersheds ranged from 0.243 to 3490 acres, with periods of rainfall-runoff records from 3 to 58 years.

The data used in this study was obtained entirely from the Water Data Center maintained by the US Department of Agriculture, the Agricultural Research Service (ARS) in Beltsville, Maryland. This national archive of variable time-series readings for precipitation and runoff contains sufficient detail to reconstruct storm hydrographs and hyetographs. Textual files containing watershed descriptive information, land use and soils are published in the Hydrologic Data for Experimental Agricultural Watersheds in the United States book series.

Rainfall and runoff events were separated using GETPQ, a software developed at the University of Arizona which uses breakpoint rainfall-runoff data, and separates hydrographs using a constant baseflow separation slope. It then matches the rainfall to this hydrograph by comparing the times of occurrence of both the hydrograph and the hyetograph.

The lag time definition used in this study is the difference from the centroid of effective rainfall and the centroid of direct runoff.

Effective rainfall was defined and computed by an initial loss followed by a continuing loss rate (phi index). The phi was determined iteratively by adjusting its value until the effective rainfall hyetograph matched observed direct runoff depth. This done, the centroid of effective rainfall is computed.

Direct runoff was defined and computed as the runoff that has occurred once the baseflow has been deducted. The baseflow separation was done by using a constant baseflow separation slope (0.0002 in/hr^2).

The rainfall-runoff events were selected based on some pre-defined criteria. This filtering followed the approaches of Gray (1961) and Eagleson (1962) to select only those hydrographs with a single peak followed by an uninterrupted recession. All rainfall-runoff events were visually inspected. The rainfall-runoff events were discarded if the hydrographs were multi-peaked; if the hydrographs started before the hyetographs, suggesting inconsistency in the timing of rainfall and runoff data; if the hydrographs started after the hyetograph ended, because effective rainfall contributing to that runoff event cannot be computed; or if the events presented a negative lag time (the centroid of effective rainfall occurring after the centroid of runoff) suggesting that there is some inconsistency in the timing of rainfall and runoff data.

A total of 31,030 events were selected (out of 55,645) for further analysis of the 168 watersheds under study. Most of the factors described above that affect lag time were evaluated in this study. The study was separated in two parts. The first one evaluated the rainfall characteristics and how they affect lag time, and the second part evaluated how the watershed characteristics affected it.

Lag time should be a constant for all storms of a given watershed if the excess rainfall-direct runoff process was truly linear. However, some differences were observed when computing lag time from observed data (Barnes, 1959; Minshall, 1960; Gray, 1961; Eagleson, 1962; Diskin, 1964; Rastogi and Jones, 1969; Laureson, 1964; Askew, 1970).

In the present study, four rainfall-runoff characteristics were used to evaluate the variation of lag time within a watershed. These factors were degree of saturation of a watershed (Ramser, 1927) - represented by the previous 48 hour rainfall; effective rainfall intensity (Ramser, 1927; Ragan and Duru, 1972; Singh and Agiralioglu, 1982) - defined as the average effective rainfall intensity, effective rainfall being defined as the rainfall that occurred after the hydrograph started; mean total discharge (Ramser, 1927; Barnes, 1959; Laureson, 1964; Askew, 1970) - ratio between total runoff depth and its duration; peak flow - introduced in this study as another hydrologic variable to explain the variation of lag time values within a watershed. Peak flow is represented by the maximum flow rate in a hydrograph.

Several watershed parameters were thought to be related to lag time, like for example length and slope of the catchment (Bell and Karr, 1969; Ragan and Duru, 1972). Vegetation cover seemed to be the most influential factor in the computation of lag time (Ragan and Duru; 1972). Imperviousness of a watershed was another factor that seemed to be important on lag time computation (Rao and Delleur, 1974).

