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Catchment Hydrology

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INTRODUCTION

Although important progress has been made in catchment hydrology research, a detailed, process based, understanding of hydrologic response over a range of catchment scales (0.01-500 km^2) still eludes the hydrologic community. Selected research efforts, primarily from refereed journals, conducted by U.S. (or U.S. based) investigators for the period of late 1986 to 1990 are reviewed. The review is restricted to examination of entire catchment response rather than that of a single process component such as routing or infiltration. Therefore, point or plot scale studies, modeling of a single process or analyses more strictly focused on erosion and water quality issues are not addressed unless they provide insights into catchment hydrologic behavior. Research that will be addressed that does not fit neatly into the above criteria includes automation of catchment modeling efforts, as well as aspects of similarity and scale in catchment hydrology. Every attempt was made to conduct a thorough review of the literature. Our apologies to authors whose contributions have been overlooked.

DISTRIBUTED CATCHMENT MODELING

New model developments, model comparisons and assessment, treatment of variability, and automation are examined here. In the case where a new model is developed and evaluated, review comments relating to both aspects are included in the new model development section. Treatment of uncertainty is a central issue in both model development and evaluation and could be the basis of an entire review topic in its own right. The issue of uncertainty is not dealt with in detail here but two reviews on the topic by *Beck* [1987] and *Haan* [1989] are brought to the reader's attention.

New Model Developments and Improvements

New modeling efforts typically included generalizations of current models or addressed specific catchment submodel component weaknesses. *Thomas and Beasley* [1986a, 1986b] modified the ANSWERS (*Beasley* [1977]) model to include interflow so that it could be used for forested catchments and tested the model on seven watersheds (1.3 to 16 ha) in the southeastern US. Thirty meter square grid elements were used, apparently with no calibration. Regressions were used to compare observed and computed runoff volumes and peak flows. A significant relationship between modeled and observed peak flows was found but runoff volumes were underestimated on four of the seven watersheds.

Donigian [1986] pointed out that many catchment runoff and water quality models do not consider the relationship between water quality and agricultural practices and must include both field scale runoff and receiving water models with integration procedures. The paper describes an integration procedure for the EPA Hydrologic Simulation Program-FORTRAN (HSPF) to link surface runoff, subsurface flow (and quality) and receiving waters.

Hammer and Kadlec [1986] developed a mathematical model for overland flow through wetland vegetated areas. Long term simulations were conducted without significant volume balance errors with a one dimensional numerical algorithm. The algorithm was validated using data from a peatland located near Houghton Lake, Michigan.

Sivapalan et al. [1987], under a number of simplifying assumptions, presented a model for storm runoff production with spatially variable, temporally constant, rainfall on heterogeneous catchments which accounts for the effects of catchment topography on runoff production via the topographic index method of *Beven* [1986]. In a subsequent paper *Sivapalan et al.* [1990] generalized the geomorphic unit hydrograph approach (GUH) to account for spatially variable initial soil moisture conditions and partial area storm runoff response from both Hortonian and Dunne runoff generation mechanisms. Physically-based flood frequency estimates are then numerically generated from spatially variable, temporally constant storm realizations, for assumed catchment characteristics. Both approaches were used to investigate catchment scale and similarity issues and are referred to in a later section.

Hirschi and Barfield [1988a, 1988b] described a physically based erosion model which utilizes a two soil layer Green-Ampt model for infiltration. Kinematic runoff routing was used for rill routing and a dynamic surface storage routine treated depression storage. Sensitivity analysis and testing of the erosion model components rather than the hydrologic components were conducted. Predicted sediment yield is very sensitive to the Manning's n value used, reflecting the influence of shear stress in the sediment detachment and transport equations.

Ormsbee and Khan [1989] conceptually incorporated the mechanisms of micro and macropore flow into an "Extended Kinematic Storage Model" and evaluated the model on four steeply sloping forested watersheds with encouraging results. *Georgakakos and Kabouris* [1989] extended the GIUH watershed modeling approach to account for subsurface runoff as well as spatial variations in land use and rainfall. *Hartley* [1987] presented a simplified procedure to estimate hydrographs from hillslopes for use in an erosion model.

