6-1-1987

Development Of An Expert System For The Analysis Of Urban Drainage Using SWMM (Storm Water Management Model)

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Baffaut, C.; Benabdallah, S.; Wood, D.; Delleur, J.; Houck, M.; and Wright, J., "Development Of An Expert System For The Analysis Of Urban Drainage Using SWMM (Storm Water Management Model)" (1987). *IWRRC Technical Reports.* Paper 180.
http://docs.lib.purdue.edu/watertech/180

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TECHNICAL REPORT NUMBER 180
G1224-03

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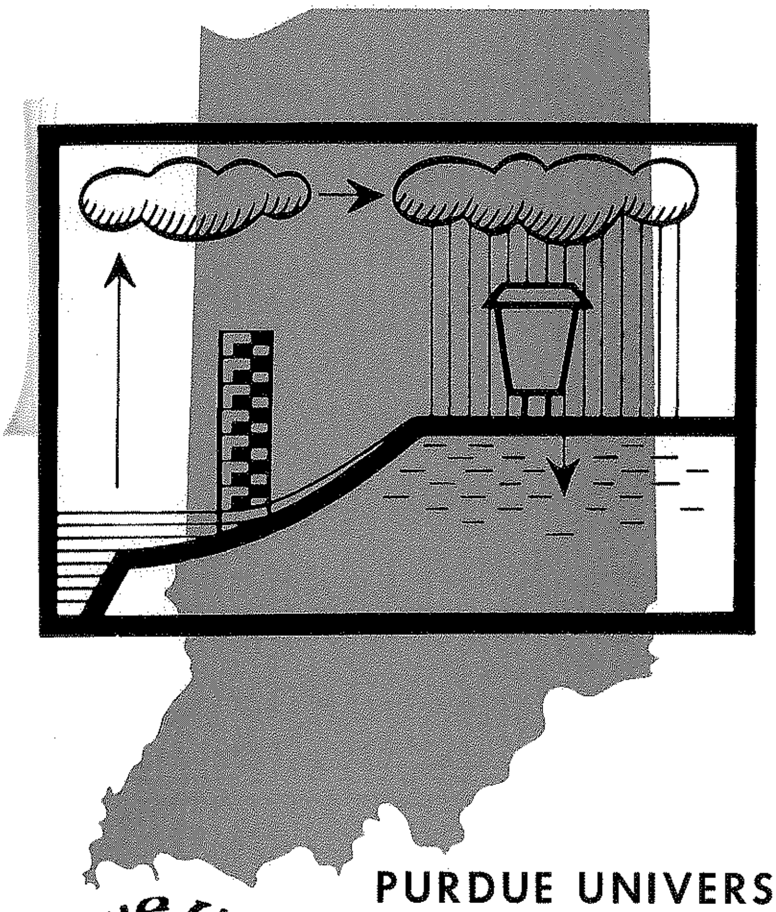

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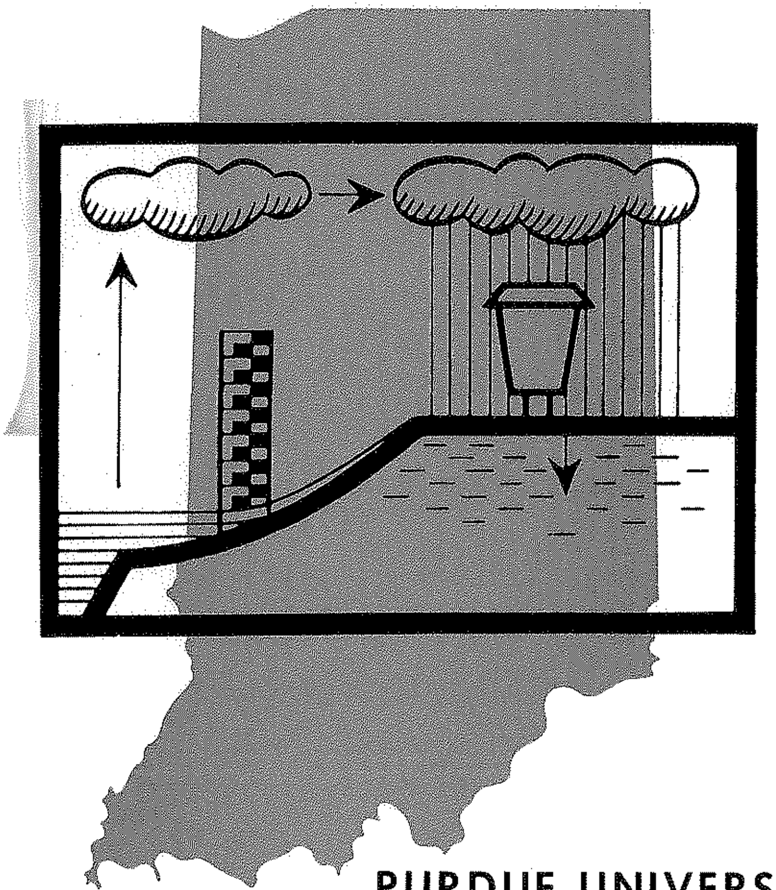

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FINAL TECHNICAL COMPLETION REPORT

Period of Investigation: 5/1/86 to 6/30/87

Project Number: G 1224-03

Grant Agreement Number: 140-08-0001-G1224

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Project Number: G 1224-03

Submitted to:

U.S. Geological Survey
United States Department of the Interior
Reston, VA 22092

"The activities on which this report is based were financed in part by the Department of the Interior, U.S. Geological Survey through the Purdue University Water Resources Research Center".

Water Resources Research Center
Purdue University, West Lafayette, IN 47907

June 1987

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ACKNOWLEDGEMENTS

The authors wish to acknowledge the kind assistance and encouragement of Dr. Wayne Huber, Professor of Environmental Engineering at the University of Florida. Dr. Huber spent two days at Purdue University discussing the rules that form the base for the expert system developed in this report.

ABSTRACT

An expert system has been built to facilitate and to automate the calibration of the runoff block of the Storm Water Management Model (SWMM). It acts as a front end to counsel the user on the choice of parameters, it interprets the results and suggests some useful changes in the value of significant parameters thus reducing the user's time and effort. The integration of new expert systems and traditional simulation models is best achieved through the use of modern expert system shells because of their ability to develop rapid prototypes and because they interface with existing and well accepted softwares such as SWMM.

CHAPTER I

INTRODUCTION

EPA's Storm Water Management Model (SWMM) simulates all aspects of the urban hydrologic and quality cycles, including surface runoff, transport through the drainage network, storage and treatment, and receiving water effects (Huber, et al. 1984). The implementation of SWMM on an actual site is not a trivial endeavor. It requires an expert hydrologist knowledgeable of modeling techniques such as non-linear reservoirs and kinematic waves. It requires a hydrologic expert knowledgeable in the modeling of unsteady free surface and pressure flow networks through the use of the St. Venant's equations and the associated numerical solution techniques. It requires an environmental engineer with expertise in the buildup and washoff of the pollutants and the diffusion of the pollutants in the receiving water body. It requires a computer specialist to prepare the data files and coordinate the execution of the program modules of the computer program. It requires the coordinated efforts of all these experts to select the appropriate modeling options provided by the model, to select the appropriate values of many of the input variables that require the professional judgement of these several experts. The coordinated efforts of these experts is also needed to evaluate and interpret the model outputs and to diagnose possible malfunctions of the drainage system and to suggest remedies. In actual situations the calibration work can take several person-months depending upon the complexity of the problem.

The principal objective of this research is the development of an automated procedure to calibrate the Stormwater Management Model (SWMM). The U.S. Geological Survey data base (Driver et al., 1985) is used as a source of hydrologic information. The quantity and quality parts of the runoff module of SWMM are calibrated using a criterion which minimizes the sum of squares of the errors while keeping the parameters close to their expected physical values.

Chapter II gives an overview of expert systems in water resources application. An expert system is a computerized procedure that mimics the decision making process of an expert in some problem domain. The development and use of expert systems are growing rapidly and this application of artificial intelligence has important implications for water resources management, engineering and planning. The principles of expert systems and their applications to water resources are reviewed.

A short overview of the Storm Water Management Model (SWMM) is presented in Chapter III. The purpose of the model and the data requirements of the Runoff Block are discussed. This overview describes the parameters to be estimated by the user and how an expert system could assist in the calibration and use of the model.

The three watersheds that have been used for the development and testing of the expert system are described in Chapter IV. The data available for each watershed are presented.

The procedures for the calibration of the quality and quantity part of the model are presented in Chapter V. The different tasks of the expert system follow closely the steps of the calibration procedure: guidance in the choice of parameters, interpretation of the results, diagnosis, and finally assistance in the change of the parameter values. Heuristics have been developed based on the data of the three watersheds. Knowledge is encoded in production rules (If ... then ...) as well as Fortran programs that interface with the system. A complete set of results obtained on the Upper Ross Ade Watershed (in West Lafayette, Indiana) is presented.

There seems to be a direct and growing link between the traditional systems methodology known as "simulation" and the dramatic new developments in expert systems. Chapter VI of this report discusses this relationship with insights as to what the benefits of such a marriage might be for improved water-related decision support systems.

While simulation techniques and tools have matured over recent years, those of expert systems are still in their infancy compared to traditional programming languages and hardware platforms. This poses a problem both to developers of expert systems as well as users who must specify their design. To complicate matters further, several hundred commercial products have hit the market, each with different strengths and weaknesses. A second focus of Chapter VI is a discussion of the technology presently available for the design and construction of expert systems prototypes with special attention placed on the evaluation of modern shells or development environments. In particular, the discussion addresses the benefits of using a complete expert system shell for prototyping expert systems both for the developer of the system as well as the intended user.

Following from the discussion in the previous sections, the next section of Chapter VI presents an example of the use of modern shell technology in the development of a prototype of the SWMM model calibration expert system ESCALOS described in previous chapters. Specific program constructs using the expert system KES are presented as well as script screen displays showing the user interface that results. Details of the interface between ESCALOS and SWMM are described.

CHAPTER II

EXPERT SYSTEMS AND WATER RESOURCES

The purpose of this chapter is to provide an introduction to expert systems and an overview of the application of this new technology to water resources problems. There are entire textbooks written on expert systems and, therefore, this introduction will be necessarily brief. It should, however, provide the basis for understanding subsequent chapters of this report dealing with the specific development of an expert system for calibrating a complex hydrologic-hydraulic model.

2.1 Expert Systems

"An expert system is a knowledge-based reasoning system that captures and replicates the problem-solving ability of human experts" (Boose, 1986). This definition of an expert system is very general and it could be argued that a great deal of work in the past could be, at least partially, considered to be development of expert systems. Typically, expert systems as they are known today have greater structure than is indicated by Boose's definition. This structure will be described later in more detail.

Why would we want to build an expert system? There are many reasons that a computerized reasoning system might be appropriate. Among these are:

- Experts retire, taking their knowledge with them.
- There may be better uses of an expert's time than answering users questions.
- Expertise may be scarce.
- Expertise may be expensive to deliver.
- Expertise may not be available when it is needed.

- Experts are not always consistent.

In any particular application these reasons or others may be important in deciding to construct an expert system.

A typical expert system can be described as having three basic components: (1) a knowledge base, (2) an inference engine or reasoning mechanism, and (3) a working memory. Each of these is connected to the others if you visualize the expert system as a flow chart. The knowledge base is the repository for information that is static and domain-wide. The domain of an expert system is the area within which the expert system would be called upon to solve problems. The knowledge base would contain not only data that apply to the domain and would not be changing from one problem to the next, it also may contain empirical rules, theoretical rules or laws, heuristics, and models that may be employed as part of the solution.

The inference engine or reasoning mechanism contains all the procedures for manipulating, searching, and exercising the knowledge base. There are many ways to structure the inference engine to use the knowledge base and expert systems may be distinguished by the inferencing mechanism used.

When a specific problem is to be solved using the expert system, the problem data are input to the working memory. It is the user interface to the expert system and the storage for the specific problem information. The working memory also serves as the explanation device for the expert system. One of the distinguishing characteristics of an expert system is that the user may ask the questions: how? and why? The result is a listing of the series of steps taken by the expert system to arrive at an answer to the problem. This may include a listing of the rules from the knowledge base that were employed as well as the order in which they were applied to the problem and any data that were input as well as any information that was deduced by the expert system along the way to finding the answer to the problem.

A small example of how an expert system might work may be helpful. Suppose that the knowledge base contained only two rules:

Rule 1: if A then B
Rule 2: if B then C

Assume that A, B and C are some conditions that are either true or false. The expert system begins by the user asking the question: is C true?

This particular expert system uses the inferencing mechanism known as backward chaining. Therefore, the inference engine when asked if C is true, will attempt to find all rules in the knowledge base that conclude C is true. In this particular case, the knowledge base is examined and there is only one rule that concludes with C is true, and that is rule 2. The question is then posed to the user: is B true? If the user can provide the information about whether B is true, then the entire process can stop. In this case, the user has responded with: don't know. Therefore, the expert system will again search the knowledge base to find rules that will help it answer the question: is B true? It finds that rule no. 1 concludes that B is true if A is true. Therefore, the user is again queried for whether or not A is true. In this case the user has responded yes. And the expert system has concluded: then C is true! At this point the user may respond with the question why? An expert system would then respond with the line of reasoning it used to arrive at the conclusion that C is true. This is just one small example illustrating how an expert system might function. There are many variants that make the use of expert systems more appropriate for different environments and different problem domains.

Along with expert systems development has come a new field or at least a new title for a specialist called a knowledge engineer. What is knowledge engineering? It is "the extraction, articulation and computerization of expert knowledge. Knowledge consists of descriptions, relationships, and procedures in the domain of interest" (Boose, 1986). It is generally agreed, that one of the largest, if not the largest, problem in expert systems development is knowledge acquisition and knowledge engineering.

How can an expert, a knowledge engineer and an expert system interact? The goal of the knowledge engineer is to elicit information from the human expert in a form that is appropriate for inclusion in an expert system. Therefore, the knowledge engineer must be the intermediary between the human expert and the computer. There are a number of ways for knowledge to be extracted from human experts. The knowledge engineer can observe the expert while he or she is working to solve real problems over some period of time. The knowledge engineer could also sit down with the human expert and have the expert analyze several real problems on which he or she is not necessarily currently working but which are representative of the problem domain. The human expert could try to describe to the knowledge engineer the data, knowledge and procedures that are typically used to solve problems in the domain. Or the expert could attempt to classify the problems that are in the domain.

Once an initial, prototype expert system has been developed, you could let the expert expand the test cases that have been employed thus far and have the knowledge engineer and the human expert discuss what changes need to be made to permit the expert system to work reasonably well on the expanded test cases. The expert could review the knowledge base directly and make suggested changes to the knowledge engineer. Depending on the problem domain, other human experts could be requested to analyze and assess the expert system that has been developed thus far and provide input to how it should be modified. All of these are only a sample of the possible techniques to extract information from the human expert. In any particular case, one or more of these would be appropriate for use in the construction of the expert system.

Unfortunately, all of these have problems associated with them. "Most knowledge engineers do not have sufficient training to interview experts efficiently and effectively" (Boose, 1986). To be an effective knowledge engineer, you must be capable of understanding the computerized end of the expert system as well as effectively deposing, interrogating, and interacting with human experts on a complex problem to extract their problem-solving methods, approaches and heuristics. In addition, "domain experts have difficulty expressing their problem-solving knowledge explicitly. They tend to create plausible lines of reasoning which may have little to do with how problems are actually solved" (Johnson, 1983). "Explanations may be in terms of idealized verbal descriptions learned in school, while much expertise seems to be compiled in heuristics accumulated over the years.... Additionally, experts may be wrong when they describe their procedures to knowledge engineers" (Boose, 1986).

2.2 Applications of Expert Systems

There have been numerous papers in the literature on the development and application of expert systems in Civil Engineering and Environmental Engineering. A soon-to-be-published volume of the ournal of Computing in Civil Engineering will contain a complete review of expert systems in Civil Engineering. There has also been a recent report entitled, "Survey of the State of the Art Expert/Knowledge-Based Systems in Civil Engineering from the Construction Engineering Research Laboratory of the U.S. Army (Kim *et al.* 1986). Both of these review in detail the existing literature describing development and application of expert systems in each area of Civil Engineering. One chapter in the CERL report by Siller is on "Expert Systems in Geotechnical and Environmental Engineering."

In addition to these reviews, there is also a soon-to-appear note in the *Journal of Computing in Civil Engineering* on "New Expert Systems in Environmental Engineering", by Ortolano and Steinemann (forthcoming). They group the emerging expert systems into three categories: hazardous waste management, water supply and wastewater management, and calibration and use of models. Under the hazardous waste management category, applications from how to respond to an accidental spill of hazardous material to analyzing unknown contents of waste containers are described. In the water supply and waste water management area, applications range from expert systems to diagnose failures and suggest remedies for trickling filter plants, to scheduling pumping operations at treatment plants, to identifying points of leakage from water distribution systems. In the calibration and use of models area, the applications of expert systems range from the selection in use of mathematical models for mixing zone analysis, to the calibration and use of groundwater flow models, and to the calibration of the storm management model (SWMM). It is obvious that the continuing development of expert systems is growing. Only the future will provide the answer to whether the application of this technology is successful.

CHAPTER III

DESCRIPTION OF SWMM, AN OVERVIEW

3.1 The Storm Water Management Model (SWMM)

EPA's Storm Water Management Model (SWMM) simulates all aspects of the urban hydrologic and quality cycles, including surface runoff, transport through the drainage network, storage and treatment and receiving water effects. Its structure, as schematized in Figure 3.1, consists of several modules : the Runoff block, the Transport block, the Extran block, the Storage and Treatment block, the Receiving block and the Executive block, (Huber et al, 1984). To use SWMM, the simulated watershed area is divided into several subcatchments that are characterized by their areas, shapes, land-uses and topographies. The runoff hydrograph and the pollutograph are computed for each subcatchment and then routed through the system and combined with the hydrographs and pollutographs from other subcatchments. A brief overview of the tasks of each block is given in the following paragraphs.

The Executive block assigns logical units and files, controls the sequencing of the different computational blocks and presents graphical outputs. The Runoff block generates the quantity and the quality of runoff from a subcatchment based on the rainfall, the antecedent conditions, the landuse and the topography. It also routes the runoff through gutters or small pipes, using a non-linear reservoir method.

The Transport block and the Extended Transport block take the hydrographs generated by the Runoff block and combine and route them through the sewer network. The Extended Transport block uses the complete St. Venant's equations whereas the Transport block uses just the kinematic wave approximation and views the system as a cascade of conduits. The Extended Transport block does not consider water quality but the Transport will route pollutographs through the sewer network.

The Storage/Treatment block simulates the effects of storage and treatment upon the flow and the quality. The Receiving block routes the outflow hydrographs and pollutographs through the receiving river, lake or estuary. The Combine block can be used to aggregate the results of previous runs for input into subsequent blocks.

Also, in case of continuous simulation, the Statistic block has the capability to treat the output results, rank the storm events according to any desired criteria,

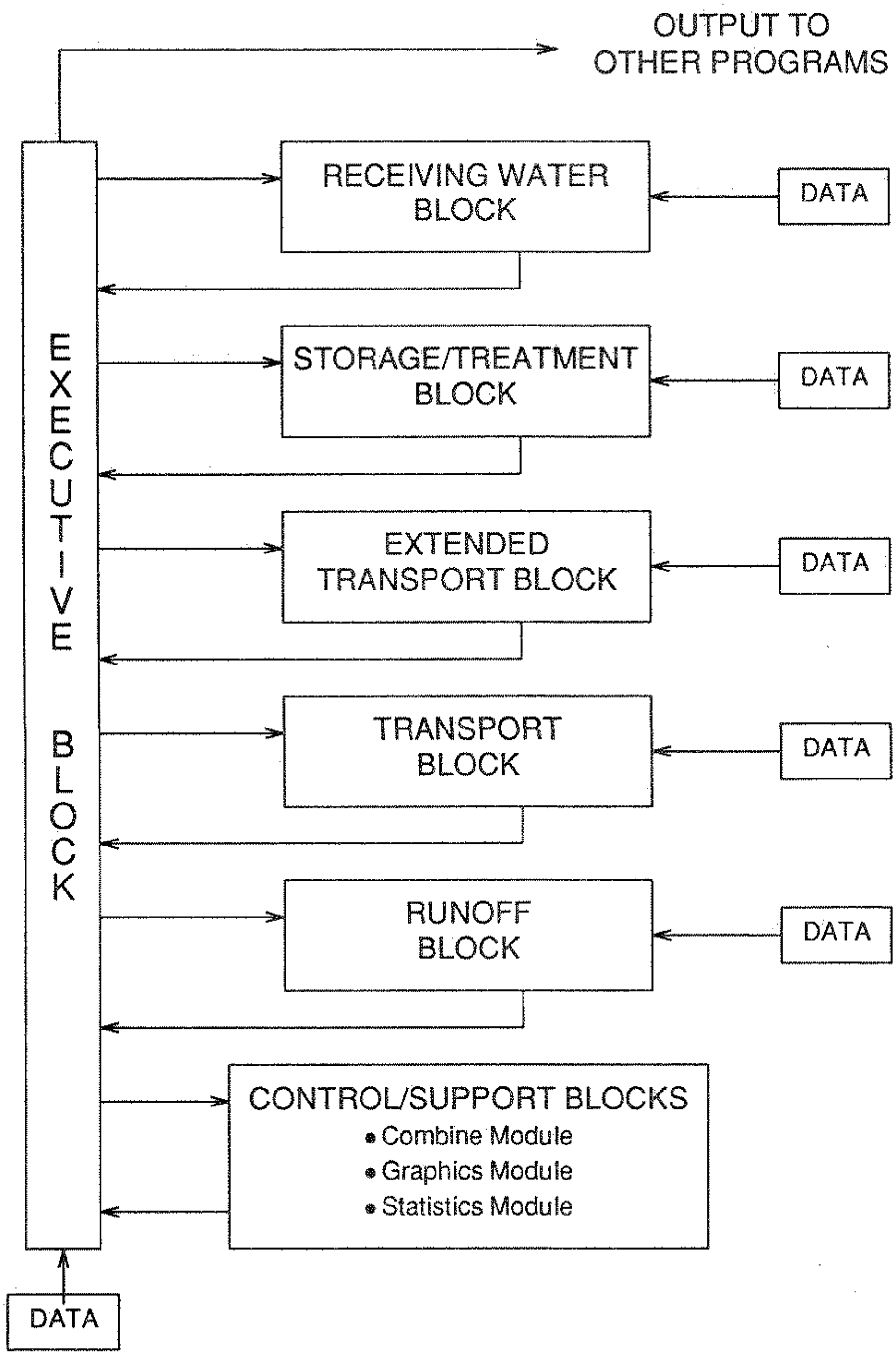


FIG. 3.1.— Block Diagram Showing the SWMM System Configuration (after Huber, et al, (1984)).

assign some empirical frequencies and calculate the statistical moments.

Most of the calibration takes place in the Runoff block because it is the first block that generates the hydrographs on each subcatchment. This is also the block where the necessary parameters are the most difficult to estimate. This is often due to insufficient data, measurements, records and time. The data needed for the Transport block are those describing the sewer network and are usually found in the City records. In the rest of this study, we will limit ourselves to the Runoff block .

3.2 Data Requirements for the Runoff Block of SWMM.

The data required for the Runoff block can be separated into data to simulate the quantity of runoff and data to simulate its quality.

To reproduce the runoff hydrographs two kinds of parameters are required :

- physical parameters
- hydrological parameters

The physical parameters include the area of the subcatchment, its mean slope and its impervious area. In the case that some gutters or small pipes are simulated,the data also include their description: length, diameter or width and slope. Most of these parameters can usually be estimated from topographic maps, aerial photographs or city maps.

Hydrological parameters include: Manning's coefficients for overland flow on pervious and impervious area and, if necessary, for channel flow in the gutters or small pipes; depression storage specifying the volumes that have to be filled before the occurrence of runoff from pervious and impervious areas ; and infiltration parameters. The characteristic width is also a hydrological parameter. In case of an idealized rectangular subcatchment, the characteristic width is simply the physical width of overland flow. However idealized cases seldom happen in reality and the characteristic width is somewhere between L and 2L where L is the length of the main drainage channel. All these parameters are very difficult to estimate and the correct reproduction of the shape of the predicted hydrograph is very sensitive to the correct estimation of these parameters.

To simulate the runoff quality two kinds of parameters are also required:

- parameters that are dependent upon the subcatchment and its land-use.
- parameters that are dependent upon the simulated pollutant.

The parameters that are dependent upon the subcatchment and its land-use concern principally the characteristics of the accumulation (or buildup) of dust and dirt on each land-use. For these the user first decides the method of buildup estimation to be used and then values of the appropriate parameters are estimated. SWMM allows the choice between three different buildup methods. The amount of dust and dirt can be a linear function of the time or of a power of the time:

buildup load = coeff * time**power

It can also be expressed as an exponential function of the time or finally as a Michaelis-Menton function of the time, respectively, as:

buildup load = limit * (1 - exp(decay rate * time))
buildup load = limit * time /(coeff + time)

In the last two cases, a limit of accumulated amount of pollutant has to be defined. In the first case, it is also possible to define such a limit that fixes a maximum amount.

The user has also to estimate the availability factor necessary to take into account the presence of cars along the street that are an obstacle to a complete cleaning, the concentration of pollutant in the precipitation and in the catchbasins, the volume of the catchbasins and other parameters that have an impact on the amount of pollutant deposited on the watershed.

Parameters that are dependent upon the different constituents characterize the buildup of these constituents and also their washoff or how much of them will be washed off the street during a given rainfall event. The user has the choice between four different buildup methods. In addition to the three methods that have been mentionned earlier, the buildup of a constituent can be calculated as a fraction of the buildup of dust and dirt. These fractions represent the amount (in milligrams) of pollutant per gram of dust and dirt. They have to be determined for each pollutant and each landuse.

The washoff of the pollutants can be estimated in two ways. The washoff can be computed by regression with the runoff rate and in that case the two regression coefficients have to be estimated by the user and specified in the input file. Otherwise the amount of pollutant that is washed off the area at time t (poff(t)) is estimated as a function of the runoff rate r and the amount of pollutant (pshed) that remains on the watershed.

poff(t) = rcoeff * (r ** washpo) * pshed

Here again, the user has to estimate the values of both the coefficient rcoeff and the exponent washpo.

Miscellaneous other parameters have to be determined such as the concentration of pollutant in the catchbasins or in the precipitation that are generally negligible but may have some importance in particular cases. These parameters characterize other sources of pollutant and mechanical removal (street sweeping).

In conclusion a large number of parameter values must be estimated: 11 parameters per subcatchment are required to simulate just the quantity of the runoff. For each pipe or gutter that connects these subcatchments, an additional minimum of five parameters is required. If a quality simulation is necessary then the user has to estimate six more parameters per land-use and possibly twelve per pollutant, depending upon the calculation of the deposition. In addition, the user has to specify the meteorological data. This first phase of estimation of parameters and preparation of the data files can therefore be long and tedious.

3.3. How could an expert system help?

As was seen for the Runoff block, there are many parameters to estimate and to calibrate. If measured hydrographs and pollutographs are available, the user can compare the predictions of the model with the observations. A calibration procedure can then take place. It consists of finding the correct set of parameter values that reproduce the observations. If there are no such observations, the user has to rely on the first estimations of the parameters. Even if the calibration phase is possible it is important to obtain some good first estimates of the values in order to have some reasonable values at the end of the calibration.

For the parameters required to simulate the quantity of runoff, the user can find estimates of their values with the help of topographic maps, aerial photographs, soil surveys and city sewer maps. To estimate the values of the parameters required to simulate the quality, the best method would be to conduct a series of tests on the area to be modeled that would characterize the buildup and washoff rates of the desired pollutants. However this method is very costly and time consuming. As is often the case, the user can then refer to the literature ;the usual sources are Sartor and Boyd (1972), and Manning et al.(1977). These are studies that have been conducted to try to characterize the buildup of different pollutants on areas of various land-use in different cities. In addition some local studies have been conducted. The EPA Urban Rainfall-Runoff-Quality Data Base by Huber et al.(1979,1980) describes the South Florida urban runoff. In 1985-86, a study was conducted in southern Ontario to try to characterize the non-point source pollution in urban runoff (Lorant, 1986). In the Lafayette area some studies have been made in 1977-78 and 1983 to characterize the quantity and quality of the runoff (Han and Delleur, 1979 ;Delleur et al., 1984) Finally, the SWMM User's Manual (Huber et al., 1984) gives indications on how to estimate the values of the required parameters and includes data from other authors as well as references.

The first task of an expert system would therefore be to counsel the user in the choice of the parameter values. This includes a guidance to find the estimate , a proposal of a range of values, and if necessary some suggested values.

The second task of the expert system would be to assist the user during the calibration of the system. The calibration stage requires a good understanding of all the parameters in order to change the value of the right parameter by a correct amount so that better results are obtained. This phase is long and tedious and could be well automated.

Some programs have already been developed to automate the calibration of SWMM and other hydrological models. These are generally not very well accepted because they are similar to "black boxes" whose results may be questionned because the method of solution is not well understood. The use of an expert system brings some advantages because the reasoning can be made identical to that of an expert: observing the differences between predictions of the model and measured data and trying to adjust the different parameters to resolve these differences. In addition the expert system has the capability to explain the reasoning it follows to obtain a result.

