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A COMPARATIVE ANALYSIS OF KINEMATIC WAVE AND SCS-UNIT HYDROGRAPH MODELS IN SEMI-ARID WATERSHED

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1 INTRODUCTION

This research explores the efficiency of kinematic wave and SCS unit hydrograph flow models at a watershed scale. The scope of this research is based on the hypothesis that flow models based on the simplest approximation of the full dynamic equations (kinematic wave, hydraulic) would produce output variables that are representative of the natural system compared to flow models that rely only on the continuity equation (SCS-unit hydrograph, hydrologic). The overall objective of this research study is to provide an improved understanding of kinematic wave and SCS unit hydrograph flow models and compare their efficiencies to the observed flow data. Physical data such as precipitation, runoff, soils, and topography was derived from the Walnut Gulch Experimental Watershed (WGEW) at Tombstone, Arizona. The Southwest Watershed Research Center (SWRC) operates the Walnut Gulch Experimental Watershed in southeastern Arizona as an outdoor laboratory for studying semiarid hydrology, rangeland ecosystem, climate change models, and erosion processes.

2 FLOW MODEL DEVELOPMENT

Flow routing procedures range in complexity from simple storage routing methods to relatively complex procedures based on simultaneous solutions to the hydrodynamic equations dealing with the conservation of momentum and mass.

2.1 Development of kinematic wave flow model

The kinematic wave theory was originally developed by Lighthill and Whitham (1955)[1] to describe flood movement in long rivers. This theory is based on the simplification of the full dynamic equations, which is achieved by combining continuity and momentum equations with inertia and pressure terms dropped. In this research, the kinematic wave flow routing method was conceptualized as shown in figure-1. This represents the watershed as two plane surfaces over which water runs until it reaches the channel. The water then flows down the channel to the outlet.

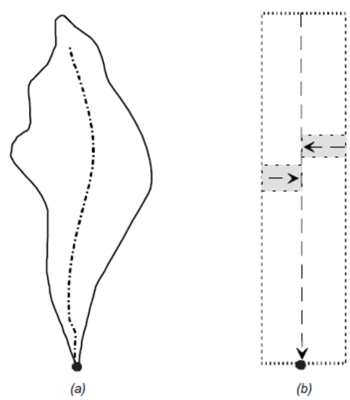

Figure 1: Simplified watershed with kinematic wave representation.

In one dimension, the momentum equation is: $Sf = S_o - \frac{\partial y}{\partial x} - \frac{V}{g}\frac{\partial V}{\partial x} - \frac{1}{g}\frac{\partial V}{\partial t}$; where Sf: energy gradient (also known as the friction slope); S_o: bottom slope; V: velocity; y: hydraulic depth; x: distance along the flow path, t: time; g: acceleration due to gravity; $\frac{\partial y}{\partial x}$: pressure gradient; $\frac{V}{g}\frac{\partial V}{\partial x}$: convective acceleration; and $\frac{1}{g}\frac{\partial V}{\partial t}$: local acceleration. These equations are described in detail in Chow (1988)[2], Chaudhry (1993)[3], and many other texts. In this research the various approximations of the continuity and momentum equations were solved in HEC-HMS (Hydrologic Modeling System)[4] using the finite difference method. In this method, finite difference equations were formulated from the original partial differential equations using an explicit scheme, where the unknown values are found recursively for a constant time, moving from one location along the channel to another. The results of one computation are necessary for the next time step.

2.2 Development of SCS unit hydrograph model

The overland flow for the hydrologic routing component was determined using the SCS Unit Hydrograph method. A full account of the SCS unit hydrograph is given by McCuen (1982)[5]. In the SCS Unit Hydrograph model the basin outflow results from one unit of direct runoff generated uniformly over the drainage area at a uniform rainfall rate during a specified period of rainfall duration. The underlying concept of the Unit Hydrograph is that the runoff process is linear, so the runoff from greater or less than one unit is simply a multiple of the unit runoff hydrograph. There are five important concepts in this definition. First, the runoff occurs from precipitation excess, which can be defined as the difference between precipitation and losses, which includes interception, depression storage, and infiltrated water that does not appear as direct runoff. Second, the volume of runoff is one inch, which is the same as the volume of precipitation excess. Third, the excess is applied at a constant rate (i.e., uniform rate). Fourth, the excess is applied with a uniform spatial distribution. And, fifth, the intensity of the rainfall excess is constant over a specified period of time, which is called duration (McCuen, 1982)[5].

