AN OVERVIEW OF THE USDA-ARS CLIMATE CHANGE AND HYDROLOGY PROGRAM AND ANALYSIS OF MODEL COMPLEXITY AS A FUNCTION OF BASIN SCALE

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ABSTRACT

The Agricultural Research Service (ARS) of the U.S. Dept. of Agriculture has initiated a global change, water resources and agricultural research program containing several key hydrologic elements. These elements and the participating locations are presented with a brief overview of the ARS experimental watersheds program. Within this program the author has addressed the issue of geometric model complexity (watershed discretization) for distributed rainfall-runoff models as a function of basin scale (Goodrich, 1990). Distributed rainfall-runoff models are gaining widespread acceptance; yet, a fundamental issue that must be addressed by all users of these models is definition of an acceptable level of geometric model complexity. The level of geometric model complexity is a function of basin and climatic scales as well as the availability of input and verification data. Equilibrium discharge storage is employed to develop a quantitative methodology to define a level of geometric model complexity commensurate with a specified level of model performance. Equilibrium storage ratios are used to define the transition from overland to channel-dominated flow response. The methodology is tested on four subcatchments in the USDA-ARS Walnut Gulch Experimental Watershed in Southeastern Arizona. The catchments cover a range of basin scales of over three orders of magnitude. This enabled a unique assessment of watershed response behavior as a function of basin scale for surface runoff dominated catchments. High quality, distributed, rainfall-runoff data were used to verify the model (KINEROSR). Excellent calibration and verification results provided confidence in subsequent model interpretations regarding watershed response behavior. An average first order channel support area of roughly 15% of the total basin area is shown to provide a watershed discretization level that maintains model performance for basins ranging in size from 1.5 to 631 hectares (ha). The impacts of infiltration and channel losses on runoff response increase with increasing watershed scale as the relative influence of storms is diminished in a semiarid environment such as Walnut Gulch. In this semiarid environment, watershed runoff response does not become more linear with increasing watershed scale but appears to become more nonlinear.

Key Words: Experimental Watersheds, Distributed Rainfall-Runoff Modeling, Semi-arid, Basin Scale, Geometric Model Complexity, Response Linearity

THE USDA-ARS CLIMATE CHANGE AND HYDROLOGY PROGRAM: AN OVERVIEW

As part of an overall USDA Global Change Strategic Plan (USDA, 1990) the Agricultural Research Service Global Change, Water Resources and Agricultural (ARS-GCWRA) research program has been initiated with two primary research program elements. They are:

1) Predicting water and energy fluxes to, within and from managed ecosystems
2) Evaluating scale effects of hydrologic processes.

This research program will build on the unique expertise, facilities, and related research programs in ARS. Additional facilities developed by ARS for evaluating the economic and environmental impacts of climate change are a network of experimental watersheds located in the major climatic regions and ecosystems within the United States (Burford et al., 1983). ARS research locations taking the lead in this research effort are located in Beltsville, Maryland; Boise, Idaho; Durant, Oklahoma; Ft. Collins, Colorado; Temple, Texas; and Tucson, Arizona. Within the ARS experimental watershed network, intensive monitoring of a variety hydro-meteorological variables, similar to Japanese efforts (Muraoka and Hirata, 1988), has been conducted for 30 to 50 years. The watershed within this network in a arid/semi-arid climate is the Walnut Gulch Experimental Watershed (150 km^2, initiated in 1954) located in southeastern Arizona (Renard, 1970). This watershed and others within the network typically contain a number of monitored subwatersheds bridging a large range of basin scales. Within the Walnut Gulch watershed research was carried out to attempt to determine the proper level of basin discretization (geometric model complexity) over a range of basin scales from 0.36 to 631 ha.

PROBLEM STATEMENT

A fundamental issue that must be addressed by any user of distributed rainfall-runoff models is definition of an acceptable level of watershed discretization or geometric model complexity. Few if any quantitatively derived criteria exist to define the level of basin discretization. The basin discretization level relates directly to the degree of data averaging and parameter lumping that is permissible for a specified range of time-space scales. A scale-based quantitative framework to predict the proper level of geometric model complexity for a given modeling objective would allow one to simplify modeling and data collection efforts. This would enable the practitioner to introduce model complexity and collect data only to the extent that is required to meet his or her needs.

