THEORY AND EXPERIMENTS IN THE PREDICTION OF SMALL WATERSHED RESPONSE

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by

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ABSTRACT

The flood response of a small watershed to flood producing rainfall was investigated in several ways. First flood hydrographs measured on small pristine watersheds were assembled along with the causal rainfall, antecedent rainfall, and a number of physiographic parameters of the watershed. Research has verified the validity of the application of the kinematic wave theory for computing the hydrograph of runoff from small watersheds. Research was carried out on deriving unit hydrographs from observed rainfall and runoff. A study was made of correlation of various methods of defining the response time of a watershed. A low pass filter method was used to remove oscillations from some of the derived unit hydrographs.

THEORY AND EXPERIMENTS IN THE PREDICTION OF SMALL WATERSHED RESPONSE

The more complex modern society is becoming more involved with problems associated with floods from small watersheds. The problem of estimating flood peaks from small watersheds is an important element in the design of storm sewers, highway drainage, diversion works, flood retarding structures, bridges and culverts. The majority of such hydraulic structures are constructed on small watersheds. Since small streams have not been gaged as extensively in the past as have large streams, more of the designs have to be prepared without the benefit of stream flow records. There is a great need to develop more satisfactory methods for obtaining design floods for these watersheds under the varied changes taking place in the modern day life.

INTRODUCTION

In a small watershed the predominant storage element is the surface detention storage. It is the storage element in the watershed which produces the difference between the input - <u>rainfall excess</u> - and the output - <u>surface runoff</u>. As the watershed increases in size, the predominant storage element in the watershed becomes the channel storage.

The small watershed with its relatively important relationship to the surface detention is therefore more sensitive to man made changes in those things which influence the transit time of the overland flow. Changes such as increasing or decreasing the surface roughness, the length of overland flow, the overland flow slope are all changes which should have a large effect on the flood response of the watershed to storm rainfall.

Research in the flood response has taken three main approaches:

1) Assemble in easy-to-retrieve form high quality records of natural floods, causal rainfall, antecedent rainfall and associated physical watershed parameters,
2) Development of a large scale model facility where rainfall-runoff experiments could be carried out at will and where some of the variables could be controlled,
3) Testing different analytical models and procedures for computing the flood hydrograph from a small watershed.

The third step would utilize the data resources assembled in the first two steps. The data assembled in Step One were data measured on small pristine watersheds. Research by Van Sickle (1962) on urbanizing small watersheds at Houston, Texas called attention to a progressive change in the unit hydrographs derived from small watersheds in the Houston area. Later Van Sickle expanded on his findings on small watersheds in a contribution at a Water Resources Symposium, Moore and Morgan (1969). These and other effects of urbanization were summarized by Schulz (1971). As a result of these findings on urban watersheds, it was decided to expand the CSU Flood Data File to include data from urbanized watersheds in order to provide a data base from which to verify predictions made about the effects of urbanizing watersheds. This project is currently being implemented at CSU.

WATERSHED RESPONSE

The response of a small watershed to storm rainfall can be measured in several ways. The unit hydrograph is a generalized way in which the flood response can be defined. The unit hydrograph can be defined by two (or three) parameters. Usually the unit peak discharge, q_p , and a measure of the response time, t_p , is used. The unit peak discharge and the response time are interrelated.

There are a number of ways to define the response time. Some of these response times can be related to measurable features in the watershed. The ability to predict changes in the flood response to storm rainfall is crucially associated with changes in the response time.

Watershed Response Time - There are several ways in which the watershed response time can be defined:

T_{lag} = Time from the beginning of rainfall excess to the centroid of runoff. (USBR, 1965),

T_{lag} = Time from center of mass of rainfall excess to centroid of runoff. (Mitchell, 1948),

T_{peak} = Time from center of mass of rainfall excess to the peak discharge. (Eagleson, 1962),

T_{rise} = Time from low water before the flood to maximum stage. (Gray, 1961),

$T_{concentration}$ = Time required for water to travel from the most remote point in the watershed to the outlet. (Kirpich, 1940),

$T_{equil.}$ = Time required for the runoff hydrograph to rise to an equilibrium runoff rate. (Kibler and Woolhiser, 1970 or Izzard, 1946).