Therefore, even a beginner user could use such a system and get some benefit from it. By looking at the reasoning of the expert, he would learn about the model behavior and about the sensitivity of the parameters.

CHAPTER IV

WATERSHED DESCRIPTION

4.1 Ross-Ade Watershed

The upper Ross-Ade watershed consists of 29 acres (11.7 ha) of residential semi urban area. The impervious area is around 30%, 8% of which produces runoff directly without depression storage from surfaces such as roofs. The shape of the watershed is a typical V shape, (Figure 4.1).

Woodland avenue, which runs down the center of this valley has a slope between 1 and 3 percent. On the upper part of the watershed, yard slopes are nearly flat and they can reach 25% in the center of the basin. The soils in the watershed are mainly from the hydrological group C.

It is possible to simulate this watershed considering one global subcatchment or seven small ones. These have been delineated using a city map of the drainage system which makes it possible to incorporate the sewer network in the simulation. A schematic representation is shown in Figure 4.2 and the lists of length, slope and diameter of the pipes are presented in Table 4.1.

Table 4.1 Physical Characteristics of Pipes in the Ross-Ade Watershed

Pipe id	Length [ft]	Slope [%]	Diameter [inches]
100	250	4.8	15
101	280	4.0	18
200	240	3.4	18
201	260	3.4	21
102	240	2.0	30
103	536	2.8	36
104	860	1.5	36

Rainfall and runoff data are continuously recorded at the outlet of the watershed and sent directly to the Civil Engineering Building, Purdue University, where they are recorded on a floppy disk. Quality samples were regularly taken during the period 1983-1984 and some of them were analysed. For this study we will use storm

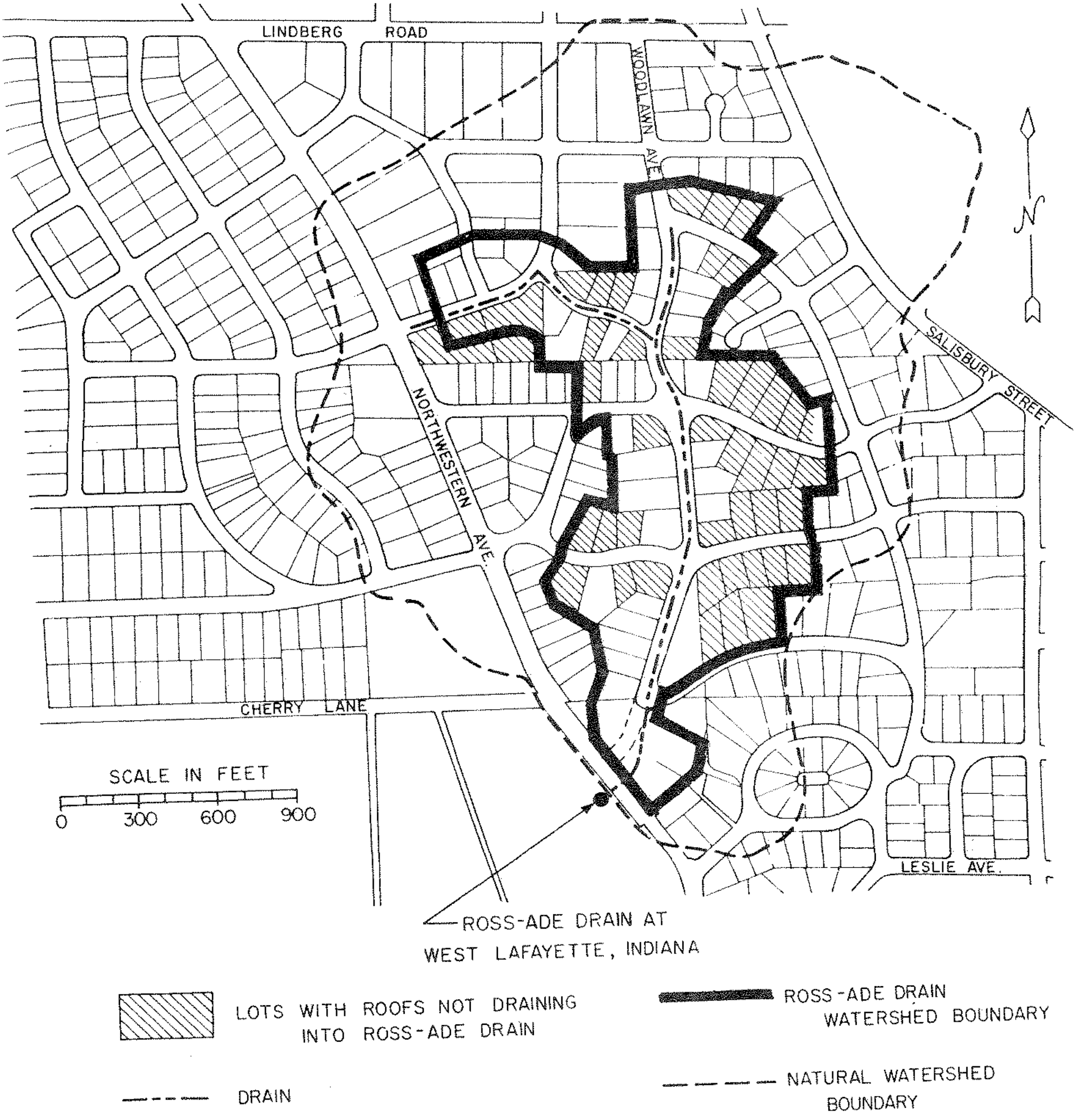


Figure 4.1 Upper Ross-Ade Watershed

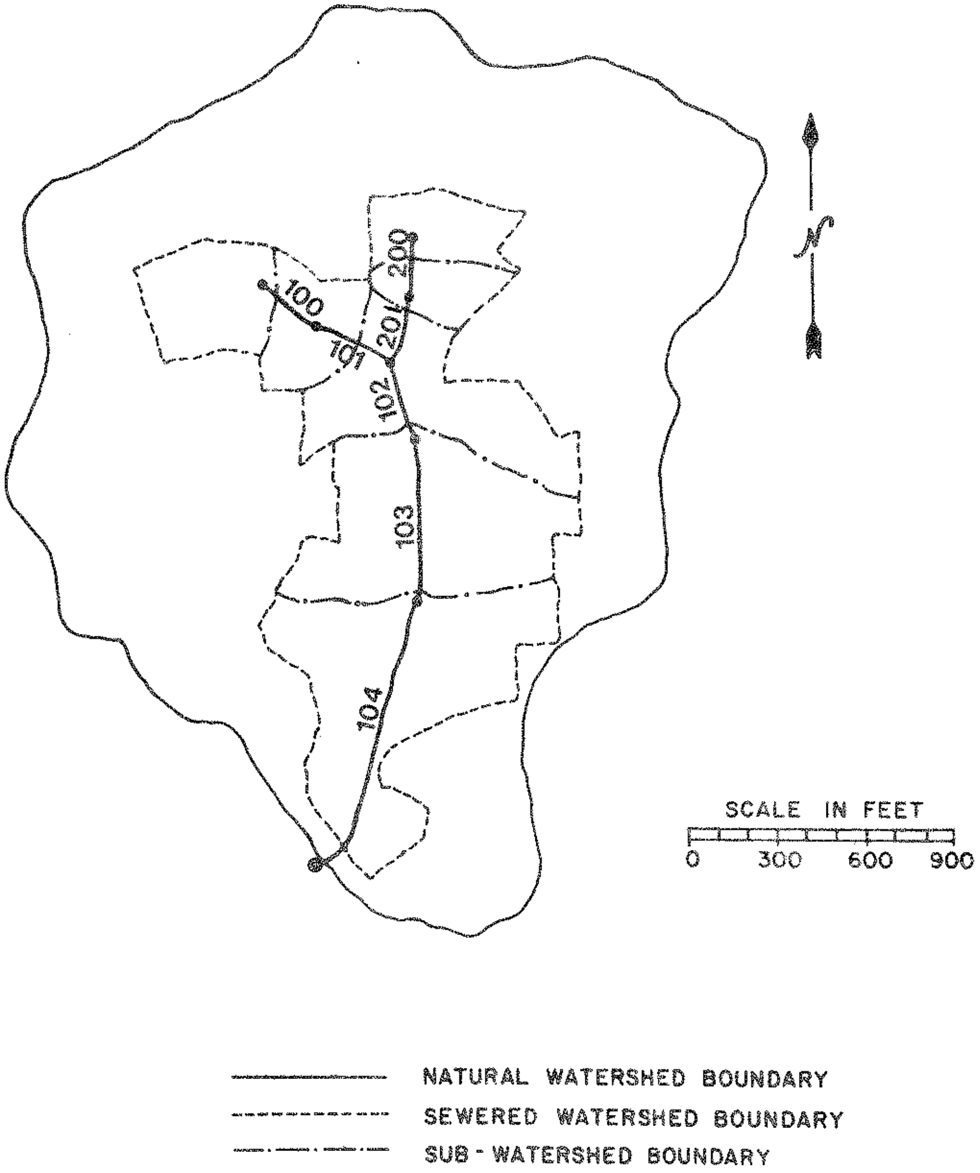


Figure 4.2 Schematic representation of the Upper Ross-Ade Watershed sewer system

events from the 1983 year when a number of samples were analysed, particularly for biological oxygen demand and suspended solids characteristics. Rainfall and runoff data as well as the results of the samples analysis are now stored on a magnetic tape.

4.2 Glen Ellyn Watershed

Glen Ellyn catchment ,located near Chicago, has a total area of 534 acres (215 ha). The area that contributes to the runoff measured at the main outlet is 418 acres (169 ha) and could be divided into two or seven subcatchments, dpending upon topographic and land-use characteristics and upon the desired amount of discretization. The main land-use is low to medium density residential (82%) with some commercial areas (10%), some parks (5%) and some high density residential areas (3%). The slope is from 1 to 2 percent (Figure 4.3).

Some previous studies have been done on this watershed (NIPC, 1980) that give its hydrological and land-use characteristics. These data are shown in Table 4.2. The rainfall, runoff and quality data were obtained from Driver et al. (1985) who give data for 22 metropolitan areas in the United States. Ten significant storm events were recorded at a five minute interval for the Glen Ellyn watershed. Quality samples were analysed for different pollutants including COD, suspended solids and several minerals. Only pollutants that had the most data for the chosen storm events were used.

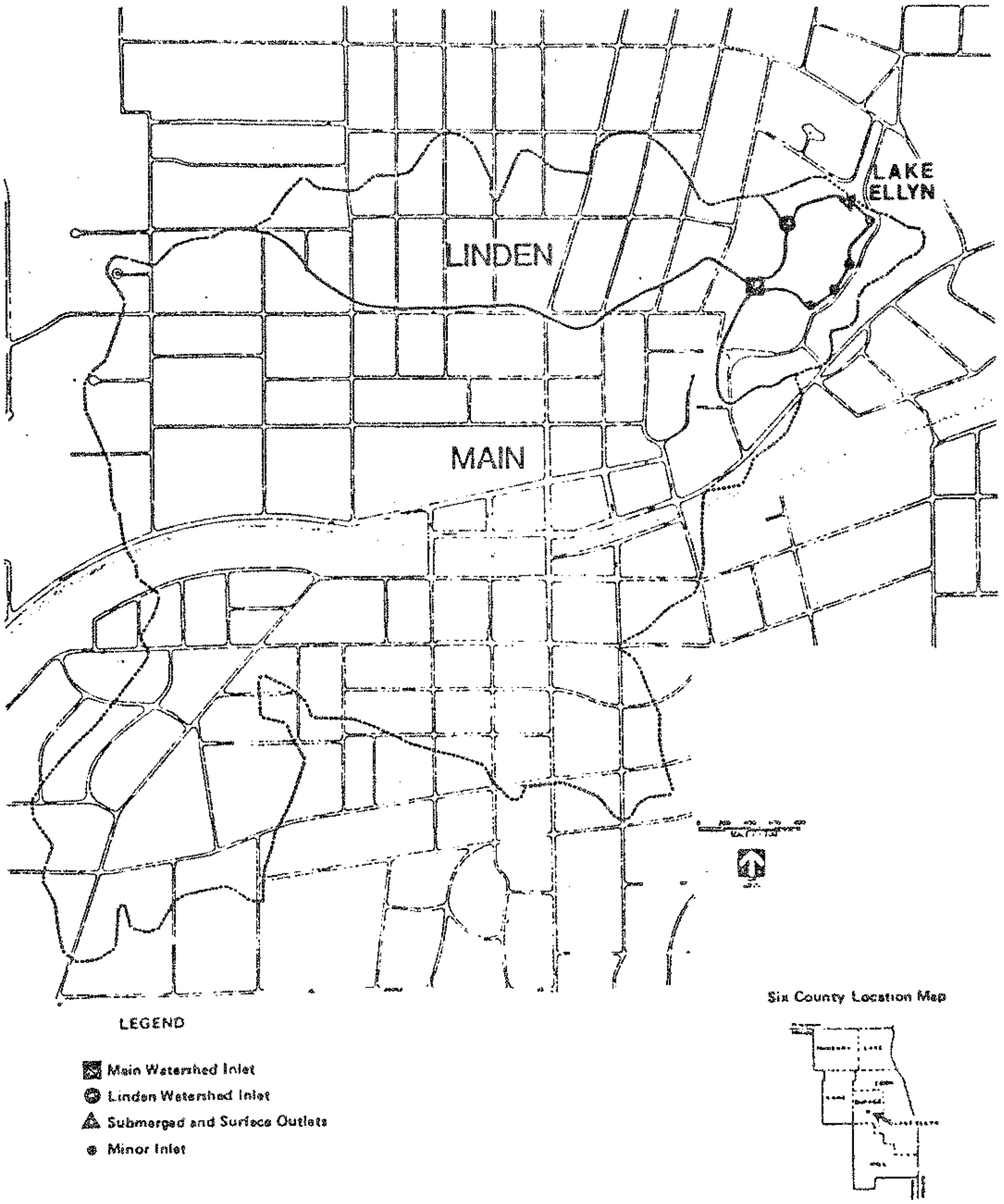


Figure 4.3 Glen Ellyn Watershed

Table 4.2 Physiographic and Hydrological Characteristics of Glen Ellyn Watershed

Downtown Watershed	
Watershed Area	162 acres
Effective Impervious Area	50 acres
Watershed slope	1%
Watershed length	4920 feet
Solids loading	4360 lb/dy
Lorraine Watershed	
Watershed Area	255 acres
Effective Impervious Area	30 acres
Watershed slope	1.2 %
Watershed length	4373 feet
Solids loading	3562 lb/dy
Average Hydrological group	C
Population Density	5000 pn/sq.mi
Street density	21.6 mi/sq/mi
Pollutant Loadings (Total Suspended Solids, lbs/curb mi)	
Low density residential	711 lbs
High density residential	267 lbs.
Commercial	611 lbs

4.3 State Highway 100

The "State highway 100" watershed ,located near St Paul, Minnesota, has a total area of 300 acres (121 ha). Two thirds of the area is a low density residential area. The watershed contains a large commercial area in the center. The impervious area percentage is about 35%. The average basin slope is very low , less than one percent. The average conveyance slope is 1.6 percent. It contains a very limited drainage system (Figure 4.4).

The rainfall, runoff and quality data were also obtained from Driver et al. (1985). Fifteen storm events were recorded along with some quality data for each of them.

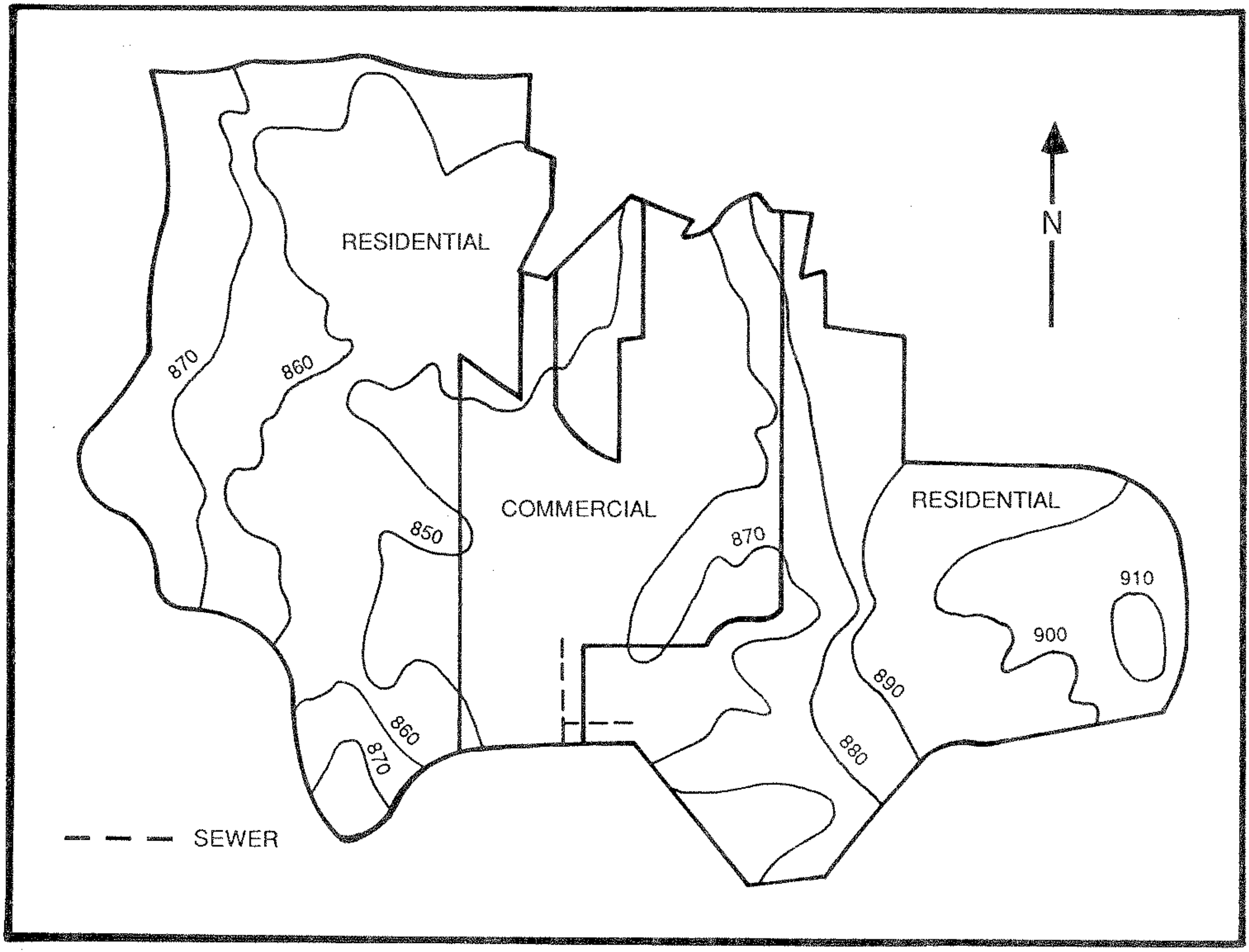


Figure 4.4 State Highway 100 Watershed

CHAPTER V

CALIBRATION OF SWMM

5.1 Methodology

The parameter adjustment of a hydrological model involves two stages: the first is the calibration proper, the second is the verification. The calibration stage requires a set of representative data, in our case hyetographs, hydrographs and pollutographs (concentration of pollutant versus time). The goal will be to minimize some function of the deviation between the predictions of the model and these data, e.g. area under the hydrograph, peak value, sum of the absolute values of the deviations, sum of the squares of the deviations, etc.. Ideally, the verification stage requires a set of data as large as the calibration set. In practice, the size is often one half to two-thirds of the calibration set. In the verification stage, the model is exercised with the calibration parameters, and the model predictions are compared to the observations not used for the calibration. If the verification results are not satisfactory it is then necessary to return to the calibration stage with a larger set of data or possibly to choose a different model. For models such as SWMM that simulate the quantity and the quality of the runoff, it is important to calibrate the quantity before the quality because predicted pollutographs are most often calculated on the basis of predicted hydrographs.

5.1.1. Quantity Calibration

As seen before, eleven parameters per subcatchment are required to simulate the runoff hydrograph. When calibrating the model by changing the values of parameters to try to minimize the differences between predicted and measured hydrographs, the user is guided by the results of the last trial set of parameters, the sensitivity of the parameters and the range of values they can take.

The first task in calibrating the model is to understand the meaning of each parameter and find the allowable ranges for each. For parameters that are difficult or expensive to estimate (such as the depression storage or the infiltration parameters) the SWMM user's manual is well documented and reports

For parameters that the user can estimate, a range can be calculated from the certainty (or belief) the user has in his or her estimation. For example, the impervious area percentage on a commercial center is very likely to be near 100% and is probably easier to estimate than on a low density residential area where there are streets, roofs, drive-ways but also yards and roofs not connected to the drains or to some impervious area. Therefore the range in the former case might be from 97 to 100 percent instead of 30 to 40 percent in the latter case.

Then one has to adjust the values of the parameters, keeping them in the range previously determined. It is recommended to start with the most sensitive parameters and finish with the less sensitive ones. However, the sensitivity of the parameters might depend on the type of watershed being modeled. In a typical example the value of the depression storage for pervious area is not changed if the watershed is mostly impervious. The sensitivity of the parameters depends also on the stage of the calibration process. Generally, it was found that the parameters become more sensitive toward the end of the process when the predicted hydrographs are almost similar to the measured ones. At the beginning of the calibration process, only a few parameters are sensitive enough to cause a valuable change.

The calibration process is terminated when the simulated hydrographs are close enough to the observed hydrographs. To simplify the comparison between measured and predicted hydrographs, the output of SWMM gives some differences criteria. The volume difference criterion is the difference between measured and predicted volume of runoff relative to (divided by) the measured volume of runoff. The peak difference criterion is the difference between measured and predicted peak flowrates relative to the measured one. When calibrating with several storm events, which is highly recommended in order to reduce the predictive errors (Maalel and Huber, 1984), then the criteria could be the arithmetic average of these volume and peak differences on all storm events. It could also be an average of the absolute values of the differences, or their maximum values.

These numerical differences are useful in the calibration process to assess the sensitivity of a parameter and to evaluate the goodness of fit of the model. Nevertheless, the determination of the success of the process is often very subjective and left to the judgment of the user. A plot of the predicted and measured hydrographs on the same graph for each storm event is another tool given by SWMM for the user to judge the quality of the fit. As with any judgment it is not consistent among different persons. The judgment of the same person in different conditions might even change.

5.1.2. Quality Calibration

Once the runoff quantity simulation model is calibrated and the runoff is correctly predicted, one can calibrate the quality model. This part can be done for each pollutant separately except when there is some dependence between them in which case they will have to be calibrated together. However, for economy of computing time it might be judicious to calibrate them together.

For each pollutant, SWMM calculates the load washed off the watershed during the storm; it also reproduces the complete pollutograph (concentration versus time) at any point of the network. The common need of the user is often just the load and the shape of the pollutograph may not be as important. In that specific case, if the correlation between measured volumes of runoff and the estimation of the storm loads is good, a regression between these two variables will be a satisfactory means to estimate the loads.

Also some pollutants on some watersheds will be better simulated when using the rating curve method. The suitability of the rating curve method can be determined graphically. If a plot of the loads (mg/s) versus the flows (cfs or l/s) for each storm on log-log paper is approximately a straight line then the rating curve method will probably be preferable. Otherwise, the washoff equation should be chosen. Any time the rating curve is satisfactory, it will save calibration time. Otherwise, the buildup and washoff parameters have to be calibrated in order to reproduce the measured data.

After the choice of the computation methods for concentrations and loads, the next task of the user is to gain an understanding, through the literature, of the meaning of the coefficients and to determine a range of values for each of them. Since the deposition and washoff processes are not well understood at this time, the ranges of values are actually very large. For example, a value of the washoff coefficient between 1 and 10 appears to give concentrations in the range of most observed values of urban runoff (Huber, 1984). However, it is not impossible to find a satisfactory washoff coefficient in the vincinity of 40 or 50.

The judgment of whether or not the model is properly calibrated for one pollutant is probably more subjective than for the quantity simulation. If the user is only interested in the loads, then it is possible to build a difference criterion as was done in the first part. This would be the difference between measured and predicted loads relative to the measured one. Again, to calibrate the model with several storm events, these differences can be averaged, averaged in absolute value or one could consider their maximum absolute value.

When the user's goal is the reproduction of the pollutograph more subjectivity is introduced. There are two reasons for this. Because of the cost and time involved in the analysis of quality samples, there are usually fewer data available to calibrate the model and to judge the shape of a pollutograph. Samples are taken every ten or fifteen minutes (sometimes the time interval is larger) and it is easy to miss variations of the concentration such as peaks. As a first consequence, the estimation of the load can be biased. Secondly, there are different ways the predicted pollutographs can be fitted to the measured points. Calibration will therefore be very sensitive to the user's interpretation of the data. The deposition and washoff processes are subject to the influence of various phenomena such as wind, seasonal effects, intensity of the rain, type of development and activity. The actions of these are not well understood and are therefore difficult to take into account. Measured data show that the storm loads are often very different from one another without any apparent reason. The model, however will predict some similar loads and concentrations. The calibration of the model is then very sensitive to the storm events that are used.

Therefore, it is very possible that different calibrations of a model using the same set of data may result in different values of the parameters. Calibrations using a different set of data will increase this possibility.

5.2 Strategy for an Expert System

5.2.1 The Expert System Guides the User in the Choice of Parameters.

For the parameters that are difficult or expensive to estimate, the user has the possibility to go to the literature to pick a value that is given for a watershed as close as possible from the watershed in question. When using ESCALOS (Expert System for the Calibration Of Swmm), if the user doesn't know the value of a parameter, there is the possibility to ask for an explanation. An explanation of the parameter and some proposed values dependent on the characteristics of the watershed will be shown on the screen (see scripts of sessions in chapter 6). If there are other ways to compute the value, typically when the value of a parameter is a function of another variable, the equation is shown to the user. For example the length of gutter on a subcatchment is a function of the area and the population density.

The use of the expert system saves some time for the user during the first phase of estimation of the parameters. The knowledge contained in the literature is present in the expert system and can be updated easily.

Once all data relevant to watershed are known by ESCALOS, the user has to give hydrological data: hyetographs of the rainfall events, measured hydrographs and time and concentration in pollutants of the samples that were analysed. Finally, once all data are entered, the system builds the datafiles to SWMM and executes the model.

5.2.2 The Expert System Assists in the Interpretation of the Results

To make a diagnosis on which parameters have to be changed and in what amount, the system needs to interpret the results in view of the objectives of the calibration. Those are to simulate correctly the volumes of runoff, the runoff peaks, the times of occurence of the peaks and the shapes of the hydrographs. For the quality simulation, the goal is to simulate correctly the loads of pollutants transported by a storm to the outlet of the subcatchment. In a few case, such as the design of a detention pond or of a treatment plant, it is necessary to reproduce the shape of the pollutograph. The volume differences and the peak differences are efficient means to quantify how well the first two objectives are met. To take into account all storms used for the calibration, the differences will be simply averaged over the number of storms. To quantify the reproduction of the times to peak the criterion used is a time difference: average difference between the measured and predicted times to peak. In addition, to quantify the reproduction of the shape of the hydrograph the criterion used is a weighted error, i.e. a weighted average of the root mean squared error of the hydrograph and of the volume difference, averaged over the number of storms.

How well the storm loads are predicted is similarly quantified with a load difference, namely the average difference between the measured loads and the predicted loads relative to the measured one. At this point, there is no way to quantify how well the shapes of the pollutographs are reproduced other than the judgment of the user by looking at the difference between the plot of measured and predicted concentrations versus time.

The different criteria expressions used for the interpretation of the results are:

$$\text{Volume difference} = \frac{1}{N} \Sigma \frac{Vm - Vp}{Vm}$$

$$\text{Peak difference} = \frac{1}{N} \Sigma \frac{Pm - Pp}{Pm}$$

$$\text{Time difference} = \frac{1}{N} \Sigma \, (Tm - Tp)$$

$$\text{Weighted error} - \frac{1}{N} \Sigma \left(\frac{1/Ni \sqrt{mj - pj)^2}}{mi} + b \left| \frac{Vm - Vp}{Vm} \right| \right)$$

$$\text{Load difference} = \frac{1}{N} \Sigma \frac{Lm - Lp}{Lm}$$

where V is volume, P is peakflow, T is time to peak, L is the load, the subcripts m and p refer to measured and predicted quantities; N is the number of storms used for the calibration, Ni is the number of data for event i, mj and pj (j=1,..,Ni) are the measured and predicted flow values of the ith hydrograph and mi is the average flow of event i.

Our goal, during the calibration phase is to obtain maximum volume and peak errors of 10% of the measured values. In other words, the volume and peak differences have to be in an interval of -10 to +10 percent. There should not be more, on the average, than five minutes of delay or advance of the peaks. The weighted error has to be minimized but no bound has been fixed.

However, this goal is not always possible to satisfy. In such case the effort will focus on getting the same number of hydrographs with overpredicted volumes (peaks) and hydrographs with underpredicted volumes (peaks).

After the model has been executed, the expert system is looking at these different values in order to form a diagnosis or to conclude that the calibration is done.