APPROACH

Beck (1987) clearly stated that there are few practical case studies with extensive field data sets that address the problem of the appropriate level of geometric model complexity for adequate modeling. The Walnut Gulch Experimental Watershed operated by the USDA-Agricultural Research Service provided the necessary high-quality, long-term rainfall, runoff, topographic, and soils data over a range of scales that was used in this study. Four subwatersheds within Walnut Gulch were selected for the study. These four watersheds allowed an examination of basin dynamics over a range of nearly four orders of magnitude of basin area (0.36 to 631 ha). Over this range of scales, both precipitation and channel morphology change significantly and their effects on basin discretization can be assessed.

To more formally focus the geometric model complexity investigation, the following thesis is offered.

> THESIS: At a certain basin scale, a maximum allowable size of overland flow elements will exist so that elements below this size will adequately model basin runoff (in terms of peak flow and runoff volume) and elements above this size will not.

This hypothesis translates directly into the required model drainage density. If a specific drainage density must be maintained, it implies that the channel processes being modeled at that scale are important. This provides an indication of the transition between overland and channel dominated flow. Criteria to define an allowable size of an overland flow element is set by specifying a level of model performance by way of an objective function. This establishes if model equivalence exists for a complex (highly discretized) versus simple geometric basin representation.

KINEROSR (Woolhiser et al., 1990) is the physically-based model used in the investigation. This model employs a kinematic wave approximation to the dynamic flow equations for both overland and channel flow. The model treats both overland flow and ephemeral channel infiltration with a realistic approximation of the Richard's equation. Other implementations of kinematic routing are also used among practitioners and other government agencies, however, all of these model implementations, the key issue of the proper level geometric model complexity (basin discretization) must still be addressed.

The level of geometric rainfall-runoff model complexity cannot be treated in isolation. Both basin scale and climatic (rainfall) variability as well as infiltration losses must be considered for a realistic treatment. Therefore the investigation proceeds from small to large scale. On the scale of a single overland flow plane, small-scale infiltration studies were conducted to better understand the interaction between climate and soils.

Moving to the scale of an elementary, first order, watershed, the role of soils, overland flow and channel processes on attenuating rainfall distributions in the transformation of rainfall to runoff was investigated. The findings from this phase of the study lead directly to the development of an objective simplification strategy.

Before application of this strategy, thorough calibration and verification for each of the four watersheds was conducted to insure model confidence and provide confidence that subsequent model interpretations reflect actual watershed behavior. With a high degree of confidence established, the geometric simplification strategy was assessed over a range of basin and climate scales to establish an easily derived level of basin discretization. In addition, the domination of hydrologic processes on watershed response as a function of basin and climate scales was analyzed (Goodrich, 1990).

Further background and the significant scientific contributions from each of the major research thrusts outlined above is presented following a review of the primary literature pertinent to this investigation.

LITERATURE REVIEW HIGHLIGHTS

Because geometric model complexity cannot be considered in isolation of other central rainfall-runoff modeling issues the following important subject areas were also reviewed. These include: (1) basin scale, (2) model process complexity, (3) hydrologic process domination and (4) spatial and temporal variability.

Geometric Simplification of Distributed Models

Geometric model simplification has been examined by several authors under situations ranging from urban to natural watersheds, with and without infiltration and routing. Shanholtz et al. (1981) noted that no criteria exist to determine the degree of permissible data averaging and evaluated the effect of several levels of watershed discretization on model results. Takasao and Shiiba (1988) incorporated a "geometric pattern function" into a kinematic wave model and then address lumping of stream order network sections.

Lyngfelt (1985) studied the simplification of urban basins without considering infiltration or the linkage to scale. For model simplification, he choose to maintain the kinematic time to equilibrium (T_{eq}). However, T_{eq} is a function of the rainfall intensity and is therefore storm dependent. This is a major distinction between Lyngfelt's work and the present study which maintains equilibrium storage in such a way that the procedure is storm independent.