The unit time or unit hydrograph duration is the duration for occurrence of precipitation excess. The optimum unit time is less than 20 percent of the time interval between the beginning of runoff from a short duration, high-intensity storm and the peak discharge of the corresponding runoff. The storm duration is the actual duration of the precipitation excess. The duration varies with actual storms.

3 OBSERVED RUNOFF AND PRECIPITATION DATA AT WGEW

Eleven major runoff and precipitation events between 1999 and 2009 were selected at the study site in WGEW. The study watershed is known as watershed number eleven. This basin is located in the northeast section of WGEW, and has an area of 7 km^2. These runoff events produced peak flows between 1- to 50-m^3/sec, with flow volume between 4000- to 90,046-m^3. The precipitation record observed via the digital gauges consists of rainfall depths at 1- min intervals during periods of rainfall. Analysis of runoff data shows that almost all of the annual runoff and all of the largest events occurred between July and September due to high-intensity, short-duration, and limited areal extent thunderstorms.

An “Inverse-distance-square-method” in HEC-HMS was used to define the spatial and temporal extents and distribution of the precipitation both for kinematic wave and SCS watershed models. This scheme relies on the notion of “nodes” that are positioned within a watershed such that they provide adequate spatial resolution of precipitation in the watershed. Watershed number eleven was divided into five sub basins each with three nodes distributed along the centroidal flow path. The precipitation hyetograph was computed for each node using gages near that node. To select these gauges, HEC-HMS constructs hypothetical north-south and east-west axes through each node and finds the nearest gage in each quadrant defined by the axes. Weights were then computed and assigned to these gauges in inverse proportion to the square of the distance from the node to the gage.

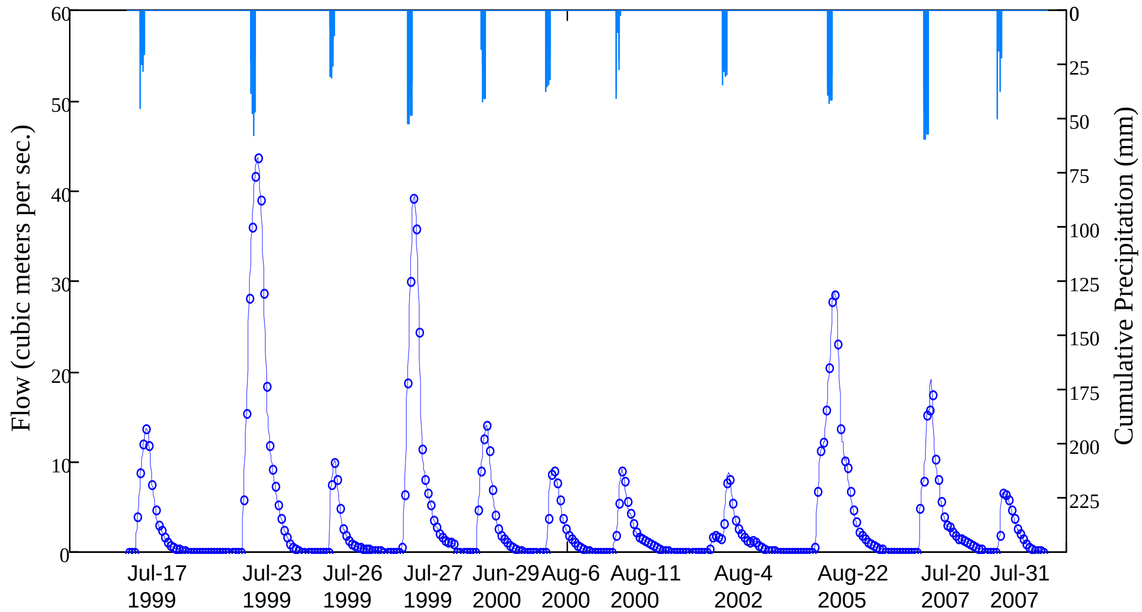

Figure 2: The left y-axis show significant runoff hydrographs recorded at flume eleven. The right y-axis shows the precipitation events that triggered these runoff events.

4 RESULTS AND ANALYSES

Several different analyses were conducted to explore the accuracy of both the kinematic wave and SCS flow routing methods compared to the observed flow data.

4.1 Comparative analyses of observed and computed peak flows

First, a comparative analysis of the kinematic wave and SCS models peak flows to the observed peak flow hydrographs was performed for the selected runoff events. For Watershed number eleven, kinematic wave flow model results shows a ± 5-percent difference in peak flows between the observed and computed hydrographs for ten runoff events. Only a single runoff event shows a negative 25 percent difference to the observed flow hydrograph. On the contrary, results from the SCS flow model show a -20 percent difference in peak flows between the observed and computed hydrographs for nine runoff events. Only two runoff events produce a +5 percent difference in peak flows to the observed flow hydrographs.