5.2.3. The Expert System makes a Diagnosis

From the values of the criteria described earlier, ESCALOS can deduce if a parameter has to be changed. It uses for that purpose some production rules (IF-THEN rules). The reasoning strategy is a backward chaining strategy that determines if any parameter has to be increased or decreased. If nothing has to be changed then the conclusion is that the calibration is done. A typical rule used to calibrate a quantity parameter would be:

> If the peaks are too high or
> if the times to peak are too late,
> then
> the slope has to be decreased with strength (0.9)

A typical rule used to calibrate a quality parameter would be:

> If the storm loads are too big and
> buildup limit is defined and
> buildup load = buildup limit

then
buildup limit has to be increased (0.7)

The number in parenthesis specifies the belief we have in the conclusion of the rule when the antecedent is true. If the certainty in the antecedent is less than one, then the obtained certainty of the conclusion is the product of the antecedent certainty by the certainty factor of the rule. If several rules yield to the same conclusion, then the certainty in this conclusion is increased using some certainty propagation rules. These propagation rules are defined by the developer of the expert system or they are dependent on the expert system shell if one is used.

Certainty factors are used mostly in a effort to classify the different diagnoses presented to the user. The final conclusions, for example "slope has to be decreased", will be given with a certainty factor. If another diagnosis, for example "characteristic width has to be decreased", is given with a larger certainty factor, then it is more likely that a decrease of the characteristic width will give a better result than a decrease of the slope. On the basis of these conclusions along with the certainty factors, the user is then asked what he wants to change and control of the action passes to him.

5.2.4. The Expert System Assists in Doing Changes in the Parameter's Values

Once a diagnosis has been made and a decision has been reached on what to change, some new values have to be proposed that will improve the fit of the predicted hydrographs or the values of the predicted loads. By varying the values of several parameters, it has been found that the difference criteria are more sensitive to certain parameters than to others. Among the sensitive parameters are the impervious area percentage, the characteristic width and the slope, for the quantity simulation. Changes in these values have an impact even if the volumes and peaks are very poorly simulated. On the other hand, parameters such as depression storage, manning coefficients and infiltration parameters have an impact only when the simulation is almost correct.

Using data from "Ross Ade" watershed and "Highway 100" watershed we have developed curves that show the changes in the volumes of runoff or in the peak values as a function of the volume difference or peak difference when a parameter's value (impervious area, slope or characteristic width) is varied by 10 percent (Figures 5.1,5.2 and 5.3). These curves are used as heuristics to estimate the new values of the parameters to reach the fixed objectives. The resulting parameter value will probably not be the right one at the first iteration, but its estimation will be better than a completely arbitrary one.

The following example of the estimation of the impervious area shows how the curves are used. After the first execution of the simulation model, suppose that the volume difference criterion is -50 %. Reading on the curve of Figure 5.1, we see that a decrease of the impervious area by 10% will produce a decrease of the volumes by 15%. This allows us to calculate the new volume difference: -27.5%. This is not satisfactory, so a second iteration is necessary. A decrease of the impervious area by 10% will produce a decrease of the volumes by 30%. The new volume difference will be 9.25%. This value is less than 10% and therefore we do not need to iterate again and the new impervious area percentage will be decreased by 20%. At this point, the model is executed and the true value of the volume difference criterion is computed which might not be within the 10 percent range. Then more iterations are necessary or another parameter needs to be changed. In this example we did not take into account the upper and lower limits that the value of a parameter can take. If such a limit should be encountered, the process would stop for that parameter and its value fixed to the bound.

This method proved to give satisfactory results and is more efficient than an arbitrary increase or decrease of the value of the parameter by a defined amount. Unfortunately, we were not able to develop similar curves for the other parameters. The possibilities are then to increase or decrease the values by 10% or to use an optimization program that finds the optimal values for the two Manning coefficients, the depression storage and the infiltration parameters. The objective of this optimization is to minimize the weighed error. Good results have been obtained when the values of the weights a and b are fixed to 0.7 and 0.3, respectively. The program uses Nelder and Mead simplex method (1965). At the present stage, a maximum number of iterations for this program has been fixed to 50. The program stops if a minimum value has been found, or if all parameters reach their upper or

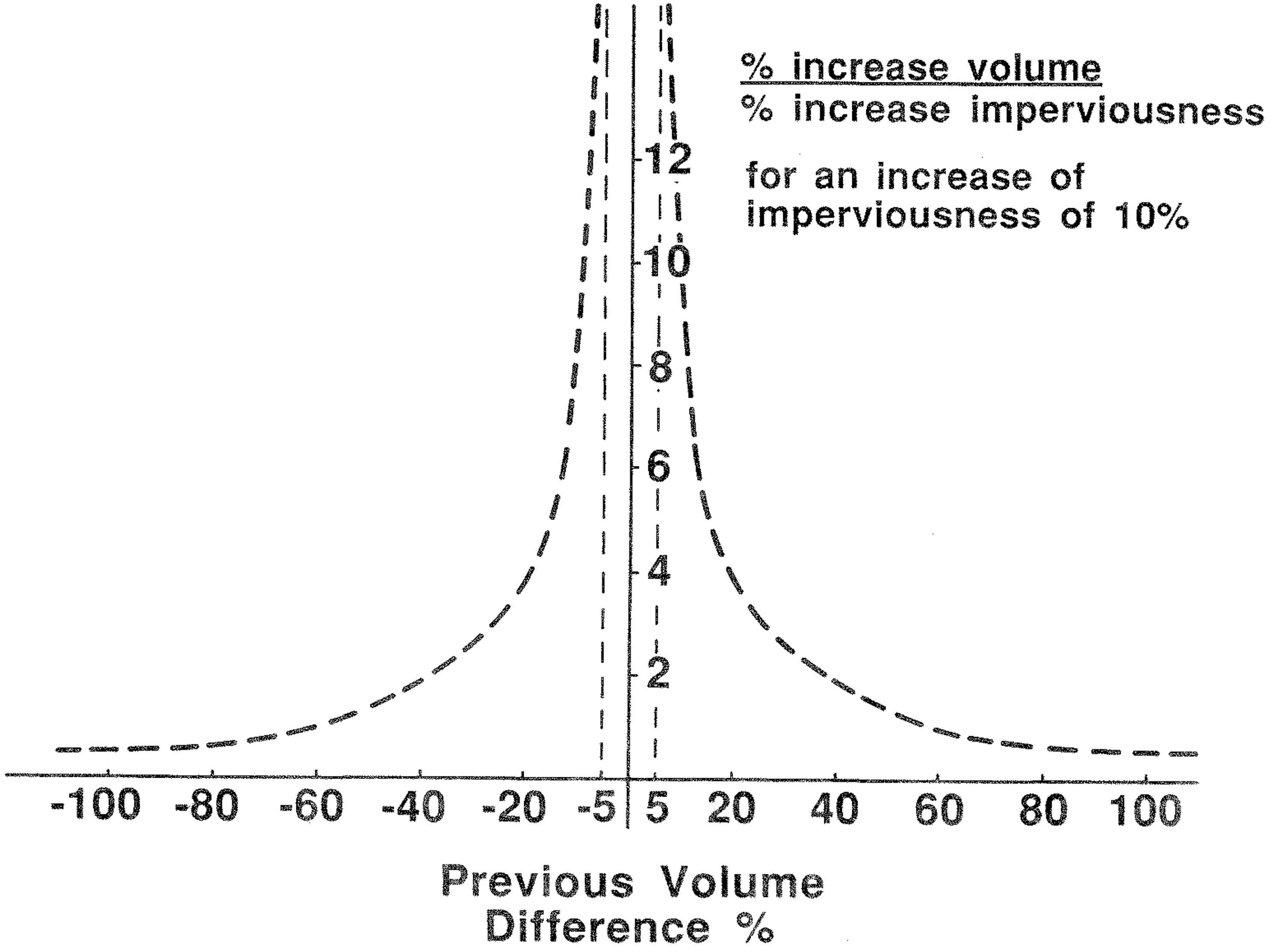


Figure 5.1 Change in the Volumes of Runoff as a Function of the Volume Difference Criterion when the Impervious Area Percentage is varied by ten percent.

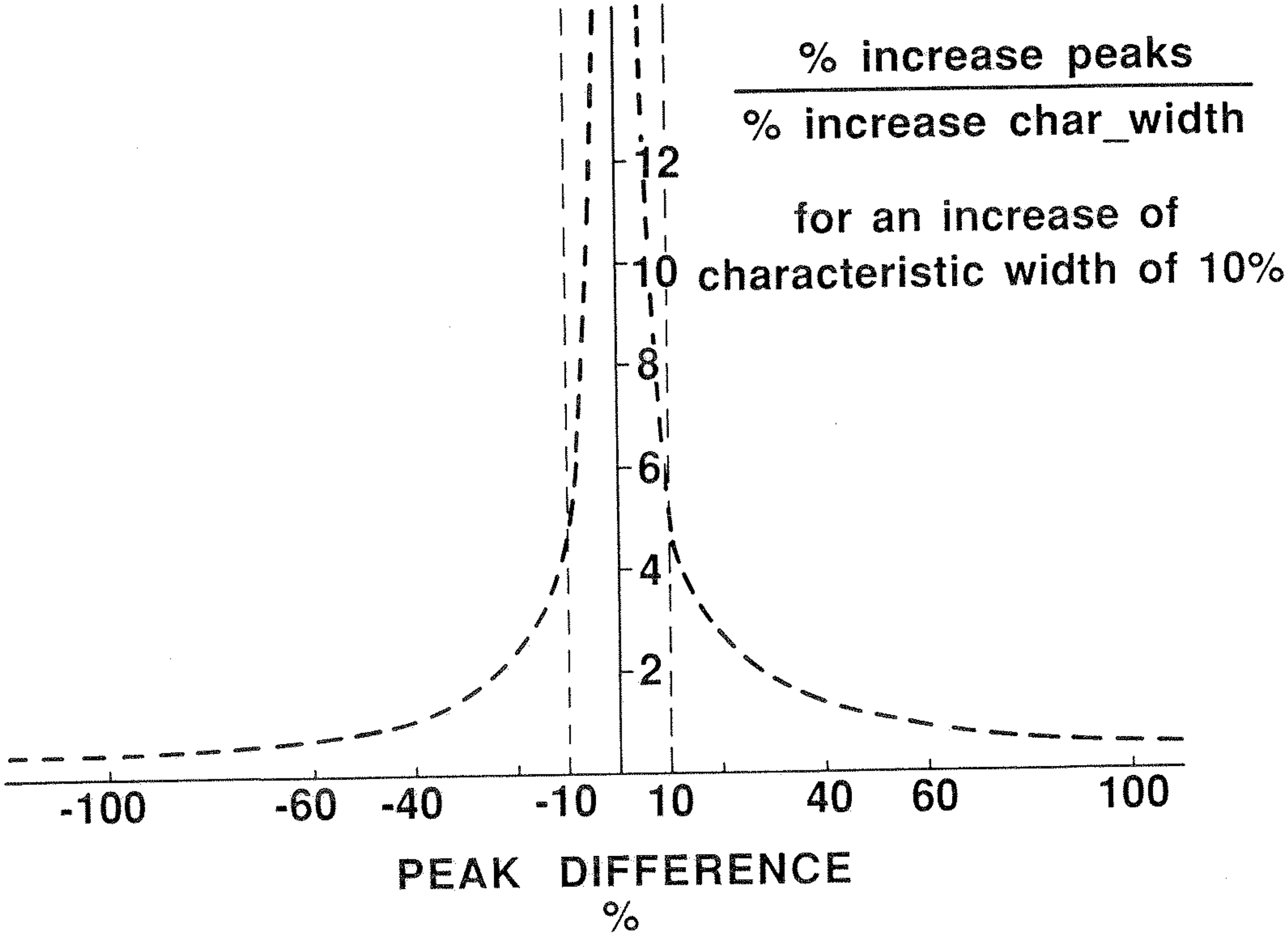


Figure 5.2 Change in the Flowrates Peaks as a Function of the Peak Difference Criterion when the Characteristic Width is varied by ten percent.

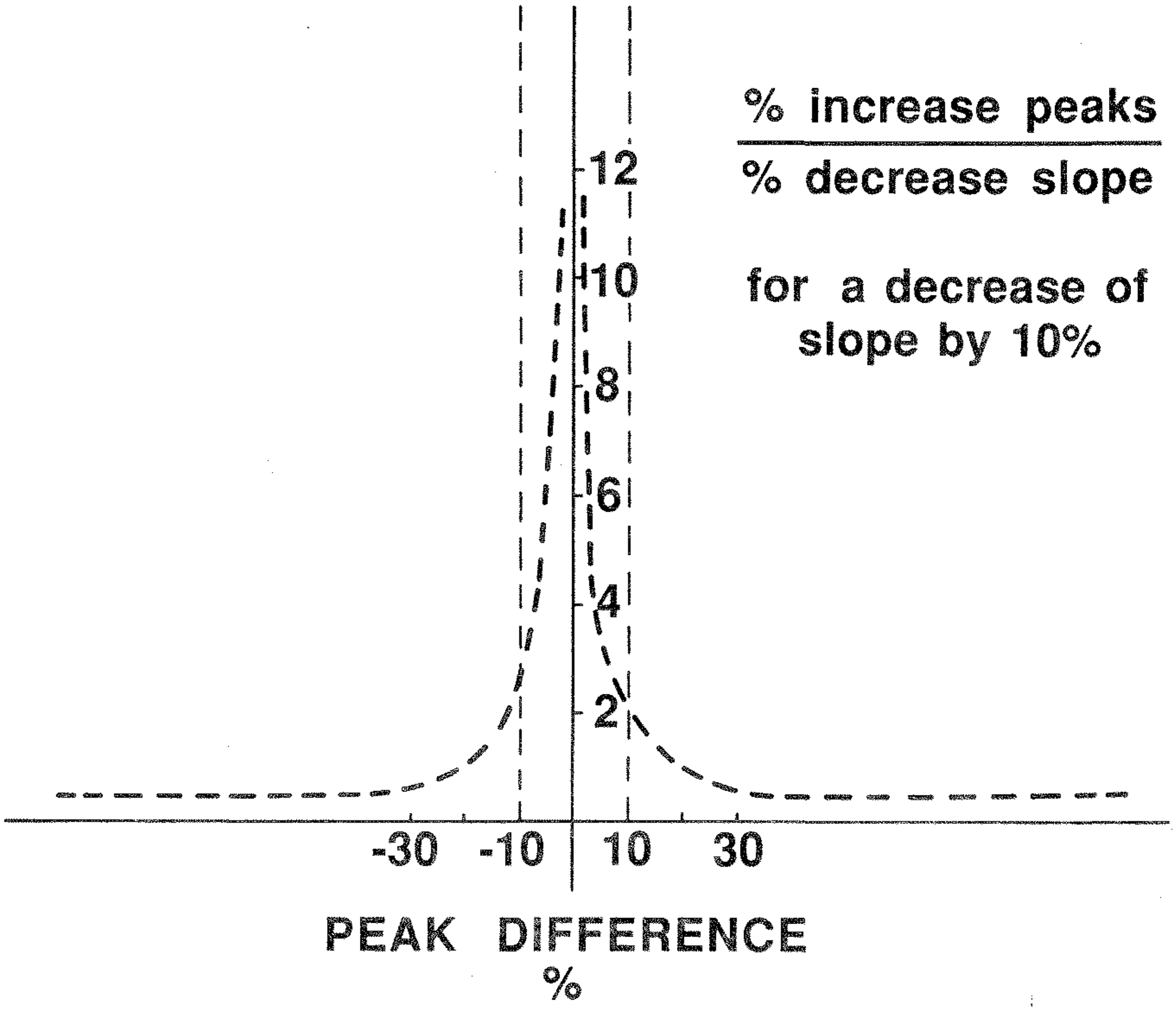


Figure 5.3 Change in the Flowrates Peaks as a Function of the Peak Difference Criterion when the Slope is varied by ten percent.

lower bounds, or if the number of iterations had been reached.

To estimate new values of the parameters used to simulate the runoff quality, the current method is to change their values by a fixed amount. This is very inefficient and we are in the process of defining some useful heuristics that will propose an increase or a decrease of the parameters in function of the load difference. The process would be accelerated.

5.2.5 Overview of the Rules Used in ESCALOLS

Two versions of this expert system were developed. An early version was developed using the coputer language Prolog. The inference engine was very similar to what is presented by Bratko in his book on Prolog (1986). Some code has been added in particular for the introduction of certainty factors and their propagation through the rules. A second version of ESCALOS was developed using a shell, namely KES. A comparison of these two methods to develop an expert system is given in the next chapter.

The first version included only the quantity calibration of the model and was limited with regard to the number of subcatchments that were possible to simulate. The second version is complete (quantity and quality) and the limitations in number of subcatchments, pipes, pollutants or land-uses are due to the limitations of the model SWMM. The only limitation of the present version is that it does not take into account any parameter used for the simulation of the erosion of soils.

A review of the different groups of rules is given in the following paragraphs. These are given as they are written in the latest version. The expression of these rules in the Prolog version does not differ very much, except maybe the name of the variables. A complete listing of the source code is available in Appendix B for the quantity calibration and Appendix D for the quality calibration. A more visual presentation of the rules used for the quantity calibration is presented in Appendix A through the attribute hierarchy.

5.2.5.1 Quantity Calibration.

The first group combines the rules that interpret the values of the criteria and express their meaning.

For example:

rule4: if
p gt 10 then peaks - peaks_are_too_low <1.00>.

should be read in English as "if the peak difference criterion is greater than 10, it means that the peaks are too low". These rules are basically used for explanation purposes. Another one would be :

rule7: if
prob1 lt 0.9 then icertainty - impervious_area_percentage_is_uncertain <1.00>

that should be read in English as "if the certainty of the impervious area percentage is less than 0.9 then the value of this parameter is uncertain. This group includes a total of seventeen rules.

The second group of rules includes the rules that infer if the value of a parameter has to be changed. This group can be divided in turn into two smaller groups: one including rules that use the different criteria, the other including rules that use the number of storms with over- or underpredicted volumes or peaks.

For example, a rule that uses the criteria is:

rule3: if
scertainty - slope_is_uncertain and peaks - peaks_occur_soon or peaks - peaks_are_too_high
then
action - slope_has_to_be_decreased <0.9>.

It should be read in English as "if the value of the slope is uncertain and if the peaks occur too soon or they are too high, then the value of the slope has to be decreased". This group includes twelve rules.

A rule that uses the number of storms is:

rule33: if numv - noswov_lt noswuv then action - impervious_area_has_to_be_increased <0.9>.

It should be read in English as "if the number of storms with overpredicted volumes is larger than the number of storms with underpredicted volumes, then the value of the impervious area percentage has to be increased". This group includes six rules.

The last group of rules concerning the quantity calibration consists of the rules that determine when the calibration of done. This group includes three rules. For example :

rule32: if

volumes - volumes_simulation_is_obtained and peaks - peaks_simulation_is_obtained and
then
action = calibration is done <1.00>.

or
rule 38: if

volumes = volumes _simulation_is_obtained and peaks = peaks_simulation_is_obtained
then
action = calibration is done <0.7>.

The estimation of the new values of the parameters that the user chose to change (counseled by the expert system) is not made using rules. The heuristic is rather included in a Fortran program that was more suitable for number manipulation and arithmetic calculation

5.2.5.2 Quality Calibration.

A first group includes rules that assign values to some parameters that are necessary in the SWMM data files when their value can be inferred from the previous answers of the user. This avoids some unnecessary questions. For example we have:

```
P:pollutant
if
  P>buildup_meth = fract dust and dirt buildup
then
  P>bmeth_code = 0.
```

which means that if the pollutant buildup method to be used is to compute the buildup as a fraction of the dust and dirt accumulation then the code to put in the data file is 0. This group includes 19 rules.

The second group, as in the case of the quantity calibration, is the interpretation of the criteria for the purpose of explanation. For example:

```
Calibration rule1:
P:pollutant
if
  P>load_diff ge 0.25
then
  P>swmm_action = storm loads are too small <1.0>.
```

which means that if the load difference criterion of a pollutant is larger than 25 percent then the storm load for that pollutant is too small. This group actually includes only two rules, one to explain when loads are too small, the second to explain when they are too big. We could include also two other rules that determine if the buildup load is too small or too big.

```
Calibration rule5
P:pollutant
if
  P>swmm_action = storm loads are too small and
```

```
    status (P>buil_lim) = unknown or
    P>buil_load le (0.9 * P>build_lim)
  then
    P>swmm_action1 = buildup load has to be increased <0.85>.
```

which should be read as "if the storm loads for the pollutant P are too small and if the buildup limit of this pollutant is unknown or larger than its buildup load then this buildup load has to be increased".

The third group concerns the rules that infer what specific parameter has to be changed. These rules take into account the method chosen for the buildup method or washoff method and what has been inferred in the rules previously described. For example:

```
User action rule8:
P:pollutant
if
  P>swmm_action1 = buildup load has to be increased and
  P>buildup_meth = Michaelis Menton and
  P>build_coeff ge 1.0
then
  P>user_action = buildup coefficient has to be decreased <0.8>.
```

which should be read as "For pollutant P, if its buildup load has to be increased and the buildup method is Michaelis Menton and the buildup coefficient is larger than 1 then the buildup coefficient has to be decreased. This group includes fifteen rules. Included in this group is the rule that determines if the calibration is done when the load difference criterion value is within the 25 percent range. At this stage there is only one rule to do this task since the graphical capabilities have not been completely included. This rule is expressed as follows:

```
User Action rule1:
P:pollutant
if
  P>load_diff le 0.25 and
```

```
  P>load_diff ge -0.25
then
  P>user_action = calibration is done .
```

Finally the last group for the quality calibration includes rules that will determine the change in the values of the parameters that the user chose to change following the counsels given by ESCALOS. For a parameter such as the buildup exponent for pollutant P to be arbitrary increased by 10 percent we have for example:

```
rule2 to adjust buildup exponent:
P:pollutant
if
  P>user_action = buildup exponent has to be increased
then
  P>new_bexp = P>build_exp + (0.1 * P>build_exp).
```

which means that "if the action is to increase the buildup exponent then its new value is the current value increased by ten percent". We are currently working on improving these rules in order to have useful heuristics to estimate the new value of a parameter.

5.3 Results Obtained with the Expert System.

The expert system has been tested on the three watersheds described previously. Results for the "Ross Ade Watershed" in Lafayette are shown in the following figures. Nine events were chosen for the calibration of the model for that watershed. Among them, six were arbitrary chosen for the calibration proper, three of them were left for the verification. These graphs show the comparison of the hydrographs predicted with the model when the calibration is done with the help of the expert system and without it. The measured hydrograph is also plotted on each of these graph. Figures 5.4 to 5.9 show the results for the storm events that have been used for calibration. Figures 5.10 to 5.12 show the results for the storm events that have been used for the verification of the model. For the storms used for calibration, the values of the volume difference criteria and peak difference criteria are less than 10 percent, respectively 3.75 and 5 percent. The weighted error value is 12.75. Only the time difference criteria is not satisfied : its value is 47 percent. Looking at the plots we observe that this is due to the second event, the storm of 7/31/83. This event shows two peaks, the principal one being the second one. The predicted principal peak is the first one, therefore it creates a time difference of almost three hours although each of the two time to peak are correctly simulated. For all the other storm events used during the calibration the times to peak are simulated with an error less than 10 minutes. In the following case one of the criteria is not satisfied because of a small error in the predictions of the peaks (Figure 5.5). Once plots are done it is possible to find the cause of the high value of the time difference and to conclude that the goodness of fit doesn't suffer very much from this. The confidence of the calibration, that was only 0.7 due to the non-satisfaction of the time difference criteria, can therefore be increased to a value close to 1.0. It is planned to improve the knowledge base once graphics capabilities are completely implemented within the expert system so that similar cases can be handled directly by the expert system.

The goodness of fit is not as satisfying for the storm events used for the verification of the model. However, except for the storm of 8/16/83 where the results are better when using the expert system, there is not very much difference when using the expert system or not. Also the storm of 4/06/83 is a event of very small magnitude and it is possible that the watershed reacts differently for small and large events.

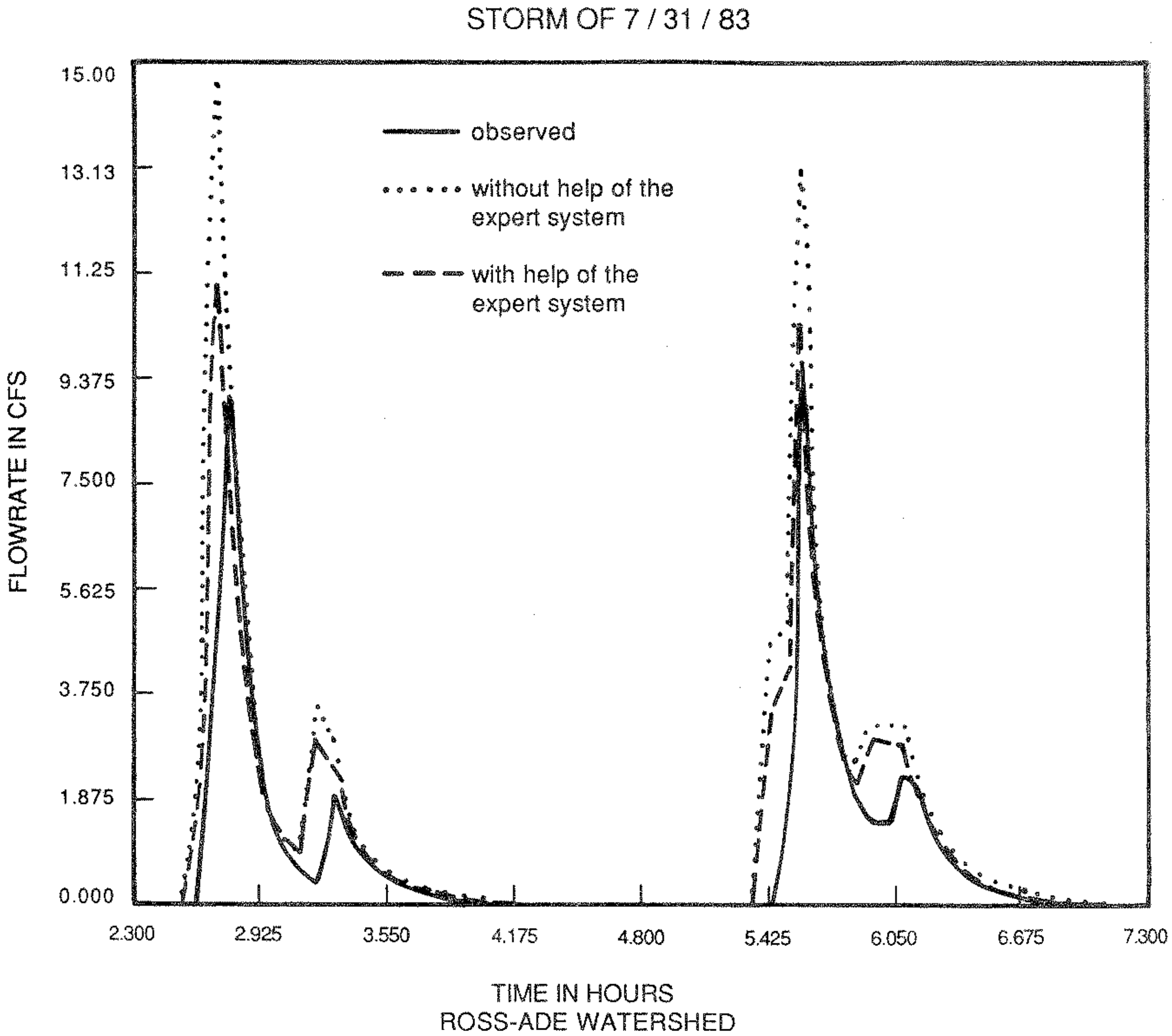


Figure 5.4 Comparison of the hydrographs for the storm of May 13, 1983.