The watershed variables observed in this study were watershed area (ac); watershed length (ft) - longest flow-path from the highest elevation to the watershed outlet; watershed slope - ratio between the maximum difference in elevation and the longest flow-path length; S_{nat} - storage coefficient (in) used in the Curve Number (CN) method. Width (ft) is the watershed area divided by the watershed length. CN was computed using the asymptotic determination of runoff Curve Numbers from rainfall and runoff data technique (Hawkins, 1992).

Multiple linear regression analysis was performed on the data. The desired form of the fitted equation was $Lag = a_0 * width^{a_1} * slope^{a_2} * S_{nat}^{a_3}$.

The watersheds were separated into four diverse groups to clarify possible grouping relationships and give more reliable fittings. The groups represented qualitative characteristics of a watershed and were: regions (East, Midwest, Central, Southwest); land use (pasture, mixed, agriculture, forest); management (high, medium and low disturbance); behavior (Complacent, Standard, Violent) (Hawkins, 1992).

Results and Discussion

<u>Variations of lag time within a watershed</u>

Lag time was not a constant for a watershed but varied considerably. Some watersheds showed a tendency towards a constant value of lag time for the bigger storms. Unlike what is described in the literature, the degree of saturation of a watershed, represented by the prior 48-hour rainfall, showed no significant or consistent relationship to lag time. As for the effective rainfall intensity, previous studies had found that time of concentration (directly related to lag time) should decrease for the higher rainfall intensity storms (Ramser, 1927; Ragan and Duru, 1972; Agiraloglu and Singh, 1981; Singh, 1982). Such relationship was not observed in this study. A non-linear relation between lag time and mean total discharge was suggested by Askew (1970). In this study, only 5 of the 168 watersheds had a coefficient of determination (r^2) above 0.50 upon for such relationships.

However, some watersheds showed a tendency to a constant value of lag time at the higher values of previous 48-hour rainfall, suggesting that the scatter observed under 'drier' conditions is perhaps because of partial area contribution to runoff. The same is true for the higher intensity storms, suggesting that the watershed might not be at equilibrium for the small storms, when the hydrology of the watershed is still not well developed. The same tendency towards a constant value of lag time at the high mean runoff rate values was found, suggesting that the hydrology of the watershed is better defined for bigger storms. Also, for bigger storms the watershed may reach steady-state conditions. The variable introduced in this study was peak flow, and similarly to the previous evaluations, lag time showed a stable value for larger peak flow values. The higher peak flow suggests bigger storms, that might be better distributed both in time and space. This might represent steady-state conditions, and the value of lag time should not be affected by the size of the storm, once these conditions are met. The best estimate of lag time was computed for each watershed.

Variations of lag time between watersheds

All variables (width, slope, S_{nat}) were significant in explaining the variation of lag time in regression analysis. Two sets of watersheds were evaluated, the first being all watersheds, and the second being composed of the watersheds that showed a stable value for the larger storms. For the first set, the groups that had a significant effect were geographical regions, watershed management practices, and the tendency towards a constant value of lag time for the bigger storms. Separation of watersheds by land use and hydrologic behavior did not significantly improve the regression analyses. When the second set of watersheds was used, no group significantly improved the regression equation. The final regression equation (second set) was

$$t_{lag} = 0.0051 \times width^{0.594} \times slope^{-0.150} \times S_{nat}^{0.313} \quad .$$

This equation had R^2= 58, and N= 78. It bears repeating that t_{lag} is in hours, *width* is in feet, *slope* is a decimal fraction, and S_{nat} is in inches.

Conclusions

There was a tendency towards a stable value of lag time for the larger storms. Peak flow was the hydrologic variable that best showed this tendency. Hydrologic relationships previously described in the literature were not verified in this study.

In order to compute lag time rainfall-runoff data should be used, especially for the larger storms. If there is not enough data available, grouping the watersheds into regions and management practices will improve the regression equation. Width, slope and S_{nat} are good variables for prediction of lag time. The model developed in this study had a higher coefficient of determination compared to other models presented in the literature.

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