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An Evaluation of Relationships Between Streamflow Patterns and Watershed Characteristics Through the Use of OPSET

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AN EVALUATION OF RELATIONSHIPS BETWEEN STREAMFLOW PATTERNS AND WATERSHED CHARACTERISTICS THROUGH THE USE OF OPSET
A SELF CALIBRATING VERSION OF THE STANFORD WATERSHED MODEL

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University of Kentucky Water Resources Institute
Lexington, Kentucky
1970

INTRODUCTION

Land use control in the tributary watershed as well as in the flood plain has been receiving increased attention as a method for reducing flood damage. One of the most complex technical questions which has to be resolved in structuring the appropriate use of this alternative is how downstream flood hazard varies with tributary watershed conditions. The approach to this problem in this research sponsored through the University of Kentucky Research Foundation and supported in part by funds provided by the United States Department of the Interior as authorized under Title II of the Water Resources Research Act of 1964, Public Law 88-379, revolved around using the Stanford Watershed Model as a tool for correlating runoff patterns with land use through model parameters as intermediate variables. The completion report for the project is in three parts..

1. Liou, Earnest Y. *OPSET: Program for Computerized Selection of Watershed Parameter Values for the Stanford Watershed Model.* Lexington: University of Kentucky Water Resources Institute, Research Report No. 34, 1970.

2. Ross, Glendon A. *The Stanford Watershed Model: The Correlation of Parameter Values Selected by a Computerized Procedure with Measurable Physical Characteristics of the Watershed.* Lexington: University of Kentucky Water Resources Institute, Research Report No. 35, 1970.

3. James, L. Douglas. *An Evaluation of Relationships Between Streamflow Patterns and Watershed Characteristics Through Use of OPSET: A Self-Calibrating Version of the Stanford Watershed Model.* Lexington: University of Kentucky Water Resources Institute, Research Report No. 36, 1970.

The first of the reports describes the development of OPSET, a version of the Stanford Watershed Model programmed to estimate best-fit values of watershed parameters directly from climatological and streamflow data, and contains a program listing. The second report describes the application of OPSET to 17 rural watersheds and correlations derived between model parameters and watershed characteristics. It also describes and examines the significance of changes noted in parameter values with urbanization in three other watersheds. The third report applies the findings of the first two to flood control management problems. The results on all three levels have been highly encouraging. The three reports need to be read together for a complete understanding of the research approach.

The study is indebted to many besides the sponsors. Considerable use was made of the facilities of the Water Resources Institute and of the Computing Center at the University of Kentucky. Much of the data was obtained through A. B. Elam, Jr., Kentucky State Climatologist and the Louisville Office of the U.S. Geological Survey. Miss Nancy Crewe and Miss Patricia Miller prepared the reports.

ABSTRACT

Selection among alternative flood control measures would be better informed if better information could be obtained on the marginal change in flood hazard associated with land use and other changes in the tributary watershed. Hydrologic modeling is the most promising approach to answering this question; however, the use of existing models is hampered by the absence of information correlating model parameters with physical characteristics of the watershed.

To deal with this situation, a method was developed for estimating the parameter values for the Stanford Watershed Model which best match recorded with simulated streamflows. Physical characteristics were measured for 17 rural watersheds. Correlations between the characteristics and the parameters were examined. Changes in parameter values with urbanization were also examined. The results were used to study variations in downstream flood peaks and in average annual flood damages associated with various tributary watershed characteristics. The end product is better information on the kinds of areas where urban development is least likely to experience large flood damage and drainage costs.

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CHAPTER I

THE NEED FOR HYDROLOGIC INFORMATION IN FLOOD MEASURE PLANNING

Every year floodwaters are sure to leave some river channel and devastate an adjacent community. Just as surely, the citizens of the inflicted area will unite behind the idea of acting to keep from suffering the same damage the next time the river floods. As the citizens raise their voices to make their wishes known through the political process, the leadership will refer their situation for study down through the administrative hierarchy to a group of experts experienced in planning measures to alleviate flood damages. If the damage on an average annual basis is found to be high, the result is likely to be a recommendation for channel improvement or levee construction.

The hydrologist within the group must select an appropriate design flow and determine the peak stage associated with that flow so that the engineers can plan a levee with adequate height and structural stability. One approach is to base the design on the flood of record. When the community wants to know just how safe it will be if its levee is designed on this basis, the hydrologist surveys the time series of historical flood peaks to associate the design flow with a frequency of occurrence and estimate the probability and extent of flooding of larger events. When he needs guidance in performing this task, the hydrologist can refer to a literature which abounds in the proposal and evaluation of techniques for estimating flood magnitude as a function of frequency (4).

Levees are expensive. A properly functioning group of planners will expand their analysis into a search for the least costly alternative. The other frequently used structural alternative is a reservoir. It may be economical to hold back part of the flood water for later, more gradual release. The information required to determine the least costly combination of detention storage and channel improvement places additional demands on the hydrologist. The design engineer will want to know more than just the flood peak. He will want an entire flood hydrograph. Only then will he be able to evaluate prospective design possibilities by routing flows through reservoirs of varying sizes and from thence downstream to a point on the river opposite the community, estimate the combined reservoir and levee cost, compare totals, and find the least cost combination of reservoir and levee construction that achieves the desired level of protection (44). The hydrologist can again select from among the multitude of techniques available for estimating flood volumes and flood hydrographs for a design frequency (9, Sect. 14).

The community may not yet be satisfied. The flood of record may not be the best design flood to use. Some citizens may fear the consequences of an even bigger event. Others may, despite the risk, want to design for a smaller flood to save construction money. If economics is taken as the sole criterion, the optimum design flood frequency has the smallest sum of construction cost and residual flood damage. Even though economics is but one of several important considerations, engineering-economic analysis is essential to sound planning. The planner can only search for the optimum design flood after the hydrologist provides still additional information. Instead of simply supplying a single flood hydrograph for a specified frequency, he must supply a series of hydrographs, each specified by frequency.

Whenever the requirement for quantitative information changes from a need for a single value to a need for a series of compatible numbers, a new dimension is added to the care required in making the estimates. If the ten-percent flood is estimated to be 10,000 cfs by a method accurate within plus or minus 5.0 percent and the two-percent flood is estimated to be 16,000 cfs by an independent method having the same degree of reliability, the difference between the two flood peaks would only be known to be between 4,700 (15,200 - 10,500) and 7,300 (16,800 - 9,500), a range of 21.7 percent from the mean difference of 6,000 cfs. Unless the hydrologist can produce estimates which are consistent by frequency, this relatively much larger error in estimating marginal quantities can have a profound effect on what the analysis shows to be the least cost level of protection.

The new dimension needed in estimating precision stems from the fact that the marginal differences between, as well as the magnitudes of, flood peaks must be watched. Otherwise, the estimate of the optimum design frequency will be biased toward the design frequency where the estimated peak is the smallest fraction of the true peak. The problem is minimized if the hydrologist can produce a flood-peak-frequency curve where the relative error in estimated flood peak is as equal as possible among frequencies. Hydrologists have learned to produce marginally consistent estimates of flood peak by frequency by fitting recorded annual flood peaks to an appropriate statistical distribution (36, pp. 250-258; 9, pp. 8-23 to 8-31). More recently, they have found it necessary to adopt a single statistical distribution for general use so that estimates would be marginally consistent among streams and marginally consistent among agencies for a given stream (4). Without this kind of consistency, one community has an advantage over another in terms of getting a flood control project, and the community can shop among planning agencies in the search for the best deal.

As the community thinks more deeply about its needs, it will recognize that watersheds change with time. The area upstream from the community may be changing from rural to urban, reverting from cropland to forest, or experiencing any of a large number of other changes affecting surface runoff or channel flows. The community will want to know how these upstream changes will affect the flood hazard within its boundaries. In a typical response, the hydrologist might develop one set of hydrographs for current conditions and a second for future conditions. Both sets of information could then be used in project formulation, the first to select the best approach for dealing with the flood hazard as it currently exists and the second to study the merits of hedging the design against the consequences of changing watershed conditions.

Where urban development is producing hydrologic change over a significant portion of its tributary watershed, a community has cause to expect a consequent increase in flood hazard. People who look upstream, see new paved areas, and then experience larger floods soon recognize the potential of another flood control alternative, tributary watershed management. Many factors, however, need to be considered in selecting from among alternative sites for urban development. Good management must explore the pros and cons with respect to many systems besides the hydrologic (transportation, air pollution, economic, ecological, etc.) before concluding that urban development of some other area is more appropriate. Downstream flood damages cannot be the sole criterion for this decision.

In order to achieve a basis for tradeoff among each consideration making urban development of a site desirable or undesirable, the effects of each factor need to be estimated in a way which is marginally consistent. How much will downstream flood peaks (damages) be increased by development in one watershed? How much by development in another? The answers to even these questions is not enough. The planner must not only determine which development should be in which watershed. He must determine where the development in a given watershed should be located. He must consider the possibility of designing urban architecture and landscaping to minimize downstream effects. What does it mean to the local community and what are the downstream hydrologic consequences of not using curbs and gutters along residential streets? He must review the design and routes of prospective storm drains and structural changes to the natural drainage system. As the community begins to recognize the full specturm of the design options available for reducing expected flood damage and as the city planner begins to want quantitative information on the downstream effects of specific decisions, the hydrologist finds himself being asked questions which tax the capability of the tools he has at his disposal.

Another new dimension has been added to marginal differences. Not only must marginal changes of flood peak with frequency be estimated, marginal changes of flood peaks with land use (by both location and type) must be estimated as well. Such marginal changes cannot be reliably evaluated from two independent estimates of flood peak for two watershed conditions because of the requirement for marginal homogeneity illustrated in the example for frequency. In order to plan a wise land development program or develop arguments capable of preventing the more severe adverse consequences of tributary watershed development, the hydrologist must be able to supply curves of flood peak vs. degree of urban development, fraction of forested area, or whatever other variable may be relevant to the decision of the moment.

The hydrologist does not get very far into his study of these relationships before he is confronted with another factor complicating the task before him. Different floods are affected by tributary watershed changes to different degrees. Effects on peaks, volumes, and timing vary from big floods to small floods, summer floods to winter floods, and floods from general storms to those from thunder showers. As reservoirs are used to store flood runoff over longer periods of time, tributary land use effects on reservoir inflows during drawdown periods and on the possibility of a second major storm occurring shortly after the first become matters of concern. The hydrologist faced with providing information for comparing land use management alternatives cannot do an adequate job by providing a few hydrographs specified by frequency, he must work with the total runoff pattern. Only with the total picture at hand will he be able to relate tributary land use differences to differences in his estimate of the 100-year 20-day runoff, the 100-year flood peak, the 100-year summer flood peak, or the pattern of flood damages over the course of a year. Urbanization affects the entire flow regime of the stream, not just the flood peaks, even though it is the peaks which have received the greatest attention in the literature (47).

As the hydrologist stretches his view of the problem to comprehend the full impact of urbanization on flow regime, he begins to appreciate the scope of the hydrologic information required for flood control planning as but one phase of the total interaction between man and stream. The stream is an intricate natural system serving man's needs in a multitude of ways. As structural works or land use changes modify flood peaks, they also modify the ability of and the demand on the stream to supply water, generate power, convey wastes, float navigation vessels, propagate fish and wildlife, provide a recreational outlet, or simply improve or degrade the esthetic environment of those who pass by. While the factors interacting to cause these changes are many and complex, a design cannot be rated by how it affects floods alone. Its affects on the frequency of extremes and patterns of all flows must be considered. The increasing complexity of physical and social interactions is multiplying the dangers of working only with short-term major storm hydrographs to make decisions which affect the total flow regime. The consequences of taking too limited a viewpoint have become evident as we have learned to better understand the ecological implications of channel improvement; they can be much more grave when tributary land use management programs change the countryside than they ever are when channelization changes only a narrow strip of land.

CHAPTER II

THE DEVELOPMENT OF A SELF-CALIBRATING WATERSHED MODEL

THE CONTEXT OF FLOOD MEASURE PLANNING STUDIES

The need for greater precision in hydrologic estimation has grown as the scope of water resources planning and management has expanded from smaller to larger projects and on to basinwide and regional systems. It has increased as an urbanizing and industrializing society has been forced to estimate design values more closely in order to minimize the high cost of building excess capacity and the adverse consequences of failure when design capacities are exceeded. More complex economic and social systems have less tolerance for estimating error.

The earliest flood control programs emphasized the problems along the main stems of major rivers. The spectacular flood disasters along large rivers made structural measures for flood control feasible from the financial, economic, social, and political viewpoints. Those responsible for dealing with the problem did not look too hard at the effects of potential changes in tributary land use because forecast events affected too small a portion of large drainage basins for hydrologic change to be significant. Furthermore, the water resources management agency is usually in no position to achieve widespread changes in tributary land use. The Soil Conservation Service works through local farmers to implement soil and water conservation measures and the Forest Service has fire control and other forest conservation programs, but neither program applies to areas around the fringes of our rapidly growing major cities to which the problem has gradually shifted and where hydrologic factors need to be considered in guiding urban growth patterns.

Men move from natural surroundings into cities; and as the trend continues, cities converge into megolopolitan areas covering thousands of square miles. Technological advances increase the power of individuals to change the earth's surface. Land use changes become bigger and more severe. New construction techniques respond to the demands of a growing society by producing larger paved areas, more extensive earth movement, greater departures between natural and artificial landscaping, and more extensive reshaping of drainage patterns.

As land development activities multiply, communities are forced to assume the role of upholding the public interest whenever land development activities by individuals have significant effects on their neighbors. People throughout the community may feel an esthetic loss from an ugly scar left on a hillside or enjoy the springtime blossoming of orchards. Planning and zoning capabilities permit a community to control undesirable land development activities and promote those types of development furthering its goals.

In no setting is the relative hydrologic effect of urbanization more severe nor the opportunity to modify development patterns to meet the community need more pronounced than in the small urbanizing watersheds which surround every growing city. Streamflow regimes are drastically altered, and the frequency and severity of damaging floods may increase manyfold. This increase is combining with the success of structural flood control in reducing damages along the larger rivers to cause a growing fraction of the total national flood damage to be associated with flood peaks from local watersheds.

While hydrology is but one of many factors to be considered in land use planning, it enters in two ways. Land development needs to be reviewed from the point of view of minimizing downstream consequences. Land development needs to be reviewed from the point of view of optimizing the entry of damage-prone uses into flood hazard areas (17). Flood plain land development regulation can complement tributary area land development regulation to minimize flood damages.

Concentrated urban development will, if located next to a stream, suffer extensive flood damage. Streambank locations are also the worst for magnifying downstream flooding because of the quickness with which impervious area runoff enters the stream. The hydrologist needs to be able to estimate both flood hazard by flood plain location and the effect of flood plain development on downstream flood hazard in order to provide the planner the information he needs to evaluate hydrologic effects as but one of many considerations to be considered in comparing alternative development patterns.

Another aspcet of the small urbanizing watershed is that it is more likely than a large river basin or a rural watershed to be under the jurisdiction of a single planning and zoning administration. Land use management is more likely to be an institutionally viable program.

BASIC HYDROLOGIC INFORMATION

When the hydrologist is asked to assess flood severity (by peak, volume, or damage) as a function of frequency, he starts from the available gaged streamflow records. Often, he is asked to develop an estimate for a specific location only to find the stream ungaged. Even where a gage is available, the record may be too short for frequency analysis to be meaningful. Hydrologists have had to devise means for using the information obtained from gaged records to estimate flows at ungaged sites and for correlating runoff with rainfall in order to extend the record with simulated flows.

When the hydrologist is asked to assess flood severity as a function of tributary watershed conditions, he must estimate runoff patterns for two or more conditions of the watershed surface. A gage can only indicate the runoff patterns produced by the combination of weather patterns and watershed conditions which occurred during the period of record. To study how runoff patterns vary *with and without* a given condition of the watershed surface, the hydrologist may consult a second gaged record. He can never find a second watershed identical to the first in all respects except for variations in the condition he seeks to study. If he is working with a small experimental watershed, he may be able to vary land use with time; but even then he will have to reconcile the effects of differences between weather patterns *before and after* he makes a change. He has no good way to extrapolate the conclusions reached on his watershed to other locations with different climate, topography, or subsurface conditions. If he is working with a larger watershed being changed by factors over which he has no control he must still overcome all the same problems and monitor the location and extent of the changes as well. If he goes to several gages representing a variety of watershed surface conditions, he must reconcile the effects of differences in subsurface conditions and weather patterns.

The complexity of the problem comes into better focus as one reflects on the countless possible variations in watershed surface conditions. A typical study might look at runoff patterns before and after the forests are cut to convert a small watershed into grasslands. However, forests come in many types (by species, density, tree size, etc.). Grasslands do too. Crops of many types can be grown. Alternatives in cultivation practice are endless. The effects of a wide variety of kinds and spatial patterns of both of these as well as all the other many possible land uses add new dimensions. Additional watersheds must be gaged to verify the consequences of more types of change, and the extent of the study grows geometrically. A framework is needed to order the collection of data and the evaluation of results.

ANALYSIS OF HYDROLOGIC INFORMATION

Correlation Approach: Two fundamentally different approaches are available for using collected hydrologic information to explain how runoff patterns vary with watershed conditions. One is to correlate observed streamflow parameters (peaks, volumes, low flows, etc.) with observed watershed conditions (forest cover, slope, soil type, etc.) (48). A reliable correlation could then be used to estimate the magnitude of a selected parameter (e.g., flood peak) for any specified change in a given watershed condition (e.g., degree of urban development). While such correlations are widely described in hydrologic literature, they possess several glaring weaknesses when they are assessed against the demands of marginal economic analysis in project formulation. These are:

1. The many possible variations in watershed surface conditions, subsurface conditions, and climate are so great that it is impossible to develop a comprehensive correlation covering all types and gradations in variation. When one considers the number of possible differences in watershed conditions and all the parameters and interactions among parameters involved, he soon finds the data requirements to develop a comprehensive correlation model to be prohibitive.

2. Correlation models do not take advantage of information on physical events during hydrologic processes. They relate observed

runoff to observed independent variables without making use of research into the processes controlling runoff. The requirements for watershed and runoff data can be reduced by making use of available information from controlled experiments on specific hydrologic processes (e.g., infiltration).

3. Correlation models are formulated to estimate a particular dependent variable (e.g., flood peak). Comprehensive planning requires information on complete flow hydrographs over extended periods of time. Such information can be developed either from correlations for estimating a series of dependent variables followed by combining the results (estimating the total hydrograph from peak, volume, and representative shapes for example, 16) or by some more general model of watershed response. In either case, the work multiplies; and the results provide little grounds for extrapolation to situations not covered in the data base.