Analysis of the plot in figure 3 indicates model (kinematic wave & SCS flow models) bias as a consequence of the selected methodology. The straight line on the plot represents equality of calculated and observed peak flows. The percent difference in peak flows between the observed data and kinematic wave flow model results fall closely and almost in equal numbers above and below the line. This indicates that the model is no more likely to over-predict than to under-predict. On the other hand, the majority of the percent difference in peak flows between the observed and the SCS flow model results falls below the equality line, which indicates that the model has consistently under predicted peak flows.

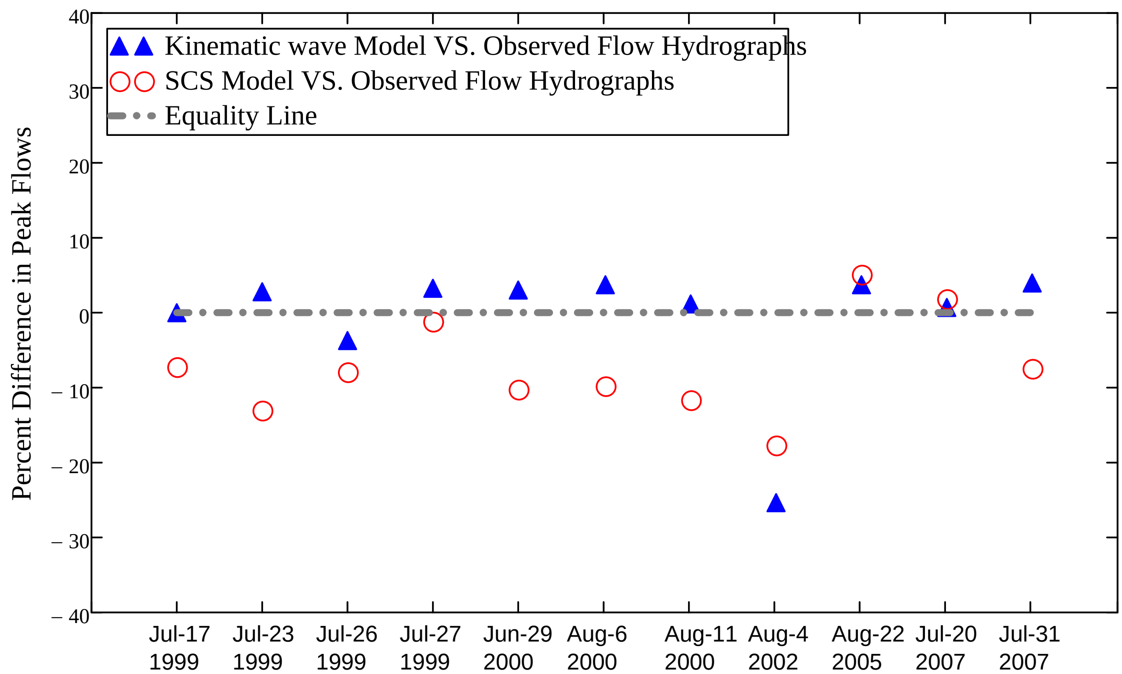

Figure 3: Percent difference in peak flows between kinematic wave and SCS outflow hydrographs to the observed flow hydrographs.

4.2 Comparative analyses of observed and computed "time of peak" values

A similar type of analyses was performed to explore the differences in "time of peak" values (minutes) between the computed and observed flow hydrographs. "Time of peak" is the time from the center of mass of the rainfall excess to the peak of the outflow hydrograph, and is considered an important variable in water quality analysis of natural streams.

Figure-4 shows differences in "time of peak" values in minutes between kinematic wave and SCS flow model results compared to the observed flow hydrographs. The plot in figure-4 indicates that the "time of peak" differences between the kinematic wave flow model results to that of the observed flow hydrograph fall closely and almost in equal numbers above and below the line. This means that the model is no more likely to over-predict than to under-predict. In contrast, the majority of the difference in "time of peak" values between the SCS flow model results and observed flow hydrograph falls above the equality line, which indicates that the model has consistently over predicted time of peak flows.