Zhang and Cundy [1989] develop a two-dimensional model for overland flow and infiltration which allows for spatial variations in roughness, infiltration and microtopography. The model was tested against characteristic solutions and experimental data. Simulations show that microtopography imparts the greatest variation in overland flow depth, velocity and direction.

Woolhiser et al. [1990] described KINEROS, a kinematic wave based distributed model for unsteady runoff and erosion computations. New aspects of the model included interactive infiltration (in

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which infiltration continues when rainfall ceases if uphill overland flow supplies water) and a variable width, interactive infiltration channel routing algorithm for channel losses. Application to various USDA-ARS Walnut Gulch Experimental (Arizona) subwatersheds was also presented.

The modeling efforts presented do offer some significant improvements but also point out several inconsistencies. The models developed by *Sivapalan et al.* [1987,1990] are specifically formulated to be scale independent. Yet their development does not include microtopography, the importance of which was pointed out by *Zhang and Cundy* [1989] and *Hirschi and Barfield* [1988a]. Clearly, the scale independent, unifying hydrologic principles discussed by *Dooge* [1986] have not been found and models must not be applied outside of the range of scales for which they where developed.

Model Comparisons And Assessment

Model comparisons were conducted both with and without observed data. In addition, more complex, distributed models, were used in some cases to acquire insights and to improve the performance of less complex, typically lumped catchment models. Alternatively, simple models were assessed to see how well they approximated more complicated rainfall-runoff models. Model assessments were restricted to those cases where simulations were compared to observed data using promising assessment methods.

Martinec and Rango [1989] examined a number of model assessment statistics. They suggested that modelers refrain from adding unnecessary evaluation criteria which do not provide new insight into model performance. With a limited number of criteria it is more likely that meaningful, not misleading, interpretations are made. A new method of model assessment using the stochastic integral equation method was developed by *Hromadka and McCuen* [1989a,b]. Confidence intervals can be developed with the proposed methodology with assumed probability distributions.

Rawls and Brakensiek [1986] compared runoff volume predictions made by a one-layer Green-Ampt model and the SCS curve number technique for 330 runoff events from 17 small, single land use, watersheds. Parameters were estimated without optimization. The Green-Ampt procedure performed better than the curve number method. *Ward et al.* [1989] tested seven runoff models for their ability to predict runoff peaks and volumes for four storms for each of 26 South African catchments ranging in size from a few hectares to 100 km^2. Land uses included urban, agricultural, forest and veld. Models included the rational method, three versions of American SCS methods, the ILLUDAS time area method, a distributed kinematic runoff model and a South African unit hydrograph method. Predictions were made without optimization of parameters. As might be expected, each method worked best for the particular land use condition it was designed to model. However the overall performance of all models was disappointing.

Clark's synthetic unit hydrograph method and the Extended Kinematic Storage Model were applied to three steeply sloping watersheds in Kentucky and West Virginia by *Khan and Ormsbee* [1988]. Both models were satisfactory when calibrated with existing data but only the Extended Kinematic Storage Model survived a series of simple validation tests. Both *Troutman et al.* [1989] and *Hetrick et al.* [1986] found that simulations from a simple model compared reasonably well with more complex model process representation.

Loague [1990] utilized additional information [*Loague and Gander*, 1990] on spatial variation of infiltration to re-evaluate a quasi-physically based rainfall-runoff model. The new data did not lead to significant improvements in model performance as measured by the Nash-Sutcliffe efficiency criterion. This finding may be due to the model's inability to deal with small scale infiltration variability within a model element.