Parametric Approach: The second analytic approach is to combine available knowledge on the individual processes occurring in the runoff phase of the hydrologic cycle into a mathematical model representing the movement of water from the time it falls on the watershed until it leaves via evapotranspiration, runoff, or subsurface outflow. The Stanford Watershed Model (12) has become the most widely used program of this type.

THE STANFORD WATERSHED MODEL

The Stanford Watershed Model attempts to represent the processes occurring in the runoff phase of the hydrologic cycle by a series of mathematical relationships, based on moisture accounting, in a digital computer program. The original published version of the Model (Mark II) appeared in 1962 (11). As do all large and complex digital computer models, the program has become almost a living entity as it is continuously developed to meet new needs, comply with the capability of a new computer, incorporate new research findings, use more refined or more quickly executed analytic approaches, or handle new hydrologic situations. Crawford presented the most widely publicized version (Model IV) in 1966 (12) and has more recently developed a system called Hydrologic Simulation Programming (24) incorporating a much more sophisticated routing technique capable of simulating simultaneous flows at a large number of points within the watershed.*

A number of others have adapted various versions of the Stanford Watershed Model for their own research or application needs. Many of these have modified the program by language translations or other changes required by locally available computer facilities. Others have increased program capabilities by refining the modeling equations or extended printed output to provide additional information. In addition to subsequent publications from Stanford (1, 38) and Hydrocomp International (25), written reports have described applications at Kentucky (28), Ohio State (2, 7), New Hampshire (18), Clemson (35), and Texas (10).

The Model simulates a continuous hydrograph from:

1. Recorded climatological data, precipitation, evaporation, and (for snowmelt situations) temperature;
2. Measurable watershed characteristics (e.g., drainage area and fraction of the watershed in impervious surfaces);
3. Parameters used in the computational process which are known to vary in magnitude among watersheds but have not been quantitatively tied to specific measurable watershed properties.

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*New developments and information on user oriented consultation are available through Hydrocomp International in a monthly "Simulation Newsletter."

For example, one parameter indexes the capacity of the soil of the watershed as a whole to retain water.

When a user applies the Model to a watershed he has to survey the available data sources and collect the necessary climatological data from historical records, measure the required watershed characteristics (45, pp. 36-46), guess at appropriate values for the parameters, and adjust these parameter values by trial and error until he is satisfied with the degree of matching between simulated and recorded flows.

The trial-and-error calibration requires ingenuity, familiarity with how the parameters interact within the model, and some understanding of the sensitivity of simulated flows to specific adjustments. The process is greatly aided by a thorough understanding of the hydrologic cycle and the published guidance provided by Crawford and Linsley (12, pp. 62-82 and 24). Through careful parameter value adjustment, one can approximate, but never exactly match, simulated to recorded flows (37, pp. 19-29). Several combinations of parameter values can produce comparable results from an over-all viewpoint, and the final choice may well hinge on whether a particular comparison emphasizes flood peaks, annual runoff volumes, or some other hydrograph feature. The final acceptance of a set of parameter values is a subjective decision.

It can be made objective if one can find an objective scalar index of goodness of fit. Claborn and Moore discuss the problems in finding a suitable index (10, p. 46). Liou presents an index he has successfully used (37, p. 102). The formulation of any such index is admittedly a subjective process, but a scalar index will unambiguously rank one set of flows above another, and a well-formulated index will rank as the higher the one on which there is the most general agreement that it is better.

If an acceptable index can be devised and practically applied, there will be some set of parameter values which when used in the model will simulate the set of flows most closely matching the recorded flows according to the index. One could logically expect difficulty in estimating these values to stem from several causes. Any measurement process is associated with a random measurement error which can be handled through well-known statistical techniques for determining the number of independent measurements which must be averaged to estimate the true value within a prescribed level of confidence. In terms of the problem at hand, a longer record will yield better estimates.

One type of error which is particularly troublesome in hydrologic modeling is that associated with differences between recorded climatological data and historical watershed experience. A certain amount of error exists in gaged streamflows, but the modeling problems caused by geographical separation of climatological gages and the watershed are much more severe. While the Stanford Watershed Model uses a precipitation multiplier to account for differences in total annual precipitation, differences in the pattern within the year are the most important single cause of poor matching. Evaporation data is often measured at a site much more remote to the watershed than is precipitation data but fortunately geographical variation in values is less pronounced and flow simulation is less sensitive.

Random errors in the annual distribution of climatological events specified by the available data are best handled by using more years of record to estimate parameters. Positive and negative differences begin to cancel. The number of years required to estimate a value with a prescribed level of confidence logically varies with the magnitude and the regularity of differences between the gaged record and historical watershed experience. The number likely increases with the average distance from points in the watershed to the gages used.

The foremost problem in correlating trial-and-error, quit-when-you-are-satisfied estimates of model parameters with measurable watershed characteristics has been that associated with variations in estimates among individual users. The scatter caused by unavoidable subjectivity may be acceptable when a parameter value is estimated for simulating flows from a given watershed (the purpose for which the model has been most generally applied), but it becomes intolerable for studies attempting to relate estimates of parameter values to measurable watershed characteristics. The scatter in estimates caused by subjective variation in estimating acceptance introduces too much noise.

The problem is not unlike that associated with the variation in lines individuals will "eyeball" through a field of scattered points. The estimate from a line drawn by one individual may be acceptable when only a single number is needed; however, the situation is altogether different when the number desired is the difference between two estimates taken from independently drawn "eyeball" curves each representing a different value for a third variable. The error in estimating the difference can be greatly reduced by using a standardized least squares approach for fitting the two lines.

An analogous standardized procedure would be very helpful in estimating the watershed parameters. It would reduce the time spent in making estimates to one computer run. It would be even more effective in reducing the training time required for the new user to develop confidence in what he was doing. The most exciting feature is the possibility of being able to reduce the subjective scatter enough to produce estimates which will reveal patterns of correlation between parameter values and watershed characterisiics.

PAST EXTENSIONS TO FLOOD MEASURE PLANNING

The first attempt to use the Stanford Watershed Model to develop hydrologic information for use in marginal economic analysis to formulate an optimum conbination of flood control measures (including both structural and nonstructural) began with a trial-and-error Model calibration to select an appropriate set of parameter values for the selected urbanizing watershed (31). The values for a given state of urban development were estimated from the four years of record. Changes in urban development within this period were considered not extensive enough to affect estimates within the precision of the trial-and-error technique. Because no record was available for estimating a set of parameter values for any other watershed state, sets for other states had to be estimated from trends known to occur in hydrologic processes. The assumption behind this approach was that the changes in parameter values could be related to changes in watershed state through qualitative knowledge of the hydrologic cycle much better than changes in flood peaks or volumes could be related to changes in watershed state directly.

Each parameter was individually reviewed in order to estimate the change in magnitude one might expect to be associated with a given change in the degree of urban development (and later channel improvement and drainage area) solely from the effects one would expect the changes to a watershed surface known to occur with urban development to have on specific processes within the hydrologic cycle. Sets of estimates were made for a variety of degrees of watershed urban development. Based on each of the series of sets of parameter values, the Model was used to simulate a long-term flow sequence (60 years), and the sequence was used to estimate flood peak by frequency. The plotted results provided a set of curves which could be used to estimate flood peak by frequency for any combination of drainage area, degree of urban development, and degree of channel improvement (31, pp. 229-331). The estimates were found sufficiently homogeneous to provide reasonable estimates of marginal changes in flood hazard with changes in the combination of urban development or channel improvement in a sample study for Morrison Creek near Sacramento, California (27).

The glaring weakness of this first attempt to systematically estimate marginal changes in flood hazard with tributary land use was the absence of hard data to check the validity of the hypothesized parameter value changes. The second attempt jumped this hurdle by finding a watershed which actually experienced significant changes in urbanization and channelization over the period of gaged record, used the trial-and-error process to estimate parameter values at two different times, and extrapolated from the observed points to develop a set of curves for estimating flood peaks under a variety of conditions within the Pond Creek watershed near Lousiville, Kentucky (16).

Much more research is needed. While two points are better than one, they scarcely cover the whole field of possible combinations of types, relative locations, and extent of urbanization and channelization. Both points were for relatively low levels of urbanization (<15%), and consequently the results are less reliable as extrapolations to higher levels become necessary. Both points reflected the type of change which actually occurred at Pond Creek, and consequently may not apply to other locations exhibiting different natural watershed properties, differences in before or after land use or differences in nature of the channel network. However, the resolution of these issues lay in obtaining more points. As more and more points could be plotted from independent trial-and-error matching of simulated with recorded flows, the scatter caused by subjective matching would obscure trends. The necessity of reducing the estimation error was the motivating force behind the development of a self-calibrating version of the Stanford Watershed Model.

UNIVERSITY OF KENTUCKY FLOOD CONTROL PLANNING PROGRAMS

Even after the necessary hydrologic information has been compiled, the job of evaluating the merits of all the alternative approaches to reducing average annual expected flood damage remains quite formidable. The range of alternatives available and the complexity of the processes required to estimate the cost and the effectiveness of each one in reducing flood damages make the burden of the numerical work excessive even after suitable analytic methods have been devised.

The alternatives may be most broadly categorized into four: do nothing--suffer and recuperate from damages as they occur; structural--build reservoirs to store peaks or build levees or channelization to contain the flood within designated areas; nonstructural--manage flood plain land use to restrict entry of damage-prone activities or design flood plain activities to suffer less damage when flooding does occur (flood proofing); and hydrologic-- manage watershed land use to retard flood runoff. Any pattern of flood plain activity, whether it be specifically developed by a well-coordinated planning effort using the most sophisticated analytic techniques or simply be the collective product of numerous individual adjustments to flood hazard, contains some mixture of the four alternatives.

The need in evaluating the do-nothing alternative is to be able to estimate flood damages for any combination of hydrologic event sequences, occupancy of the flood plain, and human activity in dealing with the flood as it occurs. Traditionally the basic tool in damage estimation has been the stage-damage curve derived from damage surveys taken following historical floods of known stage. Two recent studies have attacked specific problems. Breaden recognized that the greatest damage is not necessarily caused by the greatest stage any more than the greatest runoff is necessarily caused by the greatest rainfall and then developed a model for continuous generation of flood damages considering duration, season, and time since the last flood as well as stage (7). A better understanding of the processes through which floods cause damage is very important to a better design of measures to reduce damage. Day et al. recognized that human response to flood warning systems can effectively reduce flood damages and then developed a model for estimating damages to be used in conjunction with the planning of flood warning systems (15).

The need in evaluating the structural alternatives is to estimate the cost of various designs and their effectiveness in mitigating flood peaks. The problem is not so much theoretical (the theory of structural design and flow hydraulics is much better developed than that for any of the other three measures) as it is practical. To develop a complete design and cost estimate for a complex system is a very time-consuming task; to have to perform it repeatedly for various combinations of design details is prohibitive in time and money. The traditional way out has been to exercise the engineering judgment developed through experience to set standards for use in resolving design issues and then estimate the cost of the single resulting design.

The need in evaluating the nonstructural alternatives is both theoretical and practical. The development of functional designs and procedures for evaluating their effectiveness have only begun to be developed and tested in prototype situations. The methodology has just developed to the point where quantitative analysis can be applied during planning (32, pp. 243-261).

The need for a methodology for coordinating structural and non-structural measures to minimize the sum of their costs plus the residual flood damages became critical with the recent emphasis on nonstructural measures within established flood control agencies. A theory for ordering the computations was developed and applied (30), summarized in a journal article (29), computerized (28), and advertized through a necessarily condensed description in another journal article (26). The research sponsored by the Office of Water Resources Research (OWRR Project No. A-001-KY) produced the two University of Kentucky flood control planning programs described in detail in the project completion report (28) and companion reports referenced therein.

The approach of the two programs is for the user to divide the flood plain to be analyzed into small relatively homogeneous blocks in space by division of the total area into subwatersheds and in time by division of the total planning horizon into stages. The user develops data on subwatershed areas and arrangement, channel lengths and conditions, flood hydrology, the maximum depth and area flooded by a specified peak, land use and land values, channel stability and slope, bridge capacities, unit costs, and acceptable design standards (16, pp. 151-160). The program examines each planning block to select the least cost combination of measures considering costs caused by interactions with other planning blocks as well as costs incurred within the block itself. The least "cost" combination can be selected on purely economic grounds or may be selected by using shadow or trial values for intangibles. The greatest benefit of computerized selection is through the opportunity for dealing with estimating uncertainty through sensitivity studies.

The second planning program is used to deal with the extra complexity associated with the use of reservoir storage. The computerized procedure designs and estimates cost, both as functions of reserved flood storage, for dams and reservoirs from supplied site, design standard, and unit cost data; develops and routes flood hydrographs the length of the flood plain; determines the least cost combination of measures in each downstream planning block following the same procedures used in the first program; and varies reservoir flood storage in a systematic fashion converging on the least sum of reservoir and downstream costs. In an application to a flood problem involving some flood plain locations which are and others which are not downstream from reservoir storage, the first program is used for optimization in the reaches off the controlled stream; and the second program for analysis of storage in the context of the combination of measures selected by the first program for the tributary channels.

The need for evaluating the hydrologic alternatives is greatly accentuated in the urbanizing context. While a great deal of attention has been given to the hydrologic effects of soil conservation and forest management programs (9, Sections 21 & 22), the effects of such practices on the design of flood damage mitigation programs has been small. These measures reduce smaller flood peaks much more than the major floods usually used in measure design. The primary benefit of these programs is through increasing the productivity of agricultural and forest lands. In the context of an urbanizing community, the way out is not so easy. It is still true that urban land treatment reduces flows from lesser runoff events much more than it does those from major floods, but it is also true that even rare flood peaks from urban watersheds may be significantly attenuated by urban tributary land management programs (3). It is because hydrologic alternatives are so closely interrelated to flood measure planning in the urbanizing context that research to design the hydrologically most efficient measures is needed.

RESEARCH FORMULATION

While many researchers are studying the physical aspects of hydrologic systems and many others are studying the social and economic issues of water resources management, the two groups can profit from greater coordination. The physical scientist has a tendency to become interested in research only remotely related to the needs of practicing engineers and planners while those responsible for resolving day to day management issues operate from very limited information. The social scientist has a tendency to work on perfecting idealized concepts while responsible managing officials operate under institutional constraints in a real world setting.

This research was conceived as an attempt to increase understanding of the aspects of hydrologic system which pertain to the marginal analysis necessary for informed decision-making. It was developed with the goal of providing planners with better information for use in deciding upon the proper degree of control to exercise over watershed land use changes. The objective was to develop a tool for making the hydrologic estimates needed by the planner. Whatever interest would develop in terms of what hydrologists would like to study would only be a by-product.

The research sought to develop a tool for use in obtaining information on the effects on the full annual hydrograph of marginal changes in watershed land use. The specific means for accomplishing this goal was a more objective watershed modeling process. The three research goals presented in the original proposal in August, 1967, were:

1. To program within the Stanford Watershed Model an internal optimization procedure which will converge on the best values for the parameters describing watershed characteristics;

2. To apply the Model with the internal optimization procedure to a number of watersheds having a variety of hydrologic characteristics, to relate the resulting estimates of values for the parameters to measurable physical properties of the watershed, and to apply the results through the University of Kentucky Flood Control Planning Program to study relationships among the values of the parameters, the measurable watershed characteristics, and the optimum combination of structural and nonstructural measures to employ in a given watershed;

3. To deduce from the results relevant relationships between flood hydrology and watershed characteristics which can be applied to such diverse problems as culvert design, flood plain zoning, and analysis of the downstream consequences of channel improvement.

The original proposal outlined a five-step plan to accomplish these objectives. The steps were:

1. Select an objective function expressing the difference between synthesized and recorded hydrographs.

2. Program into the Stanford Watershed Model a procedure which will systematically vary the values of the watershed parameters to which the simulated flows are sensitive but which cannot be directly estimated from measurable watershed characteristics in order to converge on a set of parameter values which will minimize this objective function.

3. Apply the program to a variety of small relatively homogeneous watersheds and analyze the trends in the results with respect to other information which can be obtained about the watershed.

4. Apply the program to one or more urbanizing watersheds for which information on changes in urbanization with time in a period covered by gaged watershed record is available and analyze these results for trends in parameter values with urban change.

5. Consolidate the research findings and analyze the significance of the results.

While some of the details did not turn out as anticipated, the research did essentially accomplish the three goals by a process outlined in the five steps. A detailed description of the work involved in completing the first two steps through the development of a self-calibrating version of the Stanford Watershed Model called OPSET is found in a companion report by Liou (37). Ross presents the application of OPSET to 17 rural watersheds and three urbanizing watersheds (45) as planned in the third and fourth steps. This report summarizes the significance of the findings and goes on to discuss their relevance to the fundamental need for hydrologic information for marginal economic analysis.

OPSET: A SELF-CALIBRATING WATERSHED MODEL

A watershed model represents the physical characteristics of the watershed by the set of values used for parameters contained in the modeling equations. The ideal self-calibrating watershed model would quickly converge on a unique set of values yielding a synthesized annual hydrograph perfectly matching the recorded hydrograph in every respect. The convergence needs to be quick to keep computer cost reasonable. The match needs to be good for the modeling to be meaningful.

The Fortran version of the Stanford Watershed Model known as the Kentucky Watershed Model (listed in 37, Appendix A) is the watershed model on which OPSET is based. The name OPSET was chosen because the program estimates the optimum set of parameter values. The programing therein was taken as given and established the parameters whose values are sought. Ross presents the hydrologic interpretation of these parameters (45). He goes on to describe the required input data and provide suggestions for compiling the needed climatological information and measuring the needed watershed characteristics.

Parameters to be Calibrated: Two criteria pertain to the selection of which parameters should be evaluated in a self-calibrating procedure as opposed to being measured directly or indirectly by some other means. One, the parameter should be difficult to measure directly. It would be ridiculous to try to estimate drainage area by matching synthesized to recorded flows. Two, the simulated flow sequences should be sensitive to the parameter. No algorithm can objectively estimate a parameter whose value does not materially change the simulated flows. As one must deal with parameters in order of decreasing sensitivity, he finds a point where parameter's power to change simulated flows is less than the difference between the simulated and the recorded flows caused by unrepresentative data and other modeling problems. When this point is reached, estimating by matching disintegrates (37, pp. 76-78).

