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THE POTENTIAL FOR IMPROVING LUMPED PARAMETER MODELS USING REMOTELY SENSED DATA

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1. INTRODUCTION

Lumped parameter models are based upon using averaged input information for an entire drainage basin. Precipitation is the most important input data in flash flood forecasting. Simulation errors in estimating runoff may be significant if the precipitation varies spatially and temporally within the basin. Excess precipitation may be considerably underestimated in these cases. To reduce errors in simulated runoff, the model parameters that controll infiltration must be shifted from their 'actual' values, making analyses of their physical reliability difficult.

Breaking a basin into a number of sub-basins is commonly used to take into account variations of input data and basin characteristics. It is often necessary to use a large number of sub-basins and to calibrate parameters each of them using a limited number of outlets with observed runoff. An additional difficulty is that the number and location of sub-basins may also vary from one individual storm to another.

Remote sources of data, such as radar or satellite, provide estimates of precipitation values with high resolution in space and time. However, it is difficult to use this data in lumped parameter models. This data appears to be superfluous for them. There are at least three factors which can increase the accuracy of hydrograph simulations by lumped parameter models (Koren,1991): (a) better estimates of mean areal precipitation totals, (b) a reduction of time steps, and (c) use of variability characteristics of precipitation.

It is easy to make use of the first two factors in lumped models. Benefits derived from runoff simulations will depends on quality of radar calibration. Borovikov (1969) stated that accuracy of mean areal precipitation estimates for basins of less than 5000 sq. km made by radars calibrated using only historical data was 35-45% higher than accuracy levels when mean values were estimated by raingages, specifically if there was one gage per 1000 - 2000 sq. km. For operationally on-line calibrated radars, the advantage was 50-60% (Berjulov,1975). One can expect that the accuracy of precipitation estimates by radars such as the NWS WSR-88D, when utilizing lumped parameter models, will increase significantly.

This paper will present a lumped parameter model using distribution functions of precipitation.

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2. THE LUMPED PARAMETER MODEL

The model takes into account basic thermodynamic processes in the unsaturated zone and can be used for making calculations of rainfall, snowmelt, and rainfall and snowmelt induced flash floods. It consists of four main elements (Koren,1991): water inflow to a basin, soil freezing and thawing, water losses and redistribution, and transformation of surface and sub-surface runoffs.

2.1 Water inflow

Precipitation state is assumed to be rain if the air temperature is above a critical value, usually 32°F, althouth there is an altitude dependence. Below that value the assumption is snow. In the original model an areal distribution of rainfall over the basin was considered homogeneous. A gamma distribution was used for snow cover. Snowmelt rate was calculated by degree-day factor. The water retention capacity of snow was assumed to be constant.

2.2 Soil freezing and thawing

The heat transfer equation was

approximated based upon the following assumptions: no heat transfer across the lower boundary of the soil, a linear temperature distribution within the soil, and no participating in heat-transfer processes by percolating water.

2.3 Water losses and redistribution

Evapotranspiration, infiltration, percolation into deeper layer, and surface and sub-surface flow were taken into account to simulate water balance. Actual evapotranspiration were calculated as a function of air and soil moisture deficits. The infiltration rate depended on liquid moisture and ice content within upper soil layers. The effect of impermeable soil layers which can develope during the snowmelt process was described by using a distribution function of soil freezing depth.

2.4 Surface and sub-surface runoff transformation

Nash's linear cascade model with two-parametric influence function (Nash,1957) was used for both surface and sub-surface runoff.

3. MODEL REVISION TO USE REMOTELY SENSED DATA

In the original model, actual infiltration and, as a result, excess precipitation were held constant for the entire basin. However, actual infiltration at each point of the basin, I_i, should depend on precipitation at that point. If I_p is a mean areal potential infiltration calculated by the model, P is the mean areal precipitation, and P_i is the precipitation at the ith point[1]

$$I_i = \begin{cases} I_p\,, & P_i/P > I_p/P \\ P_i\,, & P_i/P \le I_p/P \end{cases} \qquad (1)$$

In this case, expectation of actual infiltration equals:

$$M_t[I] = I_p(t) \int_{I_p(t)/P(t)}^{\infty} f(K_p,\, t)\, dK_p +$$

$$P(t) \int_0^{I_p(t)/P(t)} K_p(t)\, f(K_p,\, t)\, dK_p \qquad (2)$$

where $f(K_p,t)$ is a probability density function of the relative value of precipitation, $K_p(t)=P_i(t)/P(t)$, at time t.