Zaghloul (1983) studied the catchment discretization issue using the SWMM (Storm

Water Management Model) model in an urban setting. In this study, the importance of maintaining storage between the complex and simple watershed representation is stressed. But like Lyngfelt's (1985) simplification procedure, Zaghloul's (1983) procedure suffered from a lack of objective rules to obtain hydraulic and/or geometric parameters for the simplified system.

Lane et al. (1975) presented the most thorough study of the geometric complexity issue for rainfall-excess routing. Their study proceeds in the opposite direction of the present study by starting with a simple overland flow plane and then increasing the complexity by increasing the drainage density. In the work by Lane et al. (1975), drainage density is used as an overall goodness-of-geometric-fit measure and is compared to hydrograph goodness-of-fit measures to assess the tradeoffs in simplification. In their simplification process, an a priori prediction of how the roughness will distort is predicted by a regression scheme. The current study derived an analytic rule to predict the roughness distortion. They concluded that as geometric complexity is increased, diminishing gains in model performance are attained.

The current study addresses simplification over a range of scales while treating infiltration and spatial rainfall field definition in a relatively detailed manner and develops objective procedures for geometric model simplification. In addition, it sheds light on the relative importance of hydrologic processes as a function of scale.

The Importance of Scale

The importance of scale in the hydrologic process has received great attention in recent years within the literature. An entire issue of the Journal of Hydrology (August 1983) was devoted to this topic. In the introduction to the issue, the guest editors, Rodriguez-Iturbe and Gupta stated, "The understanding of the collective type of behavior which takes place in the basin (at basin scale) is one of the most challenging and crucial problems in hydrology." The issue of scale remains crucial with the increasing need to address hydrologic problems in a global context to understand effects of possible global climate change.

Models and Model Complexity

For specified modeling objectives, one must pose the simple question: How complex must a model be to capture the essential system dynamics? Common logic leads us to conclude that the more complex the model, the better. However, several studies indicate just the opposite. Beck (1987) noted that a poor data set could explain this type of model behavior, as greater numbers of highly uncertain parameters are introduced, an amplification of model error takes place. Every effort was made is this study to avoid this situation by careful data screening.

Evidence of Process Domination

Process model simplification, by way of identification of hydrologic process (infiltration, channel routing, etc.) domination, and geometric simplification are not entirely distinct issues. A major factor in geometric simplification and initial basin discretization hinges on the fundamental distinction between processes of overland flow and channel flow. Kirkby (1988) emphasized this point stating "there is no unambiguous method for determining the exact position of channel heads. . . A satisfactory hillslope hydrological model must, therefore, be insensitive to the exact density of channels chosen."

Spatial and Temporal Variability

Within virtually any basin, various levels of both spatial heterogeneities and temporal variability are encountered. Loague and Freeze (1985) attributed poor model performance of a physically-based model to scale problems associated with the spatial variability of rainfall and basin soil properties. Adequate representation of spatial and temporal variability is essential if realistic conclusions regarding geometric model complexity are to be derived.

An attempt is made in this study to address each of the major research thrusts examined in the literature review in concert as they pertain to the central question of the proper level of distributed geometric model complexity.

CONCLUSIONS

Because of the fundamental role of infiltration on basin runoff response a detailed analysis of small-scale infiltration variability within an overland flow element was conducted over a range of soil and climatic scales. Representation of infiltration heterogeneities is typically accomplished by further basin discretization. One commonly used criteria is the "Hydrologic Response Unit". In this concept, discretization takes place until a unique combination of soil type, vegetation, and land use is achieved. The flaw in this procedure is the fact that, even within a single soil type, large variations in soil hydraulic properties occur over length scales on the order of meters. The current research resulted in a major advancement in model treatment of this observed small-scale infiltration variability. It was reported first in Woolhiser and Goodrich (1988) and is summarized below.

Because infiltration variability cannot be treated via discretization on the scale of meters, a simple, straightforward method was developed to treat it in a distribution sense by assuming the saturated hydraulic conductivity (Ks) is lognormally distributed. This assumption is well supported by field evidence from a number of investigations and the method only introduces one additional model parameter (the coefficient of variation of Ks). This method of representing variability was compared to other treatments and was found to be relatively general and robust.