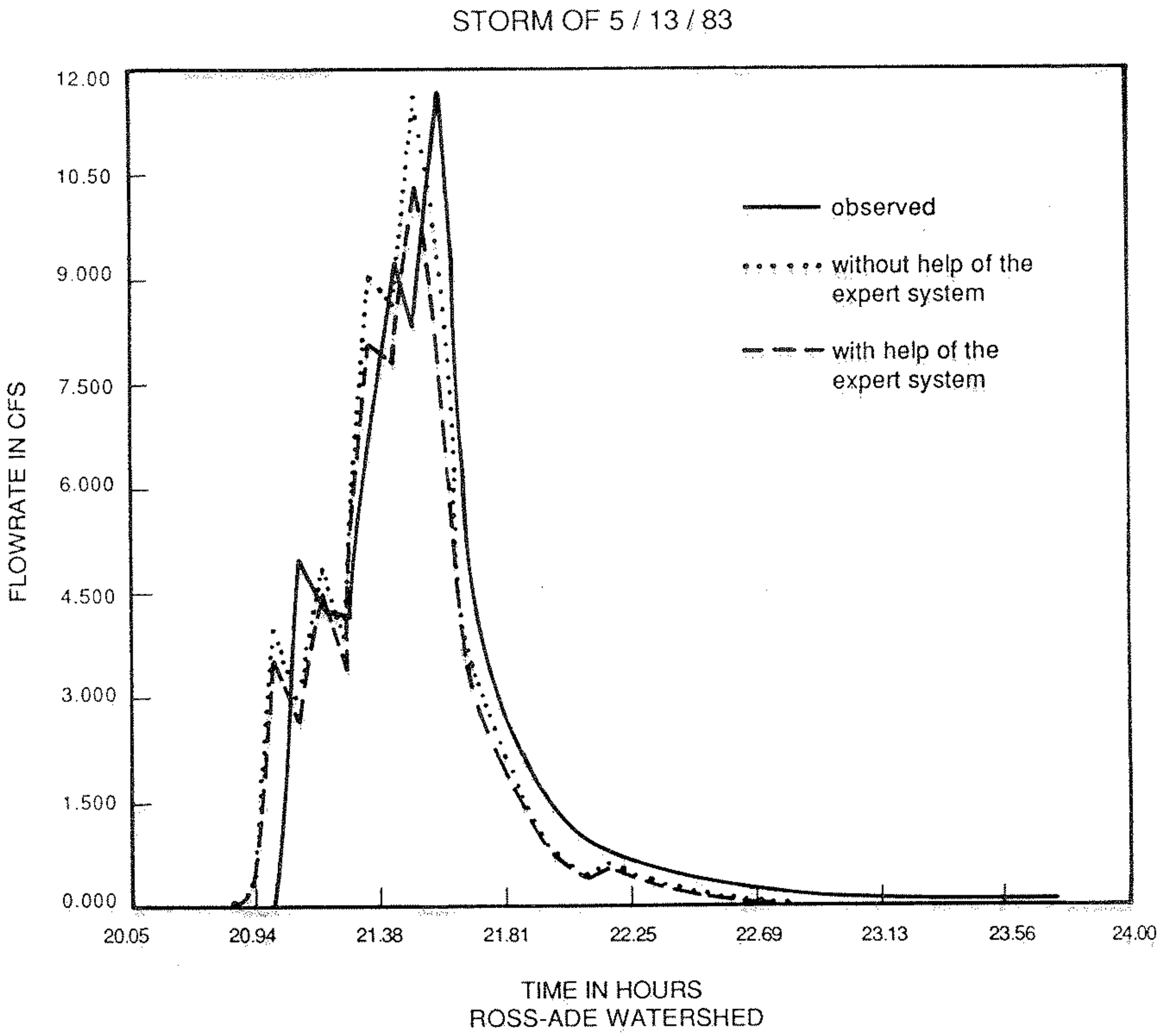


Figure 5.5 Comparison of the hydrographs for the storm of July 7, 1983

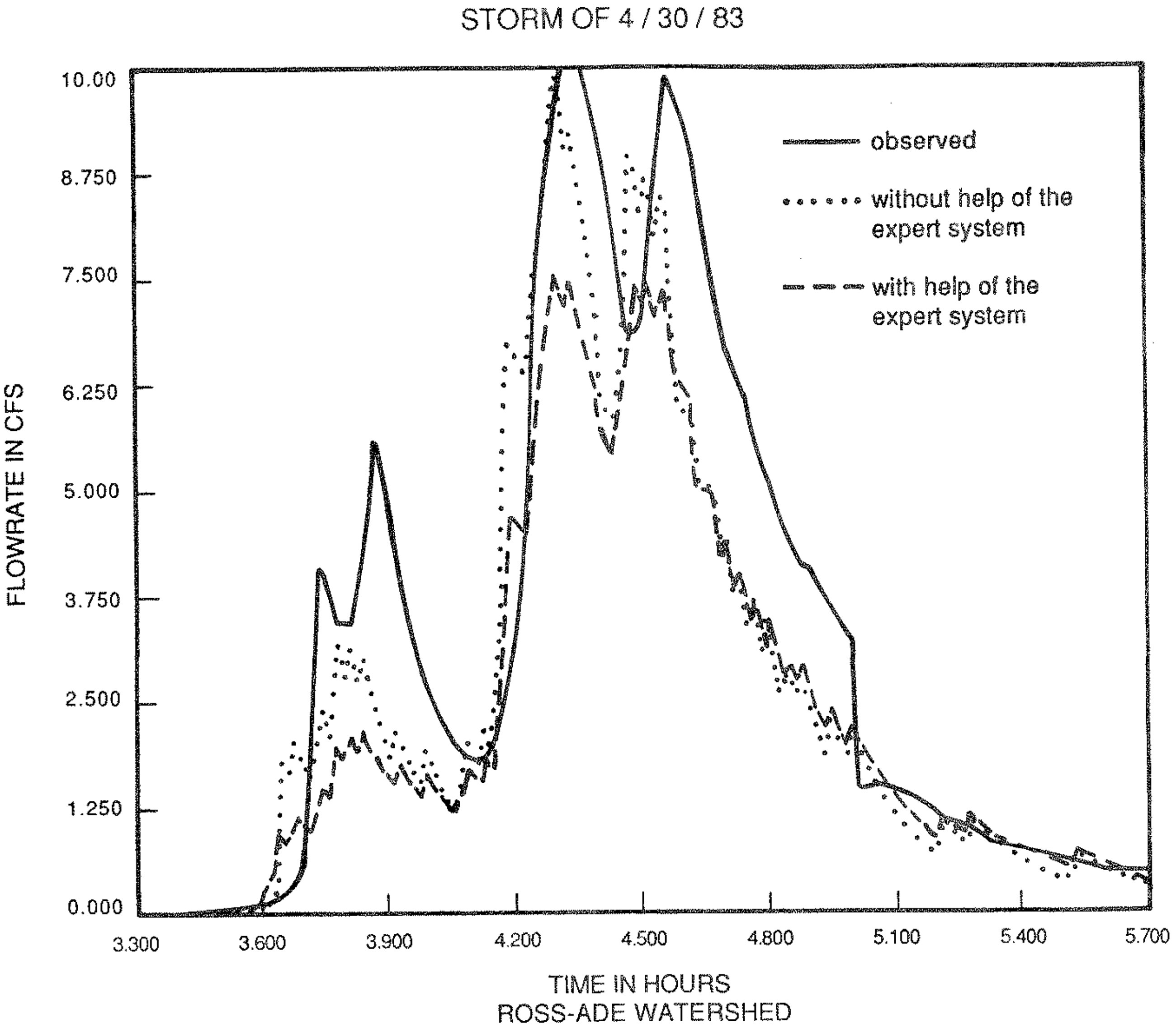


Figure 5.6 Comparison of the hydrographs for the storm of April 30, 1983

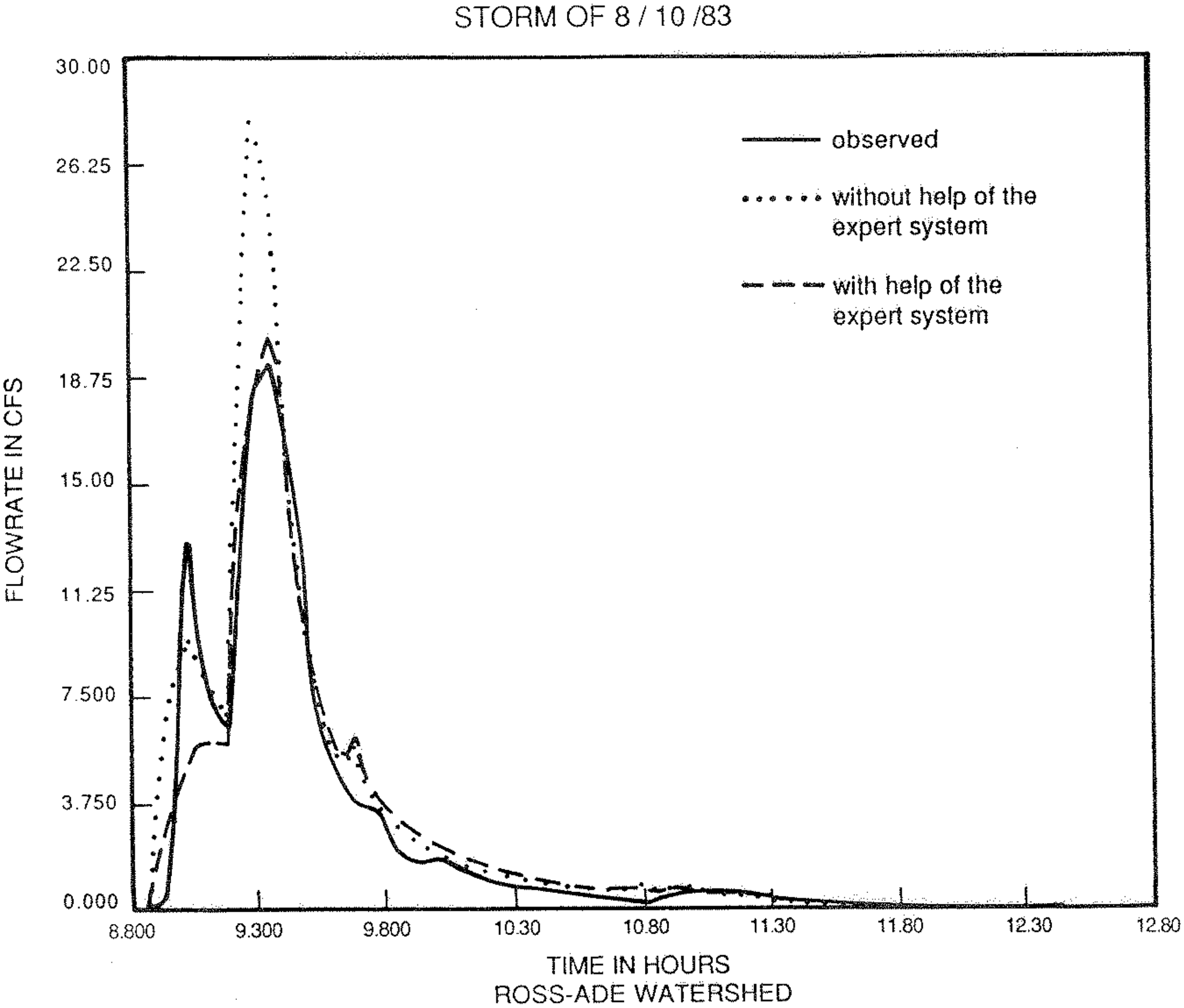


Figure 5.7 Comparison of the hydrographs for the storm of August 10, 1983

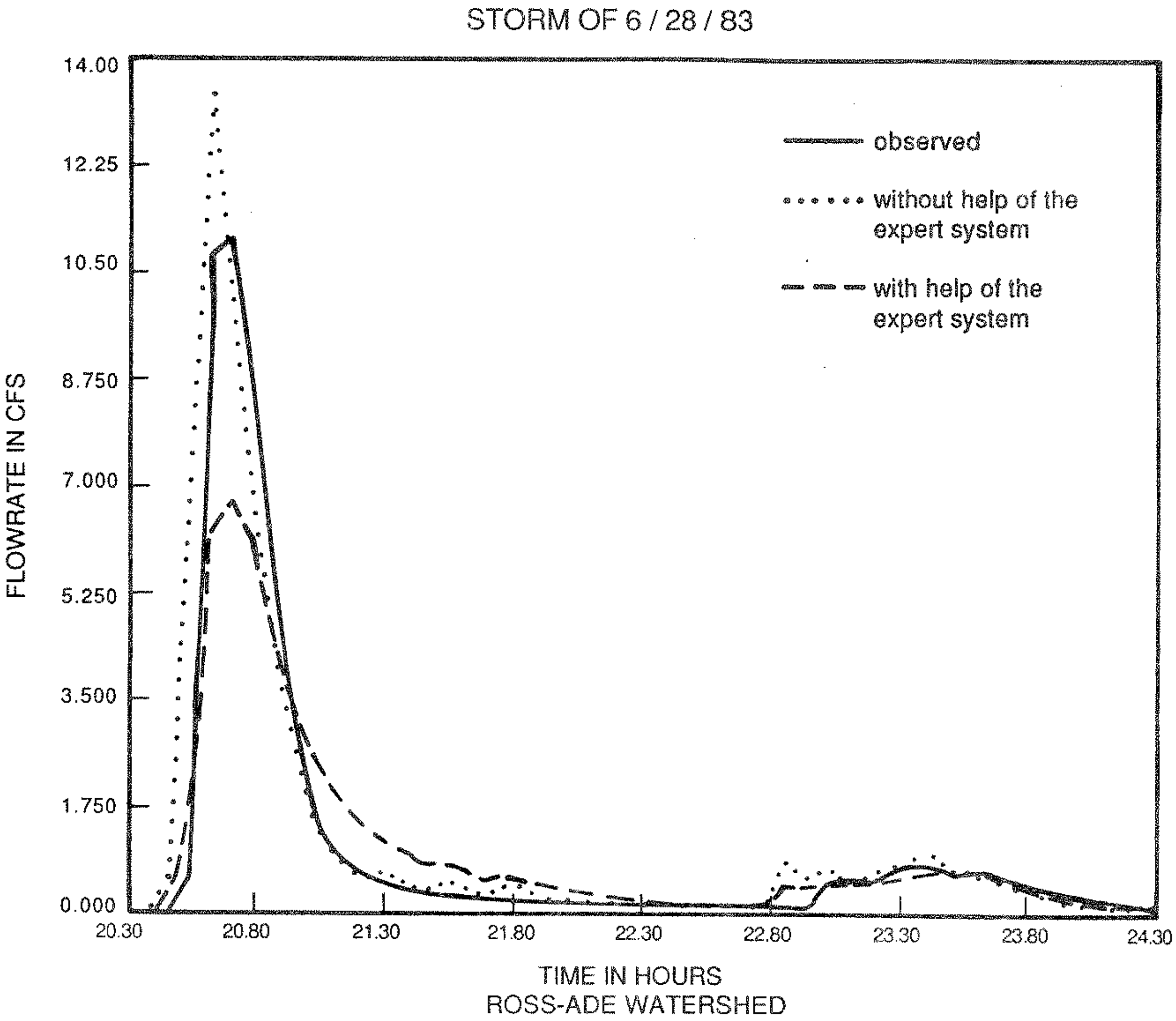


Figure 5.8 Comparison of the hydrographs for the storm of June 28, 1983

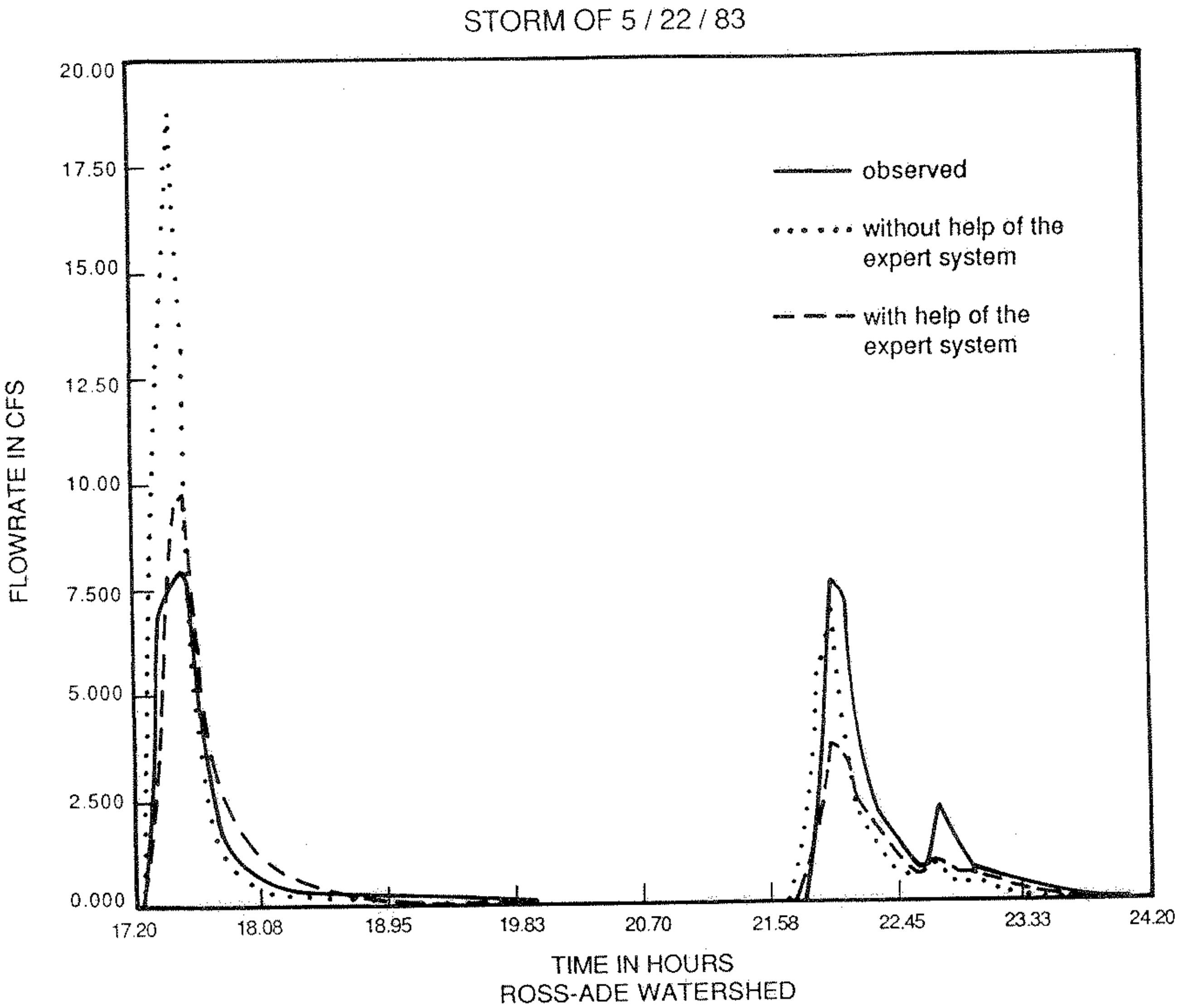


Figure 5.9 Comparison of the hydrographs for the storm of May 22, 1983

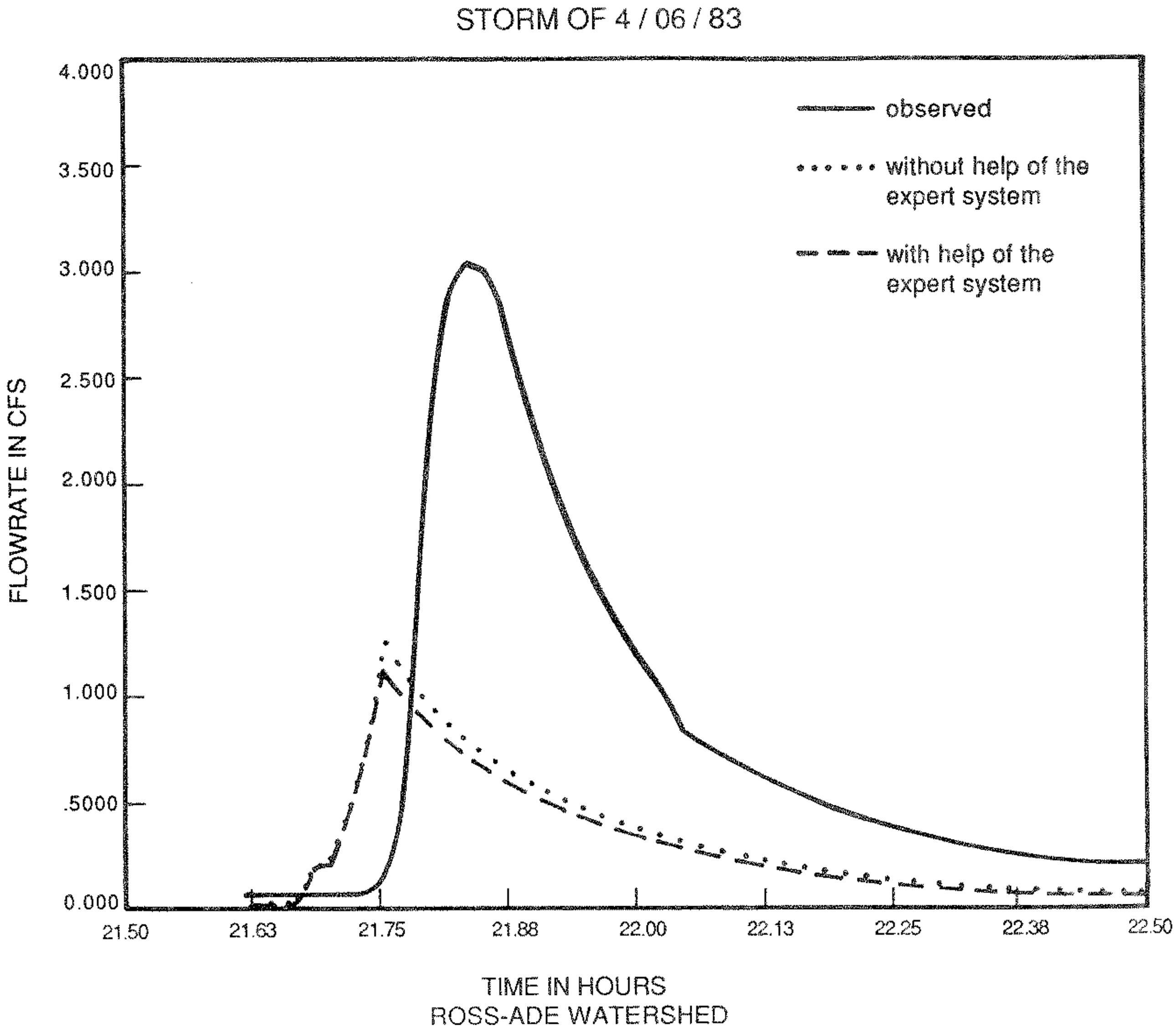


Figure 5.10 Comparison of the hydrographs for the storm of April 6, 1983

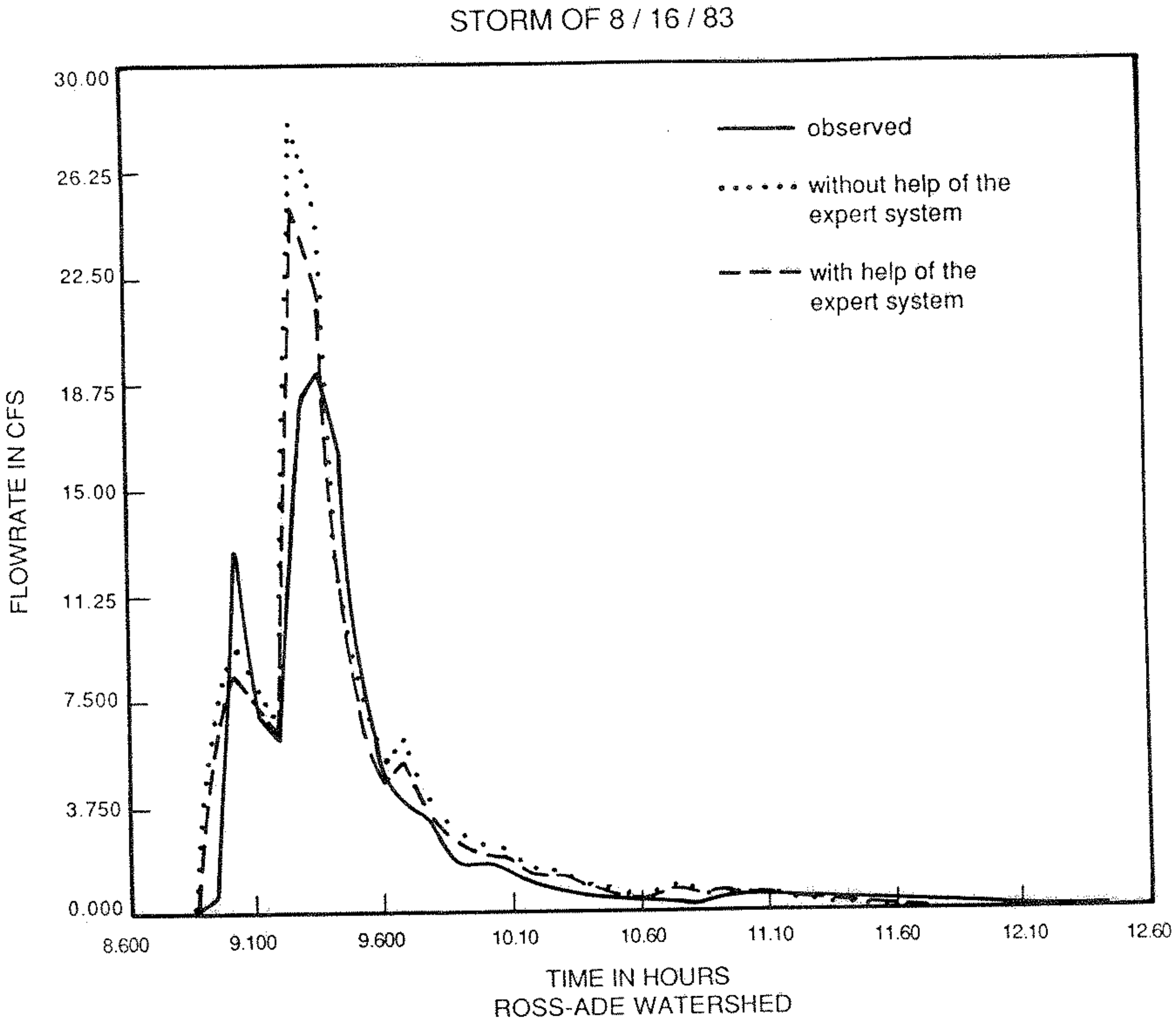


Figure 5.11 Comparison of the hydrographs for the storm of August 16, 1983

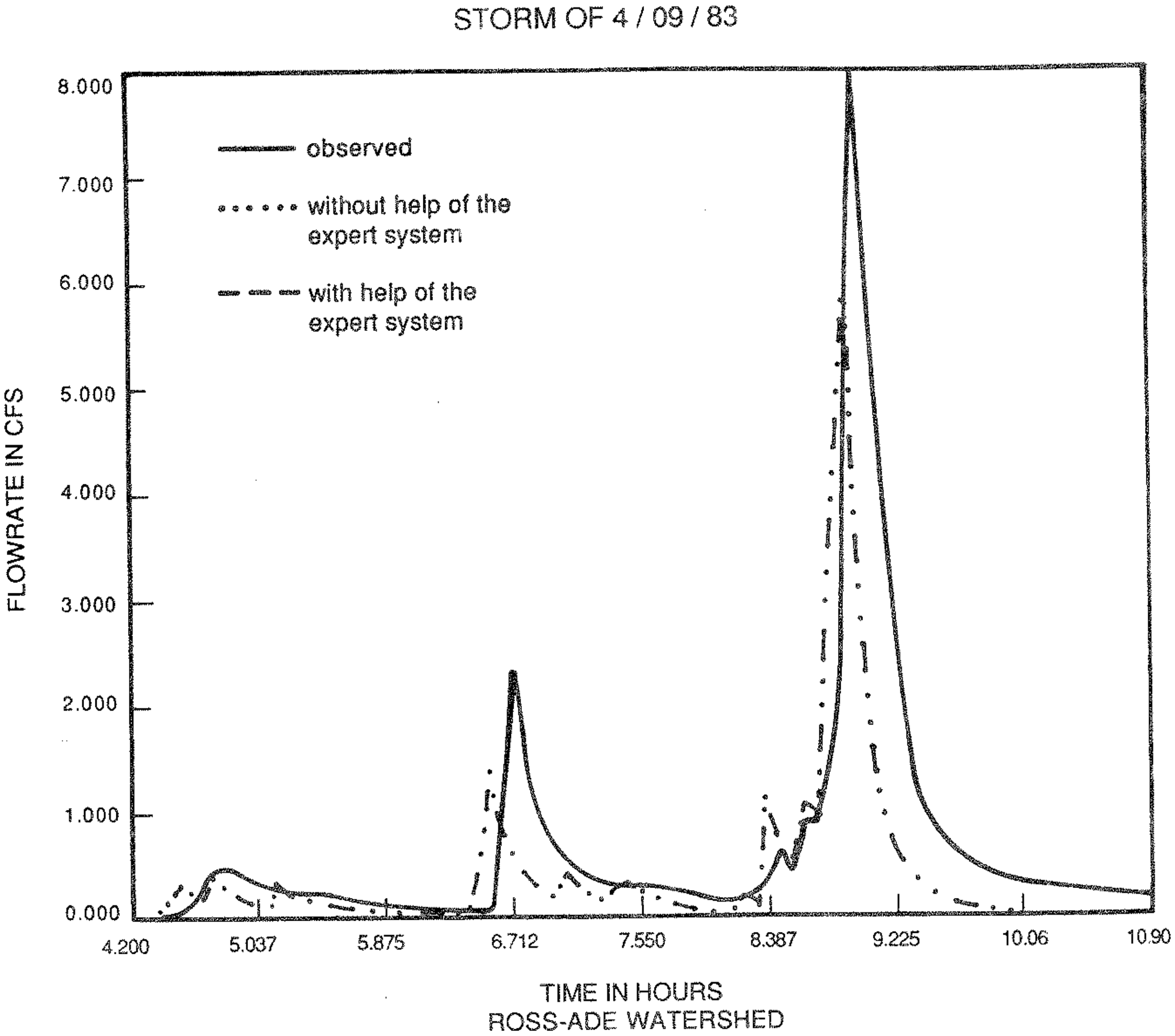


Figure 5.12 Comparison of the hydrographs for the storm of April 9, 1983

Results from the two other watersheds show that when the calibration is done with the help of the expert system, the goodness is generally better. This could be surprising since the methodology followed by the expert system is very similar to what would be done by a person. However the fact that the expert system does not get bored or tired might explain this phenomenon. The expert system is very methodical and will always propose to change the value of the parameter that is the most sensitive even if this parameter was changed during the previous iteration. On the contrary, a person easily gets bored and is tempted to change the value of any parameter with less methodology than the machine.