It is usually impossible to apply this equation using only a conventional land based raingage network because the spatial distribution of precipitation is incompletely measured. High resolution remotely sensed data provides such information, and allowes us to obtain a distribution function at any time step, to apply equation (2). This approach will be less sensitive to errors if areal averaged precipitation estimated by raingages are included. The approach assumes that errors of remote measurements are normally distributed.

An analytical solution can be derived for some distribution functions. For a gamma distribution with integer value of the parameter $\alpha=1/C_v^2$ equation (2) becomes

$$M_t[I] = I_p(t)\, e^x \sum_{i=1}^{\alpha} Y_i + P(t)\, (1 - e^x \sum_{i=0}^{\alpha} Y_i) \; (3)$$

$$Y_i = (-x)^{\alpha-i} \frac{1}{(\alpha-i)\,!}\,; \qquad x = -\frac{\alpha I_p(t)}{P(t)}$$

Relative differences of infiltration rate with and without taking into account variation of precipitation

$$\Delta = \frac{|I_p(t) - M_t[I]|}{I_p(t)}$$

can be calculated using equations (1) and (3). Simple equation can be derived if α=1, an exponential distribution:

$$\Delta = \begin{cases} 1 - \dfrac{P(t)}{I_p(t)}\,(1 - e^{x/\alpha}), & P(t) > I_p(t) \\ e^{x/\alpha}, & P(t) \le I_p(t) \end{cases} \qquad (4)$$

Differences, in this case, depend on the partition of mean areal precipitation and potential infiltration. The maximum difference is 37%, and occures when $I_p(t)=P(t)$. The smaller the variation in precipitation, $\alpha \rightarrow \infty$, the smaller the relative difference. Relative differences for selected values of the parameter α calculated by equation (3) are presented in Table 1. If the coefficient of variation of precipitation equals 0.14, (α=50), differences are rather small for the all values of $I_p(t)/P(t)$.

TABLE 1. Relative differences (%) of infiltration rate simulated with and without taking into account precipitation distribution for selected values of the parameter α

α	$I_p(t)/P(t)$				
	0.7	0.9	1.0	1.1	1.3
1	27	34	37	35	26
2	16	24	27	25	16
3	11	19	22	20	12
5	6	14	18	15	7
10	2	9	13	10	3
50	0	2	6	3	0

4. APPLICATION

This approach has been applied to the Medvenka experimental basin (U.S.S.R.). It has an area of 36.5 sq.km. Gridded fields of precipitation estimates were obtained from a one-wave meteorological radar equipped with an automated system of data processing (Berjulov,1975). Data were available for 2.5x2.5 km grid cells at every 15 min. Hourly precipitation totales when compared to the closest grid cell did not differ significantly from raingage values. In 90% cases differences did not exceed 15%. There were several instances when values differed by more than 100%.

Model runs used an hourly time step. An analyses of the spatial variability of hourly precipitation appears to be approximated by an exponential distribution, but the parameter of distribution can vary significantly for different time intervals, Figure 1. In addition, a more general gamma distribution was also used as approximation of the empirical distribution. The parameter of distribution was calculated for each time step based on the variability of hourly precipitation.