The study resulted in an important conclusion that an equivalent average effective Ks value cannot be derived for infiltration excess dominated (Hortonian) runoff generation under time varying rainfall conditions. This occurs because the fluctuation of the rainfall rate in relation to spatially varied infiltration capacity causes a unique time and area-dependent infiltration history. This underscored the importance of soil-climatic interactions in runoff generation as the effects of Ks variability are more pronounced for small runoff events where watershed characteristics (nonlinearity of infiltration) dominate runoff response. For large storms, the climate becomes dominant and overwhelms watershed infiltration variability.

The spatial scale of the research was then enlarged to consider runoff response dynamics of an elementary basin. Dimensionless parameters describing the relative effect of the hydrologic processes of infiltration, overland flow routing and first order channel routing were varied over a wide range of typical conditions for the elementary basin. Monte Carlo analysis was then conducted with a variety of dimensionless parameter combinations to assess the relative impact of each process on runoff response over a distribution of measured storms (climatic scales).

The impacts were measured by examining the attenuating influence of the elementary basin on several temporal rainfall disaggregation schemes (Woolhiser and Goodrich, 1988) by measuring differences in the resulting model runoff distributions. If a simple rainfall disaggregation scheme (i.e. constant intensity) reproduces the same runoff distribution obtained from measured rainfall intensities the watershed system is highly damped as the measured rainfall intensities are attenuated by the elementary basin. The Monte Carlo analysis enabled the attenuating effects of the three hydrologic processes to be separated.

The primary conclusion of this analysis indicated infiltration and overland flow routing, in order of importance, have a much more pronounced effect in decreasing the difference between empirical (from disaggregated rainfall) and actual peak flow runoff distributions than do channel effects. This highlights the persistent dominance of infiltration and overland flow processes for the various cases of the elementary watersheds examined. The secondary influence of the channel in the elementary basin suggested incorporating channel routing effects into the overland flow routing geometry and led to the geometric model simplification methodology.

The differentiation of overland flow and channel elements (geometric model complexity) for distributed rainfall-runoff modeling
is intimately linked to the base map used to discretize the watershed via the mapped channel network. However, the channel network on any given base map is map scale dependent as illustrated in Figure 1. Typically, for a large scale map, a higher order channel network (higher drainage density) is apparent. This results in a more complex model representation (more overland flow and channel elements). As map scale decreases, channel network order typically decreases, resulting in a simpler model representation. The primary distinction between the two representations is due to the modelers' perceived reality of the water-shed as interpreted through the map. Avoidance of the drainage density/map scale relationship cannot be accomplished by using stream networks generated from Digital Elevation Models (DEM) data as an a prior definition of the support area at the head of a first-order channel must be made. This effectively fixes a drainage density and again partitions overland flow and channel processes.

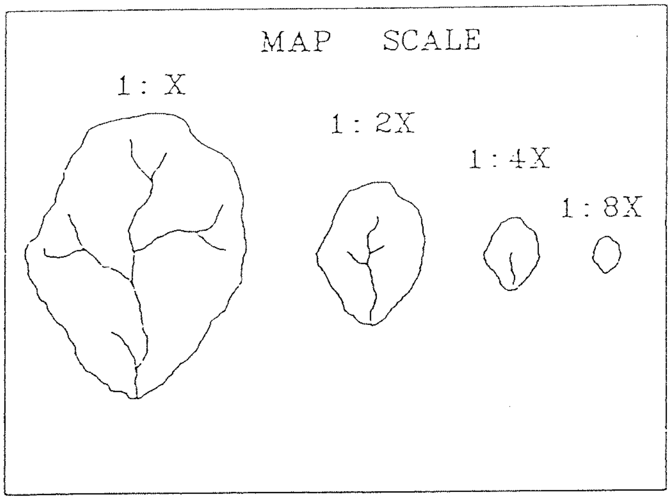

Figure 1. Basin Representation as a Function of Map Scale

It was postulated that, as the map scale is incrementally reduced, the basin channel order will decrease incrementally. In other words, the first-order channels are no longer observed at some the smaller map scale; therefore, what were elementary watersheds are now represented by single overland flow planes. As the drainage density or stream order is incrementally reduced, the first order channels and their contributing areas are replaced by overland flow model elements resulting in geometric model simplification. The degree of allowable geometric model simplification, measured in terms of some specified level of model simulation error, is hypothesized to be a function of basin scale and is discussed later.