Wilcox et al. [1989b] analyzed USDA-ARS Reynolds Creek Experimental Watershed (Idaho) data on four catchments (1-83 ha). Runoff was a small fraction of the total water budget for all watersheds and processes associated with frozen soil were significant. Both factors made it difficult to perform reliable modeling with SPUR (Simulation of Prod. and Util. of Rangelands). Subsequent application of the SPUR hydrology model [*Wilcox et al.*, 1989a] using prior calibration parameters on monthly runoff volumes for three subwatersheds in the Reynolds Creek Watershed (26 to 124 ha) were attempted. The Nash-Sutcliffe efficiencies for validation periods ranging from 4 to 12 years were 0.69, -1.40 and -0.24, indicating that mean monthly runoff was a better predictor than the model for two out of three watersheds. The authors concluded that the calibrated SPUR model can adequately predict the volume and timing of snowmelt runoff if snow cover and snowmelt is relatively uniform over the watershed. They emphasized that calibration is needed and that the model is not expected to be reliable for snowmelt predictions on rangeland watersheds.

The performance of two derived flood frequency distribution techniques was evaluated by *Moughamian et al.* [1987] for three watersheds. Each technique combined rainfall, infiltration and catchment response models parameterized by measured and assumed rainfall and catchment characteristics. They found that each method performed poorly in all of the watersheds even though good fits for individual events for the parameterized models were obtained. They suggested that the probabilistic rainfall and/or watershed response models may not be general enough to deal with the large range of events encountered for a 50-year flood frequency analysis and concluded that fundamental improvements are needed before derived flood frequency methods can be applied with confidence. This study reiterates the need for model calibration and verification over a range of event sizes and watershed conditions with reliable, well checked, distributed input-output data.

The following efforts investigated the use of complex models to understand and gain insight into simpler models. *Shen et al.* [1990] employed a distributed kinematic rainfall-runoff model with uniform rainfall using Horton's infiltration relationship on four hypothetical catchments with 48 assumed combinations of catchment characteristics. The time of concentration (T_c), peak runoff rate (Q_p), and time to peak (T_p) are numerically derived for each combination. Simplified, physically based, relationships for T_c, Q_p, and T_p are then derived using the concept of the controlling catchment (for T_c), and an average overland flow plane (for Q_p). T_c, Q_p, and T_p are then computed using the simplified relationships and compared to the numerically derived variables. The simple relationships provided good results on the synthetic data set where input errors are eliminated. They also found that three common synthetic hydrograph methods did not reproduce the results of the kinematic wave models for T_c, Q_p, and T_p nearly as well as the proposed method. *Shen et al.* [1990] then derived physically based flood frequency curves which include infiltration considerations. It was found that soil type and initial soil moisture conditions exert the greatest influence on flood frequency distributions with basin shape and slope playing secondary roles.

Akan and Al-Turbak [1988] used the hydrologic similarity concept to generalize the results of a kinematic wave model with a Green and Ampt infiltration component to interpret the runoff coefficient of the rational formula. A simple rectangular basin with uniform physical properties with time varying, uniform rainfall intensity, was used in the approach. The runoff coefficient is viewed as a nondimensional parameter which can be numerically evaluated in terms of basin and rainfall non-dimensional parameters. Using this approach T_c need not be estimated and the assumption that the peak discharge calculated by the rational formula is the same return frequency as the rainfall is not required. *Garcia and James* [1988] employed the kinematic wave version of HEC-1 to simulate the impact of urbanization on hydrologic response. Regression relationships were developed to quantify the effect of urbanization on the UH.

Gan and Burges [1990a, 1990b] used the quasi-physically based model (S-H) of *Smith and Hebbert* [1983] to generate "true" time series of runoff and evaporation for several climate-soil-basin geometry combinations on a small hypothetical catchment. This generated "true" series was then used to assess the soil moisture accounting (SMA) component of the National Weather Service Sacramento model for calibration, validation and prediction. For the scenarios studied, they concluded that the SMA proved unreliable and unsuitable to address issues of scale and heterogeneity. In particular the SMA model is unreliable in predicting hydrologic response from extreme rainfall (or behavior outside the range of calibration events), is highly sensitive to initial soil moisture, and tends to overestimate outflows during dry to wet transitions. They

At the hillslope and small catchment scale, a high degree of spatial variation of infiltration properties were found by *Wilson and Luxmoore* [1988], and *Loague and Gander* [1990]. Short correlation scales (10m) were demonstrated in the first two articles and *Wilson and Luxmoore* [1988] concluded that infiltration can be treated as a stochastic process regardless of the initial soil tension for modeling hillslope hydrology on the Tennessee watershed they studied.