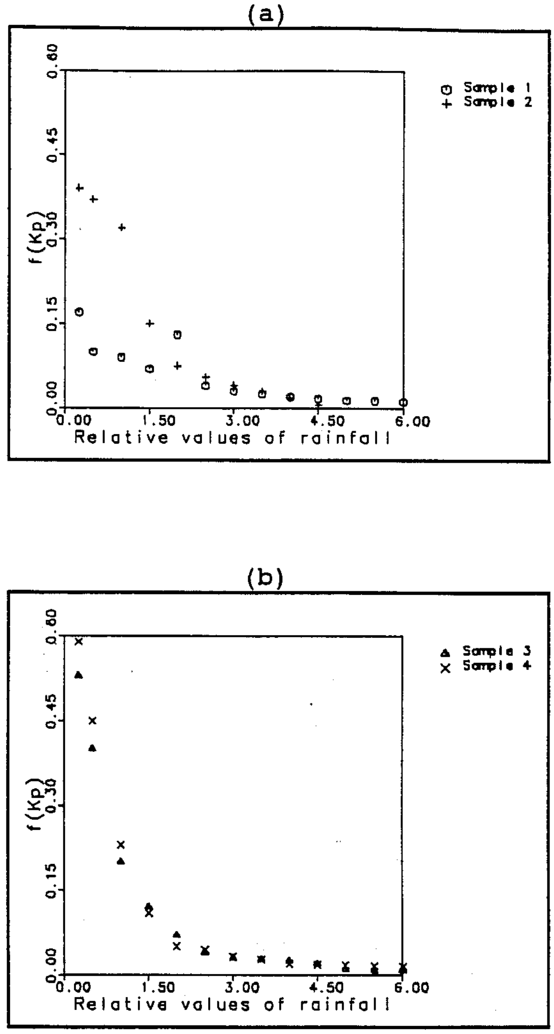

Figure 1. Distribution of relative values of rainfall at different times.

The simulated hydrographs were compared with hydrographs obtained from the same model with mean areal precipitation. Using the same model parameters and including calibration using raingage estimated mean areal precipitation,simulated discharges that accounted for the variability of precipitation generally overestimated output when compared with observed hydrographs.

To refine the simulated hydrographs, one parameter of the model, the hydraulic conductivity of saturated soil, was recalibrated using gridded precipitation estimates from radar (see Figure 2). Simulated hydrographs using this new parameter value were closer approximation of observed hydrographs, especially for the very sharply shaped hydrographs (see Figure 2). More importantly however the value of hydraulic conductivity in this case, $3 \cdot 10^{-4}$ cm$\cdot$s^{-1}, was closer to the mean value estimated in field experiments for this soil type, $5 \cdot 10^{-4}$ cm$\cdot$s^{-1}. This approach using averaged precipitation in space and time (5 sq. km areas and one hour) showed no significant difference in hydraulic conductivity. At the same time, the hydraulic conductivity obtained for uniformly distributed precipitation was ten times less than the field experiment value of $4 \cdot 10^{-5}$ cm.s^{-1}.

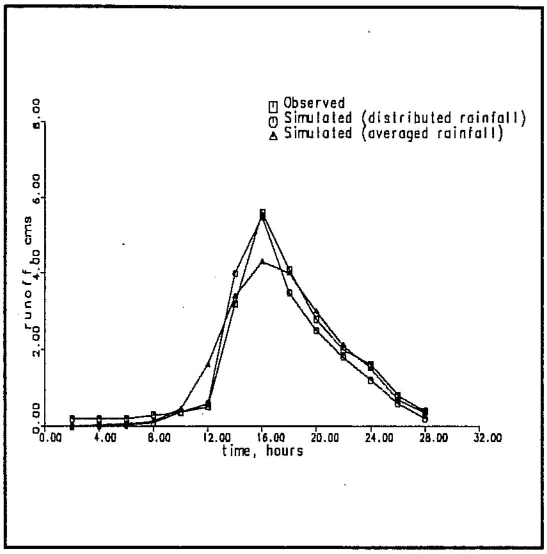

Figure 2. Observed and simulated hydrographs. The Medvenka river, July 27-28, 1974.

5. CONCLUSIONS

An approach based on the use of a non-stationary distribution function of precipitation desplays potential for assimilating high resolution remotely sensed data by lumped parameter model. The advantage of this approach is not only that the accuracy of simulated hydrographs is greater, but that the value of conductivity, one of the most important model parameters, is much more reasonable.

This approach can be incorporated into any lumped parameter model which is based on the calculation of excess rainfall. The parameters which control infiltration must be recalibrated as needed.

Additional analyses is needed to extend this approach to larger basins because heterogeneity of precipitation may cause some problems over larger basins. No rain areas, i.e., areas with zero precipitation, should be excluded when the distribution function parameters are estimated.

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