Rainfall-Sampling Impacts on Runoff

by D.C. Goodrich[1], D.A. Woolhiser[2], and C.L. Unkrich

Abstract

The sensitivity of computed peak-runoff rates to rainfall-sampling frequency over three semiarid watersheds in southeastern Arizona of increasing size is investigated using the methodology of Woolhiser (1986). The impacts of rainfall sampling on runoff computations are assessed using the distributed rainfall-runoff model KINEROS. Results provide guidelines for the sampling frequency required to maintain accurate peak computations as a function of basin scale.

Introduction

In arid and semiarid regions flash floods are caused by high intensity, short duration storms with a high degree of spatial variability (Renard, 1977). The runoff hydrographs from these storms typically exhibit very short rise times, even for large catchments. From a study in progress on distributed, physically-based rainfall-runoff modeling, we have found that the outflow hydrographs are more sensitive to the rainfall input, including it's spatial variability, than to model parameters. Because distributed rainfall data are usually not available, stochastic generation techniques will be required to provide input for design purposes. The question then arises as to what rainfall sampling frequency is appropriate. This problem has been studied by Eagleson and Shack (1966), Harley et al. (1970), Bras (1979) and Woolhiser (1986).

Approach

To address the central issue of defining an appropriate temporal rainfall sampling frequency over a range of watershed scales, three subwatersheds from the USDA-ARS Walnut Gulch Experimental Watershed were selected for the study. Lucky Hills Watershed 106 (LH-106) has an area of 0.89 acres (0.36 ha). LH-104 has an area of 10.87 (4.40 ha) and contains the smaller LH-106 watershed. Walnut Gulch 11 (WG-11) has an area of 1560 acres (631 ha). All watersheds are highly

1: Assoc. Member, 2: Member; all authors from USDA-Agr. Res. Service, Aridland Watershed Management Research Unit, 2000 E. Allen Rd., Tucson, AZ, 85719

dissected.   The vegetation on the Lucky Hills watersheds is
predominantly brush, while WG-11 has a mixture of brush and grass
cover.   Rainfall is measured with two weighing-type raingages on the
LH watersheds and with 10 similar gages on WG-11.

KINEROS was used to model watershed runoff.   A detailed description
of this model is provided elsewhere (Woolhiser, et al., 1990).
Watershed geometry is represented as a cascade of planes and channels
and the Smith-Parlange infiltration model (Smith and Parlange, 1978)
is used in an interactive manner at each computational node to
determine surface runoff rates. Interactive infiltration differs from
an infiltration excess computation by allowing upslope inflow to
infiltrate even if rainfall ceases. Channel infiltration is handled
in a similar manner.   Parameters required for each plane element
include: interception   depth,   saturated   hydraulic   conductivity,
coefficient of variation of hydraulic conductivity, soil porosity,
rock content, Manning's n, and the length, width and slope of the
plane.   Similar data are required for channel elements.   The daily
water balance component of the chemical transport model CREAMS
(Knisel, 1980) was run for the period of record at each gage to
provide an estimate of the initial soil water content for each storm.

The geometric characteristics of the watershed were estimated from
topographic maps. Soil texture and rock content were sampled in the
field and initial estimates of saturated conductivity were obtained
from regression relationships and tables presented by Rawls et al.
(1982).   Manning's n values were estimated from tables in Woolhiser
et al. (1990). Channel cross section geometry was measured in the
field.   Ten runoff events were selected as an optimization set. They
were chosen to cover a range from small to large storms, from dry to
wet initial conditions and from simple to complex rainfall intensity
patterns.   It was assumed that the relative values of saturated
hydraulic conductivity and Manning's n were correct so the parameters
to be optimized were multipliers of these values and a global
coefficient of variation of saturated hydraulic conductivity.   The
efficiency criterion of Nash and Sutcliffe (1970) was used as the
objective function and high efficiencies (> 90%) were achieved for
runoff peaks and volumes (Goodrich 1990).   This high degree of fit
establishes confidence in using the model to assess the effects of
rainfall sampling interval on peak runoff rates and volumes.

The most detailed temporal representation of the rainfall intensity
at a gage is provided by the "breakpoint" accumulated rainfall depth
data.   This data is obtained from analog charts by digitizing at
irregular time intervals corresponding to changes in the rainfall
intensity. The sampled storm data were obtained by placing sampling
grids at increments of 5, 10, 15, and 20 minutes randomly over the
breakpoint data for each storm. The starting time of the breakpoint
data was distributed as a uniform random variable over the first
sampling interval. The same random time shift was used for all gages
for a single storm. This simulates the effects of a random start time
within a given uniform sampling time interval. An interpolation

procedure has been developed to describe the spatial and temporal variability of rainfall input to individual plane elements.