For a hillslope with an arbitrary spatial arrangement of individual point infiltration capacities, *Hawkins and Cundy* [1987] established an envelope of steady state surface runoff responses. *Woolhiser and Goodrich* [1988] implemented a simple stochastic representation of small scale, cross slope, infiltration variability within a distributed model element. They found significant rainfall and soil variability interactions. Mean (equivalent) representations of saturated hydraulic conductivity were found to be incapable of reproducing variable representations for time variable rainfall.

Woolhiser and Goodrich [1988] also investigated the importance of time varying, spatially uniform, rainfall by using observed breakpoint rainfall intensities and intensities derived from several disaggregation schemes in a watershed model with a physically based infiltration component on a elementary open book watershed. The derived runoff distributions from each rainfall disaggregation flow. For overland flow with slope lengths much less than the length scale, spatial variability has little influence on runoff as the system will be predominately in a runoff equilibrium condition. For lengths greater than the computed length scale, variability of surface and input parameters will have a much greater effect on runoff (nonequilibrium conditions). This length scale can serve as a guideline for model grid size selection.

Several innovative techniques for the treatment of catchment variability are evident in the papers reviewed. In several cases hybrid schemes, incorporating both stochastic and deterministic elements, have shown promise. They represent an attempt for balanced model treatment of data and hydrologic processes known with various degree of uncertainty. These efforts are encouraged.

Automation

Increases in model complexity typically yielded concomitant increases in input data requirements, catchment descriptors, model parameterization and output interpretation. For relatively simple models, the overall modeling effort was aided by spreadsheet software [*Walker et al.*, 1989; *Dymond and McDonnell*, 1988]. For more complicated, distributed catchment modeling, extraction of basin network, drainage area, and topographic characteristics was undertaken by *Mark* [1988], *Band* [1989], *Moore et al.* [1988], and *Jenson and Domingue* [1988]. Catchment descriptors, such as percent impervious area were automatically estimated from remotely sensed video data by *Draper and Rao* [1986]. Their methodology provided estimates of impervious area as accurately as manual methods with significant cost savings. Automation of topographic and land use information for HEC-1 and subsequent graphical output was described by *Cline et al.* [1989]. For new model users, decision support systems provided an overall aid in the selection of model input values by accessing large data bases, interfacing with expert systems, suggesting default values and providing graphics [*Arnold and Sammons*, 1988].

Geographic Information Systems (GIS) were employed to estimate SCS curve numbers and subsequent runoff peaks and volumes by *White* [1988], and *Berry and Sailor* [1987]. However, *Berry and Sailor* [1987] noted that if only a one-time calculation of basin parameters is required, the automation and added precision of using a GIS might not be offset by the required digital data collection efforts. Addressing this point, *Johnson* [1989] presented an integrated catchment modeling approach based explicitly on geographic information system (GIS) functions. Interactive graphics were used to quickly develop catchment digital databases for soils, topography, land use and both point and radar derived rainfall distributions. A variety of hydrologic models ranging from unit hydrograph methods to variable source area models with various infiltration and evapotranspiration components were parameterized and used in his modeling system.

An automated model development and building methodology was described by *Arnold and Williams* [1988]. They utilized a fourth generation simulation language based on queuing theory to model the runoff from a small homogeneous watershed. Analogous queuing theory operators and constructs were used to model processes of precipitation, surface runoff, lateral flow and percolation. The feasibility of the modeling approach was demonstrated for a runoff producing storm on a small Ohio catchment.

Progress in automation of catchment hydrologic modeling has been good and continued research in this area is encouraged. Advances will further technology transfer to the practitioner and free the researcher from many tedious data and model layout tasks. However, practitioners must remember that improvements in the resolution of catchment descriptors (topography, soils, vegetation), and in the speed of obtaining them will not result in improved hydrologic prediction unless appropriate models are used.