Eighteen input parameters were initially judged as sufficiently difficult to measure directly that they should be considered for inclusion. These were BFRC, BFNLR, BIVF, BMIR, BUZC, CHCAP, CSRX, ETLF, FSRX, GWETF, IFRC, LZC, NCTRI, OFSL, SIAC, SUBWF, SUZC, and VINTMR.*

Prior to the initiation of the research a number of sensitivity studies had been run as a series of exercises in teaching a course on hydrology. These largely used data for Elkhorn Creek near Frankfort, Kentucky. Each parameter was varied over the range of values previously encountered by a number of investigators who had used

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*All variable names are defined in 37, Appendix C. These input parameters are presented in much greater detail in 45, pp. 39-55.

the Stanford Watershed Model. The values of all other parameters were held constant, and a year of flows were simulated. The results are summarized by Liou (37, pp. 83-98, 105). The sensitivity studies showed three parameters, BFNLR, OFSL (45, p. 45), and VINTMR, would have to be removed from the list because of lack of sensitivity. Liou presents a method for estimating BFNLR from OPSET output (37, pp. 170-173). Ross recommends procedures for estimating the other two.

Two other parameters, GWETF and SUBWF, presented another problem. They represent processes (direct evapotranspiration from the watertable and subsurface flow leaving the watershed) which were not taking place in any of the 20 watersheds for which data was collected. The recommendation was to use zero values for both variables except for watersheds where the indexed process was known to be significant. An indirect estimating procedure requiring several runs with OPSET was later developed for verifying estimates of impervious area made from watershed mapping and can be applied to estimating these two parameters as well (pp. 46-47).

Thirteen parameters were left. Two were recession constants (BFRC and IFRC). Six are used in modeling the land phase of runoff and were found to be particularly significant in controlling the monthly distribution of simulated flows (BMIR, BUZC, ETLF, LZC, SIAC, and SUZC). One (the parameter controlling interflow volume) was found to relate most closely to flows simulated the first few days after major flood peaks (BIVF). The remaining four are used in channel routing and were found to relate to the timing, peak, and shape of simulated flood hydrographs (CHCAP, CSRX, FSRX, and NCTRI).

Calibration Approach: Except for the two recession constants which could be directly estimated from selected recession sequences

(33), it was manifest from the complexity of the simulation alogorithm that the search for optimum set of parameter values would have to employ an estimating sequence using trial values, simulated flows, and value adjustments converging on the best estimate. Access to the simulation algorithm of the Kentucky Watershed Model would have to be streamlined as much as possible to minimize computer time expended in the trial simulations. The first step in developing OPSET was to streamline the Model by removing all statements not essential to the task at hand.

The basic structure of OPSET was predetermined by the necessity of developing an inner loop which would duplicate the essence of the simulation in minimum time. All the housekeeping work of setting up the climatological data, the parameters which would not be varied, and the constants calculated from these parameters had to be performed before the inner loop. Then, trial parameter values could be selected; the inner loop could be employed to simulate flows; a procedure could be called to adjust the parameter values; and the inner loop could be called again in a cycle terminated when an acceptable match was achieved.

The length of the continuous hydrograph to be simulated in a single pass through the inner loop was set at one year. Ideally, it would be desirable to simulate several sequential years together and adjust the parameters to get an overall best fit. This was not practical because of the additional computer storage required to simultaneously hold several years of climatological data and the additional computer time required for a single passage through the loop. Computer time would be spent in larger blocks, and any errors in the punched data or delays caused by slow convergence would be much more expensive. It would also be more difficult to employ years which were not consecutive but which because of their flow patterns seemed to have greater potential for yielding good parameter estimates. Over-all the better strategy appeared to be to estimate by individual years and average the results for watershed parameter values.

Since BFRC and IFRC could be estimated directly from recorded daily flows, eleven parameters were left to estimate by matching. The six land phase parameters were examined first. The matching of the total and seasonal distribution of annual runoff volume was based on simulated monthly flow totals (37, pp. 19-20). The use of a coarse time grid permitted a modification to the inner loop which greatly reduced simulation time and thereby greatly expanded the capability to search among flows simulated by various parameter value sets. All channel routing could be removed. The assumption of instantaneous arrival at the channel mouth does not materially affect the distribution of annual flow among months except for very large watersheds or at times when major storms occur the last day of the month.

The next major programing issue was whether it was wise to try to save additional computing time by increasing the period of time represented by the innermost loop from 15 minutes to some longer interval. Sensitivity studies were used to relate monthly flow volume to the length of time represented by this loop (37, p. 25). The outcome was a decision to use hour looping in a rough adjustment phase to bring the parameter estimates into a ballpark range and to follow with 20-minute looping to zero in on a final set of values.

A great deal of time was also spent in selecting a method to search among combinations of values for the six volume parameters. A method based on incrementing the values of the parameters in the direction of steepest ascent toward the most desirable value of the objective function (37,pp.,21-23)bogged down because of apparent irregularities of the function and because too many passes through the inner loop were required to generate points for estimating slopes. As a result, traditional search procedures were discarded in favor of programing the trial adjustments a user would likely make based on his qualitative understanding of hydrologic interactions within the watershed and on the quantitative insight provided by the Elkhorn Creek sensitivity studies. The adjustment continued until it was no longer able to reduce the difference between simulated and recorded flows as measured by a special index developed for this purpose (37, pp. 99-102). Attempts to check the minimum point by fitting a multidimensional response surface to points in the immediate area were discarded when they proved to be both time consuming and consistently showing the previous end point to be very close to the minimum anyway.

During the fine adjustment of the six volume parameters with 20-minute looping, BIVF is adjusted by OPSET to better match the volume of interflow synthesized during the first three days following storms to the volume of interflow recorded during corresponding periods (37,pp..113-117). Recorded interflow is separated out of the total hydrograph by solving for flow volumes in connection with the fitting of a linear recession constant by least squares (37, pp. 109-112).

Adjustment of the four remaining parameters, those primarily governing the shape of the routed flood hydrograph, is performed after first abstracting land phase runoff during selected storm periods in a complete simulation of the annual hydrograph with 15-minute looping. The simulated volume was then totaled and adjusted to match the recorded volume to minimize the bias in estimating routing parameters. An algorithim was developed for routing the adjusted period runoff volumes with a trial set of values for these four parameters and systematically adjusting them until converging on the recorded peak flow and time of the peak (37, pp. 124-137). A synthesized hydrograph matching the recorded hydrograph in volume, time, and peak was generally found to match it acceptably in overall shape as well.

Program Refinement: The overall strategy in developing OPSET was to write a program, test it with some real data, debug and modify the program until it worked for the original data, try it one by one on other data sets, and gradually refine the program until it could handle the full range of situations encountered.

The initial test data was that for Elkhorn Creek which had previously been used in the sensitivity studies. Once the program was working satisfactorily with this data, two other runoff years for Elkhorn Creek were tried. Then came 19 other watersheds. Time after time OPSET had to be adjusted or expanded so that it could deal with a situation not previously encountered. Recorded flows might contain recession sequences too long for the original arrays. Severe differences between gaged and watershed rainfall might throw the parameter adjustment into ridiculous values. Methods had to be developed for evaluating routing parameters from data for overlapping storms, producing a double-peaked hydrograph. Adjustments which worked on a watershed with little direct runoff and continuous high base flows might not work so well under the opposite conditions.

The 20 watersheds used covered the full range of geographical and hydrologic regimes encountered in Kentucky. Hopefully, they include a wide enough range to minimize difficulty encountered in trying OPSET at other locations; however, new users will encounter many more situations where the program will have to be modified.

Constant vigilance against unreasonable results is an essential part of good judgment in applying any program. When further bugs or other inadequacies appear, the user should modify the programing as needed. The principal investigator is ready to extend what help he can as a public service and conversely would like to be kept informed of the experiences of others so that this service can be as helpful as possible.

It would be a grave mistake for anyone to take this research or OPSET as a finished product. The programing has come a long way over the last two years. The funding by OWRR of the initial program development has produced a usable tool capable of widespread application. Several are presented in later chapters of this report. Future users are challenged to make it better.

The most obvious need for further program refinement is with respect to watersheds diverse from the Kentucky experience. OPSET does not evaluate snowmelt parameters. The Kentucky climate does not have enough snow to permit this. Furthermore, the instantaneous runoff assumption used to estimate the land phase parameters is completely unworkable where snowpack accumulation lags flows for many weeks. Areas with large swamps, seasonal rainfall, distinct orographic rainfall patterns, or tropical climates will undoubtedly reveal other needs for program adjustment. These are some specific challenges.

Program Application: Because of the practical limitations which made it necessary to program OPSET on the basis of estimating a set of parameter values for one year at a time, it is also necessary to develop a strategy for making the best possible estimate of watershed parameters from the diverse estimates OPSET will yield for individual years. Ross (45, pp. 18-20) recommends the following steps.

1. Measure or estimate the watershed parameters which are

not measured by OPSET.

2. Select three to five years (not necessarily consecutive) of gaged record representing the full diversity of recorded flow conditions.

3. Collect the necessary precipitation, evaporation, and streamflow data.

4. Use OPSET to calibrate the 13 parameters for each of the selected years.

5. Average the annual values for each parameter to get an overall watershed value. Liou tried a number of averaging methods and presents specific recommendations for each parameter (37, pp. 168-170).

6. Use the established watershed parameter values and climatological data to simulate a long-term hydrograph with the Kentucky Watershed Model.

Randomly Selected Results: The first five steps were followed based on three years of selected data each to Elkhorn, McDougal, and West Bays Creeks in Kentucky and the Clemson University Experimental Watershed in South Carolina (35) with the results summarized in Table 1. The results are encouraging but not perfect and hence challenging. The correlation between recorded and simulated quantities observed for the annual, monthly, daily, and instantaneous flows seems good subjectively, but correlation coefficients were not computed because they over-emphasize matching the largest flows.

The following observations are not intended as excuses for not doing better but rather as factors giving additional insight to the complexity of watershed modeling.

1. The three Kentucky watersheds are either all or in part at some distance from the recording precipitation gages. Average distances are 3 miles for McDougal, 10 miles for Elkhorn, and 15

TABLE 1

COMPARISON OF SIMULATED WITH RECORDED FLOWS

(All flows in cfs)

	Elkhorn Creek Kentucky		McDougal Ck. Kentucky		West Bays Fk. Kentucky		Clemson Watershed - S. Car.	
Area (sq. mi.)	473.0		5.34		7.47		0.877	
	Rec.	Sim.	Rec.	Sim.	Rec.	Sim.	Rec.	Sim.
First Year								
Annual	280000	238000	752	971	3207	2795	378	363
Peak Month	99800	84100	192	277	1418	1159	75	56
Low Month	258	175	2	1	13	6	13	9
Peak Day	17200	16900	52	91	388	165	7.9	8.3
Low Day	2	0	0	0	0	0	0.3	0.2
Peak Flow	22400	24000	320	292	1500	588	30.0	41.7
Second Year								
Annual	300000	243000	4456	3955	3955	3778	375	384
Peak Month	49100	42400	848	828	1436	1053	82	80
Low Month	2960	2990	37	55	11	3	10	10
Peak Day	12100	6850	545	404	528	245	33.7	36.0
Low Day	1	1	0	0	0	0	0.2	0.2
Peak Flow	13000	8840	2100	1460	1510	761	179.6	147.0
Third Year								
Annual	186100	167100	2259	1942	3529	3237	317	330
Peak Month	133100	120600	433	395	809	865	55	58
Low Month	150	84	24	11	17	2	12	17
Peak Day	22100	15400	260	194	235	351	22.1	22.9
Low Day	0	0	0	0	0	0	0.3	0.2
Peak Flow	23200	18100	2890	864	1650	1710	58.7	74.0

miles for West Bays. The results were much better at Clemson where the gage was located inside a very small watershed.

2. The biggest misses were associated with peak flows, and these were invariably summer thunderstorms when it is difficult to estimate areal precipitation from point values (36, pp. 30-32) and quick peaks from small watersheds are likely to result from bursts of rainfall whose intensity cannot be reflected in the hourly totals.

3. Since the three tabulated years are not consecutive, some of the observed differences stem from difficulty in estimating initial conditions at the beginning of the water year. In an actual application of the KWM, consecutive years would be used in simulating the long-term hydrograph.

4. The consistent underestimation of low flow days is caused by the use of a single base flow recession constant when actually recessions tend to flatten as the flow drops (37, pp. 170-173).

RURAL WATERSHED STUDIES

OPSET was applied to estimated watershed parameter values for 16 small rural Kentucky watersheds ranging in size from 0.67 to 24.0 square miles (45, Table 6) located in all parts of the state from steep Appalachian mountainsides to flat lands along the Mississippi River. All the rural watersheds within the state in this size range with over ten years of gaged daily flows are included. The watersheds contain a wide variety of vegetation, human activity, and soil and geologic characteristics and vary widely in distance from the nearest precipitation gage to the watershed.

Small watersheds were selected for these studies because smaller areas are more homogeneous. One research goal was to relate OPSET-determined values of the Model parameters to measurable watershed characteristics. OPSET must necessarily use stream flows originating from all parts of the watershed and thus estimates parameter values which reflect average watershed conditions. The larger the watershed is, the more difficult it is to average the full range of conditions occurring over its surface into a single number describing a watershed characteristic. Consequently, greater difficulty would be expected in correlating OPSET estimated parameters to characteristics measured in other ways. The wiser approach for an initial study is to minimize this difficulty by selecting small watersheds.

The question of how to use a correlation derived between small watershed characteristics and parameters to estimate parameter values for a larger watershed is left open by this research design. It may be the correlation can be used directly. The 473-square mile Elkhorn Creek watershed, to which OPSET was also applied because the data had already been prepared for other purposes, yielded parameter estimates which suggested this may be so for watersheds up to that size. Certainly, there is some larger size for which it is better to subdivide the total area into parts, each with its own set of parameters, and combine their runoffs by stream routing. As an unsubstantiated hypothesis, modeling accuracy may be improved by shifting to modeling by segments for watersheds large enough to contain more than one recording rain gage or large enough to have significant orographic rainfall differences.

The USDA has prepared published soil surveys covering much of Kentucky. Each survey includes a map which indicates soil types classified by a comprehensive pedological system (9, p. 5-8) for all locations within the surveyed area. Each survey also includes descriptive material for each soil type providing a great deal of information on hydrologic soil properties. Several difficulties need to be recognized in using this data. Soils vary continuously by location even within a given type; published properties are average rather than uniform values. Average values for a soil type as it occurs over several counties may not represent the small part of the total area located in a given watershed. Soil descriptions emphasize the agricultural viewpoint and, especially in the older surveys, may not be sufficiently quantitative or describe the properties to be most helpful from the hydrologic viewpoint. Boundaries between soil types may be incorrectly plotted, particularly in isolated locations removed from agricultural areas. The variety of conditions found in a given soil type is also likely to be larger at more isolated locations.

Ross (45) reviewed the maps and descriptive material in the soil surveys and supplemented what he found with information from topographic and geologic mapping and by personal contacts with soil scientists involved in the survey work. The scope of the research did not permit field work. He was able to use this information to quantitatively estimate such properties as permeability by soil type and, as an average weighted by fraction of the area represented, by watershed. Other watershed properties, such as forest cover, had already been estimated by the USGS in their stream gage assessment program, and Ross was able to obtain direct numerical values. He used these sources to estimate numerical values for each watershed; of the available moisture storage capacity, the average permeability of the soil, the average permeability of the "A" horizon, the fraction of the watershed in forest, and watershed slope. He used OPSET to estimate values for the 13 model parameters for three years each and averaged the results over years in the manner recommended by Liou (45, p. 87).

The most valuable contribution from this phase of the research turned out to be the relationships uncovered between the measured watershed characteristics and the OPSET estimated parameter values. LZC correlated very well with the available moisture storage capacity. BMIR correlated very well with the permeability of the "A" horizon. ETLF and SUZC were related, but not so well, with watershed slope and forest cover. BERC correlated very closely with watershed geology.

A review of the logic originally used to formulate the Stanford Watershed Model (11) reveals that the various parameters were conceived to index specific properties of the watershed known to influence events in the runoff phase of the hydrologic cycle. For example, LZC was conceived as an index of the capacity of the soil to hold moisture; and BMIR was conceived as an index of basin wide infiltration. Furthermore, a knowledge of hydrologic processes served well in the selection of combinations of watershed characteristics for use in drawing curves relating these characteristics to OPSET estimates of parameter values. Most trends found in these curves could well have been predicted from qualitative hydrologic reasoning, a fact which lends substantial support to the validity of the results.

The quantitative estimates of parameter values which yield the best match between recorded and synthesized flows have qualitative implications with respect to the model as originally conceived. For example, OPSET estimates one capacity for the upper zone and another for the lower zone. The original modeling used a conceptual distinction between the two zones with the upper zone considered as moisture storage on the soil surface or within forest litter or other highly pervious material at the surface (11). Moisture penetrating more deeply within the soil profile was considered lower zone storage.

The parameters in the Stanford Watershed Model were designed to index specific hydrologic processes. The nature of the design was usually considered in the trial-and-error procedure for estimating parameter values, and in fact became a subjective influence in bounding trial values. In OPSET, each parameter is in the end assigned a numerical value based on a criterion of best fit without any check that the selected value makes hydrologic sense in terms of the equations in which it was used in model design. For example, the conceptualized physical boundary between the upper and the lower zones may not be reflected in the OPSET-estimated parameter values. It cannot even be assumed without further study that the "best-fit" values would correspond with the same distinction in one watershed as they would in another. Research into factors causing parameter estimates which best match recorded conditions not being reasonable in terms of what is known about a particular hydrologic process could guide the development of a mathematical model more clearly representing the physical processes.

URBAN WATERSHED STUDIES

If OPSET were applied to each of many years of a long streamflow record from a watershed known to have experienced no hydrologically significant changes in land use or surface cover, one would expect the values estimated for any given parameter to vary somewhat from year to year; but the line of best fit through estimates of parameter values plotted against time should be essentially horizontal. The scatter of points around the line should be random and in a given climatic regime related to the distance from the watershed to the precipitation gages. The mean of all the annual values, calculated in the manner recommended by Liou (45, pp. 130-131) for that parameter would be the best estimate. The rural watershed studies sought to relate this best estimate (taken from three years) to measurable watershed characteristics.

If the watershed did experience hydrologically significant changes during the period of record, one would still expect the line of best fit through the OPSET estimates of parameter values to be horizontal if the parameter were independent of the type of hydrologic change which occurred. To the degree the parameter is dependent, a break in the horizontal line through the time series of estimates would be expected to occur at the time the hydrologic change began. If such a break is noted, the next logical step would be to plot the parameter against a third variable indexing the hydrologic change. Example indices of urban development include population, number of buildings, area of floor space, area of impervious surface, etc.