Twenty runoff-producing storms were used in this study. KINEROS was first run for each storm for each watershed using the breakpoint rainfall as input. Runs for each storm were then repeated using rainfall sampled at 5, 10, 15 and 20 minute intervals. In many modeling applications we are interested in reproducing the distributions of peak rates or volumes so the sampling effects were examined by creating quantile-quantile (Q/Q) plots of sampled versus breakpoint results. If the points on the Q/Q plot lie along the 1:1 line, then the two populations are identical. If they depart from the line in a systematic manner, additional insight can be gained.

Results

The effect of watershed size on appropriate rainfall sampling rate is demonstrated by the ranked peak rate Q/Q (dashed lines are +/- 10% slope of 1:1 line) plots shown in Fig. 1 for impervious watershed representations. As the sampling intervals increase, peak runoff rates are reduced. For the LH-106 watershed, which has a kinematic time to equilibrium on the order of 3 minutes, even the 5 minute sampling time results in a serious bias in calculated peak rates. The 5 minute sampling time is marginal for LH-104 but appears to be perfectly adequate for WG-11.

In Fig. 2 the same plots are presented for infiltrating cases. The same trends are apparent, but infiltration tends to make the runoff rates slightly less sensitive to rainfall sampling rate for the small watersheds but more sensitive for WG-11 for comparable ranges of peak rates (0-20 mm/hr on WG-11). The 5 minute sampling rate is now acceptable for LH-104. Note also that one event with rainfall sampled at 10 minutes has a higher peak rate than that calculated with breakpoint data. This phenomenon appears to be related to the way the infiltration algorithm handles a rainfall hiatus. In contrast, the 15 minute sampling interval, which was adequate for an impervious WG-11 is no longer adequate. An examination of the runoff volumes (not shown) reveals that they decrease with increasing sampling interval.

Harley et al. (1970) recommended a sampling interval equal to the basin kinematic time to equilibrium divided by 3.2. Using this criterion the calculated sampling intervals for LH-106, LH-104 and WG-11 based on a rainfall excess rate of 2 inches/hr (50.8 mm/hr) are 1.0, 2.7, and 13.3 minutes respectively. This rainfall excess rate is reasonable for the two smaller watersheds but is very conservative for WG-11 because rainfall excess rates per unit area decrease with basin size. The criterion of Harley et al. (1970) appears to be appropriate for the LH watersheds but is too large for WG-11, apparently due to the infiltration effect.
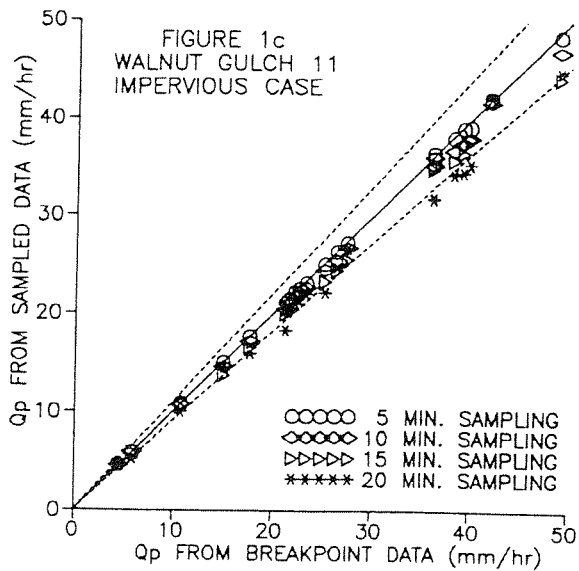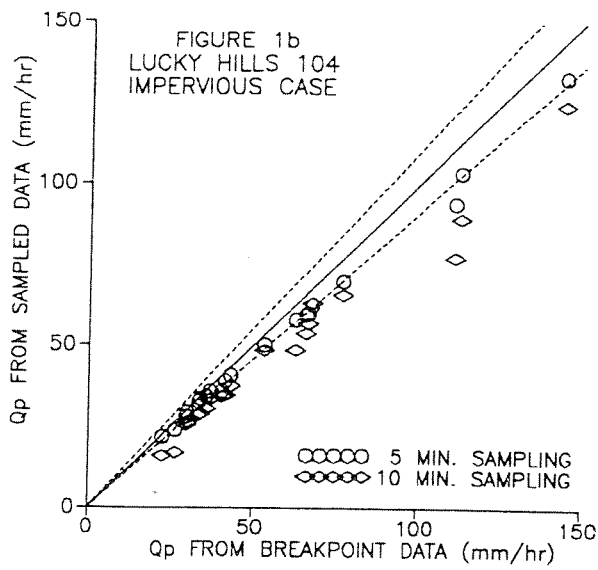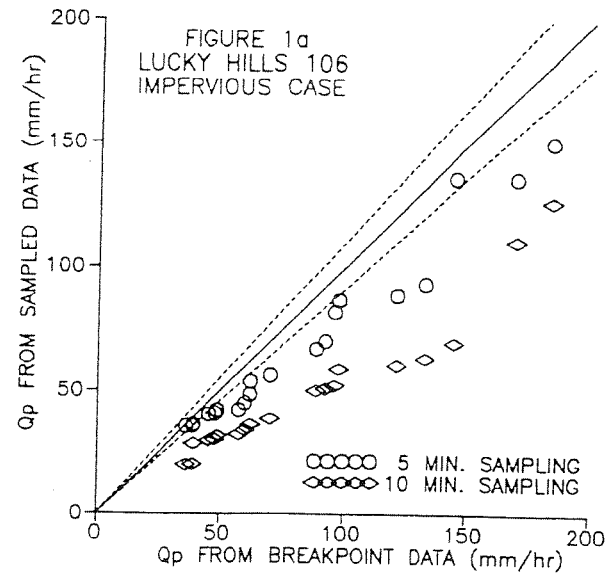
FIGURE 1a
LUCKY HILLS 106
IMPERVIOUS CASE