EXPERIMENTAL CATCHMENT HYDROLOGY

The relatively large number of reports dealing with experimental catchment research is encouraging. A primary conclusion of the *U.S. National Research Council* [1991] is that hydrology is a data poor science. Continued efforts to collect data, coupled with specific hypotheses and modeling efforts is essential for a more thorough understanding of catchment behavior. A catalog of data sources and case studies of watershed projects in the western United States and Canadian Provinces was compiled by *Callaham* [1990]. A report on long term interdisciplinary research and data collection at the Coweeta watershed was presented by *Swank and Crossley* [1988]. A nationwide effort to understand and model erosion processes (WEPP: Water Erosion Prediction Project [*Lane and Nearing*, 1989]) has also spurred detailed, interdisciplinary data collection and modeling investigations. This and other water quality efforts [*Burkart et al.*, 1990] underscored the importance of knowledge of hydrologic behavior before transport of soils and chemicals can be adequately predicted [*Lawrence et al.*, 1988].

The majority of the experimental work reviewed can be broadly grouped into categories of hydrologic effects of watershed treatment, chemical hydrograph separation, and macropore studies. Catchment response to logging, range management practices, reforestation and conversion of tree and brush areas to grasslands were addressed by *Blackburn et al.* [1990], *Higgins et al.* [1989], *Heede* [1987], *Riekerd* [1989], *Trimble et al.* [1987], *Davis* [1987], *Wright et al.* [1990], and *Keppeler and Ziemer* [1990]. Greater response differences between control and treatment catchments for small runoff events (or dry years) and smaller or negligible differences for larger events were noted by *Trimble et al.* [1987], *Wright et al.* [1990], and *Keppeler and Ziemer* [1990]. *Wright et al.* [1990] pointed out problems in previous paired watershed studies in which no large runoff events occurred in either the pretreatment or post treatment periods, thereby influencing conclusions regarding logging effects on large flows.

A large body of work on chemical hydrograph separation was conducted during the review period [*Caine*, 1989; *McDonnell et al.*, 1990; *Swistock et al.*, 1989; *Burns*, 1989; *Nolan and Hill*, 1990; *Pionke et al.*, 1988; *Lawrence et al.*, 1988; and *McDonnell*, 1990]. Hydrograph separation of "new" runoff water from "old" groundwater is directly related to the acid precipitation neutralization hypothesis. This hypothesis states that the water chemistry is determined primarily by its residence time within the soil. This line of research has spurred analyses of flow generation mechanisms where "old" groundwater or soil water has been observed to be a large portion of total storm runoff.

Nolan and Hill [1990] found that flood wave effects offer an explanation to the apparent incompatibility of observed "old water" domination of early storm runoff water for a test catchment. Flood waves, composed primarily of old channel water, tend to reach basin outlets before "new" storm runoff derived from impervious catchment areas arrives. This can occur when new water rapidly enters the channel from a localized upstream source and generates a flood wave which travels down the channel at a greater velocity than the mean water velocity. They were able to confirm the presence of flood waves in a California catchment by using data from a gaging station 600m upstream from the basin outlet. They concluded that the rapid influx of old water did not originate from the displacement of soil moisture as was proposed in earlier studies.

For small events (< 2mm/hr peak flow over the catchment area) in a New Zealand catchment, *McDonnell* [1990] concluded that near-stream, valley bottom (old) groundwater could be discharged in sufficient quantities to account for storm period streamflow. For larger storms (2mm/hr peak flow) old water production again dominated flow as it was derived from hillslope-hollow drainage into steeply sloping first order channels. Fast drainage of old water into the first order channels was facilitated by crack infiltration, slope water table development and lateral pipe flow of stored water. *Pionke et al.* [1988] also provided a detailed analysis of data from the USDA-ARS Mahantango Creek watershed in Pennsylvania to explain storm response runoff generating mechanisms. They concluded that the highly dynamic near stream hydrologic environment, although areally a small portion of the catchment, exerted a major control over streamflow hydrology and chemistry.

Macropore characterization studies were conducted by *Wilson and Luxmoore* [1988], *Edwards et al.* [1988], and *Ursic and Esher* [1988]. The latter investigation demonstrated that increases in small mammal burrowing activity can significantly increase detention-retention storage of rainfall in the upland Coastal Plains of the southern United States.