The scope of the urban watershed studies was to develop a preliminary feel for the effects of urbanization on parameter values. The method was to observe time trends in estimates and relate these to impervious area, designated as FIMP in the OPSET parameters, as an index of urban development. Analysis of how these observed trends might relate to initial rural watershed parameter values or climatological factors was left for later research endeavors.

Three watersheds were used as an initial data source. All three are located in suburban Louisville, Kentucky, and have been gaged by the USGS since 1944, a period of major urbanization. As a preliminary step to getting a feel for the hydrologic effects of urban change in the three watersheds, double-mass analyses (36, pp. 33-34) were performed (45, p. 119). Accumulated values of (1) annual flood peaks and (2) total annual runoff were summed from the data for each of these three gages and plotted against corresponding values summed from a network of ten stream gages in surrounding Kentucky and Indiana. The hope was to study the curves plotting total annual volumes for trends in total runoff as affected by land surface changes and to study the curves plotting annual peaks for trends toward more sharply peaked and higher flows as affected by channelization changes. South Fork of Beargrass Creek was dropped from further analysis because both double mass curves plotted as essentially straight lines. While the watershed had experienced significant urban change from 1945 to 1968, the most rapid change had been in recent years when the quality of the gaged record was quite poor (45, p. 123).

The other two creeks were retained. Both double mass curves for Pond Creek exhibited a significant bow toward more runoff in recent years (45, pp. 121-122). The bow in the curve depicts a gradual change as contrasted with the sharp break characteristic of such sudden changes as movement of a precipitation gage (36, p. 34). The bow was much more severe for annual peaks from the Pond Creek watershed where a widespread channel improvement program was underway. The curves for the Middle Fork of Beargrass Creek showed approximately equal and less pronounced bows. Relatively less urban development and little channelization had occurred.

Before OPSET could be employed to determine the effect of urbanization on the 13 parameters it estimates, it was necessary to explore the effect of urbanization on the parameters which have to be measured in other ways. The one parameter to which the simulated flows are highly sensitive and which manifestly changes with urbanization is FIMP, the fraction of the watershed area in impervious surface. Dempsey had previously estimated values for FIMP for Pond Creek to average 0.01 over 1945-7 and 0.06 over 1964-6 (16, pp. 21, 35) from topographic mapping and a time series of aerial photographs. Ross (45, p. 129) tried a series of runs with OPSET. For each of the two time periods he systematically varied FIMP in increments of 0.01. Values of the same objective function used by OPSET in estimating the other parameters were plotted against FIMP.

Two U-shaped curves resulted. The minimum points were at 0.01 for 1945-8 and 0.06 for 1965-8. In other words the model was able to achieve a better match between simulated and recorded flows with these values of FIMP than it could for any other values of FIMP in conjunction with any other combination of values for the other variables.

This conclusion is very important for two reasons. It means that whenever the user of OPSET has a doubt as to what value to employ for a given parameter which is not directly estimated by OPSET, he has an indirect method available. GWETF or SUBWF might be estimated by the same technique.

The success of the technique is even more important as a confirmation of the validity of OPSET as a tool for estimating watershed parameters. Ross used OPSET to estimate the value of a parameter which Dempsey had independently estimated by planimetering areas from aerial photography. The results were identical. The fact that the parameter which could be checked did check fortifies faith in estimates for parameters which could not be checked.

Four years, one more than the three used for the rural watersheds, were employed to estimate parameter values for the two urban watersheds. The years 1945-8 were used for one estimate, and the years 1965-8 were used for a second estimate. Four years provides a firmer estimate than three, and this is more important at this point where the study shifted into estimating marginal values.

Table 2 presents the OPSET results for the four first years (1945-8) and the four most recent years (1965-8) of available record on Pond Creek. While urban development within each time period was admittedly sufficient for some hydrologic change to transpire, such differences were neglected as being too small to distinguish

TABLE 2

PARAMETER VALUES ESTIMATED FOR POND CREEK WATERSHED

	1945	1946	1947	1948	Aver.	1965	1966	1967	1968	Aver.
Prec.*	45.41	44.08	42.46	38.65	--	44.90	40.89	43.32	38.63	--
Runoff*										
Rec.	21.45	12.02	12.29	17.87	--	17.19	20.98	14.43	18.69	--
Sim.	21.26	11.63	12.32	17.36	--	16.99	17.97	14.99	17.91	--
LZC	2.28	4.17	7.50	8.29	5.56	5.78	3.00	6.00	2.64	4.36
BMIR	17.15	7.36	5.17	1.12	7.70	2.56	4.11	3.28	11.22	5.29
SUZC	0.47	1.62	0.30	0.33	0.68	1.02	0.71	0.69	0.30	0.68
ETLF	0.09	0.55	0.28	0.06	0.25	0.12	0.07	0.13	0.05	0.09
BUZC	0.75	2.16	1.69	0.81	1.35	0.53	0.38	0.85	0.45	0.55
SIAC	1.73	0.00	0.03	0.06	0.09	1.25	0.90	0.45	0.12	0.50
BIVF	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
IFRC	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
BFRC	0.795	0.726	0.847	0.847	0.814	0.914	0.916	0.915	0.853	0.901
NCTRI	5	7	6	5	6	4	2	5	4	4
CSRX	0.859	0.926	0.974	0.990	0.940	0.962	0.981	0.951	0.921	0.954
FSRX	0.990	0.987	0.989	0.990	0.989	0.962	0.981	0.951	0.990	0.970
CHCAP	246	600	480	384	480	2400	2400	2400	1536	2400

*Inches

within the estimating precision of the method. Table 3 presents comparable results for the Middle Fork of Beargrass Creek. Table 4 summarizes the results of testing the data on Tables 2 and 3 for statistically significant trends. In only a few cases was the trend significant. A lot more work is needed to determine which trends are valid, and even more is needed to quantify those which do exist. Table 5 compares these results with the speculations based on hydrologic judgment or trial-and-error comparisons of other studies.

FLOOD PEAK STUDIES

The results of the rural watershed studies shown on Table 1 suggest increasing difficulty in matching recorded with simulated flows as the comparison shifts from annual to monthly to daily to peak values. The Flat Creek Watershed just north of Frankfort, Kentucky (45, p. 71), gave the greatest difficulty in simulating flow peaks. The data on Table 6 explains why. The eleven largest flood peaks recorded during the three years of record used with OPSET are tabulated in descending order starting with the largest. The largest eight all have recorded flood peaks in excess of recorded peak clock hour rainfall intensities. For the storm of July 19, 1955, the explanation is a thunderstorm which hit the watershed but missed the rain gage. The laws of chance say to look further in explaining the other seven.

The most likely explanation is that the watershed is responding to peak intensities shorter in duration than one hour. This is the reason why Liou introduced a subroutine to estimate 15-minute precipitation on an average probability basis (37, pp. 61-65). Simulated peaks were increased by about 10 percent by using Liou's subroutine to increase peak 15-minute precipitation intensities to 1.84 times the peak hourly intensities on Table 6, speeding stream

TABLE 3

PARAMETER VALUES ESTIMATED FOR MIDDLE FORK OF BEARGRASS CREEK WATERSHED

	1945	1946	1947	1948	Aver.	1965	1966	1967	1968	Aver.
Prec.*	45.41	44.08	42.46	38.65	--	44.90	40.89	43.32	38.63	--
Runoff*										
Rec.	20.52	13.43	13.97	16.83	--	18.62	17.31	14.68	20.16	--
Sim.	19.70	14.64	13.70	15.22	--	21.51	18.43	12.93	20.00	--
LZC	4.96	6.86	3.42	7.16	5.60	4.31	2.00	5.39	1.87	3.20
BMIR	18.00	6.83	12.06	8.02	11.23	10.53	21.85	6.20	1.60	9.50
SUZC	0.30	1.01	0.60	0.65	0.64	0.41	1.10	1.15	0.25	0.80
ETLF	0.13	0.16	0.26	0.14	0.17	0.10	0.05	0.37	0.05	0.14
BUZC	4.00	1.17	4.39	1.35	2.73	0.66	0.20	1.14	0.27	0.55
SIAC	0.16	0.03	0.23	0.45	0.15	0.46	0.60	1.80	0.01	0.32
BIVF	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.751	0.00
IFRC	0.354	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.332	0.10
BFRC	0.888	0.909	0.885	0.876	0.891	0.893	0.903	0.947	0.871	0.905
NCTRI	2	3	2	3	3	4	3	4	3	4
CSRX	0.900	0.943	0.922	0.919	0.920	0.961	0.961	0.938	0.889	0.936
FSRX	0.900	0.943	0.922	0.987	0.948	0.961	0.961	0.980	0.982	0.970
CHCAP	600	600	600	384	600	600	600	246	384	600

*Inches

TABLE 4

SIGNIFICANCE OF CHANGE IN PARAMETER VALUES ASSOCIATED WITH URBANIZATION

Parameter	Watershed	Value at FIMP = 0	$\frac{\text{Value}}{\text{FIMP}}$	F Statistic	Level of Confidence
LZC	Pond Creek	5.80	-24.1	1.59	75%
	MF Beargrass	7.20	-40.0		
BMIR	Pond Creek	8.18	-48.2	0.24	~
	MF Beargrass	12.38	-28.8		
SUZC	Pond Creek	0.68	0.0	0.11	~
	MF Beargrass	0.54	2.6		
ETLF	Pond Creek	0.28	- 3.1	1.22	~70%
	MF Beargrass	0.19	- 0.5		
BUZC	Pond Creek	1.51	-16.0	5.94	95%[2]
	MF Beargrass	4.18	-36.3		
SIAC[1]	Pond Creek	-10.65	14.9	1.37	~70%
	MF Beargrass	-1.04	5.4		
BFRC	Pond Creek	0.78	1.9	7.15	99%
	MF Beargrass	0.88	0.2		

[1] Logarithms of SIAC are used

[2] F test not valid because of change in variance with FIMP, but the trend is believed significant.

TABLE 5

TRENDS IN PARAMETER VALUES WITH URBANIZATION RESULTS FROM VARIOUS INVESTIGATORS

	Morrison James (30)		Pond Dempsey (16)		Chicago Crawford (25)		Pond		Middle Fk.	
	Rural	Urban	Rural	Urban	Rural	Urban	Rural	Urban	Rural	Urban
FIMP	0.00	0.10	0.01	0.06	.05	.52	0.10	0.06	0.04	0.10
LZC	10.00	10.00	30.00	14.00	7.5	7.5	5.56	4.36	5.60	3.20
BMIR	*		0.65	0.65	.020	.017	7.70	5.29	11.23	9.50
SUZC	0.55	0.50	1.00	0.65	*		0.68	0.68	0.64	0.80
ETLF	0.40	0.40	0.50	0.50	0.25	0.25	0.25	0.09	0.17	0.14
BUZC	2.20	2.00	1.10	0.75	1.20	1.10	1.35	0.55	2.73	0.55
SIAC	0.50	0.50	0.80	0.50	*		0.09	0.50	0.15	0.32
BIVF	*		0.95	0.95	3.50	3.50	0.00	0.00	0.00	0.00
IFRC	0.20	0.20	0.62	0.62	0.50	0.50	0.10	0.10	0.10	0.10
BFRC	0.9967	0.9967	0.920	0.995	0.97	0.97	0.814	0.901	0.891	0.905
NCTRI	22	22	6	4	**		6	4	3	4
CSRX	*		0.955	0.957	**		0.940	0.954	0.920	0.936
FSRX	*		0.955	0.990	**		0.989	0.970	0.948	0.970
CHCAP	*		600.	2400.	**		480.	2400.	600.	600.

*Variable did not appear in the version used, but no change for urbanization was made in the approach.

**Channel routing performed by a method which does not use the parameters.

TABLE 6

COMPARISON OF FLOOD PEAKS WITH RAINFALL INTENSITIES FOR THE FLAT CREEK WATERSHED, KENTUCKY

Date	Recorded Peak Flow		Peak Storm Intensity in/hr
	cfs	in/hr	
July 8, 1955	7100	1.97	1.14
July 19, 1955	4330	1.20	0.05
Mar. 22, 1952	3460	0.96	0.78
July 24, 1955	2640	0.73	0.43
Jan. 21, 1959	2150	0.60	0.47
Mar. 10, 1952	1770	0.49	0.30
Apr. 13, 1952	1730	0.48	0.39
Jan. 22, 1952	1460	0.41	0.23
Feb. 28, 1955	1380	0.38	0.81
Mar. 20, 1955	1380	0.38	0.46
Jan. 4, 1952	1150	0.32	0.34

Watershed Characteristics:

Drainage Area	5.63 mi^2
Stream Length	3.41 mi.
Maximum Relief	230 ft.

routing to one value of unity in the 15-minute histogram (an implied stream velocity of 20 feet per second), and using one third of the estimated value of OFSL. Most of the peaks were still less than half their recorded value. Further research is needed to better model these sharp peaks; however, the problem was not nearly as severe in any of the other watersheds.

The fact that the simulated peaks for the Clemson Watershed as shown on Table 1 seem to be much better than those for the much larger McDougal and West Bays Fork watersheds suggest that a major difficulty may be with trying to simulate small watershed flood peaks from precipitation gages located too far away. Both Kentucky simulations are based on gages many miles away (45, p. 143), the Clemson precipitation is gaged within the watershed (35, p. 119). This line of thinking implies that the watershed intensities may be consistently higher than the gaged intensities for Flat Creek.

CONCLUSION

The findings as described in this chapter are very significant in terms of developing a basis for the type of marginal hydrologic analysis presented in Chapter I as being so badly needed. OPSET provides a tool for developing a bank of compatible sets of parameter values covering all watersheds to which the Stanford Watershed Model is applied. Where estimates were once inherently incompatible because of differences in subjectively incremented and terminated series of trial-and-error adjustments, a standardized procedure now gives estimates which are a function of the available data alone. Differences among values can be compared with differences among watershed properties. The applications to rural and urban watersheds summarized in this chapter and described by Ross in greater detail are but a token of what can be done to correlate watershed characteristics with model parameters once a large number of users begin to apply OPSET in diverse settings and begin to pool their results. As a better handle on these interrelationships develops, it will be possible to measure the characteristics of an ungaged watershed, estimate values for the model parameters from the relationships, and simulate a long-term, complete sequence of flows from climatological data. Any change to the watershed can be measured or forecast and again related to model parameters, and a new flow sequence can be simulated. The planner will have a quantitative estimate of marginal hydrologic change to a degree of precision never before possible.

For the moment, this is a dream. Whether it becomes a reality is going to be determined by the degree to which the research described here continues. The principal investigator will be applying OPSET to additional watersheds in his own research. He is able and willing to provide any assistance he can to other interested parties in helping them use OPSET. This packet of three reports is available free of charge from the University of Kentucky Water Resources Institute as long as the supply lasts. Card decks are available at nominal charge through the principal investigator at the Georgia Institute of Technology Environmental Resources Center. All that is asked of the user is for him to report his results back to the principal investigator. What was the nature of the watershed where OPSET was applied? What values were estimated for each parameter? Further results can then be distributed among all users, and hopefully we will all be able to move toward more successful hydrologic modeling.

CHAPTER III

PATTERNS IN SMALL WATERSHED HYDROLOGY

WATERSHED DIFFERENCES

Watershed characteristics evolve through geologic processes. In humid climate, such as Eastern United States including Kentucky, water is the primary natural agent acting to change the watershed surface. The underlying rocks provide the raw material. Water directly transforms the watershed surface as rainfall impact disturbs the soil and runoff erodes, transports, and deposits material on its way downstream. Water acts indirectly as it promotes the growth of vegetation which sends down roots which gradually pulverize underlying rock to form a soil mantle and sends up shoots which later die, decay, and blend vegetative with inert matter at the soil surface. The type of vegetation is a function of both the climate and the parent underlying formations.

Geologic differences are much more important than climatic differences in explaining the variation among small Kentucky watersheds. Kentucky watersheds experience much the same variety of weather patterns over a long period of time but vary widely in underground formations. The same climatic consistency and geologic variation is true of most moderately sized geographical areas. Climatic patterns are unlikely to vary much over the normal metropolitan area, but soil, rock, and resultant vegetative conditions are. Of course at a given time, rain may be falling in one part of a city while the sun is shining in another part. For the purpose of this discussion, climatic similarity refers to the same mean annual rainfall falling in the same monthly distribution and having the same peak short-term intensities.

The activities of man also play an important part in the development of soil and watershed surface conditions. Even apart from the changes which occur with urbanization, watersheds are changed by tillage practices, fertilization efforts, grazing and forest management policy, agricultural drainage, and a number of other activities. A thorough analysis must consider differences in land management history as well as geology.

The pattern of climatic consistency with geologic variety has important implications to urban planning. Those planning the growth patterns of metropolitan areas need information on the hydrologic consequences of urban development. Two important questions are (1) whether urban development in certain types of watersheds has a more severe effect than development in other types in increasing downstream flood hazard (or otherwise altering downstream flow patterns) and (2) whether urban development in the flood plains downstream from certain types of watersheds is likely to experience more severe flooding problems than development in flood plains downstream from other types of watersheds of equivalent area. Where such differences do exist, they should be used by urban planners in weighing alternative city expansion patterns. If the differences can be expressed quantitatively, the planner has more solid information on which to base his choice.

The data base available to this study consists of 17 rural watersheds scattered over a large variety of Kentucky geological conditions and two urbanizing (i. e., becoming noticeably more urban with time) watersheds located within the same county and on the same geologic base. This data base is of little help in studying differences in the effect urbanization of watersheds of different types has on downstream flows, but it is very helpful in evaluating differences in runoff patterns and flood hazard found downstream from a variety of watersheds.

The differences in rural watershed runoff patterns are conceived in terms of watersheds of less than 25 square miles. These are not areas where one would expect to see extensive flood plain zoning or federally financed structural measures. They are areas where local government has traditionally financed the necessary urban drainage facilities. If local government could distinguish certain areas as requiring fewer or less costly drainage facilities than others, the potential expenditure reduction could be a significant factor in planned urban expansion.

GAGED RECORD DIFFERENCES

One approach to analyzing variation in flood hazard by watershed type would be through analysis of the stream gage records of a large number of diverse watersheds for flood peak by frequency. One might then compare 50-year flood peaks and order watersheds by hazard according to flood peak magnitude. Two problems soon become apparent. Gaged watersheds are of different sizes. Gaged watersheds, entirely by chance patterns of random events rather than by true climatological differences, experience different combinations of storm severity over a given period of record. For example, one watershed may experience a 200-year rainfall during a period when another watershed may experience no larger than the 8-year event. Adjustments are needed for both effects to achieve a commensurate hazard ordering.