A relationship between two of these definitions (T_{lag} and T_{peak}) had been established by Schulz et al. (1971). Wilson (1972) reported a more comprehensive study on response time utilizing a large number of the observed floods found in the CSU small watershed data file. Unit hydrographs were derived from a large number of the natural watersheds in the CSU data file using a Matrix Inversion Method for a digital computer developed by Kavvas (1972). The different response times were cross-correlated by Wilson in his investigation. The various measures of the response time were classified into two main groups by Schulz and Wilson (1972). The first classification was related to measurements on the unit hydrograph which is derived from the observed rainfall-runoff data set. The second classification of the response time is obtained from measurements of overland flow slope and length and an assumed surface roughness factor. These two classifications really go back to the basic analytical approach used in obtaining the watershed response function. Yevjevich et al. (1972) classified those analytical procedures based on the unit hydrograph type of concept as a "*black-box*" technique.

When basic physical laws are applied to the analysis of the problem the term "*grey-box*" was used. Izzard's (1946) early work was a pioneering effort in this direction. The application of the kinematic wave theory is a contribution in the grey box technique, Kibler and Woolhiser (1970). When the kinematic wave theory can be applied without any reference to empirical-type roughness factors, the "*white-box*" technique will evolve. The results of the thesis investigation of Fawkes (1972) is a contribution in this direction.

The application of the kinematic wave to a design problem requires the ability to predict whether the overland flow regime will be laminar or turbulent. Correia (1972) carried out dye tracing experiments on the CSU Experimental Rainfall-Runoff Facility and found that during rainfall impact the overland flow regime was turbulent. Schulz and Fawkes (1972) presented a paper in which a diagram was given which would establish four different overland flow regimes:

1. Disturbed turbulent,
2. Disturbed laminar,
3. Turbulent,
4. Laminar.

KINEMATIC WAVE THEORY

The kinematic wave approximations were first applied to the problem of overland flow by Iwagaki (1955). Veal (1966) and Woolhiser (1969) have proposed the overland flow on a natural watershed could be represented by a linearly converging surface such as a segment of a cone. (It was Veal's thesis that provided the analytical basis for the design of the conic sector watershed in the CSU Experimental Facility).

The kinematic wave equations for unsteady flow over a linearly converging surface are:

$$\frac{\delta h}{\delta t} + \frac{\delta uh}{\delta x} = q(x,t) + \frac{h}{(L_0 - x)}$$

and

$$u = \alpha h^{n-1}$$

the coefficient α can be evaluated using the Darcy-Weisbach relationship:

$$\alpha = \sqrt{\frac{8g}{f} S_0}$$

and the exponent term, n, is

$$n = 3/2 .$$

Figure 1 is a diagram in which the terms of these equations are defined. Experimental verification of these equations using data from the CSU Experimental Rainfall-Runoff Facility was reported by Woolhiser et al. (1971).

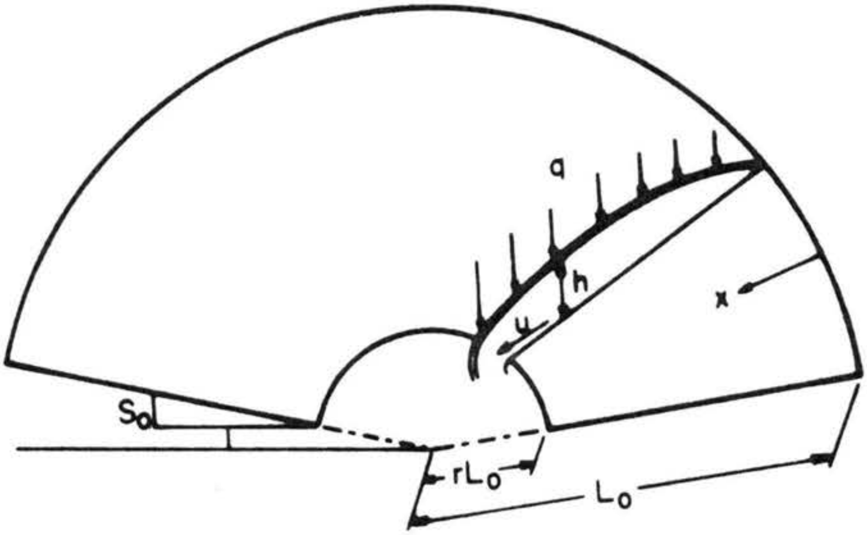

Figure 1. Definition Sketch for Converging Surface.