Jarrett [1990] described an ongoing research investigation by the USGS to improve the understanding of hydrologic and hydraulic processes in mountainous regions. The goal of this multidisciplinary investigation is improving paleohydrologic techniques with thorough data analysis as well as identification of the sources and magnitude of data errors.

Experimental studies are essential if we are to attain a truly scientific understanding of hydrologic phenomena. The simultaneous measurement of solute concentrations as well as water fluxes and stores promises to provide data that will aid our understanding of runoff generation mechanisms. However, interpretations of intensive but short-term studies must be made carefully because they sample a very limited set of catchment states. Ideally such short term intensive studies should be carried out on an experimental catchment that has been monitored for a long period of time.

BASIN SCALE AND SIMILARITY

Understanding catchment response over a wide range of basin scales and identifying easily derived measures that quantify differences and similarities of catchment behavior remain important and active area of research. Progress in these fields is paramount if our collective knowledge of catchments is to aid in understanding regional and global hydrologic phenomena [*see Wood this issue*]. *Gupta et al.* [1986] is referenced here for completeness as it provides relevant information on the topic.

In the quest to scale up point based process knowledge *Morel-Seytoux* [1988] argued that nature embodies both the elements of chance and the descriptive laws of physics. Therefore, excessive process description at one scale is lost through the processes of integration in time and space, and via expectation. This justifies model simplification as long as the essential behavior is retained. He illustrated how simplifications can be made so that straight forward scaling integration can be accomplished in a physical-stochastic modeling framework.

In exploring runoff response at the catchment scale, *Rogers and Singh* [1986] studied the number of first order channels and the distribution of first order channel lengths from the outlet. They found that the number of first order channels was inversely proportional to basin soil infiltration capacity and cite the importance of first order channels as a major source of surface runoff. The general shape of frequency histograms of first order channel distances from the basin outlet were quite similar to hydrographs from general storms for basins in Pennsylvania. They concluded that the surface runoff hydrograph shape was closely controlled by the distribution of first order channel distances.

The study of catchment geomorphology has been used as a key to acquire insight into scale issues and basin response behavior. Other investigations, more strictly related to catchment geomorphology, could not be reviewed in detail due to space limitations but are listed for reader convenience. They include *Deutsch and Ramos* [1986], *Hjelmfelt* [1988], *Gupta and Mesa* [1988], *Gupta and Waymire* [1989], *Tarboton et al.* [1988, 1989], and *Montgomery and Dietrich* [1989].

In a series of papers *Wood and Hebson* [1986], and *Sivapalan et al.* [1987, 1990] discussed basin response similarity and derived a methodology utilizing TOPMODEL. The model is expressed in dimensionless form with consideration of water table and initial local storage deficit conditions prior to a storm. Five dimensionless catchment similarity parameters and three conditions are used in the model equations. Under the assumptions of their analysis, two catchments are considered hydrologically similar if they are identical in the five parameters, regardless of scale.

Theoretically derived flood frequency distributions were also described in terms of scaled dimensionless parameters with consideration of relative catchment to storm scales by *Sivapalan et al.* [1990]. They concluded that for infiltration excess dominated catchments, with assumed uniform Hortonian overland flow generation, the flood frequency distribution is completely defined by a rainfall-soil scale parameter and the scaled catchment area emphasizing the need for accurate rainfall distribution information. These analyses provided a theoretical framework to compare storm response for catchments with different characteristics at different scales for both infiltration and saturation excess runoff generation. Much of this work was also summarized in a review by *Wood et al.* [1990].

The length scale derived by *Julien and Moglen* [1990] (also see above), based on concepts of kinematic equilibrium, can also serve as an indicator of hillslope similarity. They found that the time to equilibrium is essentially the same for spatially varied conditions or spatially averaged surface parameters. In addition, runoff sensitivities were typically the same for uncorrelated and correlated surface parameters.

THE FUTURE

An improved understanding of many conjunctive use, water quality, and climate change issues requires parallel advancement in catchment hydrology. Unfortunately in the present atmosphere of prioritized research, this fact is often overlooked. Clearly if we cannot accurately predict catchment runoff response, prediction of sediment or chemical transport by water are even more suspect.