Furthermore, floods do not create a significant hazard until they reach peaks in excess of the available channel capacity. Natural channel capacity varies among watersheds of a given size. An important factor is flood frequency because larger flows tendto wash larger channels, but other factors, such as soil erodability, are also important. Channel sizes may characteristically be bigger in some types of watersheds than they are in others even though the flows may be the same. It is not within the scope of this study to evaluate differences in stream channel capacity for two reasons. Stream cross sections for estimating capacity were unavailable and would be costly to obtain. The planner can readily measure the cross section of any stream of interest, hydraulically estimate channel capacity, and thereby ascertain the flood hazard associated with any known flood peak.

UNIT WATERSHED CONCEPT

The concept of a unit watershed provides a useful tool for examining flood hazard for various types of watersheds while adjusting for the effects of differences in watershed size and historical storm patterns. The unit watershed is a hypothetical area of one square mile which is created by use of the Watershed Model. By specifying a set of parameter values for a unit watershed which are similar to those actually found by OPSET for a real watershed, a unit watershed which has characteristics similar to a real watershed can be studied. By using the same precipitation record to simulate flows, the unit watersheds provide a basis for comparing the differences associated with such variables as cover, soil, and geologic conditions; these differences are created by using different sets of parameters specifying the watersheds. Because cover and soil conditions in a given climate so closely relate to underlying hydrology, little is to be gained by looking at all theoretical combinations of these watershed characteristics. The practically important combinations are those which have actually developed as exhibited by observed watersheds.

A unit watershed was established to represent each of the 17 rural watersheds by using in the Watershed Model the respective derived set of parameter values except for AREA, which was uniformly taken as unity, and other parameters known to vary with area or believed to be little dependent on geology. The adjustment of such parameters is discussed below. The recorded hourly rainfalls at Louisville, Kentucky, during the 64 years from 1905 through 1968 were available for use in simulating flows for each unit watershed. Differences could then be quantitatively compared. To facilitate later interpretation, each unit watershed was named after the watershed from which the parameter values were derived.

FLOOD FREQUENCY DISTRIBUTION

One purpose of the unit watershed studies was to compare flood peaks by frequency. In accordance with the recommendation reported by Benson (4), it was decided to use the log Pearson Type III distribution as the basis for flood frequency analysis. Since skew coefficients had to be estimated from a record too short to yield reliable values, the longer records from the ten gages used as a data base in plotting the double mass curves (45, pp. 119-127) were studied. To further improve precision, three other nearby streams for which annual flood peaks were also readily available were added (Little River, Tygarts Creek, and Red River, all in Kentucky). All streams had about 30 years of record. The annual peaks from the 13 streams had an average coefficient of skew of -0.14. This small negative skew was judged to be not sufficiently different from zero to justify a nonzero value. Accordingly, the regional skew was taken to be zero. The log-Pearson Type III distribution with zero skew is a log normal distribution.

THE POND CREEK UNIT WATERSHED

The major difficulty with working with a unit watershed is in estimating flood peaks. The problem stems from two causes. Certain parameters relate to watershed size. Obviously, a small watershed will have different stream routing than a large one. Second, the time of concentration from one square mile is usually less than one hour. Consequently, peaks may result from short intense rainfalls which are not adequately reflected in the hourly totals. Because this study is looking, in part, at comparative flood peaks, it was necessary to begin by estimating the mean annual and 200-year flood peaks outside the Watershed Model. These could then be correlated with those estimated from Model generated annual peaks to establish a relationship between the two for use in evaluating comparative flood peaks in the several watershed types.

The previous work by Dempsey was used to begin this process. The Pond Creek watershed (16, pp. 10-15) has been gaged at a point where its drainage area is 64.83 square miles since 1944. After fitting the model parameters for 1966 watershed conditions by trial and error he simulated 63 years of flows for 1905-1967 (16, pp. 46-47). This information provided a basis for examining how well the flows in the period of gaged record (1945-1967) represented the longer period. While flows generated with constant parameters poorly represent historical flows during a time of watershed change, they do provide helpful information for evaluating the representativeness of a short-term precipitation record of long-term conditions.

The 63 years of annual flood peaks had a mean of 4023 cfs and a standard deviation of 1273 cfs. The most recent 23 years had a mean of 4276 cfs and a standard deviation of 1213 cfs. Higher moments were not compared because of the prior decision to use zero skew based on regional data. The small differences were partially compensating when substituted in the formula for estimating larger flood peaks by frequency and not large enough to change flood peak estimates to a degree which was significant in terms of this study. Therefore, it was concluded that the rainfall patterns of the period of the 24 years of stream gaged record are representative of conditions over the 64 years of precipitation record. Computer time could be saved by simulating 24 rather than 64 years of record without significantly changing the results.

The 24 years of recorded annual flood peaks are listed in the second column of Table 7. Direct flood frequency analysis of these numbers, however, would be meaningless because of the change in watershed conditions over the period of record. By plotting a double mass curve of Pond Creek versus regional flood peaks (<u>45</u>, p.122), Ross found a significant break in the line after 1957. The later 1950's was a period of intensive channelization within the Pond Creek watershed. The recorded flood peaks through 1957 were not adjusted, but the more recent ones were adjusted by the standard method based on the change in slope of the double mass curve (<u>36</u>, p. 34).

The logs of the adjusted annual flood peaks (Table 7, Column 4) have a mean of 3.2081 and a standard deviation of 0.1389. By using the value for K (the number of standard deviations from the midpoint to the 0.995 point in the normal distribution) of 2.5758 for the 200-year event,

$$\log_{10} Q_{200} = 3.2081 + 2.5758\ (0.1389) = 3.5658$$

$$Q_{200} = 3680 \text{ cfs.}$$

The mean annual flood was estimated as the average of the numbers in Column 3 or 1690 cfs.

TABLE 7

ANNUAL FLOOD SERIES FOR POND CREEK UNIT WATERSHED

Year	Recorded Flow cfs	Adjusted Flow (Q) cfs	$\log_{10} Q = x$	$\frac{x - \bar{x}}{\sigma_x}$	Freq.	Area Factor	Unit Watershed Flow cfs
1945	2000	2000	3.3010	0.669	0.75	0.096	192
1946	1740	1740	3.2405	0.233	0.59	0.088	153
1947	1460	1460	3.1644	-0.315	0.38	0.080	117
1948	2060	2060	3.3139	0.762	0.78	0.097	200
1949	1530	1530	3.1847	-0.168	0.43	0.082	125
1950	1590	1590	3.2014	-0.048	0.48	0.084	134
1951	1690	1690	3.2279	0.143	0.56	0.087	147
1952	1421	1421	3.1526	-0.400	0.34	0.079	112
1953	1330	1330	3.1239	-0.606	0.27	0.077	102
1954	607	607	2.7832	-3.059	0.0011	0.056	34
1955	1380	1380	3.1399	-0.491	0.31	0.078	108
1956	1660	1660	3.2201	0.086	0.53	0.086	143
1957	2290	2290	3.3598	1.092	0.86	0.104	238
1958	2590	1904	3.2797	0.515	0.70	0.093	177
1959	3260	2360	3.3729	1.186	0.88	0.106	250
1960	2490	1722	3.2360	0.201	0.58	0.088	152
1961	3080	2013	3.3038	0.689	0.75	0.096	193
1962	2520	2154	3.3332	0.901	0.82	0.100	215
1963	3360	1444	3.1596	-0.349	0.36	0.080	115
1964	8020	3122	3.4944	2.061	0.98	0.129	403
1965	4310	1098	3.0406	-1.206	0.11	0.070	77
1966	4380	1217	3.0853	-0.884	0.19	0.074	90
1967	3220	1211	3.0831	-0.900	0.18	0.073	88
1968	4320	1561	3.1934	-0.106	0.46	0.083	130

$\bar{x} = 3.2081 \qquad \sigma_x = 0.1389$

In order to estimate flood peaks for a large number of subwatershed drainage areas under a variety of conditions, Dempsey defined an area factor for use in the equation

$$Q_A = A\ A_f Q_u \qquad (1)$$

where Q_A is the peak associated with drainage area A as estimated with an appropriate area factor (A_f) and unit watershed flood peak (Q_u) for the desired frequency and state of urban development and channel improvement. Dempsey found the area factor for 64.83 square miles to be 0.121 for the mean annual flood and 0.083 for the 200-year flood (16, p. 153).

Substitution into Equation 1 of $Q_A = 1690$, $A = 64.83$, and $A_f = 0.121$ yields $Q_u = 215$ cfs for the mean annual flood. The same process gives $Q_u = 680$ cfs for the 200-year flood. A reference to Table 7 shows these estimates to be based on the annual flood series adjusted to 1945-57 conditions. Dempsey through studying watershed conditions during this period found 2.3 percent of the watershed in urban land use and 18.6 percent of the channels improved. Consequently, it also became necessary to adjust the unit watershed flood peaks downward to reflect a condition of no urbanization nor channelization. Again using factors derived by Dempsey (16, p. 56), the adjustment for the mean annual flood gives 215 (1254/1817) = 148 cfs. For the 200-year flood, it is 680 (3231/4060) or 541 cfs.

The unit watershed flood peak for the mean annual flood of 148 cfs turns out to be 0.0875 times the gaged watershed mean annual flood peak of 1690 cfs. The factor is 0.1470 for the 200-year event. These two factors are plotted on extreme probability paper on Figure 1. On Table 7, the normal deviate associated with each adjusted flood at the gage location is calculated and used to estimate the frequency with which the flood peak is not exceeded. An area factor is read for each frequency from Figure 1, shown on Table 7, and multiplied by the adjusted flow (Column 3) for the gaged watershed to develop a unit watershed annual flood series for 1945 through 1968. A frequency analysis of these 24 years of annual flood peaks based on the log normal or zero skew distribution yields a mean annual flood of 154 cfs and a 200-year flood of 482 cfs. The differences between 148 and 154 and between 541 and 482 are estimates of the bias introduced when the frequency analysis is performed directly on the hypothetical unit watershed data.

UNIT WATERSHED PARAMETERS

The Kentucky Watershed Model was used to simulate flow sequences for 18 unit watersheds, Pond Creek plus the 17 rural watersheds. The input data were assembled in the form shown by Ross (45, Appendix A). All 14 options were exercised as zero except that one was used for CONOPT (2) and CONOPT (5) and two was used for CONOPT (3). A three-element, 15-minute time array histogram of 0.4, 0.5, and 0.1 was used. The parameters held constant for all unit watersheds were RMPF at 1.0, RGPMB at 1.0, AREA at 1.0, FIMP at 0.00, FWTR at 0.00, VINTMR at 0.10, OFSS at 0.02, OFSL at 400.0 OFMN at 0.25, OFMNIS at 0.015, CSRX and FSRX at 0.90, CHCAP at 160.0, and BFNLR at 1.0. The other parameters were varied according to the OPSET determined values for the watershed. The climatological data for Louisville, Kentucky was used.

Several considerations went into the decision on which parameters to hold constant. Some were held at values reflecting rural conditions. Some were reduced to values appropriate for areas of one square mile. The parameters governing overland flow routing and interception were held at the Pond Creek values, used in the OPSET runs.

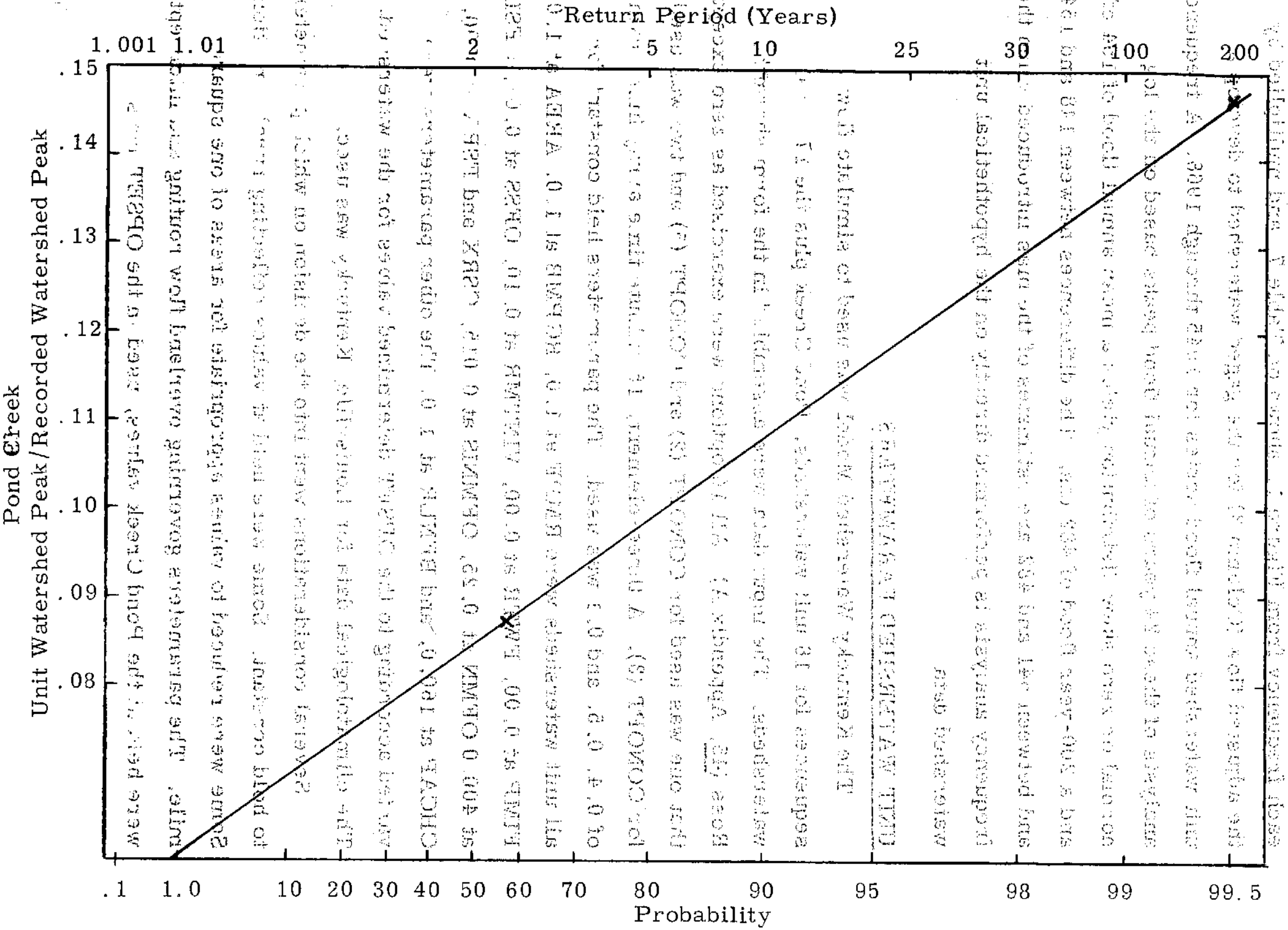

Figure 1. Unit Watershed Peak as a Fraction of Recorded Peak by Flood Frequency

UNIT WATERSHED SIMULATION

Five years (1962-1966) of flows were simulated for each unit watershed. The simulation for the Pond Creek Unit Watershed yielded annual flood peaks of 96, 87, 250, 122, and 97 cfs compared with the 215, 115, 403, 77, and 90 shown on Table 7. The amount by which the second group of numbers exceeds the first verifies the tendency of the Model to underestimate flood peaks for small watersheds using hourly data.

After a corresponding set of five annual flood peaks was simulated for each unit watershed, the procedure was to fit the model $y = \alpha + \beta x$ to the 5 points $\{y_i, x_i\}$ where the x_i equal the Pond Creek values and the y_i equal the other unit watershed values and then estimate the other y's by using $\hat{y} = \hat{\alpha} + \hat{\beta} x$ where x's are the 24 values for Pond Creek on Table 7. As can be seen by comparing the rows of numbers on Table 8, correlations between x and y in the basic model are uniformly very good. All correlation coefficients were over 0.97 except for 0.94 for Green River and 0.95 for Stillwater Creek.

The result was a 24-year record for the other unit watershed. A frequency analysis of this sequence was then used to estimate mean annual and 200-year events for each watershed. The raw estimates were multiplied by 148/154 for the mean annual event and 541/482 for the 200-year event to correct for the bias noted previously as being associated with direct use of a frequency analysis of these 24 years of unit watershed data. The simulated annual flood peaks for each of the 16 small rural unit watersheds and for Pond Creek with the parameters adjusted to reflect rural conditions are listed on Table 8 together with estimates of the mean annual and 200-year events.

TABLE 8

UNIT WATERSHED FLOOD PEAKS

	Simulated Annual Peaks					Frequency Floods	
Watershed	1962	1963	1964	1965	1966	Mean Annual	200-Year
Bear Branch	162	148	323	156	130	202	583
Cane Branch	147	131	303	147	111	186	574
Cave Creek	145	129	300	147	107	184	573
Flat Creek	172	159	337	161	136	212	600
Green River	143	127	300	124	72	174	645
Helton Branch	133	117	285	135	92	171	574
McDougal Creek	143	130	299	148	128	187	547
McGills Creek	99	88	253	115	88	147	574
Perry Creek	133	131	301	134	113	182	586
Pond Creek	96	87	250	122	97	148	542
Rock Lick Creek	140	122	295	145	124	183	552
Rose Creek	158	145	322	148	126	199	594
South Elkhorn Creek	95	80	238	114	82	139	539
So. Fk. L. Barren R.	131	124	297	136	112	179	585
Stillwater Creek	57	75	185	67	36	99	662
West Bays Fork	92	87	243	112	84	141	551
Wood Creek	105	93	255	125	98	153	531

Note: All flood peaks in cfs.

UNIT WATERSHED FLOW PATTERNS

Watershed Classification: A quick look at Table 8 suggests significant differences in the patterns of flow among the several watersheds. While each watershed is a unique entity, complete tabulation and discussion of the results becomes bulky and confusing. It is more advantageous at this point to first categorize the runoff patterns so that subsequent discussion can be based on representative watersheds from each category. This abbreviated approach brings out the major points without burdening the presentation with excessive detail.

OPSET was not able to distinguish three types of runoff from the small watersheds. For most of them, no interflow was detected. For Stillwater Creek, the best modeling divided all but a very small portion of the runoff between base flow and interflow. Only for the larger watersheds, Elkhorn Creek is the best example, were parameters selected which simulated significant amounts of all three types of flow. However, the rural watersheds did vary greatly in the division of total simulated annual runoff between direct runoff and baseflow. This distinction proved very useful in classifying watersheds. A second useful classification was by annual runoff volume. Some watersheds consistently produced much greater volumes of annual runoff than others.