UNIT HYDROGRAPH THEORY

The unit hydrograph theory first used by Sherman (1932) and subsequently improved and generalized by Snyder (1938), Taylor and Schwarz (1952), Dooge (1959), Minshall (1960) and others. The concept of the synthetic unit hydrograph is an accepted tool in engineering for developing a design hydrograph for an ungaged catchment given a design storm and some knowledge about the watershed soils and the watershed physiographic characteristics.

The work of Van Sickle (1962) and Eagleson (1962) have demonstrated that some of the characteristics of the unit hydrograph change with urbanization of the watershed. The flood events assembled in the CSU Data File are floods recorded on essentially pristine watersheds and therefore constitute a data base of observed floods from undisturbed watersheds.

Optimum Matrix Inversion - A computer program was developed to derive unit hydrographs from the observed flood events in the data file, Kavvas (1972). The optimum matrix inversion computer program was called FINVER. In many instances the derived unit hydrographs exhibited oscillations in the recession limb. It is known that the recession after the point of inflection on the recession side of the peak is water supplied from various storage elements in the watershed. Since the equation of recession is known to be of the form:

$$Q = Q_o e^{-kt} \quad ,$$

where

k is a constant.

The oscillations appear to be related to the time periods selected for the quantizing of the observed rainfall and runoff data. If the intervals are too small, the oscillations are more prevalent. If the time intervals are made to large, desired accuracy about the response time is lost.

There are several other computer based procedures for deriving a unit hydrograph from the observed rainfall runoff pairs. They all appear to suffer from the same difficulty of oscillations when computing values of the recession limb. Kavvas and Schulz (1972) described a procedure for the removal of the unit hydrograph oscillations by means of filtering. It was demonstrated that the undesireable oscillations could be removed by applying a low pass filter to the derived unit hydrograph. It was shown that the actual watershed behaves as a low pass filter.

Time-Area Histograms - An instantaneous unit hydrograph can be computed from watershed characteristics using Clark's method, Clark (1945). Clark's method is a parametric system synthesis method where the instantaneous unit hydrograph (IUH) is derived by routing the time-area curve of the particular basin through a linear reservoir whose storage constant, K, is determined from the recession side of the runoff hydrograph. Isochrones of travel time are drawn on a map of the watershed. The time-area curve is obtained by planimetering the area between adjacent isochrones. The method reflects the influences of the watershed shape and utilizes the basin storage concepts to find the translation time of a flood wave through the stream pattern of the basin. This translation time is called the travel time. Clark (1945) defined the travel time as a ratio of the storage to discharge.

$$K = - \frac{S}{Q} = - \frac{\Sigma Q}{\frac{dQ}{dt}}$$

The value of K was found from a semi-log graph of the recession side of a hydrograph using the relationship:

$$K = - \frac{t - t_o}{\ln Q_t - \ln Q_t} .$$

Kavvas (1972) found that the Clark method produced a reasonable unit hydrograph from observed floods on small watersheds. (See Fig. 2 for an example). It was also found that an observed hydrograph from the experimental watershed could be reproduced using the Clark time-area method.

CONCLUSIONS

This investigation has shown that the hydrograph of runoff could be computed for a relatively simple watershed by method based on the Kinematic Wave Theory (Woolhiser et al, 1971). The uncertainty in applying this procedure is associated with the selection of the flow regime and the selection of the appropriate friction factor (Schulz and Fawkes, 1972).

For a large diverse natural watershed, the synthetic unit hydrograph can be used for obtaining a flood hydrograph. (Schulz et al, 1971). When radical changes take place in the watershed, changes in the unit hydrograph can be predicted using estimates of the response time in the altered watershed. (Van Sickle, 1962 and Moore and Morgan, 1969).