CHAPTER VI

USING AN EXPERT SYSTEM SHELL FOR THE ESCALOS PROTOTYPE

6.1 Introduction

The professional engineering community has experienced rapid growth in the development and use of two powerful decision-support technologies: *simulation* and *intelligent* or *expert systems*. To date, however, relatively little has been done to integrate these modeling methodologies though it has been argued that major benefits might result from so doing. Moser (1986) points out that while simulation has enjoyed a great deal of popularity among management scientists and operations researchers, the problems of model calibration and interpretation of model results may preclude their use in practice. To the extent that these problems result from inexperience on the part of the user, the integration of knowledge-based systems may reduce the barriers to model use.

Similarly, while there have been major advances in expert systems technologies during the recent past, these systems have not been widely integrated into operational decision settings. Successful applications have been limited to time-neutral systems with fixed variables such as with diagnostic systems and when reasoning by analogy or common sense is not important. Again, the integration of modern simulation techniques into knowledge-based systems might reduce these limitations and improve the likelihood that these models might be used in areas where decisions must be made about dynamic systems.

The similarity between simulation and expert systems methods is their "descriptive" perspective; the important characteristics of the system being studied are incorporated into a modular representation with the adhesive being some type of inference mechanism. System representation within expert systems include networks, frames and rules, and, within simulation, events, activities, process interaction, and differential equations. Inferencing within expert systems includes forward and backward chaining, Bayesian techniques, set-covering inferencing and fuzzy logic (or an ever increasing number of other methods). While inferencing in simulation takes the form of such algorithms as next-event time scheduling or equation solving time-slicing methods.

O'Keefe (1986) argues that the most important benefits from the integration of simulation and expert systems technologies will result not from our ability to develop better or more powerful models but rather from the incorporation of intelligent "front ends" to already powerful simulation systems. The result will be a transfer of technology to inexperienced users so that they might more efficiently integrate these analytical tools into the decision-making schema.

O'keefe presents a taxonomy for the integration of simulation and expert systems ranging from *embedding* (a structure where either the simulation system is included in the architecture of the expert system or vice versa) to the use of an expert system as a *front end* to the simulation (a structure where the expert system resides "between" the user and the simulation model to handle dialogue and aid the inexperienced user in model execution).

The present research focuses on the integration of a knowledge-based "front-end" with a traditional and well known simulation model; the Storm Watershed Management Model (SWMM). After presenting some background on the state of modern expert system development technology, this chapter presents the details of a prototype expert system for the calibration of a portion of SWMM. For a more thorough and complete introduction to expert systems and the development of knowledge-based systems, the interested reader is referred to Wos, et al.,(1984), Feigenbaum (1979), Fox (1984), Hayes-Roth (1984), Harmon and King (1985), Waterman (1986), and Brachman, et al.(1983).

6.2 Expert System Development Technologies

The emergence of expert systems shells has resulted from the need for software tools that can be used for rapid system development. Shells are particularly useful when the system development must be done by non-programmers or engineers unfamiliar with traditional expert systems development in languages such as LISP and PROLOG.

A shell is a software module designed to promote the development of knowledge-based systems much the same as spreadsheets promote rapid development of accounting and business decision-support systems. Shells can be very narrow, application oriented tools or broader more general-purpose tools. Because of the wide range of expert systems shells presently available, it is important that the proper development tool be selected for any given application. In this section, we discuss some of the features to be found in the more popular shells.

The oldest shell systems grew out of the programming language LISP. While LISP has proven to be a very flexible tool for system development in the hands of expert programmers, it is difficult to use. Intolerably low levels of machine performance are frequent with systems developed by less-than-expert programmers. Higher level language type tools (frequently distinguished from high-level languages by being called "environments") such as OPS-5 have evolved in response to these problems.

Apart from the scope of the application, proper shell selection depends on the experience of the knowledge engineer and the target end user. Some shells provide a wide variety of support features useful at system development time, while others stress end-user support in the form of "user-friendly" interaction and on-line guidance. Frequently, extremes in either of these areas come at the expense of performance and/or flexibility in the other.

With most shells, a distinction is made between "development-time" and "run-time". Development-time involves the design and construction of the knowledge base and inference engine by the knowledge engineer working closely with the individual possessing the domain knowledge. The result of this process is a program module containing the knowledge and inference structures for the system. This is the system that is subsequently made available to the user. At "run-time" the user executes the expert system module and interacts with the system in a real-time mode.

Among the most useful development-time expert system shell utilities are the following:

- *Trace facilities:* A command line option at "compile time" that invokes a listing of important system operations including a list of rules as they fire and executable modules as they are invoked.

- *Break package:* A program command that causes a "stop point" within the executing module where the user can elect to issue run-time commands for diagnostic purposes or redirect exection.

- *Run-time knowledge acquisition:* The ability to input knowledge structures by the user at the keyboard in response to system prompts or by specifying the appropriate file during execution.

- *Operating system accessibility:* The ability to make calls to the operating system from within the shell either in a pre-programmed fashion, or from the keyboard during execution.

- *Syntax checking:* An editing environment that is part of the shell that is able to interpret program statements immediately and check for correct spelling and format.

- *Explanation expansion:* The ability to include information that allows the end user to get more elaborate explanations of system prompts or question facilities.

- *How and why explanation:* Allows the user to question the inference engine as to the rationale for specific actions and to see which rules apply to a given request for information.

- *Display format utilities:* Mechanisms for the design and implementation of more appropriate user interfaces including menu construction and graphical display of intermediate and/or final results.

- *Cases saved:* Allows the designer to save and use well-known cases until the system can solve them correctly.

- *Hooks to databases:* Procedures that make it possible to access information from other databases directly by using communication files or system calls.

- *Hooks to other languages:* Allows the designer to make calls to other language modules during execution of the expert system. In some cases this includes libraries that allow embedding of one system into another.

The expert system shell environment selected for this application contains many of these features that will be discussed in detail in the following section of this report.

6.3 Rules-Based SWMM Calibration

6.3.1 The KES Expert System Development Package

Prior to the development of an expert system, the knowledge engineer must decide what construction method will be used to build the system. A traditional high level programming language such as Lisp, Prolog, Pascal, Fortran, etc. is one option while a tool known as an expert system shell can also be used. A shell is a program which assists in the creation of an expert system. It provides the operational inference engine and control mechanism necessary for most systems. When a shell is utilized, the programmer need only be concerned with building the rules and knowledge attributes necessary for the particular application, and not the details of the operating system and inferencing procedure.

The ESCALOS system discussed subsequently is based on the KES (Knowledge Engineering System) shell developed by Software Architecture & Engineering, Inc. (1986). A special "port" of this software to a Gould PN 9080 multiuser computer was conducted specifically for this research after thoughtful evaluation of several commercial expert systems development environments.

KES has three separate inference engines that can be utilized. They are the following: Production Subsystem (KES PS), Hypothesize and Test (HT), and KES BAYES. An inference engine is the mechanism by which an expert system simulates domain knowledge. As an example of inferencing, consider the existence of attributes named cloudy and clear which can take on a value of either true or false. Also, suppose that a rule of the form "if cloudy = true then clear = false" exists. Now, once the value of cloudy is established, KES can use inferencing to obtain the value of clear.

In KES PS, production rules are used to represent the domain knowledge. A production rule consists of the logical if antecedent, then consequent rule. The antecedent is a statement that can be determined to be true or false. The consequent contains one or more commands which will instantiate the value of one or more knowledge attributes. KES PS is most useful in situations where certain outcomes follow directly from certain inputs, i.e., deductive reasoning.

The KES HT inference engine begins with the formulation of a set of hypotheses based on a list of manifestations, it then proceeds in verifying each hypothesis. HT strives to discern the hypothesis with the smallest number of disorders that explain all manifestations. This procedure is termed minimal set covering. HT is most useful in diagnostic systems.

For situations in which there is a large body of preexisting data that is expressed as probabilities, the KES BAYES inference engine is superior. The inference engine is designed to perform statistical pattern classification based on BAYES THEOREM. The pre-existing knowledge is referenced in the interpretation of new data and a diagnostic is performed based on statistical or probabilistic events.

The inference engine selected for the current application was the KES PS system. The particular domain or expert knowledge seemed best suited to this type of inferencing. The knowledge base format required for this inference engine is discussed subsequently.

The KES knowledge base contains up to nine sections. Each section serves to represent or manipulate domain knowledge in some way unique to the section. It is not necessary that all sections be utilized. However, they must appear in the knowledge base sequentially in the following order: constants, text, patterns, types, attributes, classes, externals, rules, actions.

Because attributes are referred to in the discussion of several KES sections, we discuss the attributes section first. Attributes are declared in the attributes section of the knowledge base. An attribute is a string that represents knowledge. It can be factual or representative. Attributes are instantiated during the course of a KES session. When an 'obtain' command is executed, there are two methods by which instantiation occurs, input and inferencing. An input attribute value is obtained from the response by a user to a system query, external files or an embedded interface. An inferred attribute value is obtained when rules containing the inferred attribute in the consequent are fired (invoked). All attributes have the value 'unknown' at the beginning of a KES session. If a particular attribute is not instantiated, it will retain this value.

In the constants section, a name is given to a phrase or string of characters that will appear frequently in the end user KES session. Once declared in the constants section, the name can be used throughout the knowledge base in place of the cumbersome sequence of characters represented by the name.

The text section contains textual attachments that are associated with the knowledge base as a whole. Textual attachments are designed to furnish information that the end user can access if desired. The user can at any time ask for available textual attachments associated with the knowledge base and then specify that which he would like to see. Instructions for use of the knowledge base, information as to source of domain knowledge, and references are examples of textual attachments. Textual attachments can also be associated with other entities defined in the knowledge base such as rules, attributes, and attribute values.

The patterns section contains string formats known as patterns. These patterns serve as templates to which end user inputs can be matched. The system can be instructed to perform certain operations if the given pattern is matched. In addition, certain portions of the pattern can be extracted when matching occurs. The pattern section is especially useful in dealing with large databases with repetitive formats, such as name, address, telephone no.

The types section is where the type of an attribute is declared. There are six predefined types that do not have to be declared: string, integer, real, truth, single, and multiple. However, if there exists many similar attributes of a type different to those specified above, it may be desirable to define an additional type in the types section. Color is an example of a attribute type that can be declared.

The classes section is the location at which classes or groups of objects having the same set of characteristics are declared. Class members all have a set of associated attributes. However, these attributes usually take on a separate value for each member of a class.

The externals section is used when it is desirable for the expert system to communicate with and execute programs outside of the KES system. Externals, declared in the externals section, can be used to both send and retrieve information.

Any UNIX command can be issued via an external. Thus, an executable file from various programming languages can be activated from within KES.

The rules section contains the production rules which allow knowledge to be represented in a logical, conditional format. Conjunctions and disjunctions can be included in the rules to cut down on the number of rules necessary to adequately represent a given piece of knowledge. Rules will be fired (used) when it is necessary for the value of a given attribute to be ascertained. If the system cannot instantiate an attribute through inferencing, the end user will be prompted for the value.

The last section in any KES knowledge base by necessity is the actions section. The actions section controls the execution of a KES session. Commands within the actions section are similar to those in more traditional programming languages. They are used to garner information from the user and display information to the user. In addition, the actions section will perform looping in which different execution occurs with respect to the evaluation of a condition. The actions section also controls inferencing.

This discussion attempted to provide a general overview of the major prototyping features of the KES development tool. Following a similar overview of the SWMM simulation model, detailed listings of the source code and scripts of terminal sessions from the present KES-based application will be presented. For a more thorough discussion of KES, the interested reader is referred to the KES documentation (Software A&E, 1986).

6.3.2 The Storm Watershed Management Model (SWMM) Executable

The concepts and capabilities discussed in the previous section will be demonstrated using the example of a shell-based system developed to aid engineers in the calibration of a well known, and difficult to use deterministic simulation model. Originally written in the programming language PROLOG, this system was designed to help the users of the Storm Watershed Management Model (SWMM) through the long and complicated calibration process.

SWMM is a widely used and accepted deterministic model designed to simulate real storm events in an urban area. The simulation is based on rainfall inputs and the characterization of catchment properties, conveyance (sewer) systems and storage/treatment/receiving water systems. The model determines stormwater flows and water quality at locations throughout a stormwater system and its corresponding receiving body of water. Output from the model consists of hydrographs (flow vs time) and pollutographs (concentration vs time for a given constituent) for flow at specified locations. The model is a useful tool for a user who wishes to discern whether waters from a given storm will be propagated quickly and efficiently through an existing or proposed urban area. In addition, the model will give an estimate of the movement of pollutants from the land surface of the area to combined sewers or storm drainage outfalls. A general overview of SWMM was presented in Chapter III.

SWMM has been proven to be reliable as a tool for the water resource engineer. It accurately deals with the many and varied computations inherent in stormwater simulation. However, it does have its inadequacies. In particular is the fact that many of the paramaters and data required by the model are complex and highly ambiguous. The user of SWMM will find himself many times making educated guesses as to the value of a particular parameter. In addition, once the input has been established, and output generated, the user is faced with the equivocal task of calibrating the model for the particular catchment. Much effort will be expended by a novice user of SWMM both in determining the initial values of parameters and the adjustments necessary for calibration. The focus of this research is to utilize an expert system to transcend the deficiencies of SWMM mentioned above, such that a user need not be one of the esoteric few that understands all of the intricacies and ambiguities associated with the model.

6.3.3 ESCALOS Structure and Function

The structure of the rules-based system designed as an interactive mechanism for the calibration of SWMM is presented in Figure 6.1. The run-time inferencing module was developed using the commercial expert system shell KES (Software Architecture & Engineering, Inc., 1986) and has been named ESCALOS for Expert

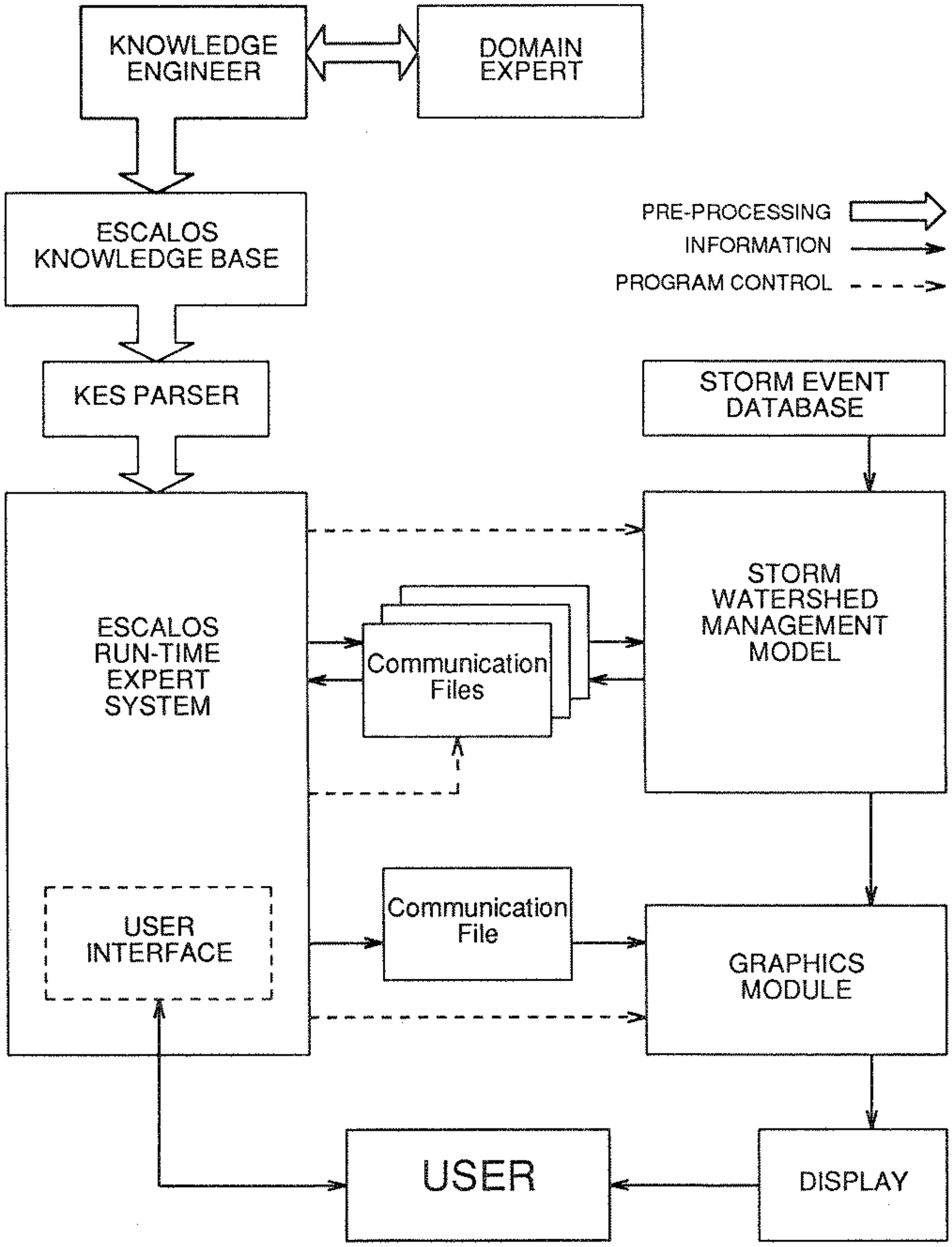


FIG. 6.1.— Schematic Diagram Showing the Structure of the Expert System Environment ESCALOS.

System for the CALibration Of SWMM. A description of the architecture of the decision-support system is followed by excerpts from a typical terminal session. The goal is to provide readers knowledgeable with SWMM an overview of how the integration of expert systems technologies might facilitate its use by inexperienced water managers. In addition, a hope is to provide readers knowledgeable with expert systems developed using conventional programming languages an overview of how modern shell technology facilitates prototyping.

Arguably, the most important and complex phase in the development of modern expert systems is the acquisition of knowledge from the domain expert (see Waterman, 1986; Harmon and King, 1985 and Wos, et al., 1984). Knowledge acquisition is usually achieved through some formalized interview process conducted by an experienced (or at least trained) *knowledge engineer.* The knowledge engineer understands various inferencing techniques, the structure of rule and frame-based knowledge systems and the capabilities and limitations of one or more expert systems development systems. While not possessing a deep understanding of the domain of interest, the knowledge engineer is generally skilled in a variety of interviewing techniques that will help the domain expert to articulate important concerns about the system of interest in an efficient and orderly manner.

After several intense interview sessions, a prototype emerges in the form of a *source program* following precisely the syntax of the language or shell that has been selected for use. In the present example, this prototype source program is shown as the ESCALOS KNOWLEDGE BASE in Figure 6.1. Once completed, this program is passed through a software filter called a *parser* (specifically the KES PARSER) and emerges as an executable module for use at run-time. The parser is actually a separate program that converts the source program into a representation—usually a tree or hierarchical structure—greatly simplifying the syntactic structure of the program (Tucker, 1986). While not all commercially available expert systems shells employ an intermediate parse phase, parsing the knowledge base typically produces a run-time system that is fast end efficient. A great deal of research is presently being done to extend and improve parser operation, particularly in the areas of natural language systems design (Emerson, 1987).

The development stages discussed thus far are part of *pre-processing* as indicated by the broad arrows of Figure 6.1; the domain expert, the knowledge engineer and the source program are not intended to be part of the system at run-time. The parsed knowledge base (labeled ESCALOS RUN-TIME EXPERT SYSTEM) is the actual executable expert system and contains the structure for the knowledge base and the logic for the inferencing mechanism. In the present application, inferencing will be achieved primarily using a formal rules structure. In addition to the knowledge structure and inferencing logic, ESCALOS contains modules that control program flow and that establish the user interface in the form of menu displays and help utilities.

As discussed in the previous section, the purpose of this application is to aid the inexperienced user in the calibration and use of a well-accepted, though difficult to use, engineering design/analysis model known as SWMM. For this case, SWMM is essentially unmodified and resides as a separate executable on the resident host (Huber, et al., 1984) that requires separate input from and data file, and which produces output that can be passed on to an external file or output program. Communication between ESCALOS and SWMM takes two forms: 1) passage of control instructions directly from ESCALOS to SWMM (dashed arrows), or 2) through external communication files using a pre-specified and common data format (solid arrows to/from communications files). Note also the use of program control to achieve administrative file handling and control of other (graphics) routines.

At run-time, the user interacts with the system through a USER INTERFACE that has been designed and integrated into the ESCALOS system adhering to the syntax of the program and using a variety of special support features of the expert system shell as will be demonstrated in the following section. Through that interface, the user may request graphical displays of intermediate results that might be of use in the analysis of the specific problem being studied. In addition to providing specific prompt-driven responses, an application-independent command language is made available to the user offering additional flexibility and support.

6.3.4 Quantity Simulation - Script Discussion

Most of the features and procedures discussed above will be described through the presentation of excerpts from a typical user session. Program action is initiated and controlled within the ACTIONS section of the source program. The relevant segments from the ESCALOS ACTIONS section are listed in Table 6.1 which will be referred to throughout the session description. Other segments from the source program will be presented in the text where needed and a series of screens showing actual displays will be presented as Figures 6.2a - 6.2j, also referenced to the appropriate program segments. The full and complete listing for the ESCALOS program may be found in the Appendices to this report.

The first command appearing in the actions section of Table 6.1 causes the textual attachment named 'welcome1' to be displayed to the user. 'Welcome1' is simply lines of characters and spaces fashioned in such a way as to present a welcome header to the end user at the outset of a KES session. Figure 6.2a is a depiction of what appears on the terminal screen in response to this actions section command. The contents of the text section where 'welcome1' resides is shown below. Note that the text to be displayed is contained within quotation marks.

```
text:
\
\  The following text is used for a welcome banner to the system.
\
{welcome1:"   *      #########################################      *",
          "   *      #                                       #      *",
          "   *      #               WELCOME                 #      *",
          "   *      #                  TO                   #      *",
          "   *      #                                       #      *",
          "   *      #               ESCALOS                 #      *",
          "   *      #                                       #      *",
          "   *      #  Expert Sys. for Calibration of SWMM  #      *",
          "   *      #                                       #      *",
          "   *      #########################################      *",
        "             Please Enter <RETURN>  To Continue          "}
%
```

The next excerpt from Table 6.1 (2) shows the command 'obtain attribute' being issued in order to instantiate the attribute. As mentioned earlier, an attribute value can be determined through inferencing or user input. When KES encounters the obtain command it first scans the rules section to see if that particular attribute value can be ascertained via inferencing. If not, then the end user will be queried for the attribute value.

TABLE 6.1.—Summary of ESCALOS "actions" Program Segment

```
     actions:

(1)  display attach welcome1 of kb.
          ⋮        ⋮        ⋮
(2)  obtain quantity.
          ⋮        ⋮        ⋮

     obtain file.
     obtain nucat.
     obtain nupipe.
     obtain infmethod.
          ⋮        ⋮        ⋮
(3)  message "****** Please Enter The Data For Each Subcatchment ******".
         forall x: subcatchments do
                obtain x>idsubc.
            obtain x>idpipe.
          ⋮        ⋮        ⋮

                obtain x>areac.
          ⋮        ⋮        ⋮

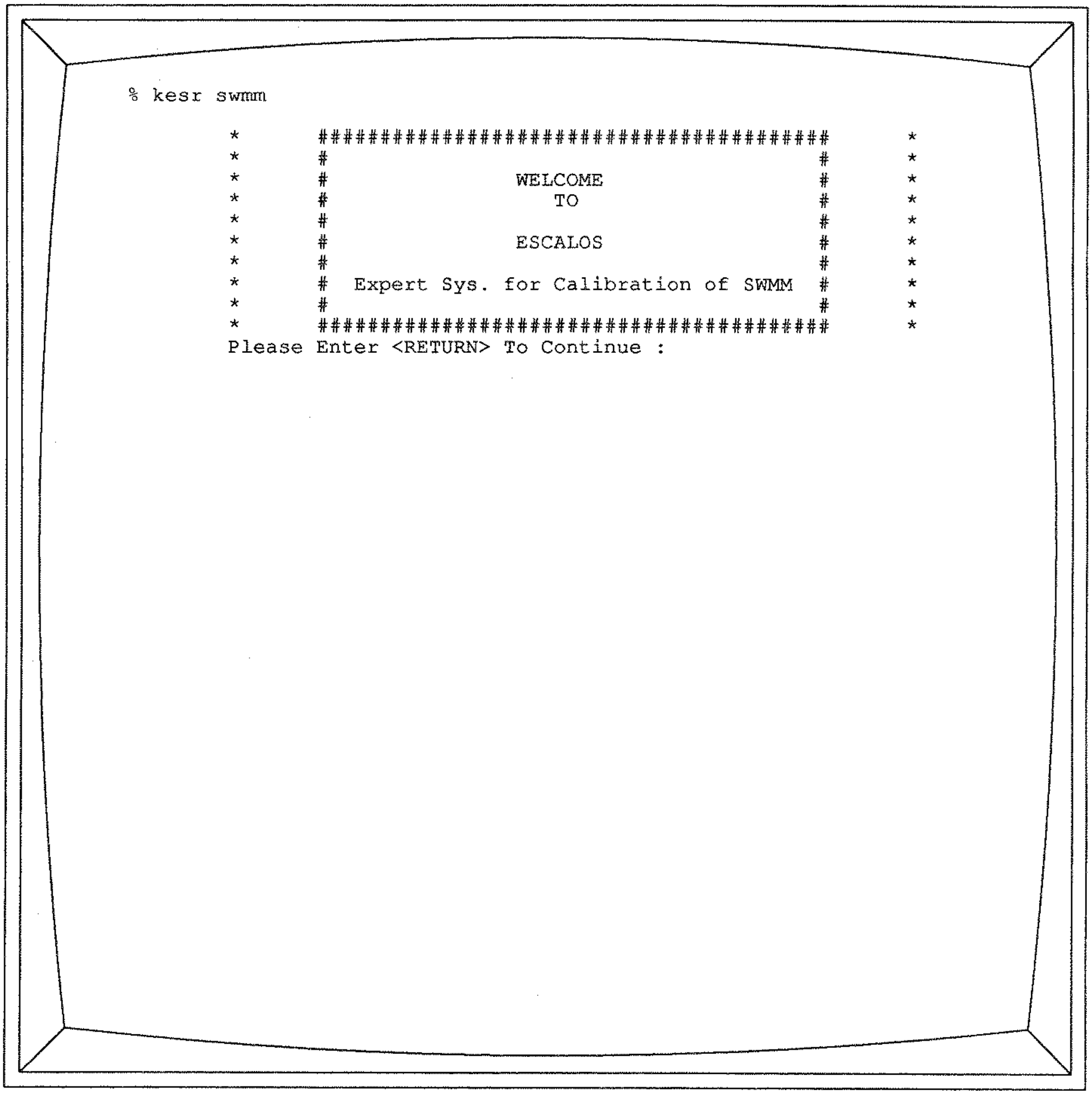
            obtain x>prob2c.
         endforall.
          ⋮        ⋮        ⋮
(4)   run datafile.
      message continuer.
      break.
      message "*** NOW SWMM PROGRAM IS RUNNING YOU MAY GO GET A DRINK ***".
      run model.
      message "         /////// SWMM: TERMINATION CODE : SUCCESS !!!!!!!!".
      run datainput.
      read "data", t, v, p, e, nosov, nosuv,nosop,nosup.
      message continuer.
      break.
      obtain action.
      if action = calibration is done
         then message " ","*****************************"," ",
                      " ","======= GONGRATULATIONS ======="," ".
      endif.
      display value of action.
(5)   obtain justification.
      if justification = Yes
         then justify action.
      endif.
          ⋮        ⋮        ⋮
(6)   while action # calibration is done do
            obtain operamenu.
            if operamenu = Char_length
               then obtain minchar_length.
                    obtain maxchar_length.
          ⋮        ⋮        ⋮

            endif.
            obtain action.
          ⋮        ⋮        ⋮

            display value of action.
            justify action.
          ⋮        ⋮        ⋮

      endwhile.
          ⋮        ⋮        ⋮

%
```



```
% kesr swmm

        *      #########################################       *
        *      #                                       #       *
        *      #               WELCOME                 #       *
        *      #                  TO                   #       *
        *      #                                       #       *
        *      #               ESCALOS                 #       *
        *      #                                       #       *
        *      #  Expert Sys. for Calibration of SWMM  #       *
        *      #                                       #       *
        *      #########################################       *
        Please Enter <RETURN> To Continue :
```

FIG.6.2a.— ESCALOS Script Screen Display Demonstrating the Use of "text" Constructs.