Six streamflow pattern categories were selected. One of the watersheds falling in each category was picked for use in the subsequent discussion. As a category representative, each selected watershed had generally similar flow patterns to the other watersheds in the same category. Of course, there were also differneces. The total population of watersheds lies on a continuum rather than in discrete groups, and individual watersheds within a category may fall one way or the other from their representative. The categories and watersheds are:

1. High runoff volumes with base flow predominate.
   Representative: McDougal Creek (LZC = 4.63, BMIR = 4.94).
   Other watershed in category: Wood Creek.
2. Medium runoff volumes with base flow predominate.
   Representative: Pond Creek (LZC = 5.80, BMIR = 8.18).
   Other watersheds in category: Cane Branch, Cave Creek, Helton Branch, Rock Lick Creek, South Elkhorn Creek, and South Fork of Little Barren River.
3. Low runoff volumes with base flow predominate.
   Representative: McGills Creek (LZC = 9.95, BMIR = 7.08).
   Other watershed in category: West Bays Fork.
4. High runoff volumes with flow approximately equally divided between base flow and direct runoff.
   Representative: Bear Branch (LZC = 2.45, BMIR = 7.62).
   Other watershed in category: Green River.
5. High runoff volumes with direct runoff predominate.
   Representative: Flat Creek (LZC = 4.40, BMIR = 0.87).
   Other watershed in category: Stillwater Creek.
6. Low runoff volumes with direct runoff predominate.
   Representative: Perry Creek (LZC = 28.05, BMIR = 0.27).
   Other watershed in category: Rose Creek.

Summary Tables: The results from the simulation of 5 years of flows for each of the six representative unit watersheds are summarized on Tables 9 through 15. These tables provide a quantitative basis for the watershed-by-watershed discussion to follow. Table 9 lists for the Pond Creek Unit Watershed for the precipitation patterns represented by the Louisville rainfall data for each of the years

TABLE 9

SYNTHESIZED FLOWS
FOR POND CREEK UNIT WATERSHED

Year	1962	1963	1964	1965	1966
Annual Precip. (in.)	40.86	43.91	40.34	44.90	40.89
Annual Runoff (in.)	10.17	6.66	11.23	10.36	11.65
Annual Coefficient	0.249	0.152	0.278	0.231	0.285
Peak Runoff Day	2-27	3-16	3-9	3-29	4-30
Peak Runoff Month	MAR	MAR	MAR	MAR	APR
Precipitation (in.)	3.58	9.04	14.91	4.82	9.56
Runoff (in.)	3.06	4.51	10.06	3.10	3.74
Coefficient	0.855	0.499	0.675	0.643	0.391
Peak Precipitation Month	FEB	JUL	SEP	SEP	JAN
Precipitation (in.)	6.58	7.33	4.16	8.41	5.73
Runoff (in.)	2.83	0.18	0.01	0.37	2.29
Coefficient	0.430	0.025	0.0024	0.044	0.400
Low Flow Month	AUG	NOV	AUG	AUG	SEP
Precipitation (in.)	2.20	1.59	2.63	2.18	2.59
Runoff (in.)	0.002	0.014	0.002	0.008	0.003
Coefficient	0.0009	0.0088	0.0007	0.0036	0.0011
Peak Rainfall (in./hr.)	0.760	1.620	0.990	1.400	1.750
Peak Runoff (in./hr.)	0.342	0.253	0.587	0.435	0.252
Coefficient	0.450	0.156	0.593	0.311	0.144
Peak Flow Date	2-23	3-16	3-9	3-29	4-30
Daily Average (cfs)	13.2	28.2	101.4	21.5	23.1
Peak (cfs)	95.9	87.4	250.0	122.3	96.5
Second Peak Date	1-22	3-4	3-25	2-11	1-2
Daily Average (cfs)	10.2	2.9	10.8	14.9	9.2
Peak (cfs)	39.4	13.1	81.0	85.0	33.3
Third Peak Date	6-11	4-29	3-4	12-26	4-24
Daily Average (cfs)	4.0	0.7	18.9	4.9	6.2
Peak (cfs)	22.0	8.0	53.0	19.3	33.4

1962 through 1966 the annual runoff, runoff during two high flow and one low flow month, and runoff during selected peak events. Table 10 lists the same information as multipliers of the Pond Creek values for the other five representative unit watersheds. Table 11 lists the total rainfall for each of the 60 months. Table 12 lists the simulated Pond Creek Unit Watershed total runoffs for each of these months. Table 13 lists the monthly runoff totals as multipliers of the Pond Creek values for the other five representative unit watersheds. Table 14 lists all simulated daily flows totalling more than 10 cfs per square mile for each representative watershed. Table 15 summarizes the annual precipitations, simulated evapotranspirations, simulated total runoff, and division of this total runoff between surface and base flow for each of the representative unit watersheds.

Pond Creek Unit Watershed: The Pond Creek Unit Watershed as recreated to reflect rural conditions proved to have flow patterns representative of the largest single group of watersheds. Its mixture of farmed flatlands, meadows, and forested slopes and a basically limestone geology is representative of large areas of Kentucky. The value of both LZC and BMIR fall in a medium range. The simulated runoff volumes vary from 61 percent base flow in a year with the rainfall heavily concentrated in March to 87 percent base flow in a year with precipitation more evenly distributed throughout the year. Annual runoff volumes are generally near an average between the extremes of the other types of watersheds.

The monthly precipitation totals on Table 11 show 1964 to be the driest year but also the one with the greatest potential flood hazard because about 35 percent of the annual precipitation fell on nearly saturated soil in March. The next year, 1965, had the greatest precipitation but much less runoff because so much more rain fell

TABLE 10

SYNTHESIZED FLOW RATIOS

Bear Branch Unit Watershed

Year	1962	1963	1964	1965	1966
Annual Runoff	1.25	1.25	1.25	1.30	1.19
Annual Coefficient	0.313	0.191	0.351	0.300	0.339
Peak Runoff Month	FEB	MAR	MAR	DEC	APR
Precipitation	1.84	----	----	1.21	----
Runoff	1.51	1.41	1.26	1.14	1.21
Coefficient	0.82	----	----	0.93	----
Peak Precipitation Month					
Runoff	1.63	0.07	0.50	0.73	1.51
Low Flow Month	AUG	AUG	AUG	AUG	JUL
Precipitation	----	1.34	----	----	0.82
Runoff	0.00	0.36	0.00	0.25	0.00
Coefficient	----	0.22	----	----	0.00
Peak Runoff	1.48	1.63	1.23	1.25	1.37
Coefficient	0.665	0.254	0.731	0.388	0.197
Peak Flow	1.69	1.69	1.29	1.28	1.22
Second Peak	2.76	5.67	1.33	9.03	3.30
Third Peak	0.05	0.75	2.88	3.56	2.24

Flat Creek Unit Watershed

Year	1962	1963	1964	1965	1966
Annual Runoff	1.22	1.14	1.19	1.19	1.11
Annual Coefficient	0.303	0.174	0.331	0.274	0.317
Peak Runoff Month	FEB	MAR	MAR	FEB	APR
Precipitation	1.84	----	----	0.97	----
Runoff	1.64	1.39	1.24	1.07	1.16
Coefficient	0.89	----	----	1.11	----
Peak Precipitation Month					
Runoff	1.78	0.20	0.10	0.37	1.49
Low Flow Month	AUG	NOV	AUG	AUG	SEP
Precipitation	----	----	----	----	----
Runoff	0.50	0.50	0.17	0.38	0.33
Coefficient	----	----	----	----	----
Peak Runoff	1.51	1.80	1.28	1.26	1.42
Coefficient	0.681	0.281	0.761	0.391	0.204
Peak Flow	1.80	1.82	1.35	1.32	1.40
Second Peak	3.14	7.11	1.43	1.72	3.92
Third Peak	0.60	0.57	3.26	4.13	2.31

TABLE 10 (cont'd.)

McDougal Creek Unit Watershed

Year	1962	1963	1964	1965	1966
Annual Runoff	1.41	1.64	1.27	1.45	1.29
Annual Coefficient	0.352	0.250	0.356	0.335	0.352
Peak Runoff Month	FEB	MAR	MAR	MAR	APR
Precipitation	1.84	----	----	----	----
Runoff	1.23	1.16	1.15	1.09	1.17
Coefficient	0.67	----	----	----	----
Peak Precipitation Month					
Runoff	1.33	3.97	4.20	5.21	1.21
Low Flow Month	AUG	NOV	AUG	AUG	JUL
Precipitation	----	----	----	----	0.82
Runoff	6.00	8.22	7.50	13.25	13.67
Coefficient	----	----	----	----	17.50
Peak Runoff	1.36	1.47	1.16	1.20	1.37
Coefficient	0.612	0.229	0.690	0.374	0.197
Peak Flow	1.49	1.49	1.20	1.20	1.33
Second Peak	2.27	3.53	1.28	1.41	2.11
Third Peak	4.18	7.36	2.29	2.37	2.17

McGills Creek Unit Watershed

Annual Runoff	0.94	0.91	0.93	0.87	0.87
Annual Coefficient	0.235	0.138	0.259	0.201	0.250
Peak Runoff Month	MAR	MAR	MAR	MAR	APR
Precipitation	----	----	----	----	----
Runoff	0.88	0.88	0.92	0.84	0.81
Coefficient	----	----	----	----	----
Peak Precipitation Month					
Runoff	0.93	0.94	2.30	1.15	0.93
Low Flow Month	AUG	NOV	OCT	AUG	DEC
Precipitation	----	----	0.31	----	0.44
Runoff	3.33	1.36	2.00	2.25	2.67
Coefficient	----	----	1.37	----	6.37
Peak Runoff	1.03	1.02	1.02	0.94	0.91
Coefficient	0.464	0.159	0.602	0.291	0.131
Peak Flow	1.03	1.01	1.01	0.94	0.91
Second Peak	1.24	0.93	0.91	0.99	1.07
Third Peak	0.58	0.29	1.06	0.69	0.71

TABLE 10 (cont'd.)

Perry Creek Unit Watershed

Year	1962	1963	1964	1965	1966
Annual Runoff	0.64	0.61	0.87	0.58	0.65
Annual Coefficient	0.154	0.093	0.244	0.134	0.186
Peak Runoff Month	FEB	MAR	MAR	MAR	APR
Precipitation	1.84	----	----	----	----
Runoff	1.12	0.84	0.94	0.68	0.79
Coefficient	0.61	----	----	----	----
Peak Precipitation Month					
Runoff	1.21	0.10	0.30	0.20	0.58
Low Flow Month	AUG	NOV	OCT	AUG	SEP
Precipitation	----	----	0.31	----	----
Runoff	1.00	0.29	0.50	0.25	0.67
Coefficient	----	----	1.76	----	----
Peak Runoff	1.19	1.44	1.15	1.05	1.17
Coefficient	0.535	0.225	0.685	0.326	0.169
Peak Flow	1.39	1.51	1.20	1.09	1.17
Second Peak	2.28	3.84	1.51	1.28	2.20
Third Peak	0.13	0.29	2.34	2.28	1.62

Note: All flow and coefficient ratios are multiples of numbers on Table 9 except for the annual runoff and peak runoff coefficients which are actual estimated values.

TABLE 11

MONTHLY RECORDED RAINFALLS FOR POND CREEK UNIT WATERSHED

	inches				
	1962	1963	1964	1965	1966
October	2.00	4.70	0.81	0.62	2.54
November	4.23	1.59	1.69	3.32	1.33
December	3.75	2.74	1.06	5.86	1.14
January	4.03	1.18	2.45	2.76	5.73
February	6.58	1.11	2.45	4.67	5.01
March	3.58	9.04	14.91	4.82	1.02
April	1.01	1.87	3.06	3.31	9.56
May	3.33	4.56	1.85	1.60	3.91
June	4.75	4.18	2.24	2.27	0.75
July	1.84	7.33	3.03	5.08	2.13
August	2.20	2.13	2.63	2.18	5.18
September	3.56	3.48	4.16	8.41	2.59

TABLE 12

MONTHLY SYNTHESIZED FLOWS FOR POND CREEK UNIT WATERSHED

	inches				
	1962	1963	1964	1965	1966
October	0.036	0.128	0.002	0.028	0.142
November	0.103	0.014	0.006	0.030	0.013
December	0.698	0.106	0.002	1.633	0.007
January	1.837	0.221	0.097	1.358	2.288
February	2.828	0.079	0.300	2.565	2.646
March	3.063	4.513	10.059	3.098	0.497
April	0.745	0.526	0.528	1.041	3.729
May	0.121	0.606	0.143	0.100	2.253
June	0.717	0.183	0.068	0.032	0.040
July	0.017	0.177	0.009	0.093	0.009
August	0.002	0.043	0.002	0.008	0.024
September	0.004	0.062	0.010	0.367	0.003

TABLE 13

MONTHLY SYNTHESIZED FLOW RATIOS

Bear Branch Unit Watershed

	1962	1963	1964	1965	1966
October	1.39	1.56	0.50	1.39	1.48
November	1.58	1.21	0.17	1.20	1.08
December	2.47	2.86	0.50	2.16	0.86
January	1.52	2.13	1.47	1.31	1.51
February	1.63	2.18	2.43	1.28	1.29
March	0.87	1.41	1.26	1.13	1.01
April	0.83	0.85	0.82	0.89	1.21
May	0.46	0.40	0.74	0.95	0.73
June	0.12	0.38	0.44	0.09	1.18
July	0.18	0.07	0.00	0.13	0.00
August	0.00	0.12	0.00	0.25	0.17
September	0.25	0.15	0.50	0.73	0.33

Flat Creek Unit Watershed

	1962	1963	1964	1965	1966
October	0.33	0.77	0.50	0.29	1.10
November	2.42	0.50	0.17	1.33	0.69
December	2.11	4.73	0.50	1.88	0.57
January	1.50	0.95	0.69	1.21	1.49
February	1.78	0.23	1.53	1.30	1.29
March	0.72	1.39	1.24	1.06	0.73
April	0.48	0.42	0.44	0.67	1.16
May	0.33	0.19	0.44	0.86	0.55
June	0.26	0.33	0.15	0.28	1.18
July	0.59	0.20	0.22	0.12	0.33
August	0.50	0.37	0.50	0.38	0.13
September	0.25	0.11	0.10	0.37	0.33

TABLE 13 (cont'd.)

McDougal Creek Unit Watershed

	1962	1963	1964	1965	1966
October	5.75	4.20	23.50	4.43	4.60
November	4.81	8.22	8.50	3.53	8.93
December	2.04	2.40	15.00	1.58	7.86
January	1.27	2.15	2.57	1.22	1.21
February	1.33	2.12	1.94	1.09	1.11
March	0.95	1.16	1.15	1.09	1.47
April	1.43	2.30	2.02	1.40	1.17
May	3.12	1.64	2.69	3.84	1.30
June	2.28	3.40	3.72	4.13	6.15
July	5.76	3.97	8.33	4.10	4.56
August	6.00	5.91	7.50	13.25	5.54
September	9.50	6.36	4.20	5.21	16.67

McGills Creek Unit Watershed

	1962	1963	1964	1965	1966
October	1.58	2.03	2.00	2.39	1.03
November	2.50	1.36	2.17	1.70	1.00
December	1.25	1.40	3.50	0.79	1.14
January	0.95	1.29	1.95	0.82	0.93
February	0.93	1.09	1.14	0.85	0.89
March	0.88	0.88	0.92	0.84	0.90
April	0.92	0.86	0.77	0.45	0.81
May	0.62	0.66	0.69	0.93	0.88
June	0.72	0.79	0.93	0.94	1.05
July	1.41	0.94	1.89	1.40	2.00
August	3.33	1.18	4.00	2.25	2.29
September	3.75	1.24	2.30	1.15	3.33

TABLE 13 (cont'd.)

Perry Creek Unit Watershed

	1962	1963	1964	1965	1966
October	0.06	0.16	0.50	0.07	0.25
November	0.11	0.29	0.33	0.10	0.31
December	0.28	0.23	0.50	0.53	0.28
January	0.68	0.15	0.10	0.39	0.58
February	1.21	0.28	0.15	0.71	0.84
March	0.43	0.84	0.94	0.68	0.46
April	0.27	0.15	0.51	0.55	0.79
May	0.07	0.05	0.08	0.11	0.38
June	0.06	0.66	0.07	0.13	0.05
July	0.18	0.10	0.33	0.12	0.33
August	1.00	0.09	1.00	0.25	0.37
September	1.00	0.11	0.30	0.20	0.67

Note: All flows are multiples of numbers on Table 12.

TABLE 14

SYNTHESIZED DAILY FLOWS EXCEEDING 10 SFD

	1962		1963		1964		1965		1966	
Pond Creek	2-27	21.3	3-16	28.2	3- 9	101.4	3-29	21.5	4-30	23.1
	2-23	13.2			3-10	19.6	2-11	14.9	4-12	10.0
	2-28	10.8			3- 4	18.9				
	1-22	10.2			3-11	13.9				
					3-12	11.5				
Bear Branch	2-27	43.9	3-16	50.0	3- 9	154.4	3-29	29.0	4-30	30.5
	2-23	25.6	3- 4	17.1	3- 4	81.0	12-11	27.0	1- 2	25.5
	1-22	24.0	3-11	12.8	3-25	14.7	2-11	24.3	2-10	23.9
	2-26	19.3	3- 5	12.4	3- 8	13.9	2-24	16.4	4-12	18.3
					3-10	12.6	3-17	15.9	2-13	18.1
							12-26	12.9	2- 1	14.5
							1- 2	10.2	4-25	13.5
									4-24	12.1
									1- 6	11.7
									4-11	10.0
Flat Creek	2-27	51.1	3-16	56.0	3- 9	165.6	12-11	33.2	4-30	32.2
	2-23	28.9	3- 4	22.4	3- 4	93.1	3-29	30.8	2-10	31.8
	1-22	28.0	3- 5	16.3	3- 8	19.7	2-11	28.1	1- 2	29.8
	2-26	25.0	3-11	16.1	3-25	15.9	2-24	21.0	1- 1	23.1
	1-15	16.7	12-29	12.3	3-10	10.6	3-17	18.8	4-12	22.5
	12- 9	14.9	3-1	11.2			12-26	14.8	2-13	22.4
	2- 9	14.2					3- 4	13.4	2- 1	21.7
	3-21	10.0					2- 7	13.2	1- 6	14.2
							1- 2	11.5	4-25	13.6
									4-24	12.4
									1- 5	11.7
									4-11	10.6
McDougal Creek	2-27	33.1	3-16	42.5	3- 9	134.8	3-29	25.8	4-30	28.8
	2-23	21.5			3- 4	61.4	2-11	20.6	4-24	14.8
	1-22	18.8			3-25	14.6	9-15	17.5	1- 2	14.7
	6-11	14.1			3-10	10.9	12-11	16.2	2-10	14.3
	6- 4	13.7					9- 1	13.6	4-12	13.0
	2-26	11.5					3-17	12.8	2-13	12.1
							2-24	11.8	4-25	11.6
									5-18	11.5

TABLE 14 (cont'd.)