El-Kadi [1989] reviewed numerous currently available watershed models to assess how they might be used to describe surface-groundwater interactions for conjunctive water use management. The review concluded that it is not yet feasible to extend the models examined to handle conjunctive use for both surface and ground water resources. A need therefore exists to improve the surface water-groundwater linkage in new and existing watershed models while ensuring that model components treat complexity and scale in an integrated manner.

Simulations by *Davis and Goldstein* [1988] demonstrated that the effectiveness of mitigation strategies for lake acidification are critically dependent upon knowledge of the dominant hydrologic flowpaths within a catchment. *Siegel* [1988] argued that unless a more detailed understanding of wetland hydrology, water chemistry, and biota is acquired it will be extremely difficult to assess the cumulative impacts of changing catchment conditions.

Hakonson et al. [1986] pointed out the shortcomings of current water balance model feedback mechanisms to account for long term, time dependent, changes in hydrologic, biotic and soils regimes. Their particular study concerned the long term viability of low level radioactive waste trench caps. However, models capable of dealing with evolving regimes will also be critical for evaluation of climate change scenarios.

Understanding catchment processes and response as a function of time and space scales in a variety of hydroclimatic regimes is crucial if we are to deal with the impacts of global climate change and feedbacks of the Earth's large scale dynamic climate. To attack this problem in a cost effective manner, hydrologic models must be reformulated to directly utilize available and anticipated remotely sensed data. However, for predictive capability, these reformulations must remain process based and be verified with experimental data.

A new age of interdisciplinary experimental and modeling study is upon us. Future large scale field experiments, such as STORM, GEWEX (Global Energy and Water Balance Experiment) and NASA Earth Observing System efforts, offer exciting possibilities to couple hydrologic models over a broad range of scales and directly incorporate remotely sensed data.

Future research in the area of catchment model formulation must address the determination of proper model component representation (system complexity), the scales over which the components are valid, and integration of the components. Pulling sub-model components from varying sources and patching them together without considering the issues of commensurate complexity and scale treatment will only invite trouble. Nor can integrated model formulation ignore the sources of uncertainty induced by uncertain input and parameter distributions.

Objective model assessment is an area we must improve upon. Far too many published works have not followed a rigorous protocol of split sample model calibration and verification (validation) with high quality, distributed catchment data. Simple, graphical comparisons of observed and simulated sequences for a small number of events, with few correlation statistics, provide insufficient knowledge of likely operational model performance. Several objective evaluation criteria, as well as graphical comparisons [*Martinec and Rango*, 1989; *Willmott et al.*, 1985]; while testing over a wide range of input-output conditions [*Sorooshian et al.*, 1983; *Gan and Burges*, 1990a, 1990b], should be considered a minimum for model testing. The problem of parameter identifiability and proper model structure should also be addressed [*Sorooshian and Gupta*, 1983, 1985; *Hendrickson et al.*, 1988]. Verification using stormflow measures will be difficult if runoff per unit area is of the same magnitude as rainfall measurement errors (low signal to noise ratio). This is especially true when uncertainty in catchment rainfall can be large for the typical assumption of uniform rainfall from a nearby gage.

For distributed model testing, internal (subwatershed) response behavior should also be verified. *Klemes* [1986] described a systematic methodology for the calibration and verification of hydrologic simulation models. His work is cited by many as an example of how model testing should be done but apparently is heeded by few. Without thorough testing to establish model confidence, subsequent conclusions regarding catchment behavior are often speculative.

To perform defensible model calibration and verification, well checked data sets from a variety of hydroclimatic regimes must be made easily available in electronic format. *El-Kadi* [1989] reiterated that most watershed models have been tested with some field data but a need exists for a set of standardized test problems with respective data sets. Rainfall-runoff data and a watershed topographic map alone are insufficient for distributed catchment model testing. Soils, land use information, soil water content, and internal (subwatershed) response measurements are also required. The importance and integration of field data into our research efforts cannot be overemphasized.

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