The following display shows the attributes as they are listed in the attributes section of KES:

```
attributes:

!
 INPUT ATTRIBUTES

!
         iqual: int.
         quantity: sgl(YES, NO)
   {question: "DID YOU ALREADY CALIBRATE QUANTITY FOR THIS PROBLEM ?"}.

         quality: sgl(YES, NO)
   {question: "DO YOU WANT TO CALIBRATE QUALITY ?"}.

         file: sgl(YES,NO)
   {question: "HAVE YOU PREVIOUSLY INPUT THE QUANTITY DATA ?"}.

         nucat: int
   {question: "WHAT IS THE NUMBER OF SUBCATCHMENTS ON YOUR SITE ?"}.

         nupipe: int
{question: "HOW MANY PIPES AND/OR GUTTERS DO YOU WANT TO SIMULATE?"}.

           infmethod: sgl(Green_Ampt method
    {explain: "Green-Ampt method :                                         ",
              "The original equation was developed in 1911 and it........."},
                         Horton method
    {explain: "Horton method :                                             ",
              "Horton equation was developed in 1940. It predicts........."})
    {question: "DO YOU WANT TO SIMULATE INFILTRATION PROCESS WITH"}.
%
```

Note that numeric attributes can be declared integer or real. For each non numeric attribute, a type must be declared. This can be a predefined type such as single, multiple, etc. or a user defined type listed in the types section. The question clause associated with each attribute instructs KES to display a question in a particular format if a user query is the mechanism by which the attribute is to be instantiated. Figure 6.2b illustrates the instantiation of input attributes by the user query method. Two other clauses that can be associated with attributes are 'explain' and 'why'. Figure 6.2c illustrates execution of the 'explain' attachment while the 'why' clause is illustrated in Figure 6.2d. The explain and why features are special attachments that KES will display when called by the user. If a user is unsure of the meaning or context of a question (input attribute), he can type 'explain' whereupon KES will clarify the type of input desired by displaying the string contained in the explain attachment of the particular attribute. Similarly, if a user is unsure of the reason why an answer is needed, he can type 'why' to have KES display the reason

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   {question: "DO YOU WANT TO CALIBRATE QUALITY ?"}.

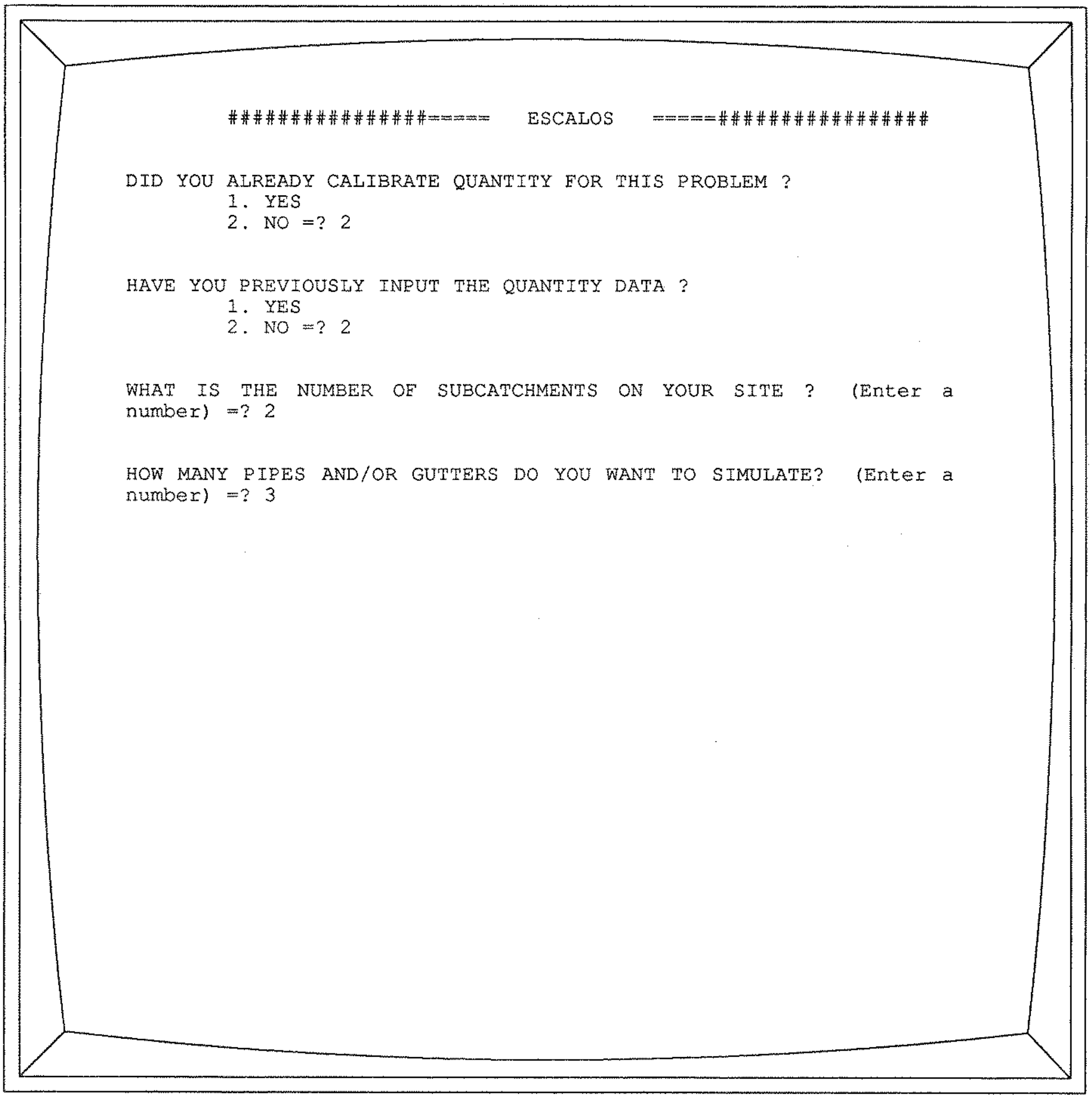
         file: sgl(YES,NO)
   {question: "HAVE YOU PREVIOUSLY INPUT THE QUANTITY DATA ?"}.

         nucat: int
   {question: "WHAT IS THE NUMBER OF SUBCATCHMENTS ON YOUR SITE ?"}.

         nupipe: int
{question: "HOW MANY PIPES AND/OR GUTTERS DO YOU WANT TO SIMULATE?"}.

           infmethod: sgl(Green_Ampt method
    {explain: "Green-Ampt method :                                    ",
              "The original equation was developed in 1911 and it........"},
                          Horton method
    {explain: "Horton method :                                        ",
              "Horton equation was developed in 1940. It predicts........"})
    {question: "DO YOU WANT TO SIMULATE INFILTRATION PROCESS WITH"}.
%
```

Note that numeric attributes can be declared integer or real. For each non numeric attribute, a type must be declared. This can be a predefined type such as single, multiple, etc. or a user defined type listed in the types section. The question clause associated with each attribute instructs KES to display a question in a particular format if a user query is the mechanism by which the attribute is to be instantiated. Figure 6.2b illustrates the instantiation of input attributes by the user query method. Two other clauses that can be associated with attributes are 'explain' and 'why'. Figure 6.2c illustrates execution of the 'explain' attachment while the 'why' clause is illustrated in Figure 6.2d. The explain and why features are special attachments that KES will display when called by the user. If a user is unsure of the meaning or context of a question (input attribute), he can type 'explain' whereupon KES will clarify the type of input desired by displaying the string contained in the explain attachment of the particular attribute. Similarly, if a user is unsure of the reason why an answer is needed, he can type 'why' to have KES display the reason



```
         ################=====   ESCALOS   =====#################

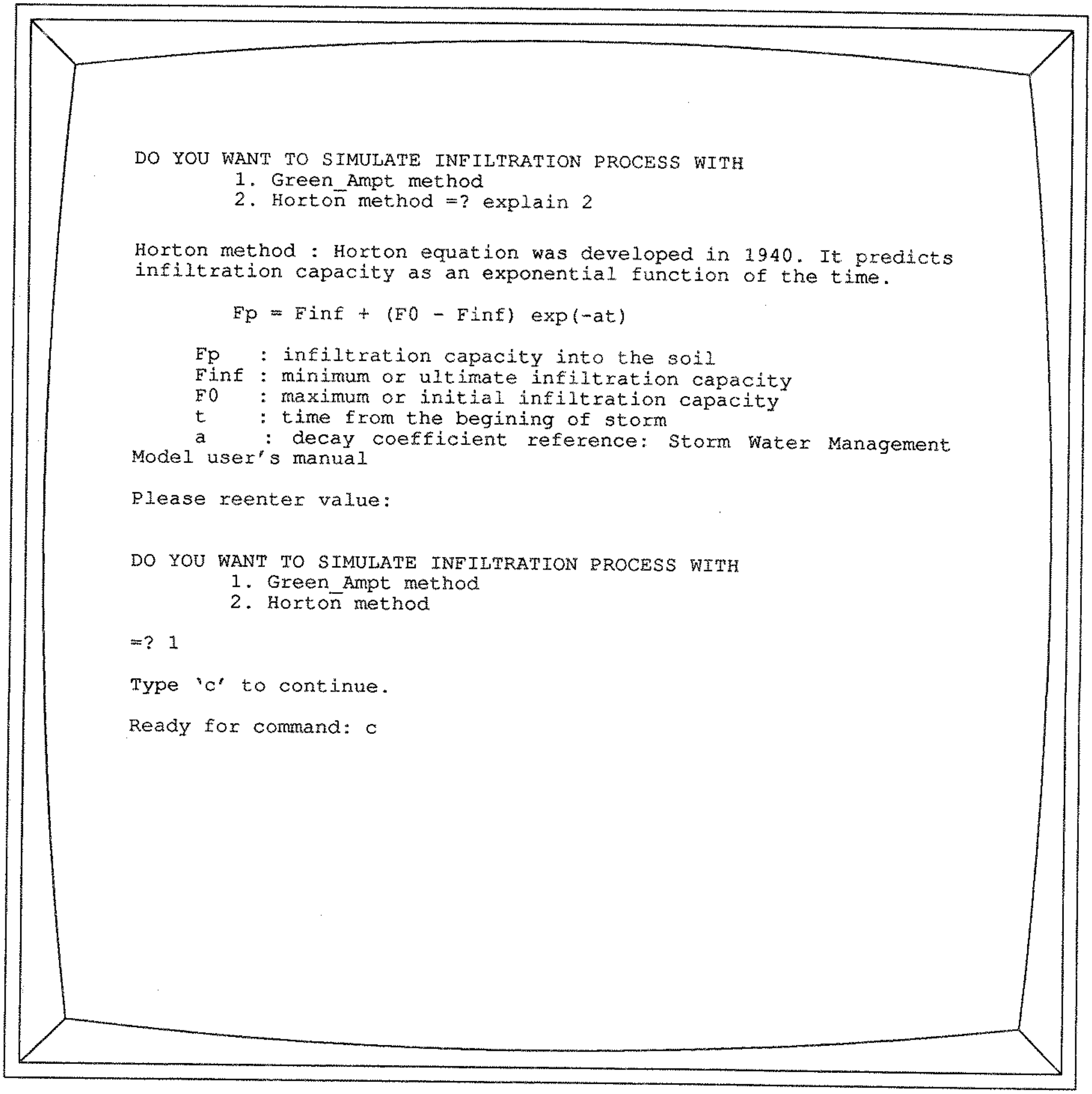
DID YOU ALREADY CALIBRATE QUANTITY FOR THIS PROBLEM ?
        1. YES
        2. NO =? 2


HAVE YOU PREVIOUSLY INPUT THE QUANTITY DATA ?
        1. YES
        2. NO =? 2


WHAT  IS  THE  NUMBER  OF  SUBCATCHMENTS  ON  YOUR  SITE  ?   (Enter  a
number) =? 2


HOW MANY PIPES AND/OR GUTTERS DO YOU WANT TO SIMULATE?  (Enter a
number) =? 3
```

FIG.6.2b.—ESCALOS Script Screen Display Demonstrating the Instantiation of Input Attributes Used for Program Control and the use of "question" Input Attribute Attachments.



```
DO YOU WANT TO SIMULATE INFILTRATION PROCESS WITH
        1. Green_Ampt method
        2. Horton method =? explain 2

Horton method : Horton equation was developed in 1940. It predicts
infiltration capacity as an exponential function of the time.

        Fp = Finf + (F0 - Finf) exp(-at)

     Fp   : infiltration capacity into the soil
     Finf : minimum or ultimate infiltration capacity
     F0   : maximum or initial infiltration capacity
     t    : time from the begining of storm
     a    : decay coefficient reference: Storm Water Management
Model user's manual

Please reenter value:

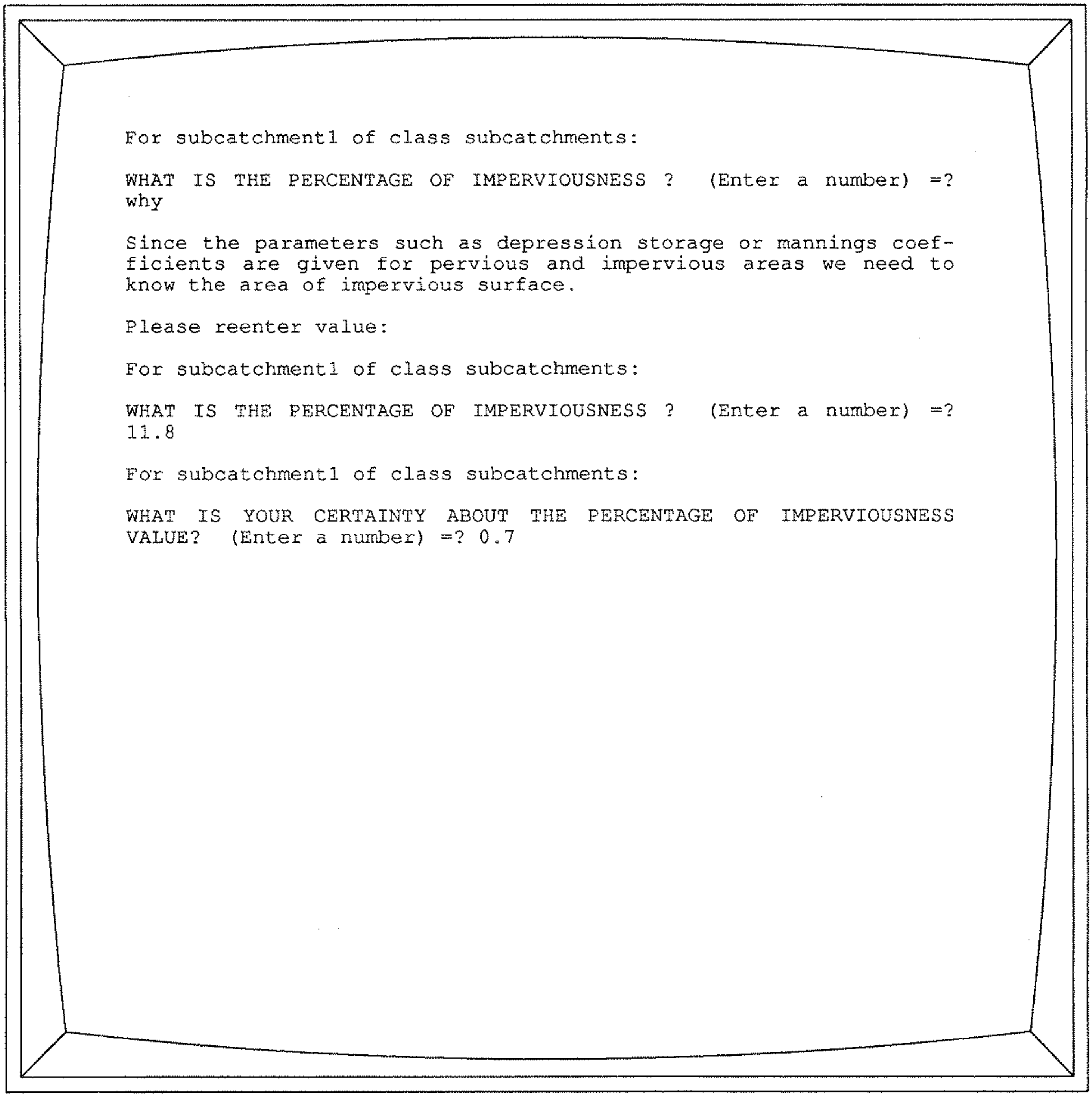

DO YOU WANT TO SIMULATE INFILTRATION PROCESS WITH
        1. Green_Ampt method
        2. Horton method

=? 1

Type 'c' to continue.

Ready for command: c
```

FIG.6.2c.—ESCALOS Script Screen Display Demonstrating the Use of "explain" and "reference" Input Attribute Attachments.



```
For subcatchment1 of class subcatchments:

WHAT IS THE PERCENTAGE OF IMPERVIOUSNESS ?  (Enter a number) =?
why

Since the parameters such as depression storage or mannings coef-
ficients are given for pervious and impervious areas we need to
know the area of impervious surface.

Please reenter value:

For subcatchment1 of class subcatchments:

WHAT IS THE PERCENTAGE OF IMPERVIOUSNESS ?  (Enter a number) =?
11.8

For subcatchment1 of class subcatchments:

WHAT IS YOUR CERTAINTY ABOUT THE PERCENTAGE OF IMPERVIOUSNESS
VALUE?  (Enter a number) =? 0.7
```

FIG.6.2d.—ESCALOS Script Screen Display Demonstrating the Use of the "why" User Command and the Use of "Classes".

or significance of the query.

Part (3) of Table 6.1 illustrates the 'message' command which simply displays a message to the end user. In addition, the forall/endforall looping construct is shown. This feature enables a sequence of actions to be executed for each member of an existing class. In this case the class is named subcatchments where each subcatchment is a member of the class. The relevant excerpt from the classes section of the expert system source code is shown below.

```
classes:
     subcatchments:
     attributes:

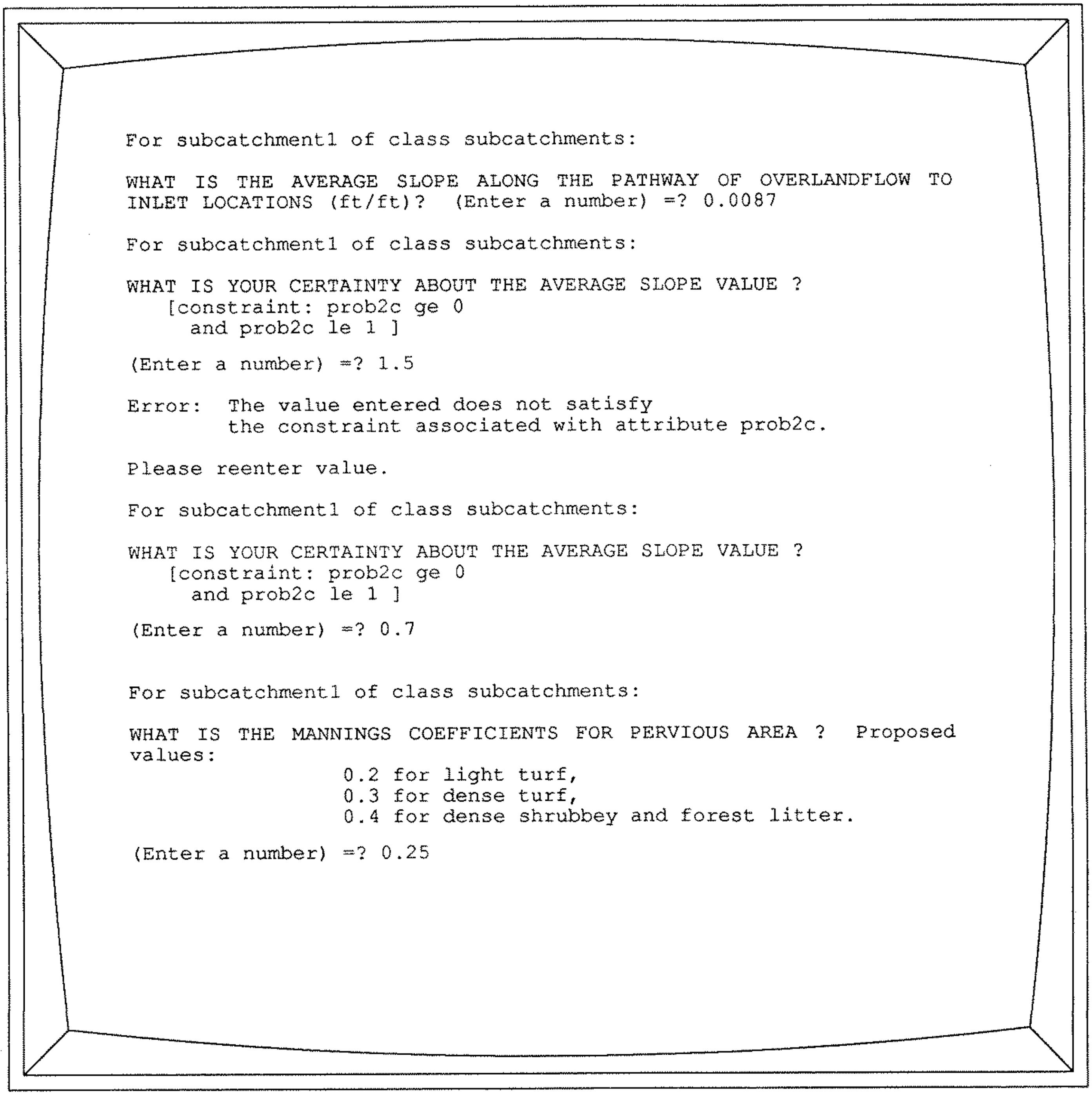

         idsubc: int
   [constraint: idsubc ge 1 and idsubc le 99]
   {question: "WHAT IS THE ID OF THE SUBCATCHEMENT ?"}.

         idpipe: int
   [constraint: idpipe ge 1 and idpipe le 999]
   {question: "WHAT IS THE ID DRAINING MANHOLE OR GUTTER/PIPE?"}.

         areac: real
 {question: "WHAT IS THE TOTAL AREA OF THE MODELIZED CATCHMENT (acres) ?"," "}.
     .
     .
         prob2c: real
         [constraint: prob2c ge 0 and prob2c le 1]
   {question: "WHAT IS YOUR CERTAINITY ABOUT THE AVERAGE SLOPE VALUE?"}.
     .
     .
       %
endclass.
%
```

Each subcatchment in the class will have associated attributes to represent ID, ID draining manhole, total area, etc. The variable 'x' in Table 6.1 (3) represents, in turn, each member of the class subcatchments. Thus, all of the commands contained between the forall/endforall loop will be executed once for each member of the class. The variable will take on the value of a different member each time through. Figures 6.2d and 6.2e show user queries for the instantiation of attributes associated with the class subcatchment1 of class subcatchments. Note that prior to this, the class must be defined, i.e., the system must know the members contained within each class.

Some of the class attributes listed include a constraint clause. The constraint clause specifies limits on the values that an attribute may take on. The clause is an



```
For subcatchment1 of class subcatchments:

WHAT IS THE AVERAGE SLOPE ALONG THE PATHWAY OF OVERLANDFLOW TO
INLET LOCATIONS (ft/ft)?  (Enter a number) =? 0.0087

For subcatchment1 of class subcatchments:

WHAT IS YOUR CERTAINTY ABOUT THE AVERAGE SLOPE VALUE ?
   [constraint: prob2c ge 0
     and prob2c le 1 ]

(Enter a number) =? 1.5

Error:  The value entered does not satisfy
        the constraint associated with attribute prob2c.

Please reenter value.

For subcatchment1 of class subcatchments:

WHAT IS YOUR CERTAINTY ABOUT THE AVERAGE SLOPE VALUE ?
   [constraint: prob2c ge 0
     and prob2c le 1 ]

(Enter a number) =? 0.7


For subcatchment1 of class subcatchments:

WHAT IS THE MANNINGS COEFFICIENTS FOR PERVIOUS AREA ?  Proposed
values:
                 0.2 for light turf,
                 0.3 for dense turf,
                 0.4 for dense shrubbey and forest litter.

(Enter a number) =? 0.25
```

FIG.6.2e.—ESCALOS Script Screen Display Demonstrating the Use of "constraint" Input Attribute Attachments.

optional feature of the attribute declaration. An illustration of the constraint clause at work is contained in Figure 6.2e. Here the constraint specifies that the attribute must be greater than or equal to 0 and less than or equal to 1. Since the user has entered 1.5, KES displays the error message and asks the user to reenter the value of the attribute.

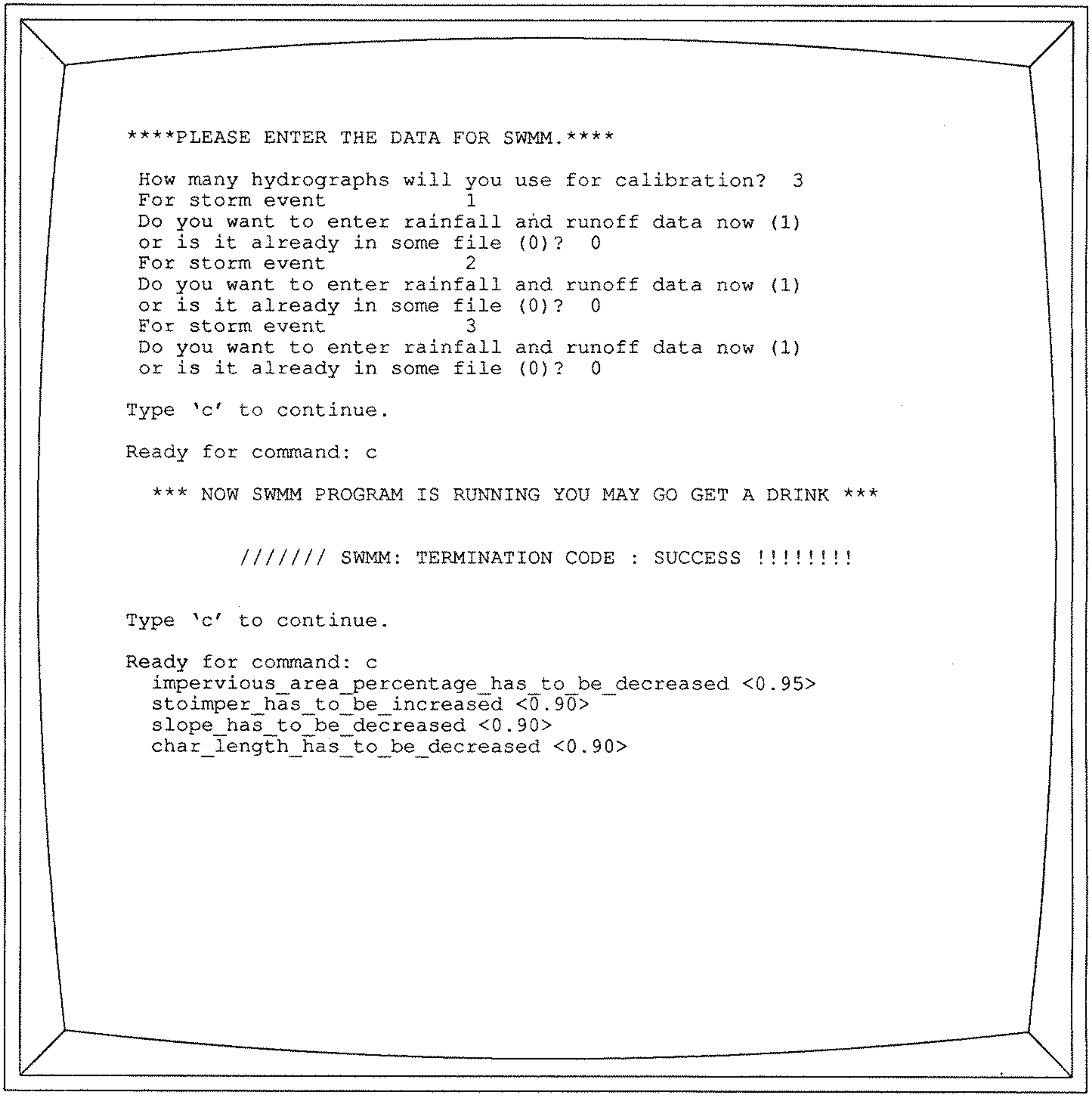
Table 6.1 (4) shows a sequence of commands used to execute programs, unix commands, or shell scripts, (termed externals) outside of the KES system. The terminal session associated with these commands is depicted in Figure 6.2f. The command 'run' followed by a name causes KES to execute the sequence of commands that are associated with that name in the externals section. The commands "run datafile", "run model", and "run datainput" correspond to the following entities in the externals section:

```
externals:
               datafile: [program: "makefiles"].
               datainput: [program: "trans"].
               model: [program: "swm"].
%
```

The command "run datafile" causes the executable Fortran program makefiles to run. This program handles storm event data which is required by SWMM. The user is asked the number of hydrographs which will be used for calibration. For each of these, the user must then indicate whether the data is contained in a file or is to be submitted during the session.

Now the SWMM model is ready to be run. This is accomplished through the "run model" external command. Since the output from SWMM is lengthy and not in a form conducive to retrieval by the expert system, we have devised an external called "datainput" to sort and format the output from SWMM into a comunication file. The information contained within the communication file conforms to KES syntax specifications.

Next, the KES 'read' command is utilized to retrieve the results from the communication file. The expert system is now ready to perform its most vital function--calibration of SWMM. It uses rule based inferencing to determine what actions are necessary, if any, to achieve calibration for the particular watershed. Thus, it is necessary for the attribute 'action' to be determined. The command



```
****PLEASE ENTER THE DATA FOR SWMM.****

 How many hydrographs will you use for calibration?  3
 For storm event           1
 Do you want to enter rainfall and runoff data now (1)
 or is it already in some file (0)?  0
 For storm event           2
 Do you want to enter rainfall and runoff data now (1)
 or is it already in some file (0)?  0
 For storm event           3
 Do you want to enter rainfall and runoff data now (1)
 or is it already in some file (0)?  0

Type 'c' to continue.