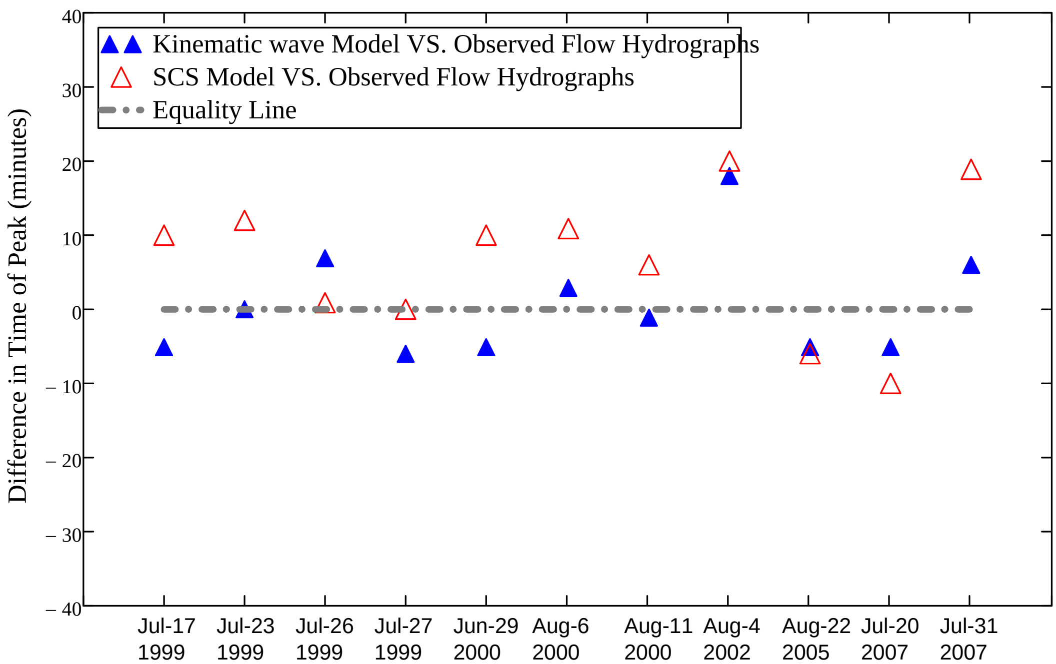

Figure 1: Difference in "time of peak" between kinematic wave and SCS outflow hydrographs to the observed flow hydrographs.

4.3 Comparison of peak weighted root mean squared error outputs

Another analysis of the “goodness-of-fit” between the computed flow hydrographs (kinematic wave & SCS flow models) to the observed flow hydrographs was performed using the “Peak-Weighted Root Mean Square Error (USACE, 2000)[5]” (PRMSE) as an objective function. The peak-weighted root mean square (PRMS) error objective function is a modification of the standard root mean square error (RMS). An objective function measures the degree of variation between computed and observed data. It is equal to zero if the hydrographs are exactly identical.

Though several other methods such as “the sum of absolute errors” and “sum of squared residuals” could be used to compute the “goodness of fit” indices, but the “peak weighted root mean squared error” was selected because it provides an implicit measure of comparison of the magnitudes of the peaks, volumes, and times of peak of the two hydrographs. The PRMSE results show that the kinematic wave outflow hydrographs have lower objective function values compared to SCS outflow hydrographs (figure 5). Since this function is an implicit measure of comparison of the magnitudes of the peaks, volumes, and times of peak of the two hydrographs, it means that the kinematic wave flow routing model is more accurate than the SCS flow routing model.