To systematically assess changes in model performance during simplification, the following objective, reproducible rules were developed to simplify an elementary watershed to an equivalent overland flow plane: (1) Maintain subwatershed area, (2) Maintain the mean overland flow length, (3) Compute slope and soil parameters using area weighted averages, and (4) Maintain a characteristic response time by requiring the equilibrium storage from uniform rainfall to be equal on both the complex and simple system. The importance of equilibrium storage as introduced by Wu et al. (1978) and reiterated by Lane et al. (1975) and Takasao and Shiiba (1988) as a measure of characteristic basin response cannot be overemphasized. The equilibrium storage is defined as the volume of water on an impervious watershed representation under constant uniform rainfall at kinematic equilibrium. This measure integrates the effects of topography, slope convergence, and hydraulic roughness.

The simplification methodology is storm independent and enables the degradation in model performance to be quantified and assigned to specific hydrologic processes as simplification proceeds. Before assessing the impact of geometric model simplification, model confidence was established by thorough calibration and verification using observed data of exceptional quality for the four study watersheds.

Basin discretization for each of the four watersheds was carried out with the most detailed maps available to obtain a "most complex" representation of the watersheds. Detailed parameter sensitivity analysis over a range of observed storms, for parameters with high initial uncertainty (i.e. roughness, Ks, etc.), was then conducted to select parameters to vary during calibration. The parameters selected were uniform multipliers applied to the distributed, field estimated, values of Ks, the coefficient of variation of Ks and the hydraulic roughness. The calibration parameter space is, therefore, three-dimensional. The small number of parameters is important as problems associated with parameter identifiability and interaction are avoided (Beven, 1989). Model performance was judged using the Nash-Sutcliffe coefficient of efficiency (E) for runoff volume and peak runoff rate. This measure was selected because it is dimensionless and is easily interpreted and has been used by a number of other investigators. If the model predicts observed runoff with perfection, $E = 1$. If $E < 0$, the model's predictive power is worse than simply using the average of observed values. A refined grid search was used to find a set of near optimum parameter multipliers for each basin over the calibration set of events. Verification was then conducted on an independent set of events. The results are contained in Table 1. Also note that LH-106 and LH-102 are nested within watershed LH-104 so that internal distributed model consistency and performance could be verified. As Beven (1989) pointed out, without observed data internal to the basin being modeled, reliable conclusions concerning internal basin dynamics inferred using a distributed rainfall-runoff model are impossible.

Table 1. Calibration and Verification Coefficient of Efficiency (forecast) for Runoff Volume (V) and Peak Rate (Qp) for All Study Basins (n = No. of Events)

Basin	Area (ha)	Calibrat. Eff. n	V	Qp	Verif. Eff. n	V	Qp
LH-106	0.36	10	0.98	0.95	17	0.98	0.79
LH-102	1.46	10	0.97	0.97	17	0.93	0.93
LH-104	4.40	9	0.97	0.98	16	0.99	0.96
WG11	631.00	10	0.86	0.84	20	0.49	0.16

The calibration and verification efficiencies are very good and are exceptional when compared to efficiencies obtained by other studies both in Walnut Gulch and on other experimental watersheds (Loague and Freeze, 1985). This instilled a high degree of confidence that model results and interpretations based on the model are soundly grounded in realism and reflect actual watershed runoff response behavior. Without such verification, any conclusions based on computer simulations, must be restricted to the realm of the computer.

With model confidence well established an assessment of catchment response over a range of scales and the geometric simplification methodology was carried out. Using the simplification rules, successive levels of simplification on each watershed was accomplished by reducing the stream order by one at each level of model aggregation.