	1962		1963		1964		1965		1966	
McGills Creek	2-27	20.8	3-16	28.4	3- 9	101.8	3-29	19.7	4-30	20.4
	2-23	13.6			3- 4	20.7	2-11	14.3		
	1-22	11.3			3-10	15.7				
					3-11	10.9				
Perry Creek	2-27	38.4	3-16	44.3	3- 9	143.5	3-29	24.4	4-30	26.0
	2-23	21.2	3- 4	10.7	3- 4	59.7	2-11	18.5	2-10	22.5
	1-22	18.4			3-25	16.3	3-17	15.9	2-13	15.5
	2-26	15.5			3- 8	11.2	2-24	13.9	1- 2	15.4
									2- 1	14.1
									4-12	12.1

Note: All flows are total daily volumes in sfd.

TABLE 15

UNIT WATERSHED ANNUAL RUNOFF SUMMARIES

	Annual Totals (inches)			Fractions	
	Precipitation	Evapotranspiration	Runoff	Surface	Baseflow
1962					
Pond Creek	40.86	30.91	10.17	0.141	0.859
Bear Branch		28.47	12.77	0.476	0.524
Flat Creek		29.61	12.33	0.793	0.207
McDougal Creek		27.50	14.35	0.336	0.664
McGills Creek		32.42	9.59	0.158	0.842
Perry Creek		34.44	6.46	0.845	0.155
1963					
Pond Creek	43.91	35.80	6.66	0.168	0.832
Bear Branch		35.29	8.34	0.490	0.510
Flat Creek		35.48	7.63	0.828	0.172
McDougal Creek		31.60	10.97	0.305	0.695
McGills Creek		36.29	6.06	0.190	0.810
Perry Creek		38.29	4.06	0.882	0.118
1964					
Pond Creek	40.34	28.66	11.23	0.389	0.611
Bear Branch		24.33	14.10	0.707	0.293
Flat Creek		25.72	13.34	0.908	0.092
McDougal Creek		25.61	14.33	0.577	0.423
McGills Creek		30.02	10.42	0.441	0.559
Perry Creek		31.69	9.82	0.950	0.050

TABLE 15 (cont'd.)

	Annual Totals (inches)			Fractions	
	Precipitation	Evapotranspiration	Runoff	Surface	Baseflow
1965					
Pond Creek	44.90	32.68	10.36	0.167	0.833
Bear Branch		30.64	13.45	0.478	0.522
Flat Creek		31.23	12.30	0.801	0.199
McDougal Creek		28.55	15.02	0.352	0.648
McGills Creek		33.63	9.02	0.178	0.822
Perry Creek		35.52	6.01	0.866	0.134
1966					
Pond Creek	40.89	32.20	11.65	0.128	0.872
Bear Branch		29.44	13.82	0.489	0.511
Flat Creek		30.68	12.94	0.801	0.199
McDougal Creek		28.10	15.01	0.336	0.664
McGills Creek		33.35	10.19	0.131	0.869
Perry Creek		35.50	7.61	0.874	0.126

on a drier fall or summer watershed. Flow volumes are highly concentrated around late winter and early spring except when extreme drought occurs this time of year or extremely heavy rains occur some other time. Even though 1963 was one of the wetter years, much less runoff occurred because of low rainfalls in January, February, and April. Even the heavy March rains fell on a relatively dry watershed. Conversely, low flows regularly occur in late summer or early fall even when some other time of year has less rainfall. All the days with more than 10 sfd/mi^2 of runoff occurred between January 22 and April 30 (Table 14), and this must be regarded as the season of primary flood hazard.

Bear Branch Unit Watershed: The Bear Branch Unit Watershed represents a flow pattern with a high runoff volume approximately equally divided between base flow and direct runoff. The simulated runoff volumes were only 30 percent base flow in a year with the rainfall heavily concentrated in March but a little over 50 percent in most years. The watershed is very steep from the narrow ridge lines down to the bottom of its "V" canyons and heavily forested on a shallow soil of medium permeability on Pennsylvanian fine sandstones and shales. The high value of SIAC materially reduces infiltration rates during the high runoff months. The watershed has experienced only minimal disturbance from human activity with no history of agriculture, minimal and well managed logging activity, and few inhabitants. The Green River Unit Watershed (the other one in this category) is much the same in all respects except for its farmed bottom lands next to the main creek.

The effects of the shallower soil can be seen in the numbers on Table 10. Peak flow months tend to come earlier in the wet season when the earlier months have high rainfalls (Table 11). The soil moisture storage capacity approaches saturation earlier in the season. This factor causes the primary gain in runoff volume over that found for Pond Creek to be in December through February. As evapotranspiration rates increase into the summer, the soil dries out more quickly and flows continue much lower through the summer (Table 13). Low flow months tend to come earlier in the dry season when such months have low rainfalls. Even late spring and summer storm runoffs are reduced by the drier soil (See June 11, 1962 and April 29, 1963); however, a reverse trend could be expected for exceptionally large summer storms. Even with the heavy forest, the annual evapotranspiration loss is lower than for Pond Creek because of greater moisture depletion through the summer. The season including days with over 10 sfd/mi^2 of runoff began six weeks earlier than for Pond Creek on December 11 but also ended on April 30 (Table 14).

The overall effect of these differences on flood hazard is to extend the season of greatest hazard, greatly increase flood peaks from smaller storms during this season, effect a lesser increase in peaks from major storms during all seasons, and reduce peaks from smaller storms during the off-season. The overall flood hazard is significantly higher (Table 8), but the summer flood hazard is less. Areas downstream from a watershed of this type can expect to experience higher urban but lower agricultural damages than do areas downstream from a watershed like Pond Creek.

Flat Creek Unit Watershed: The Flat Creek Unit Watershed represents a flow pattern with a high runoff volume with direct runoff predominate. The simulated runoff volumes were less than 10 percent base flow in the year with heavy March rainfall to just barely 20 percent in a year with more evenly distributed rainfall. The watershed is moderately steep with rounded ridges and valleys and scattered low grade forest among pasture land on a shallow soil of low permeability on Ordovician shales and limestones. The watershed contains scattered farmsteads and small areas have been cultivated from time to time.

In comparing the Flat Creek with the Bear Branch Unit Watershed, one sees that the lower permeability reduces infiltration and causes more of the moisture to remain at the watershed surface. The wet surface magnifies direct runoff and increases the opportunity for evapotranspiration. Consequently, total annual runoff is a little lower than for Bear Branch even though the shallower soil keeps the value higher than that for Pond Creek. Table 10 reveals a tendency for soil moisture capacity to approach saturation earlier in the wet season than occurs with the deeper soil at Pond Creek but not as early as occurs with Bear Branch because of the reduced permeability. Flat Creek low flows are very small but some runoff occurs with almost every storm in the summer months. Peak runoffs are the highest yet. They are higher than for Bear Branch in all cases and higher than for Pond Creek in all cases except for certain later spring and summer storms occurring on a dry watershed. The season including days with over 10 sfd/mi^2 of runoff begins December 9 and ends April 30 (Table 14). The number of such days is greater than for any other unit watershed with 40 as compared with 30 for Bear Branch and 14 for Pond Creek.

The net effect of these characteristics is for the Flat Creek Unit Watershed to have the highest flood peaks of any of the unit watersheds. The increase is especially pronounced for smaller storms. Flood hydrographs develop from storms which do not even cause a rise in the flows in most other unit watersheds. Like Bear Branch, this effect is more pronounced in the wet than in the dry season. The fact that runoff events are already so large suggests that wet season flood peaks are not too likely to be increased much by urbanization, but dry season peaks will be.

McDougal Creek Unit Watershed: The McDougal Creek Unit Watershed represents a flow pattern with high runoff volume with base flow predominate. The runoff volumes were consistently the highest of any of the unit watersheds. The simulated runoff volumes varied from 42 to almost 70 percent base flow. The watershed has moderately steep and lightly wooded hillsides, but most of the area is crop and pasture land along the creek or on the hill tops. The moderately shallow but highly permeable soil is largely underlain by a coarse dolomitic limestone. The area is lightly populated and has been under light cultivation for 150 years.

The primary distinctiveness of the McDougal Creek runoff pattern is the high rate of infiltration into the soil and on down to groundwater throughout the year. Summer-time groundwater recharge keeps flows much higher in the late summer. Higher soil moisture increases runoff from summer storms. Simultaneously, the rapid infiltration of any moisture which would remain standing on the surface of the other watersheds after a storm period reduces evaporation opportunity and contributes to the high runoff volumes. Peak flows are generally smaller than those for Flat Creek because of the slightly deeper and much more permeable soil except during the late spring and summer when the higher watershed moisture retention increases runoff. Table 14 shows how the watershed can approach saturation any time of the year. The days with over 10 sfd/mi^2 of runoff are not as seasonally concentrated as they are for the other watersheds. They occur in December, January, February, March, April, May, June, and September. High runoff periods continue longer into the spring, and even summer storms are likely to cause a significant rise in base flow.

The McDougal type of watershed does not produce floods as severe as the Bear Branch or Flat Creek types, but it generates many more summer floods. Urban flood damages would be smaller than for these other two, but agricultural damages are likely to be higher than for any of the others. The high total annual runoff and the much higher flows in low flow months make watersheds of this type a very good source of water supply.

McGills Creek Unit Watershed: The McGills Creek Unit Watershed represents a flow pattern with low runoff volume with base flow predominate. The simulated runoff volumes varied from 56 to usually between 80 and 90 percent baseflow. The watershed has very steep and largely wooded hillsides but also has some flatter pasture and crop land comprising about 20 percent of the area. The permeable, deep soil lies on Mississippian shales and siltstones. Except for a few small areas the watershed has never been cultivated.

McGills Creek soil is both deeper and more permeable than that at McDougal Creek. The deeper soil provides more moisture storage capacity and consequently reduces wet season flows by maintaining higher infiltration rates and reduces dry season flows by holding more water in the soil for subsequent evapotranspiration and passing less down to the watertable. The higher permeability maintains a relatively constant base flow throughout the summer. Table 13 shows a trend toward increasing flow multipliers through the summer. Table 10 shows a tendency for low flow months to be later in the year than with the other watersheds. Peak flows tend to be lower than those for Pond Creek for most events but a little higher for major storms and for storms earlier in the wet season. The days with over 10 sfd/mi^2 of runoff are fewer (11) than for any other unit watershed and are confined to the same January 22 through April 30 season as are those for Pond Creek.

The pattern and magnitude of the flood hazard is very similar to that for the Pond Creek Unit Watershed except for being slightly accentuated toward more of the damage occurring in rarer events (see also West Bays Fork on Table 8). The low total runoff reduces yield from long term storage but the higher summer flows make water supply more dependable on a run-of-the-river basis.

Perry Creek Unit Watershed: The Perry Creek Unit Watershed represents a flow pattern with low runoff volume with direct runoff predominate. Runoff volumes were consistently the lowest of any of the unit watersheds. The simulated runoff volumes varied from 5 to 15 percent base flow. The watershed has a few steep hillsides, rolling hilltops, and broad flat valley areas. Most of the deep soil with relatively low permeability is farmed, but there are a few small wooded areas. The watershed is underlain by tertiary alluvium at the north end of the Mississippi Coastal Plain. The area has been farmed for over 100 years.

The deep soil of the Perry Creek Unit Watershed seldom approaches saturation but holds large volumes of water for later use by vegetation. This accounts for the high volume of moisture loss by evapotranspiration (Table 15) and the relatively low runoff volumes every month of the year (Table 13). The watershed holds so much moisture it is never likely to completely dry out and maintains a very small but very constant base flow through the driest periods.

Even though runoff volumes are very low, flood peaks from intense storms are relatively high (Table 10). The low permeability prevents the deep soil from acting as much of a buffer during intense storms. The upper zone has a high moisture storage capacity which only very slowly percolates into the ground and during the low evaporation season maintains a wet surface over long periods. Runoff from precipitation falling on this surface is relatively high during intense storm periods. However, runoff drops very quickly as the storm slackens because there is so little soil drainage entering the stream. As this surface wet condition builds up earlier in the winter than does the soil wet condition for the Pond Creek Unit Watershed, the 20 days with flows over 10 sfd/mi^2 begin a few weeks earlier in the water year. A high upper zone storage capacity greatly reduces summer flood hazard.

The flood hazard from major events on a watershed of this type is as high as that for any of the other types. The hazard from lesser events is high but not as high as for Flat Creek or Bear Branch. Watershed yield must depend on catching the direct runoff from major storm events and is hence very low. Low runoff volumes also makes urban storm drainage less expensive (3).

SUMMARY

This comparison of the hydrology of the unit watersheds has revealed significant differences in downstream flood hazard. For watersheds of identical size and stream channel conditions, mean annual floods varied from 99 to 212 csm (Table 8) and 200-year floods varied from 531 to 662 csm. It remains to go on to examine the consequences of these differences in terms of average annual flood damage and appropriate combinations of damage reduction measures.

CHAPTER IV

WATERSHED VARIATION IN FLOOD HAZARD

FLOOD HAZARD VARIABILITY

The unit watershed concept was developed the last chapter to portray the variability in runoff patterns among tributary watersheds of different characteristics. A number of aspects of the annual hydrograph (volumes, low flows, etc.) were considered but the emphasis was on the frequency and seasonal pattern of peak runoff events. Quantitative information on the diversity of runoff peaks generated from fixed climatological data for a set of diverse watersheds was tabulated. Trends were described qualitatively. The next step is to examine the implications of these trends in peak runoff events with respect to average annual flood damages and to the types of measures most appropriate to deal with these damages. Do the runoff patterns from some types of watersheds favor flood proofing? Do the runoff patterns from other types favor structural measures? How can a metropolitan area containing undeveloped land possessing a large diversity of land surface characteristics evaluate the hydrologic consequences of alternative growth patterns?

These questions are important because tributary watersheds vary. Naturally, they vary in size, and bigger watersheds produce larger runoff events, but that is not the issue here. The issue is the degree to which average annual flood damage and the pattern in which damages occur (7) vary with tributary watershed properties other than size and climate. However, in order to translate runoff peaks to flood damages, we need to consider the properties of the flood plain.

Flood plains vary too. They vary in the frequency at which flows leave the main channel to cause flooding. They vary between wide, flat locations where the water can spread over large areas to stream banks in canyons. They vary between being only susceptable to shallow flooding to being in locations where backwater or other confining factors can cause water to accumulate to great depths. The purpose of considering the types of flood plain is not to study how flood damages vary from one flood plain type to another. It is rather to study how the patterns of flood damage which result downstream from a variety of tributary watersheds vary from one type of flood plain to another.

The analysis required a two-way classification of flood hazard. One way was by tributary watershed type. Six types were selected in Chapter III. The other way was by flood plain type. Some method for classifying flood plains by type was needed, and the four descriptors listed on Table 16 were devised for this purpose. Each descriptor was subdivided into three ranges as shown. For example, an LFLD flood plain would be one downstream from a drainage area over 25 square miles, flooded more often than 4 years out of 10, and with deep flooding extending over a large area. While 25 square miles is a relatively small watershed from many points of view, it is large in terms of the source areas creating local flooding in urban areas and this is the context in which land use planners need most frequently to consider hydrologic factors as they direct urban growth patterns.

THE POND CREEK AREA

Again, Dempsey's work provided a basis for studying a wide variety of flood plains. He divided the area subject to flooding in the 72.4-square mile Pond Creek watershed into 25 smaller watersheds and compiled the necessary data to analyze flood hazard and determine the optimum combination of flood control measures for each one (16, pp. 151-

160). He used the University of Kentucky Flood Control Planning Program II (28) to perform the necessary computations.

While his data provided a general context for use in this research, some modifications were needed to divide the flood plains among a wider range of types in terms of Table 16. When classified by the tributary area descriptor, 5 of the 25 areas were large, 6 were middle size, and 14 were small. The modification was to change the input data to convert the 25 real watersheds into 25 hypothetical watersheds as indicated on Table 17. The divisions were selected to represent as wide a range of combination of conditions as possible. Obviously, there were not enough watersheds to include all possible combinations of descriptors, but a study of this sort need not be exhaustive. On Table 17, the 4-letter mnemonics combine the descriptors from Table 16 applying to the flood plain, and the numbers are those Dempsey used to designate the subwatershed (16, p. 12).

The watersheds are tabulated in numerical order on Table 18. AW designates the tributary watershed area in square miles as measured by Dempsey (16, p. 151). The following data designate properties assigned each flood plain to reflect the assigned classification. QO designates the flow at which flooding begins and was estimated to achieve the desired frequency based on the second descriptor. AK12 is the flooded area in acres, and DK12 is the maximum depth in feet of flooding associated with a flow of QK12 cfs. This flood is used by Planning Program II to interpolate for areas and depths of floodings associated with other flood peaks. QK12 was taken as QO plus the magnitude of the mean annual flood. AK12 was taken as 1000 for L, 200 for M, and 50 for S. DK12 was taken as 10 for D, 5 for I, and 1 for S.