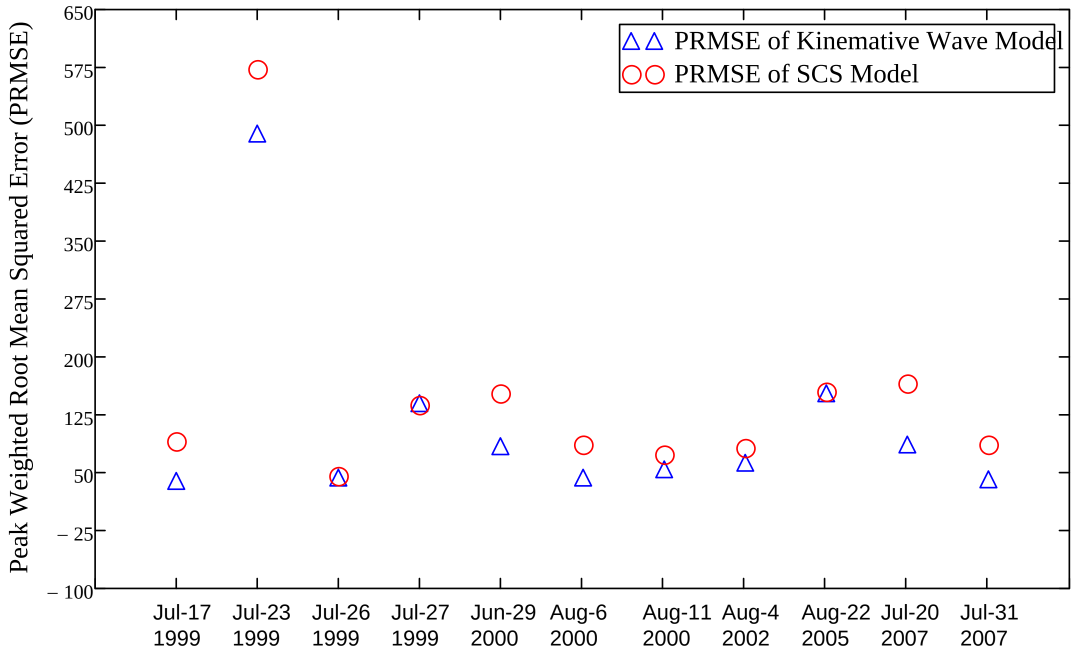

Figure 5: A comparative analyses of "peak weighted root mean squared error" between kinematic wave and SCS outflow hydrographs to the observed flow hydrographs.

5 DISCUSSION AND CONCLUSIONS

Ponce (1991)[6], argues that because of the numerical properties of the solution algorithms in kinematic wave method "…is intended primarily for small watersheds [those less than 1 sq mi (2.5 km_2)], particularly in the cases in which it is possible to resolve the physical detail without compromising the deterministic nature of the model." But this was not the case observed during this research study. For example, analyses of results for Watershed number eleven, which is approximately 7-km^2, indicates that outflow hydrographs computed with the kinematic wave model show a better match with the observed flow hydrograph compared to the outflow hydrographs computed with the SCS-UH model. This is primarily because of the, 1) high level of discretization of watershed characteristics (physical data) achieved for the study area with the use of GIS; prior to 1991, use and availability of GIS technology and high-resolution data was limited, and 2) the subdivision/discretization of the study watershed into a number of smaller sub-basins.

The SCS method is a conceptual model of runoff generation, spatially lumped, and based exclusively on hydrologic data (stream flow measurements), therefore with the use of GIS data kinematic wave method has significant advantage that it can describe spatial and/or temporal rainfall and roughness variations, which the SCS method, by virtue of it being lumped, cannot do.

Several important conclusions have emerged from the study that can be useful to a practicing engineer/hydrologist. First, the kinematic-wave model has proven to be a satisfactory tool to predict surface runoff in semiarid watersheds, where transmission losses are a significant factor besides initial abstraction in the overall water budget computations. Analysis of the PRMSE values between the computed (kinematic wave & SCS flow models) and observed flow data for the study watershed show that the kinematic wave flow model have lower values of objective function compared to SCS flow model. Since PRMSE function is an implicit measure of comparison of the magnitudes of the peaks, volumes, and times of peak of the two hydrographs, it means that the kinematic wave flow model is more accurate than the SCS-UH flow model. And finally, the percent difference in "peak flows" and 'time of peak" between the observed data and computed flow results indicates that the kinematic wave model is no more likely to over-predict than to under-predict. On the other hand, the majority of the percent difference in "peak flows" and 'time of peak" between the observed and the SCS flow model indicates that the model has consistently under predicted peak flows.

REFERENCES

[1] Lighthill, M. J.; Whitham, G. B. (1955). "On Kinematic Waves. I. Flood Movement in Long Rivers". *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* **229** (1178): 281.

[2] Chow, V. T., D. R. Maidment, and L. W. Mays, (1988), "*Applied Hydrology*". McGraw-Hill, New York.

[3] Chaudhry, M. H., (1993), "*Open channel flow*", Englewood Cliffs, N.J., Prentice Hall, 483-p.

[4] U.S. Army Corps of Engineers, Hydrologic Engineering Center, (2000), "Hydrologic Modeling System, Technical Reference Manual, HEC-HMS".

[5] McCuen, R.H., (1982), "A guide to hydrologic analysis using the SCS Methods:" Englewood Cliffs, N.J., Prentice-Hall, 145 p.Moore, I. D., R. B. Grayson, and A. R. Ladson. 1991., "Digital Terrain Modeling: A Review of Hydrological, Geomorphological and Biological Applications." *Hydrological Processes*, 5(1): 3-30.

[5] Ponce, V.M., (1991). "*The Kinematic Wave Controversy*", Journal of Hydraulic Engineering, 1991, Vol. 117, No. 4, pp 511-525.