Model degradation from using the simplified model geometry is measured by computing the coefficient of efficiency (E) for runoff simulations on the simplified system and comparing it against the "true", most complex, runoff simulations. Because the most complex runoff simulations are assumed to be true and error free, deviations of E from 1.0 represent a measure of model error due to geometric simplification. At each level of stream order reduction a number of geomorphic stream network measures were also computed. These measures are easily derived from a base map and for a specified level of model performance (E = 0.9) they can be computed based on an acceptable level of basin discretization (geometric complexity). The results of the analysis are contained in Table 2. For basins as small as LH-106 the attenuating influence of the basin itself is very small in relation to the climatic scales and therefore they can be entirely simplified to a single element. At a threshold between the basin area scales of LH-106 and LH-102 significant basin attenuation occurs for the climatic scales represented by the calibration event set. At this basin scale threshold, total basin geometric simplification imparts significant impacts on model performance as concentrated flow from channels has been replaced by overland flow processes. If overland flow no longer dominates the runoff measured at the basin outlet this degree of simplification cannot be made without serious model impacts. The transition from overland to channel dominated flow is an important threshold to define for both geometric simplification and hydrologic process studies. The equilibrium storage provides a key indicator to define this transition as it integrates the effects of topography, hydraulic roughness and slope convergence. When significant flow concentration occurs the equilibrium storage in the channels in relation to the total basin equilibrium storage will be large. The ratio of the equilibrium channel storage to total subbasin storage (ST_c/ST_t) at the downstream outlet of every model element was plotted as a function of the contributing area to each element. Stabilization of the (ST_c/ST_t) ratio corresponds very well with the allowable stream order reduction by simplification for watersheds LH-102, LH-104 and WG11 (Table 2). The stabilization of the (ST_c/ST_t) ratio, which can be computed a priori from basin geometry, appears to provide a good measure of the transition from overland to channel dominated flow for the topography and channel morphology of the Walnut Gulch study basins. The measures in Table 2 and the (ST_c/ST_t) ratio provide a quantitative basis for defining an acceptable level of basin discretization.

Table 2. Suggested Levels of Geometric Model Complexity to Maintain Model Performance (Ec > 0.9)

Basin	Area (ha)	Number of Model Elements	Percent Average Support Area		Average Support Area (ha)	Drainage Density (m)
LH-106	0.36	1	100		0.36	0.0
LH-102	1.46	15	16	(6.00)	0.23	$1.52X10^3$
LH-104	4.40	11	12	(6.00)	0.53	$0.65X10^3$
WG11	631.00	17	16	(.00)	101.00	$1.32X10^3$

Numbers in parenthesis denote the standard deviation in percent

Another key conclusion resulted from individual hydrologic process sensitivity and input proportionality analysis over the range of study basin scales. Results indicate that in arid and semiarid regions runoff response does not become more linear with increasing basin scale. The evidence presented here would support the argument that runoff response becomes more nonlinear with increasing basin scale. This runs counter to observations and analysis made by several investigators who conclude that rainfall-runoff response typically becomes more linear as basin size increases. This may be largely due to the fact that effluent streams (runoff per unit area increases with increasing basin size; gaining watersheds) are much more widely studied. These watersheds also often have large, highly damped, base and throughflow runoff components that are not observed in Walnut Gulch. The increase in nonlinearity with increasing basin scale likely occurs in semi-arid regions because of the decrease in climatic influence relative to the increasing role of basin attenuating influence resulting from routing and infiltration losses.

In summary, the research has developed methods for a rigorous and realistic treatment of watershed response dynamics over a range of basin scales. Excellent modeling results were confirmed with observed runoff data on four watersheds. An objective method to quantitatively define the level of basin discretization or geometric model complexity was developed and applied. In addition, new light was shed on watershed response as a function of basin scale as runoff response linearity was not found to increase with increasing basin scale.

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PROCEEDINGS OF THE WORKSHOP ON THE EFFECTS OF GLOBAL CLIMATE CHANGE ON HYDROLOGY AND WATER RESOURCES AT THE CATCHMENT SCALE

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