OOOOO 5 MIN. SAMPLING
◇◇◇◇◇ 10 MIN. SAMPLING

Qp FROM SAMPLED DATA (mm/hr)

Qp FROM BREAKPOINT DATA (mm/hr)

FIGURE 1b
LUCKY HILLS 104
IMPERVIOUS CASE

OOOOO 5 MIN. SAMPLING
◇◇◇◇◇ 10 MIN. SAMPLING

Qp FROM SAMPLED DATA (mm/hr)

Qp FROM BREAKPOINT DATA (mm/hr)

FIGURE 1c
WALNUT GULCH 11
IMPERVIOUS CASE

OOOOO 5 MIN. SAMPLING
◇◇◇◇◇ 10 MIN. SAMPLING
▷▷▷▷▷ 15 MIN. SAMPLING
***** 20 MIN. SAMPLING

Qp FROM SAMPLED DATA (mm/hr)

Qp FROM BREAKPOINT DATA (mm/hr)
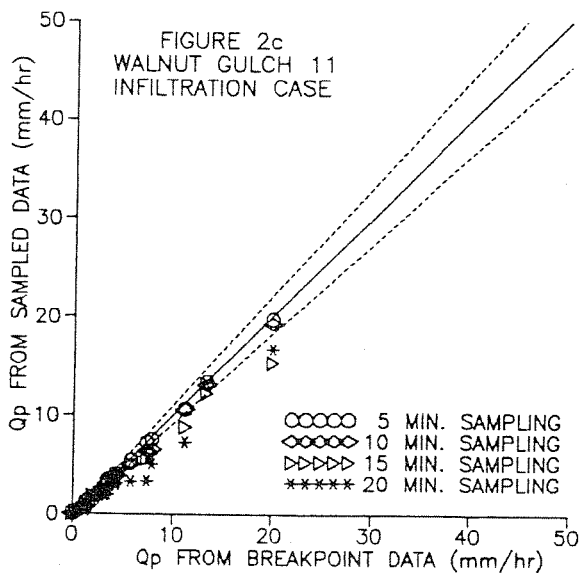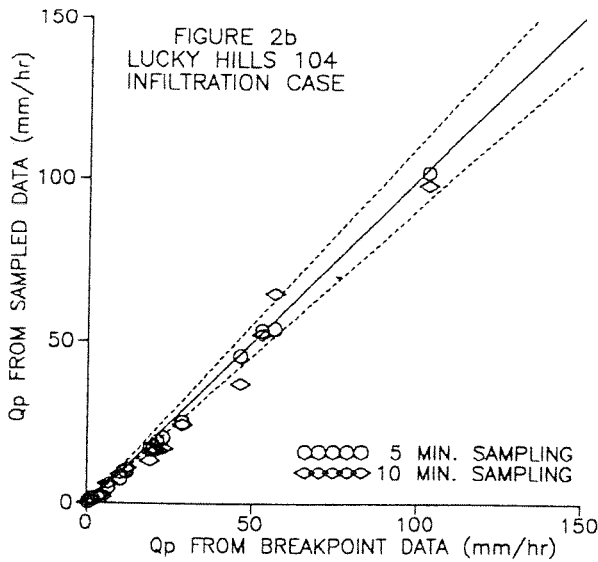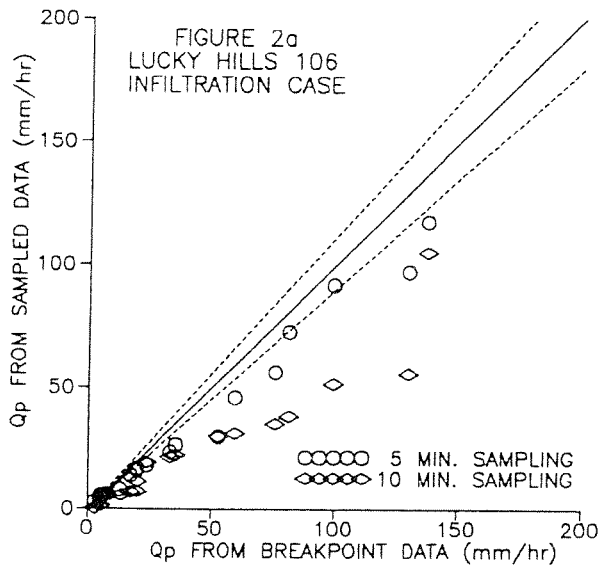
Figure 1 — Impervious Cases

Figure 2 — Infiltrating Cases

Discussion and Conclusions

The appropriate rainfall-sampling interval for aridland watersheds depends on many factors including the temporal pattern of rainfall intensity, watershed response time and infiltration characteristics. The results of this study in which real watershed geometry was used agree with the analysis made by Wooliser (1986) based on runoff from a single plane. It is recommended that either breakpoint rainfall data or data sampled at uniform time increments according to the criterion of Harley et al. (1970) be used for watersheds with equilibrium times smaller than about 15 minutes and that a maximum interval of 5 minutes be used for more slowly responding basins.

References

Bras, R. L., 1979. Sampling of interrelated random fields: The rainfall-runoff case. Wat. Resour. Res. 15(6):1767-1780.

Eagleson, P. S., and W. J. Shack, 1966. Some criteria for the measurement of rainfall and runoff. Wat. Resour. Res. 2(3):427-436.