Ready for command: c

  *** NOW SWMM PROGRAM IS RUNNING YOU MAY GO GET A DRINK ***


         /////// SWMM: TERMINATION CODE : SUCCESS !!!!!!!!


Type 'c' to continue.

Ready for command: c
  impervious_area_percentage_has_to_be_decreased <0.95>
  stoimper_has_to_be_increased <0.90>
  slope_has_to_be_decreased <0.90>
  char_length_has_to_be_decreased <0.90>
```

FIG.6.2f.— ESCALOS Script Screen Display Demonstrating the Use of Externals and Rule Certainty Through the Inferencing Process.

"obtain action" begins the inferencing process. An example of a rule used during the inferencing process is shown below.

```
rules:
rule char_length_has_to_be_decreased :
       if
          peaks = peaks_occur_soon or
          peaks = peaks_are_too_high
       then
          action = char_length_has_to_be_decreased <0.9>.
       endif.
%
```

The consequent in this rule states that characteristic length has to be decreased. This follows from the antecedent condition of hydrograph peaks being too high or occurring too soon. The antecedent is determined true or false based on the information read following the SWMM run. When the inferencing process is complete, the expert system presents all of the values determined for the attribute action (action is a multiple type attribute). The "display value of action" command in the actions section accomplishes this.

The possibility exists that calibration may be achieved after a single SWMM run. Hence, one possible value of the attribute 'action' must be "calibration is done". To account for this possibility we have included a simple if then construct to check and see if calibration has been achieved. If calibration has been achieved a message indicating this will be flashed to the user.

When KES displays to the end user values of an attribute, it also specifies a certainty factor (see Figure 6.2f). A certainty factor is a measure of the confidence or reliability of a value. Certainty factors in KES range from 1.0 to -1.0 and reflect the strength of belief in the presence of a specific value of an attribute. A certainty factor of 1.0 indicates an absolute belief in the presence of that value. On the other hand, a certainty factor of -1.0 indicates an absolute belief that the value is not present. A certainty factor of 0.0 indicates a lack of belief either for or against the presence of a value.

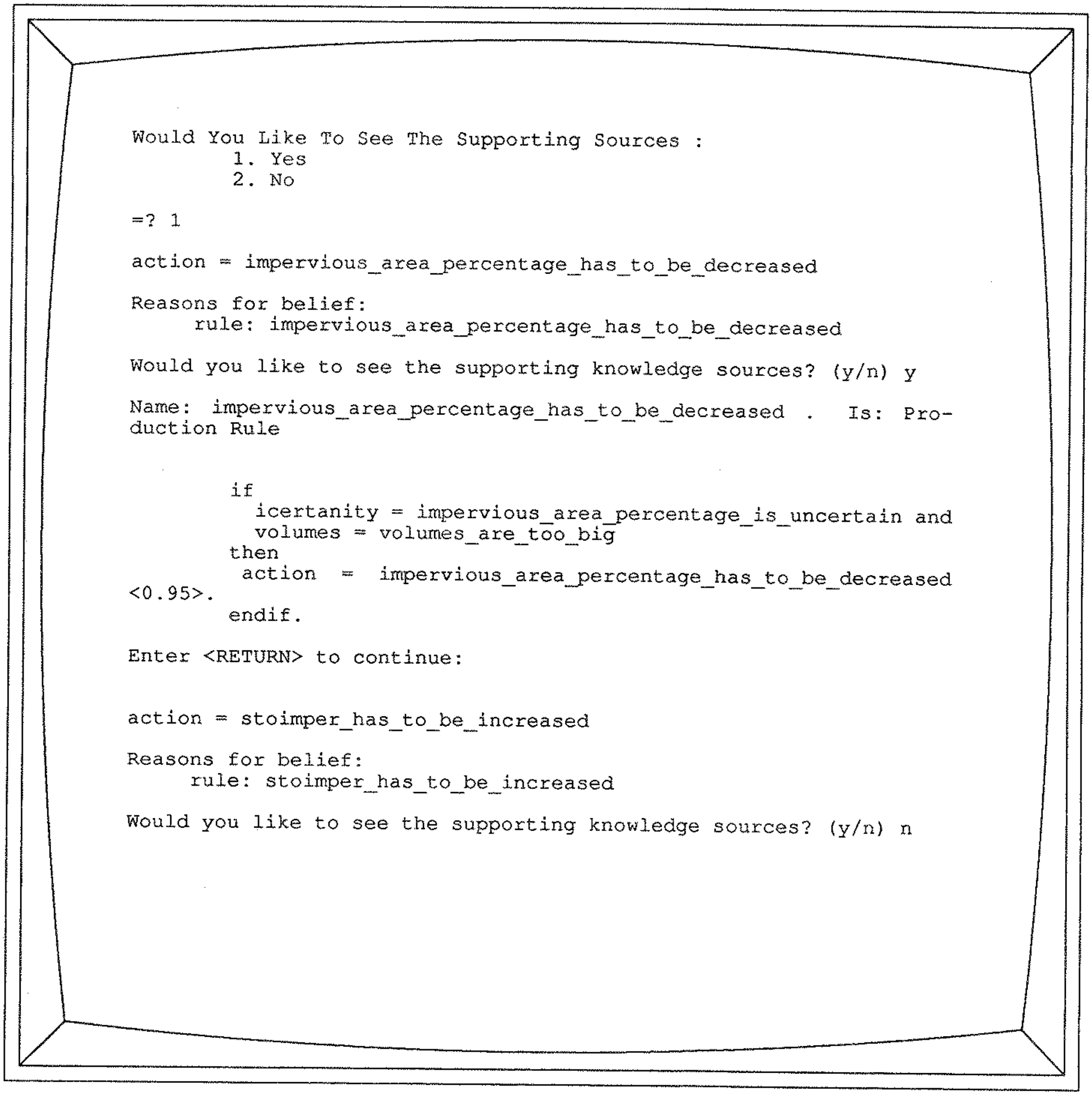
Two additional features of KES that appear in part 4 of the actions section of Table 6.1 are constants and break. The 'continuer' constant causes the message "Type 'c' to continue" to be printed out. An excerpt from the constants section follows:

```
constants:
\
   continuer: " ","Type 'c' to continue.".
   start again: " ","Type 'nextcase' to start again, or 'stop' to quit.".
%
```

The break command causes KES to pause and wait for the user to type in a command. At this point, the user can enter any interactive KES command desired. A break command interrupts the flow of control in the actions section and can thus be used to control paging if an actions command causes more than a screenful of information to be scrolled up. In addition, a break is inserted at such a point where the user may wish to verify the value of a particular attribute or to see the rules that contributed to the inferencing conclusion. The interactive command 'justify' accomplishes this and is discussed subsequently.

Part 5 of Table 6.1 is an example of the justification feature of KES. This feature is the method by which KES displays to the user the knowledge sources which contributed to the value of an attribute. Upon execution of the justify command, KES will show the user the rule, external, or calculation/default clauses used to arrive at the diagnosis. Figure 6.2g demonstrates the manner by which KES determines the four actions that the user should take to achieve calibration in response to the commands in Table 6.1 (5).

In part 6 of Table 6.1, a flavor for the 'while' iterative capability of KES is given. Commands in the 'while' block are executed repeatedly until a certain condition is met. In this case the condition is that calibration is not done. So, after the results of SWMM are obtained, the value of the attribute "actions" is determined. If it is not equal to "calibration is done", the recommended action(s) are displayed and the user is asked which action he would like to take. In other words, the user must specify which parameters are to be adjusted for the next SWMM run. The expert system has been programmed to adjust the parameters by a certain amount, thus the user only has to specify which parameter is to be changed and not by how much. Once new parameter values are established SWMM is activated once again. The sequence continues until the criterion for calibration is met, whereupon the user is informed that calibration of the model has been accomplished and the final parameter values are displayed. A script of the events occuring in relation to Table 6.1 (6) and the above discussion is presented in figures



```
Would You Like To See The Supporting Sources :
        1. Yes
        2. No

=? 1

action = impervious_area_percentage_has_to_be_decreased

Reasons for belief:
     rule: impervious_area_percentage_has_to_be_decreased

Would you like to see the supporting knowledge sources? (y/n) y

Name: impervious_area_percentage_has_to_be_decreased .  Is: Pro-
duction Rule


        if
          icertanity = impervious_area_percentage_is_uncertain and
          volumes = volumes_are_too_big
        then
         action  =  impervious_area_percentage_has_to_be_decreased
<0.95>.
        endif.

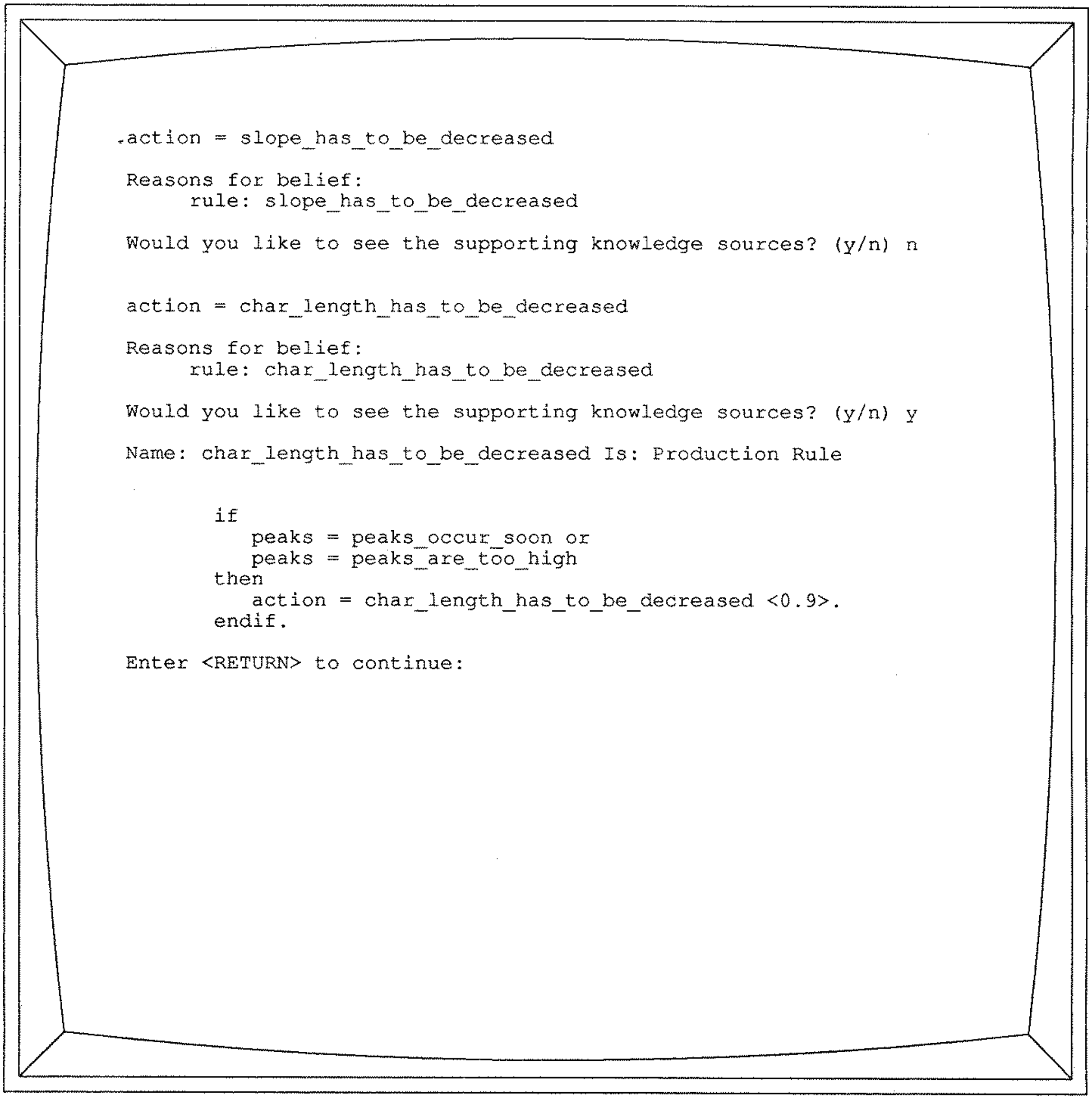
Enter <RETURN> to continue:


action = stoimper_has_to_be_increased

Reasons for belief:
     rule: stoimper_has_to_be_increased

Would you like to see the supporting knowledge sources? (y/n) n
```

FIG.6.2g.—ESCALOS Script Screen Display Demonstrating the Justification of Inferencing to the User at Run-time.



```
action = slope_has_to_be_decreased

Reasons for belief:
     rule: slope_has_to_be_decreased

Would you like to see the supporting knowledge sources? (y/n) n


action = char_length_has_to_be_decreased

Reasons for belief:
     rule: char_length_has_to_be_decreased

Would you like to see the supporting knowledge sources? (y/n) y

Name: char_length_has_to_be_decreased Is: Production Rule


       if
          peaks = peaks_occur_soon or
          peaks = peaks_are_too_high
       then
          action = char_length_has_to_be_decreased <0.9>.
       endif.

Enter <RETURN> to continue:
```

FIG.6.2g. (cont.)— ESCALOS Script Screen Display Demonstrating the Justification of Inferencing to the User at Run-time.

6.2h - 6.2j.

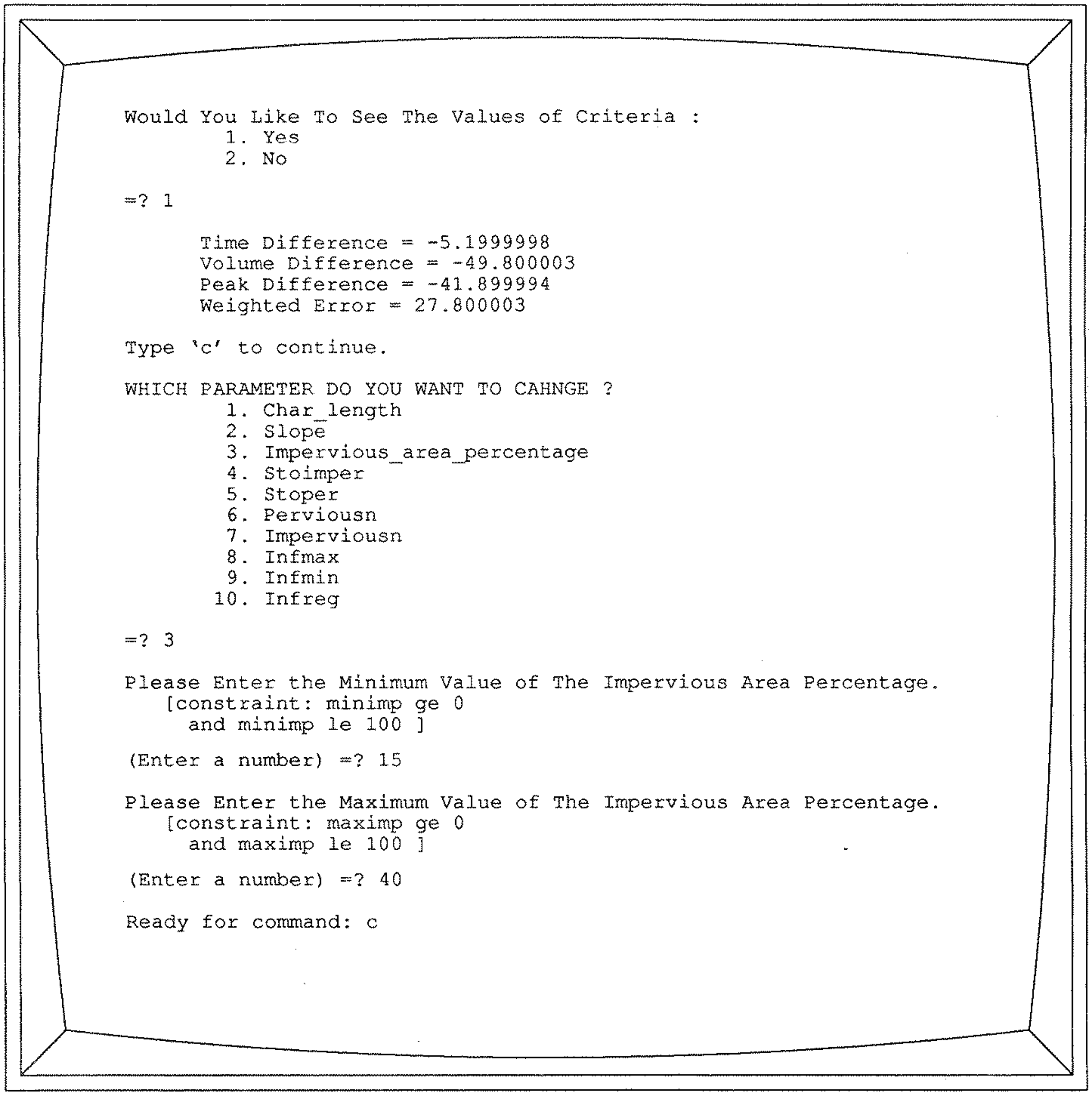
6.3.5 Quality Simulation - Discussion

The preceding discussion of the prototype expert system developed for the Runoff block of SWMM concentrates on the quantity simulation portion. A separate expert system was developed to handle the quality simulation. Because the two systems are extremely similar, an in depth discussion of the quality portion would inevitably lead to repetition and is thus unnecessary. (The quality portion of ESCALOS as well as a typical script session listing are presented in the Appendix of this report.) However, there are some features of KES used in the quality portion and not the quantity portion that deserve mentioning. Specifically they are patterns, classes in rules and an if/forall type of construct.

As mentioned earlier, the patterns feature of KES serves to define patterns against which the form of a string expression may be compared. This feature came in particularly handy in the development of a portion of the quality knowledge base. In one instance, the user is required to enter the concentration units for each pollutant being simulated. However, the input file for SWMM, which is being built by the expert system, requires a code of 0, 1, or 2 representing the concentration units to be specified in addition to the name of the concentration unit (0 for "mg/l", 1 for "other unit/l", and 2 for "other conc. unit").

There are three ways in which KES can be programmed to deal with this. First, the user can be queried to enter the code associated with the concentration unit just entered. Secondly, if, then, endif rules can be built such that the system can use inferencing to determine the code. Yet, each of these methods is cumbersome in its own way. The first requires addititional effort by the end user and the second requires an if then clause to be included for every possible concentration unit. The third possibility and the method incorporated into ESCALOS quality is use of the KES pattern matching capability.

Three pattern names are defined, each having an associated list of elements



```
Would You Like To See The Values of Criteria :
        1. Yes
        2. No

=? 1

      Time Difference = -5.1999998
      Volume Difference = -49.800003
      Peak Difference = -41.899994
      Weighted Error = 27.800003

Type 'c' to continue.

WHICH PARAMETER DO YOU WANT TO CAHNGE ?
        1. Char_length
        2. Slope
        3. Impervious_area_percentage
        4. Stoimper
        5. Stoper
        6. Perviousn
        7. Imperviousn
        8. Infmax
        9. Infmin
       10. Infreg

=? 3

Please Enter the Minimum Value of The Impervious Area Percentage.
   [constraint: minimp ge 0
     and minimp le 100 ]

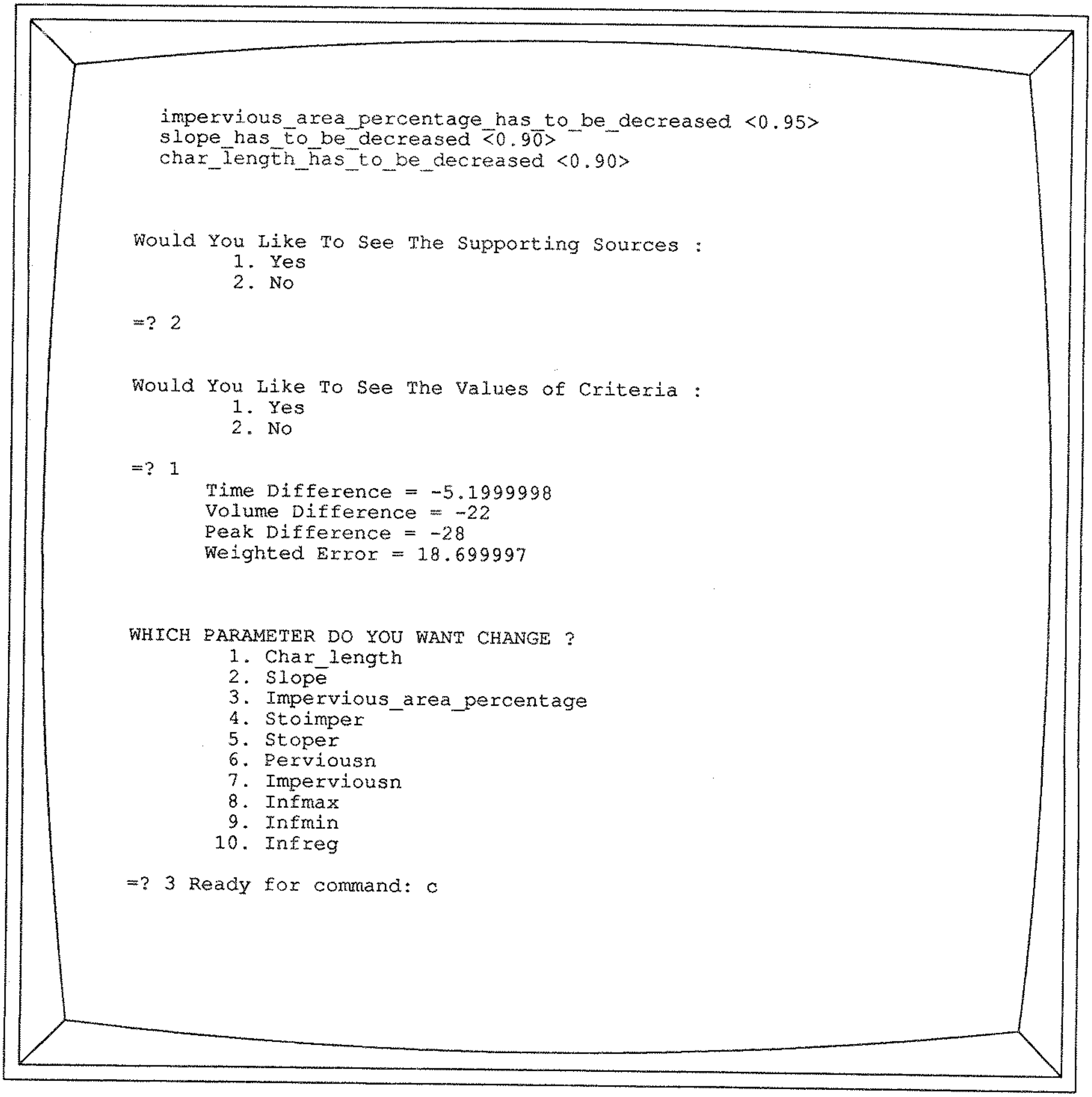
(Enter a number) =? 15

Please Enter the Maximum Value of The Impervious Area Percentage.
   [constraint: maximp ge 0
     and maximp le 100 ]

(Enter a number) =? 40

Ready for command: c
```

FIG.6.2h.—ESCALOS Script Screen Display Showing the Second Interation Procedure Required to Calibrate the Model.



```
     impervious_area_percentage_has_to_be_decreased <0.95>
     slope_has_to_be_decreased <0.90>
     char_length_has_to_be_decreased <0.90>



   Would You Like To See The Supporting Sources :
           1. Yes
           2. No

   =? 2


   Would You Like To See The Values of Criteria :
           1. Yes
           2. No

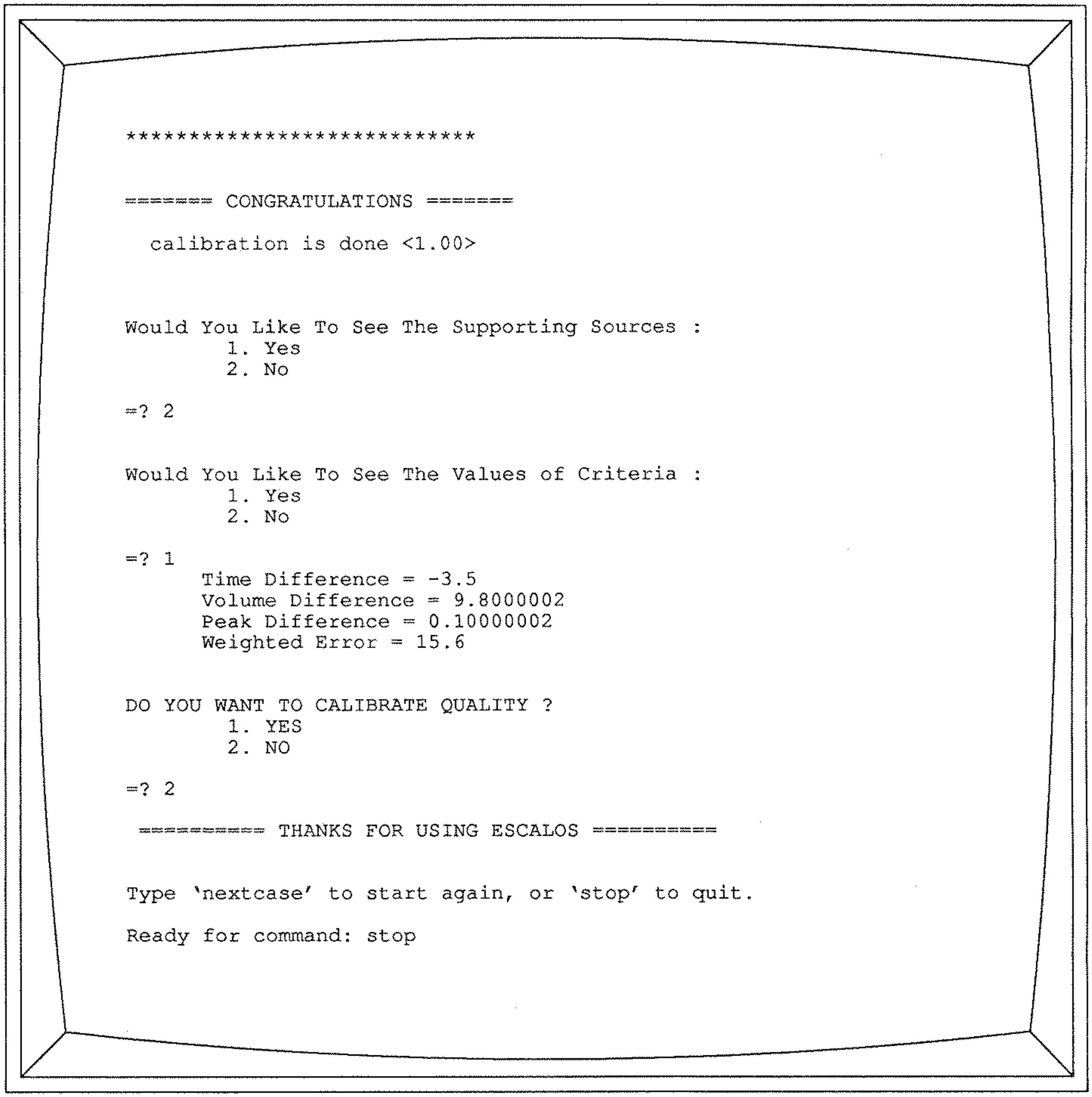
   =? 1
         Time Difference = -5.1999998
         Volume Difference = -22
         Peak Difference = -28
         Weighted Error = 18.699997



   WHICH PARAMETER DO YOU WANT CHANGE ?
           1. Char_length
           2. Slope
           3. Impervious_area_percentage
           4. Stoimper
           5. Stoper
           6. Perviousn
           7. Imperviousn
           8. Infmax
           9. Infmin
          10. Infreg

   =? 3 Ready for command: c
```

FIG.6.2i.— ESCALOS Script Screen Display Showing the Third Iteration Procedure Required to Calibrate the Model.



```
****************************


======= CONGRATULATIONS =======

  calibration is done <1.00>



Would You Like To See The Supporting Sources :
        1. Yes
        2. No

=? 2


Would You Like To See The Values of Criteria :
        1. Yes
        2. No

=? 1
      Time Difference = -3.5
      Volume Difference = 9.8000002
      Peak Difference = 0.10000002
      Weighted Error = 15.6


DO YOU WANT TO CALIBRATE QUALITY ?
        1. YES
        2. NO

=? 2

 ========== THANKS FOR USING ESCALOS ==========


Type ‘nextcase’ to start again, or ‘stop’ to quit.

Ready for command: stop
```

FIG.6.2j.— Final ESCALOS Script Screen Showing Termination of the Session.

called components:

```
patterns:
      mg_per_liter: "mg/l".
      other_per_liter: other [alternatives: "MPN/l","meq/l"].
      other_conc_units: unit [alternatives: "pH","JTU","PCU","oC"].
%
```

The first pattern name has only one associated component name while the second and third have alternative ones. Now once the value of the attribute representing the concentration unit for the pollutant is obtained, the 'match' function can be used in the actions section to determine the value of the attribute representing the unit code. The relevant excerpt from the actions section follows:

```
obtain P>unit_abbr.
if match (mg_per_liter,P>unit_abbr) = true then
  P>typ_units = 0.
endif.
if match (other_per_liter,P>unit_abbr) = true then
  P>typ_units = 1.
endif.
if match (other_conc_units,P>unit_abbr) = true then
  P>typ_units = 2.
endif.
```

The second aspect of KES used in the quality and not the quantity system is the incorporation of class variables in rules. A single rule can be declared that will pertain to all members of a specified class. An example of this type of rule taken from the rules section of the quality knowledge base is given below.