The plan was to estimate average annual flood damages by applying the Flood Control Planning Program to the 25 flood plains described

TABLE 16

FLOOD PLAIN DESCRIPTORS

Tributary Area Descriptor

L	Over 25 square miles
M	Between 5 and 25 square miles
S	Under 5 square miles

Flood Frequency Descriptor

F	Frequent Flooding - Floods more often than 4 years out of 10
O	Occasional Flooding - Floods between 1 and 4 years out of 10
R	Rare Flooding - Floods less often than 1 year out of 10

Flood Area Descriptor

L	Large, flat flood plain
M	Medium size, sloping flood plain
S	Small, steeply rising flood plain

Flood Depth Descriptor

D	Subject to deep flooding
I	Subject to flooding of intermediate depth
S	Subject only to shallow flooding

TABLE 17

DIVISION OF FLOOD PLAINS BY TYPE

Division of Flood Plains with Large Tributary Areas

LFLD - 22   LFSS - 18
LRLD - 6   LRSS - 25
LOMI - 9

Division of Flood Plains with Middle Size Tributary Areas

MFLD - 12   MFSS - 15   MFLS - 17
MRLD - 2   MRSS - 4
MOMI - 1

Division of Flood Plains with Small Tributary Areas

SFLD - 13   SFMI - 14   SFSS - 16   SFLS - 20   SFSD - 23
SRLD - 5   SRMI - 7   SRSS - 8   SRLS - 11   SRSD - 19
SOLD - 3   SOMI - 10   SOSS - 21   SOLS - 24

TABLE 18

SUBWATERSHED FLOOD PLAIN DATA

Number	Type	AW mi^2	QO cfs	QK12 cfs	AK12 acres	DK12 feet
1	MOMI	9.8	350.	700.	200.	5.
2	MRLD	11.3	700.	1100.	1000.	10.
3	SOLD	3.5	250.	450.	1000.	10.
4	MRSS	6.2	500.	750.	50.	1.
5	SRLD	2.2	470.	670.	1000.	10.
6	LRLD	26.1	1700.	2350.	1000.	10.
7	SRMI	1.1	450.	630.	200.	5.
8	SRSS	1.5	460.	650.	50.	1.
9	LOMI	30.3	1400.	2300.	200.	5.
10	SOMI	2.3	300.	500.	200.	5.
11	SRLS	4.2	550.	750.	1000.	1.
12	MFLD	6.1	200.	450.	1000.	10.
13	SFLD	2.9	160.	360.	1000.	10.
14	SFMI	3.8	170.	370.	200.	5.
15	MFSS	14.5	350.	720.	50.	1.
16	SFSS	2.6	160.	360.	50.	1.
17	MFLS	5.8	200.	450.	1000.	1.
18	LFSS	25.7	500.	1100.	50.	1.
19	SRSD	1.9	470.	660.	50.	10.
20	SFLS	4.4	180.	400.	1000.	1.
21.	SOSS	1.8	270.	460.	50.	1.
22	LFLD	64.8	1200.	2500.	1000.	10.
23	SFSD	1.7	150.	350.	50.	10.
24	SOLS	1.8	270.	460.	1000.	1.
25	LRSS	72.4	2700.	4000.	50.	1.

in Table 18. All the input data were kept the same as what Dempsey used (16, pp. 151-160) and thus represent watershed conditions as they existed in 1968 except that the program control parameters were adjusted so the program would only estimate average annual flood damages, that the inputs specifying prestudy channelization were all taken as zero to eliminate the effects of channel improvement, that a discount rate of 5.0 percent was used, and that QO, QK12, AK12, and DK12 were taken as on Table 18. QB43 and QB05 are used in the Flood Control Planning Program to designate the mean annual and 200-year unit watershed flood peaks respectively. These values were varied to represent each of the six tributary watershed types (Table 6).

The program was run once for each of the six watershed types by using its values for QB43 and QB05. The output was the expected average annual damages for each hypothetical flood plain as specified by the four-letter mnemonic containing the property subject to flood damage of the real Pond Creek flood plain portion specified by number. The fact that the estimated average annual damage may be higher for one flood plain than for another does not necessarily signify a difference in flood hazard because of the variation in damageable property among the real flood plains. The purpose of this study is to look at relative differences in flood damage marginal to each of the flood plain descriptors (Table 16) in the context of each of the six watershed types.

Average annual damages are estimated within Planning Program II from flood peaks estimated as a function of frequency by interpolation using extreme value probability (as in Figure 1) between the 200-year and the mean annual events. The flood peak for each of these two frequencies is estimated by multiplying together the rural unit watershed flood peak for that frequency, the tributary drainage area, an area factor, and a factor to account for the effect of urban development and channel improvement within the tributary watershed. For this analysis, both the factors expressing how flood peaks vary with drainage area and with urban development within that area were taken directly as the values Dempsey derived for the real subwatershed. Analysis of how these factors vary among watershed types was considered beyond the scope of this study. The Program also used damage factors reflecting the historical seasonal flood distribution of the Pond Creek watershed for estimating agricultural damage. The seasonality differences among watershed types were thus also neglected. All three effects merit further study. To be more specific,

1. How do curves plotting flood peak for a given frequency against drainage area vary in shape among watershed types?
2. How do curves plotting flood peak for a given frequency against the extent of urban development vary in shape among watershed types?
3. How do differences in seasonal patterns of flood events among watershed types affect flood damages?

FLOOD DAMAGE PATTERNS

The average annual flood damages for each of the 25 flood plains based on each of the six unit watershed hydrologies are listed on Table 19. The Pond Creek Values are in dollars per year. The numbers tabulated for the other unit watersheds are multipliers of the Pond Creek values. Table 20 contains the frequency at which flooding begins in each situation.

Pond Creek Unit Watershed: The Pond Creek Unit Watershed with its medium to high values of both moisture storage capacity and infiltration rate and its relatively low flood peaks was used as a basis for comparing differences among the watersheds. The decision to use Pond Creek as a basis was arbitrary, but it was important to pick some basis as a means for comparing relative differences.

TABLE 19

AVERAGE ANNUAL DAMAGES BY UNIT WATERSHED HYDROLOGY

		Ratios				
Flood Plain	Pond Creek $/year	Bear Branch	Flat Creek	McDougal Creek	McGills Creek	Perry Creek
LFLD-22	77641	2.39	2.75	1.93	1.05	1.74
LFSS-18	1871	2.24	2.50	1.80	1.02	1.70
LRLD-6	433	1.28	1.49	0.70	1.57	1.50
LRSS-25	70	2.17	2.71	1.21	1.47	1.97
LOMI-9	863	2.27	3.01	1.24	1.62	2.08
MFLD-12	423872	2.07	2.28	1.71	1.05	1.60
MFSS-15	1702	2.27	2.54	1.81	1.06	1.70
MFSL-17	7891	2.06	2.29	1.63	1.06	1.60
MRLD-2	5689	1.90	2.59	1.13	1.60	1.80
MRSS-4	169	2.04	2.50	1.17	1.38	1.85
MOMI-1	6634	2.38	2.79	1.70	1.16	1.82
SFLD-13	223162	1.82	2.00	1.51	1.04	1.49
SFMI-14	12413	1.91	2.09	1.57	1.05	1.52
SFSS-16	721	1.77	1.96	1.48	1.05	1.47
SFLS-20	5673	1.96	2.20	1.59	1.05	1.55
SFSD-23	2710	1.71	1.87	1.46	1.04	1.44
SRLD-5	58752	1.87	2.21	1.22	1.38	1.75
SRMI-7	3993	1.76	2.10	1.15	1.36	1.65
SRSS-8	83	1.71	2.10	1.11	1.34	1.66
SRLS-11	462	1.81	2.16	0.99	1.62	1.88
SRSD-19	900	1.81	2.14	1.18	1.42	1.73
SOLD-3	317226	2.01	2.26	1.58	1.09	1.62
SOMI-10	16152	1.90	2.16	1.39	1.19	1.63
SOSS-21	85	1.78	2.05	1.37	1.14	1.52
SOLS-24	1164	1.78	2.05	1.37	1.14	1.51

TABLE 20

FREQUENCY OF FLOODING BY UNIT WATERSHED HYDROLOGY

Flood Plain	Pond Creek	Bear Branch	Flat Creek	McDougal Creek	McGills Creek	Perry Creek
LFLD-22	42.2	87.8	92.8	77.9	41.6	68.5
LFSS-18	53.7	94.9	97.5	89.0	51.9	79.8
LRLD-6	0.1	0.2	0.2	0.1	0.2	0.2
LRSS-25	1.7	3.8	4.9	2.3	2.3	3.3
LOMI-9	1.3	3.0	4.0	1.7	1.8	2.6
MFLD-12	45.3	81.9	86.6	73.7	44.5	66.1
MFSS-15	42.5	84.4	89.6	74.9	41.9	66.3
MFLS-17	42.6	78.2	83.3	69.6	42.1	62.6
MRLD-2	0.8	1.6	2.0	0.9	1.1	1.5
MRSS-4	1.8	4.0	5.0	2.5	2.5	3.4
MOMI-1	16.6	39.3	45.7	30.0	17.9	28.9
SFLD-13	46.0	74.6	78.8	68.0	45.2	62.2
SFMI-14	47.3	78.5	82.8	71.6	46.4	65.0
SFSS-16	45.1	72.3	76.4	65.9	44.5	60.5
SFLS-20	45.3	78.2	82.8	70.7	44.6	64.0
SFSD-23	47.1	72.4	76.0	66.6	46.4	61.4
SRLD-5	2.2	4.2	5.1	2.8	2.8	3.7
SRMI-7	2.1	3.8	4.5	2.6	2.7	3.4
SRSS-8	2.0	3.5	4.2	2.5	2.6	3.3
SRLS-11	0.6	1.1	1.4	0.7	0.9	1.1
SRSD-19	1.6	2.9	3.5	2.0	2.1	2.7
SOLD-3	22.9	45.1	50.4	37.1	23.9	35.3
SOMI-10	11.7	22.1	25.1	17.3	12.9	18.1
SOSS-21	14.9	26.6	29.8	21.6	16.1	22.1
SOLS-24	14.7	23.8	29.5	21.3	15.9	21.8

Note: All numbers are percentage of years in which flooding occurs.

Bear Branch Unit Watershed: The Bear Branch Unit Watershed with its low moisture storage capacity and medium permeability produced a mean annual flood 1.36 times that of Pond Creek and a 200-year flood 1.07 times as large. Average annual damages were in every case increased by a larger multiple. Small differences in flood peaks cause large differences in average annual damage because damage is only caused by flows in excess of channel capacity. Naturally, the percentage increase in excess flow (flood peak minus channel capacity) is much larger than the percentage increase in flood peak. While this point may be so obvious as to seem trite, it is extremely important because small errors in hydrologic estimates are significantly amplified in their effect on average annual flood damages and hence on the decision on appropriate damage reduction measures.

The multipliers tend to decrease as the first descriptor changes from L to M to S. Floods get larger as one moves downstream. Mathematically, the unit watershed flood peak is multiplied by a bigger area to get the local flood peak. Physically, an extra increment of runoff from more unit areas accumulates to a greater total. This means a bigger absolute difference in cfs and hence a larger increase in damage to a fixed flood plain property.

The multipliers tend to be larger for flood plains frequently flooded than for those rarely flooded, but the pattern is irregular because it is determined by the dominant of two counteracting trends. Smaller floods vary more than do larger floods with watershed type. A rarely flooded area means a channel of larger capacity, and hence damages are amplified more by a given change in flood peak magnitude.

The multipliers tend to be larger for small flood plains prone to deep flooding over extensive areas than they are for flood plains more likely to suffer shallower flooding confined to more limited areas, but the opposite trend is seen for the middle size watersheds. For the smaller areas, the flows are not large enough to do major damage, and an increase in flows, especially for the more frequent floods which are much larger for Bear Branch than for Pond Creek, can bring a large increase in damage. With the larger areas, major damage is done by the relatively frequent flood so that less remains to be added from even larger floods.

By far the lowest ratio was for the LRLD flood plain. This is because of the vary rare frequency at which flooding begins (Table 20). These large floods are the least variable with watershed properties because they are caused by such large storms that differences in watershed infiltration are small in comparison with total precipitation.

The basic principles used to evaluate the significance of the differences in flood damage pattern between the Pond Creek and the Bear Branch Unit Watersheds for flood measure planning have been outlined in a previous study on the factors favoring each alternative flood control measure (27). The larger damages make all measures more economical. The greater frequency of flooding works particularly to favor flood proofing. Where alternate growth areas vary between watersheds with Pond Creek characteristics and those with Bear Branch characteristics, urban development should favor the Pond Creek type area because of the lesser hazard and hence lesser financial burden for corrective measures. Since the Bear Branch pattern accentuates small more than large floods, the benefits will increase much more than the cost for structural measures providing the typical high level of protection. Structural measures will be easier to justify economically. The optimum level of protection is likely to be higher. The "natural" zoning associated with the greater hazard is likely to increase the importance of land enhancement as a flood control objective.

Flat Creek Unit Watershed: The Flat Creek Unit Watershed with its low moisture storage capacity and low infiltration rates produced a mean annual flood 1.43 times that of Pond Creek and a 200-year flood 1.11 times as large. It represents an extrapolation of the trends noted in comparing Bear Branch to Pond Creek. The trend of the multipliers with frequency is reversed because with the larger increment of change the initial-capacity effect becomes more important than the small-flood effect.

The pattern seen in the Bear Branch results and even more strongly in the Flat Creek results has both its favorable and its unfavorable aspects with respect to flood hazard adjustment. The larger floods are going to magnify the cost of the adjustment, but the more frequent severe flooding will also serve as a continual reminder of the hazard. People are less likely to be unaware of the hazard when they build on the flood plain. Nature's reminder will be much more regular. During urbanization, the flood plains are more likely to experience only minimum development until protection by structural measures becomes economical and is provided. The economics as well as the intangible factors will favor a high degree of protection.

McDougal Creek Unit Watershed: The McDougal Creek Unit Watershed with its medium to low moisture storage capacity and relatively high infiltration rates produced a mean annual flood 1.26 times that of Pond Creek and a 200-year flood 1.01 times as large. The flood peaks thus range from significantly larger than those for Pond Creek for frequent events to about the same size or even a little smaller for very large events. The two flood plains with the smallest frequencies for incipient flooding had ratios less than 1.00 (Table 19). Otherwise, the same general trends noted for Bear Branch and Flat Creek apply. The trend toward smaller floods being increased more than larger floods favors use of nonsturctural measures, makes them more effective through the psychological stimulus of continual reminder, and then makes it easier to justify structural measures after alternative land is developed.

McGills Unit Watershed: The McGills Creek Unit Watershed with its high moisture storage capacity and high infiltration rates produced a mean annual flood 0.99 times that of Pond Creek and a 200-year flood 1.06 times as large. The flood-frequency curve is thus more sharply accented toward large floods than that of any of the other unit watersheds. The large porous soil layer is able to absorb lesser events. When a very large storm occurs, the watershed becomes saturated and about the same storm hydrograph develops. Base flow during storm periods is likely to be much higher because of the long periods when delayed runoff is still draining from previous storms over the watershed. The total peak from the large storm is thus higher.

The trends are all reversed as McGills Creek is on one side of Pond Creek in a continuum on which all the other unit watersheds are on the other side. Flood hazard is more associated with rare disasters than with repeated smaller events.

Perry Creek Unit Watershed: The Perry Creek Unit Watershed with its high moisture storage capacity and low infiltration rates produced a mean annual flood 1.23 times that of Pond Creek and a 200-year flood 1.08 times as large. The flood frequency curve is not as sharply accented toward larger floods as is McGills and has larger flows associated with the more frequent events. The relatively sharply rising flood frequency curve tends toward more of damage being associated with infrequent events.

The watershed hydrology is of the type least likely to be transformed by urban development to much larger and more damaging flood peaks.

of runoff pattern characteristics.

5. Specific relationships were demonstrated between flood hazard patterns and the characteristics of the watershed soil. Such a correlation provides a starting point for better informed decisions on urban drainage design.

RESEARCH NEEDS

Each of the five listed research accomplishments is only a starting point because of the large opportunity remaining for further development. Taking them in order,

1. OPSET can be improved. The version of the Stanford Watershed Model used as its basis will need to be modified to more faithfully represent runoff processes as further research sheds new light on their nature. Virtually every Model user has developed a set of ideas for changes to obtain improved results. Crawford already uses a much more sophisticated scheme for channel routing. As such changes are employed, OPSET will need to be adjusted to work in the new context. Other OPSET changes may improve results even if the Model is kept as given. One does not need to be a prophet to predict that virtually every hydrologist who reviews the detailed presentation of OPSET by Liou (37) will find sections of the programming he would like to change. Still other OPSET changes will be needed to cope with hydrologic processes or runoff patterns not encountered in the Kentucky test data. Snowmelt is the most obvious. Frozen ground (25), swamps, and deep alluvial soils are others. It may also become feasible to expand OPSET to estimate values for GWETF and SUBWF or other parameters in certain contexts.

2. The relationships between the parameter values and the characteristics of rural watersheds can be improved. A wider range of watersheds in a wider range of climates can be used to extend the

relationships. Watersheds with more carefully instrumented precipitation and more carefully measured physical characteristics can be used to firm up lines now roughed through widely scattered points. Different independent variables and combinations of variables can be tried. The history of watershed cultivation practice is known to influence infiltration (39), and better historical information may add to the understanding of the geomorphological evolution of watershed characteristics.

3. The information on changes in parameter values with changes in land use can be expanded. Urban effects can be evaluated for a much wider range of initial watershed conditions and for a much wider range of urban land use categories or urban land use intensity. Effects may vary with the spatial distribution of urban change over the watershed. Many other types of land use change can be studied, each in its own context of initial conditions. Possibilities include strip mining or strip mining reclamation, forest management or forest fires, cultivation practices or patterns, grazing policy, land drainage projects, and many others.

4. The information on runoff patterns by watershed soil type can also be expanded. Studies are needed to determine how patterns vary among a wider variety of watershed and climate combinations. Studies are needed to determine how to predict flow patterns changes consequent to the full spectrum of land use change possibilities.

5. The information on flood hazard patterns by watershed soil characteristics needs to be supplemented to encompass a wider range of combinations of parent soil type, human activity, and climate. The long term consequences of differences among patterns on human activity in the flood plain need to be explored. The consequences of different flow patterns with respect to flood control planning are but one aspect of understanding consequences with respect to a wide variety of water resources development projects for water supply, recreation including

fishing, land drainage, power generation, etc. Differences in flow patterns transcend economic implications to be associated with differences in esthetics, ecology, water quality, and yet other factors.

CONCLUDING STATEMENT

The development and initial applications of OPSET have only opened the door to studies on a wide variety of hydrology related water resources problems. The reader will likely think of many not even suggested in the preceding section. OPSET is available as a research tool to all who can profit from its use. This is but one of a set of three reports. The other two present the theory used in program development with program listings (37) and a description of procedures for collecting input data with data listings and of applications to selected watersheds (45). All three are available free of charge, while the supply remains, through the University of Kentucky Water Resources Institute. The principal investigator can provide punched decks of the Fortran programming at cost through the Environmental Resources Center at Georgia Institute of Technology, and is willing to offer assistance in program interpretation and data collection procedures to the potential user. The only obligation to the user is to report back his results so that the principal investigator can maintain a file of information to benefit all. The motive for providing this service is simple. Research unused is wasted.

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