The CSU Experimental Rainfall-Runoff Facility can be used to study intimate details of the hydraulics of the overland flow (Correia, 1972 and Fawkes, 1972).

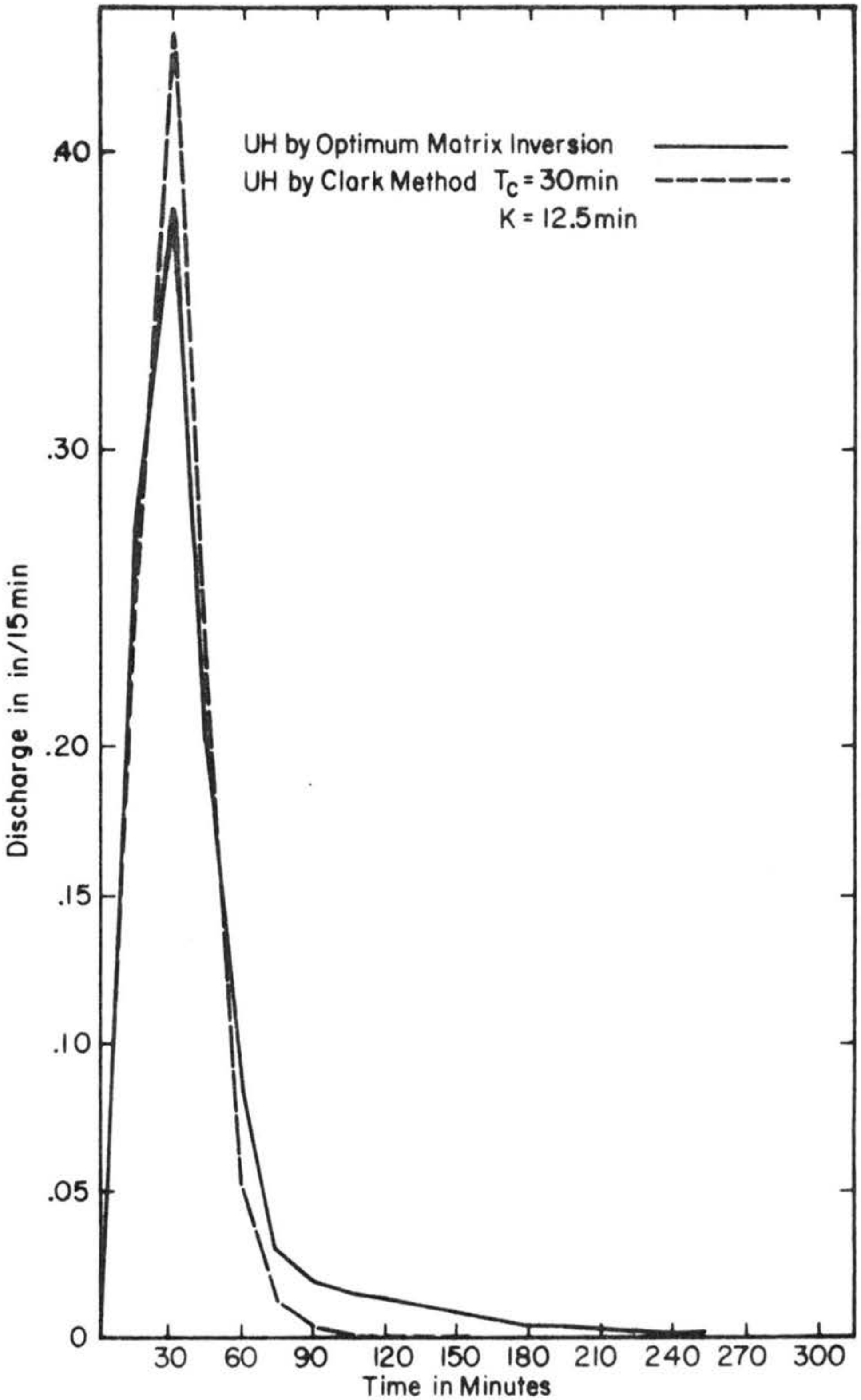

Figure 2. Unit hydrograph for the event 1030600212 at Watershed W-II. Safford, Arizona.

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