Goodrich, D. C., 1990. Geometric simplification of a distributed rainfall-runoff model over a range of basin scales. Ph.D. Diss., Dept. of Hydrol. and Water Resour., Univ. of Ariz., Tucson, AZ.

Harley, B. M., F. E. Perkins, and P. S. Eagleson, 1970. A modular distributed model of catchment dynamics. Report No. 133, Ralph M. Parsons Laboratory, Dept. of Civil Engr., M.I.T., Cambridge, Mass.

Knisel, W. G. (ed.), 1980. CREAMS: A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems, U. S. Dept. of Agric., Sci. and Ed. Admin., Cons. Research Report 26, 643 pp.

Nash, J. E., and J. V. Sutcliffe, 1970. River flow forecasting through conceptual models, J. of Hydrol., 10:282-290.

Rawls, W. J., D. L. Brakensiek and K. E. Saxton, 1982. Estimation of soil water properties. Trans. ASAE, 25(5):1316-1320, 1328.

Renard, K. G., 1977. Past, present and future water resources research in Arid and Semiarid areas of the Southwestern United States. Australian Instit. of Engr., 1977 Hydrology Symp., Brisbane, p 1-29.

Smith, R. E. and J.-Y. Parlange, 1978. A parameter efficient hydrologic infiltration model. Wat. Resour. Res. 14(3):533-538.

Woolhiser, D. A., 1986. Sensitivity of calculated peak-runoff rates to rainfall-sampling frequency. IAHS Publ. No. 158, pp. 161-171.

Woolhiser, D. A., R. E. Smith and D. C. Goodrich, (1990). KINEROS, a Kinematic Runoff and Erosion Model: Documentation and Users Manual. U.S. Dept. of Agriculture, Agricultural Research Service, ARS-77.