```
User Action rule4:
P:pollutant
if P>swmm_action = storm loads are too big and
  P>buildup_meth = Michaelis Menton and
  P>build_coeff lt 1 then
  P>user_action = buildup limit has to be decreased <0.8>.
endif.
```

This rule states that if, for any member of the class 'pollutant', it is determined from the output generated by SWMM that storm loads are too small and the buildup method is Michaelis Menton and the current buildup coefficient is less than 1 then action required to achieve calibration is that the buildup limit has to be decreased wtih a certainty of 0.8 on a scale of 0-1. Thus, we can specify a knowledge source in the form of a rule for any member of a particular class.

The third discrete aspect of KES used in the quality system conjoins two distinct features of KES. The goal of the quality simulation is to achieve model calibration for all of the pollutants being simulated. However, it may occur at the end of a SWMM run that the model is calibrated for some pollutants and not for others.

Hence, we need a feature that in words would be described by the following: "if for all pollutants being simulated, calibration is achieved then the quality portion of SWMM is calibrated". In order to accomplish this, we used the while feature discussed in the previous section in conjunction with the classes in rules feature discussed above.

An attribute 'calib_done' is declared which can take on the value "calibration is done" or "calibration is not done". In addition, the following rule is declared pertaining to all members of the class pollutant (members being pollutants specified by user to be simulated):

```
Calibration rule3:
P:pollutant
if P>user_action # calibration is done then
calib_done = calibration is not done.
endif.

Calibration rule4:
P:pollutant
if P>user_action = calibration is done then
calib_done = calibration is done.
endif.
```

Now, in the actions section we specify that while 'calib_done' is not equal to "calibration is done" the iterations en route to calibration will continue. The attribute 'calib_done', by virtue of the classes in rules feature, will only take on the value of "calibration is done" if it is true for each individual pollutant. Thus, the calibration process will continue until the model is calibrated for all pollutants being simulated, as desired.

While the above section describes the major aspects of the quality system not found in the quantity system, there remain some minor differences in structure and control flow between the two knowledge bases. Yet, the overall goal of the two is the same, that is to facilitate construction of the parameters required by SWMM as well as calibration of the model for quantity and quality of flow through a particular catchment.

Chapter VII

CONCLUSIONS

The use of the expert system ESCALOS for the estimation and the calibration of the parameters used in the Runoff Block of the Storm Water Management Model saves a large amount of time for the user independently of his or her experience. The guidance in the choice of the parameter's values and the building of SWMM input files is a valuable assistance to the user. The automation of the change in the parameters values and the interpretation of the results substantially decrease the files manipulations.

Generally the fit between measured and predicted hydrographs is better when the calibration is done with the help of ESCALOS than when it is done by the traditional methods. The reason is that the expert system is very methodical and always tries to go in the most promising direction. It can also perform as many iterations as is necessary.

Due to the powerful possibility of explanation, the user is constantly aware of the reasoning of the expert system. He also has full control on the actions to be taken. ESCALOS is counseling and assisting the user but does not do any change without his or her agreement. This is important so that the user understands the behavior of the model and the response of the watershed.

Modern simulation techniques can benefit from the integration of expert systems methodologies by extending the simulation models in areas such as reasoning by analogy and by providing an interactive user-support framework for systems administration.

Modern expert systems can benefit from the integration of simulation models by allowing the expert systems models to account for such things as dynamic (time-varying) parameter changes.

The integration of new expert systems and traditional simulation models is best achieved through the use of modern (commercial) expert systems shells because of the ability to develop rapid prototypes and interface with existing (and well accepted) software systems.

CHAPTER VIII

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Chapter IX

PROJECT STAFF

The project personnel was the following:

The principal investigators were:

Dr. J.W. Delleur, Professor of Hydraulic Engineering
Dr. M.H. Houck, Associate Professor of Civil Engineering
Dr. J.R. Wright, Assistant Professor of Civil Engineering

The graduate research assistants were:

C. Baffaut, doctoral student
D. Wood, master candidate

both in the Hydraulic and Systems Engineering Area of the School of Civil Engineering. Mr. S. Benabdallah, also a master student, was an extra labor student who assisted during the Spring Semester, 1987. All the graduate students involved in the project will continue further graduate studies.

APPENDIX A

RULES HIERARCHY

Through the rules hierarchy, one can see the reasoning that leads to the conclusion that the value of a parameter has to be increased or decreased. If an arc is joining two or more branches, it means that all conditions described in the branches have to be verified for the conclusion to be true. This represents an "AND" condition. Otherwise one of the conditions has to be true; it represents an "OR" condition.

A table of the names of the variables and their meanings is presented first to avoid any confusion during the reading of the hierarchy or the rules.

NAME OF THE VARIABLE	ABBREVIATION USED
impervious area percentage	impervious_area_percentage
slope	slope
characteristic width	char_length
depression storage for impervious area	stoimper
depression storage for pervious area	stoper
Manning's coefficient for impervious area	imperviousn
Manning's coefficient for pervious area	perviousn
first infiltration parameter maximum infiltration rate if Horton is used capillarity suction if Green Ampt is used	infmax
second infiltration parameter minimum infiltration rate if Horton is used Hydraulic conductivity if Green Ampt is used	infmin
third infiltration parameter infiltration decay rate if Horton is used moisture deficit if Green Ampt is used	infreg
percentage of impervious area that produces direct runoff (no depression) storage)	direct_runoff

NAME OF THE VARIABLE	ABBREVIATION USED
number of storms with overpredicted peaks	noswop
number of storms with underpredicted peaks	noswup
number of storms with overpredicted volumes	noswov
number of storms with underpredicted volumes	noswuv
status of the peaks: too low, too high, too soon	peaks
status of the volumes	volumes
diagnosis reached by the expert system	action

NAME OF THE VARIABLE	ABBREVIATION USED
type of buildup calculation	buildup_meth
code corresponding to the type of buildup calculation	bmeth_code
type of washoff calculation	washoff_calc
code corresponding to the type of washoff calculation	washoff_code
buildup deposition	func_dep
buildup deposition	func_dep
code corresponding to the dependence of the buildup deposition	funcdep_code
type of calculation of dust and dirt deposition for each land-use	buil_eqn
code corresponding to this type of buildup	buil_code
functional dependence for the deposition of dust and dirt	funcdep_code
load difference criteria	load_diff
status of the calibration	calib_done
diagnosis of the expert system	swmm_action, swmm_action1, user_action

NAME OF VARIABLE	ABBREVIATION USED
buildup limit of a pollutant	build_lim
buildup coefficient of a pollutant	build_coeff
buildup exponent of a pollutant	build_exp
washoff coefficient for a pollutant	washoff_coeff
washoff exponent for a pollutant	washoff_exp

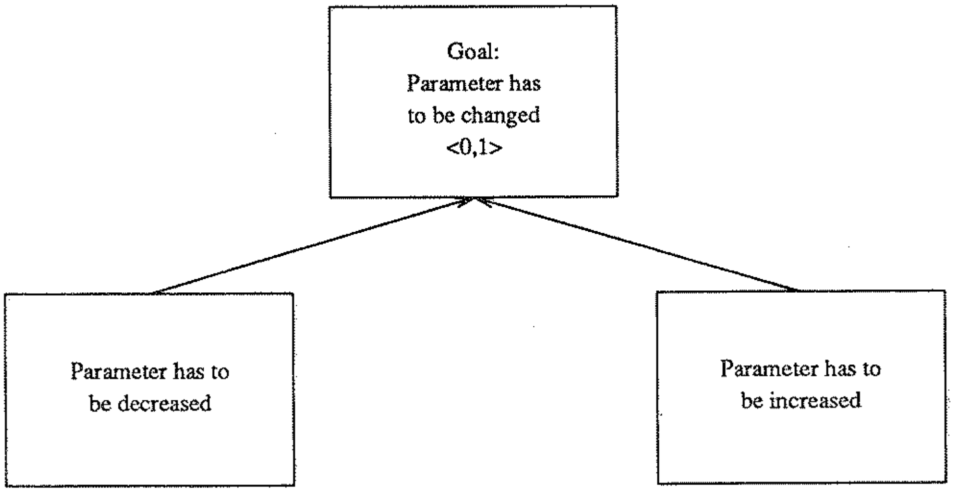

Figure A.1 **Parameter Change**

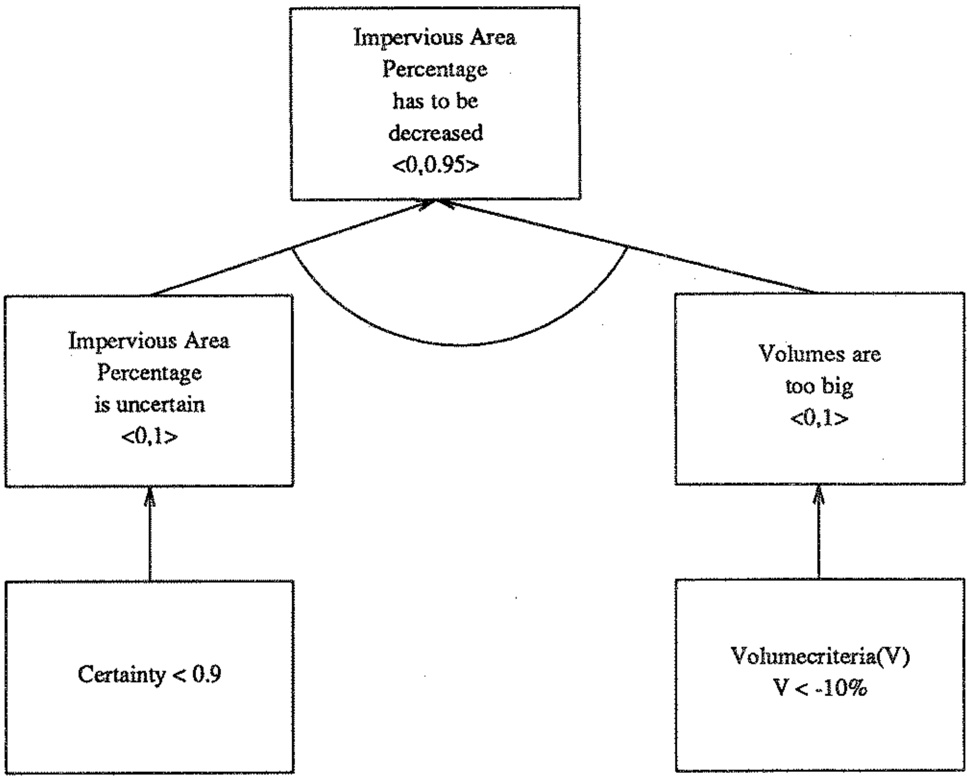

Figure A.2 **Decrease of the Impervious Area**

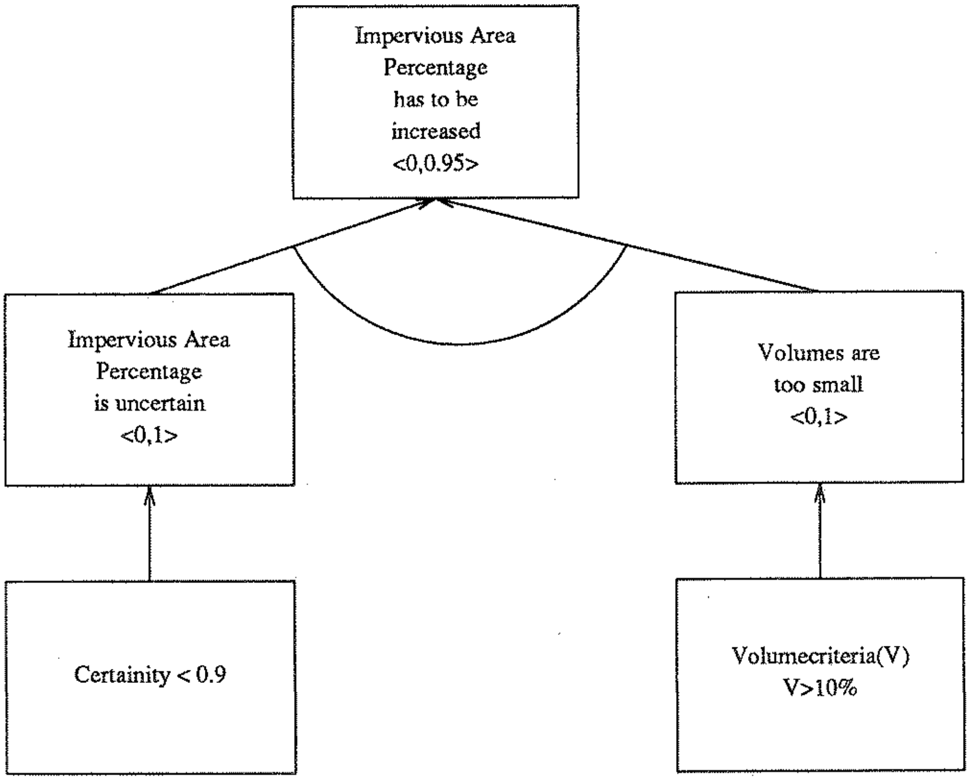

Figure A.3 **Increase of the Impervious Area**

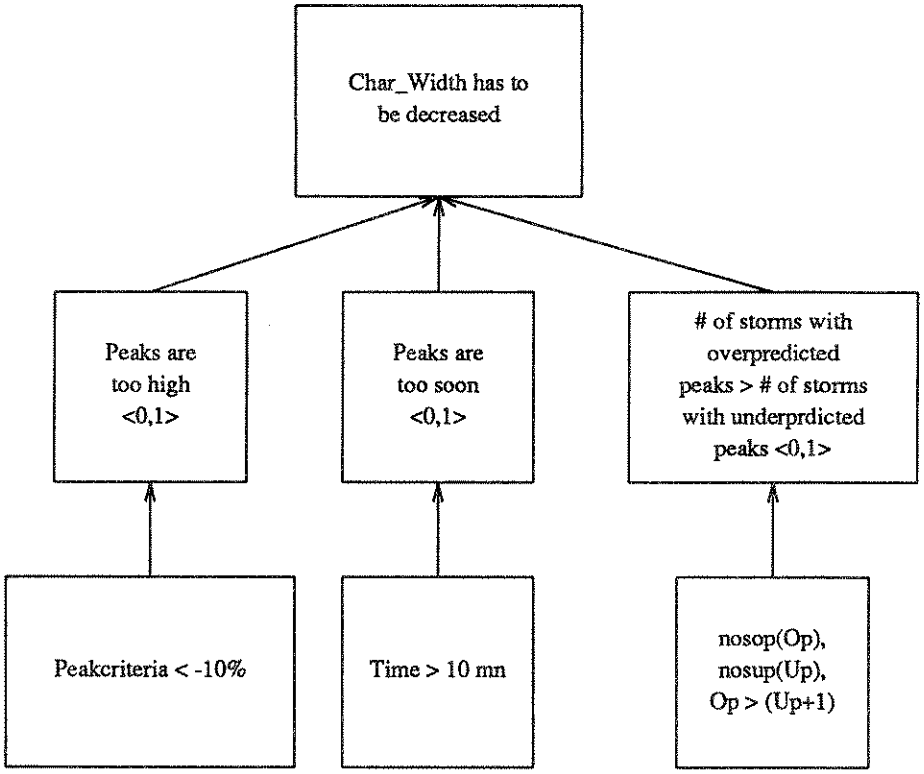

Figure A.4 **Decrease of the Characteristic Width**

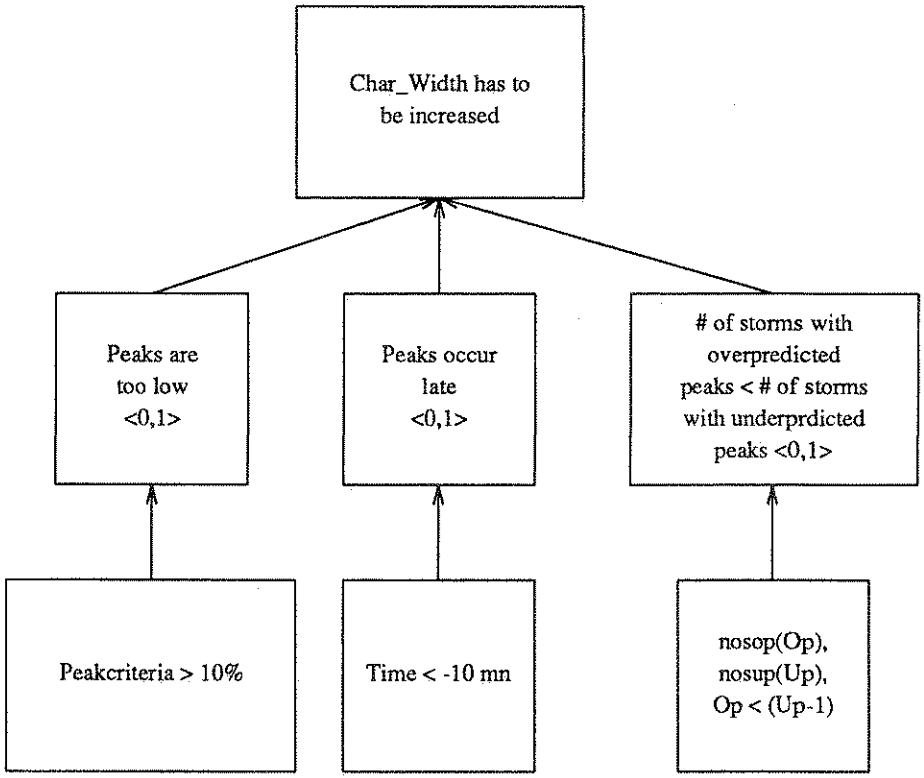

Figure A.5 **Increase of the Characteristic Width**

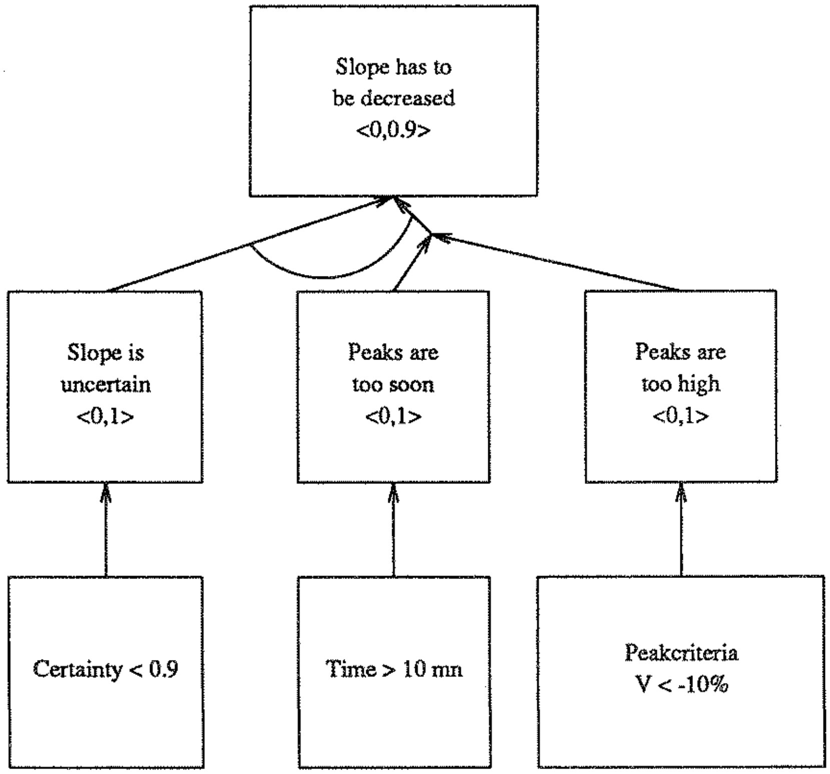

Figure A.6 Decrease of the Slope

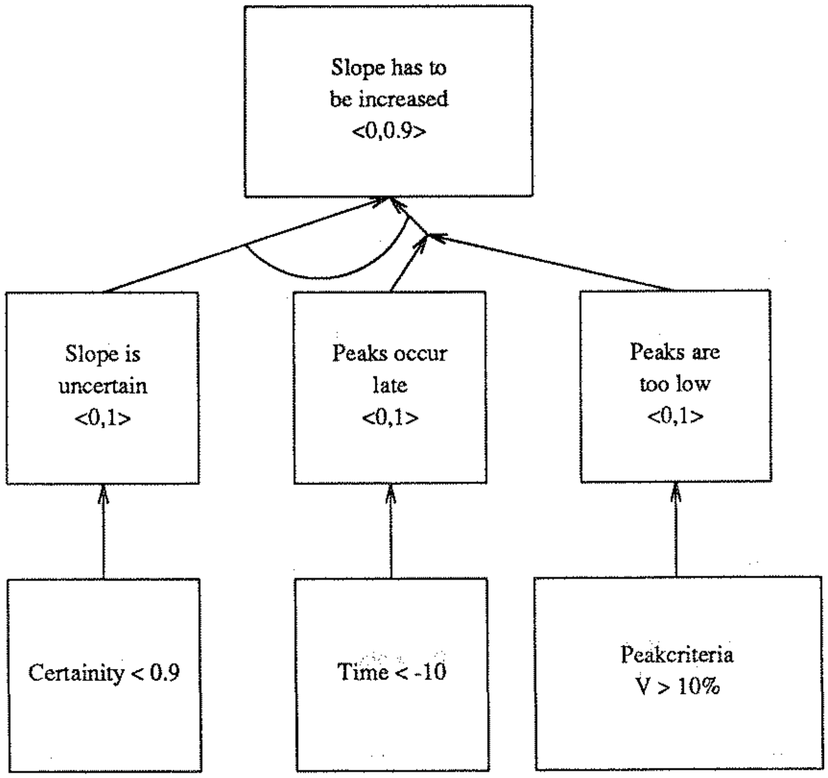

Figure A.7 Increase of the Slope

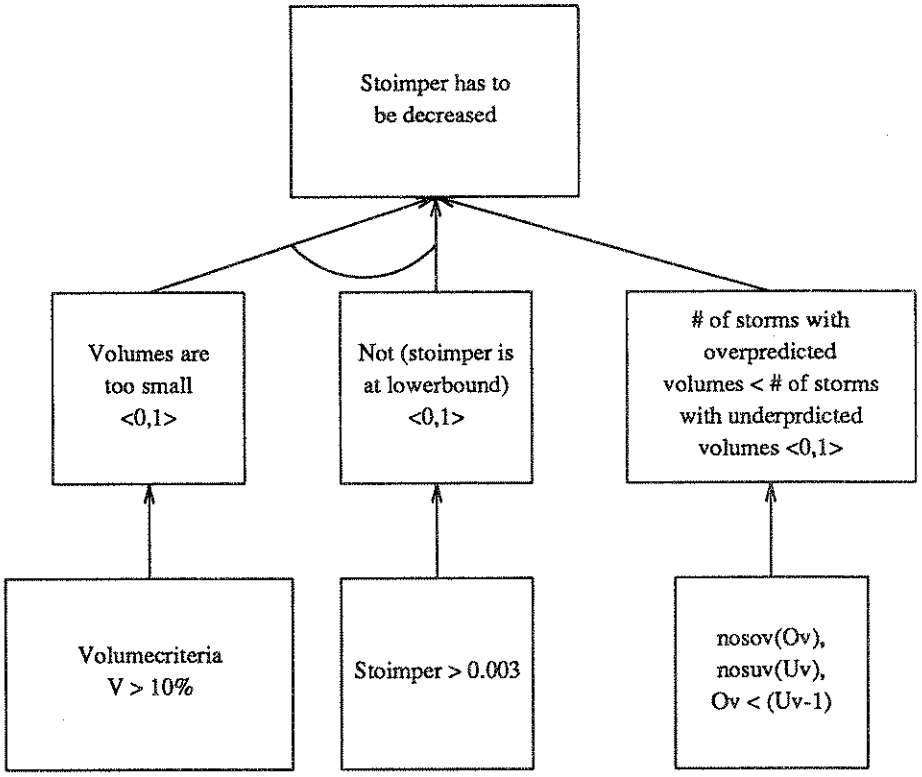

Figure A.8 Decrease of the Depression Storage for Impervious Area

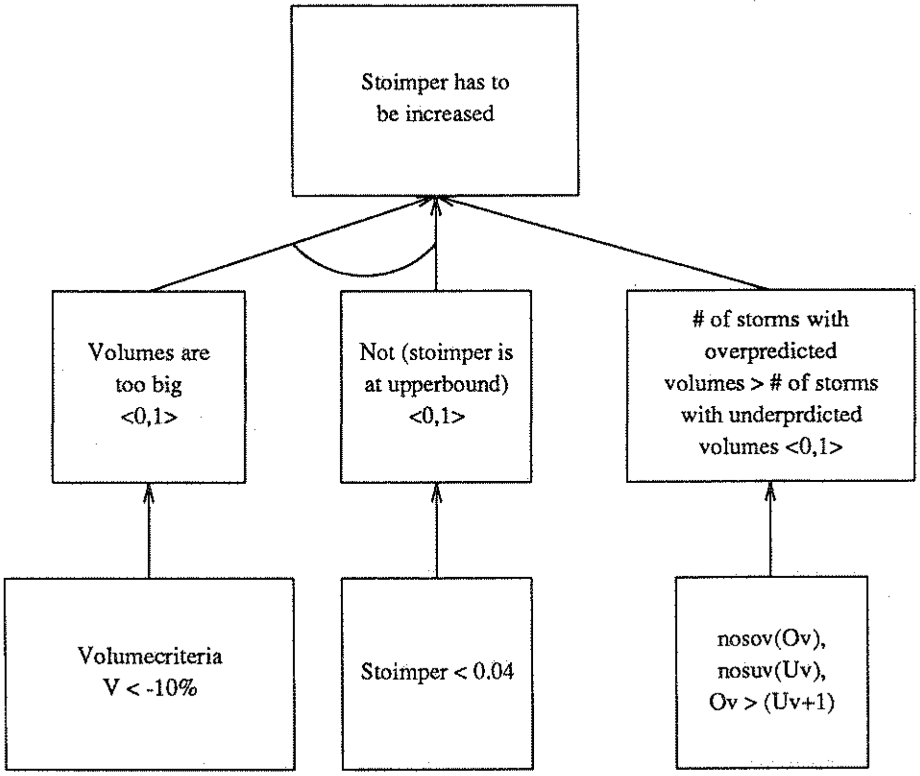

Figure A.9 Increase of the Depression Storage for Impervious Area

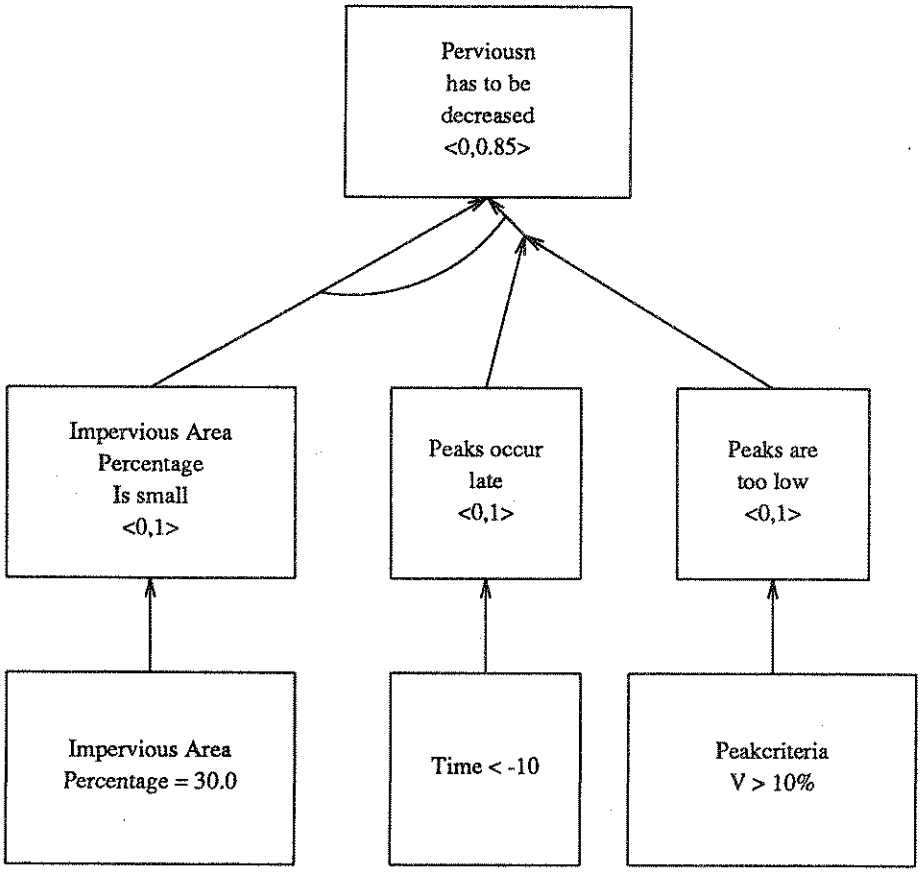

Figure A.10 Decrease of the Manning's Coefficient for Pervious Area

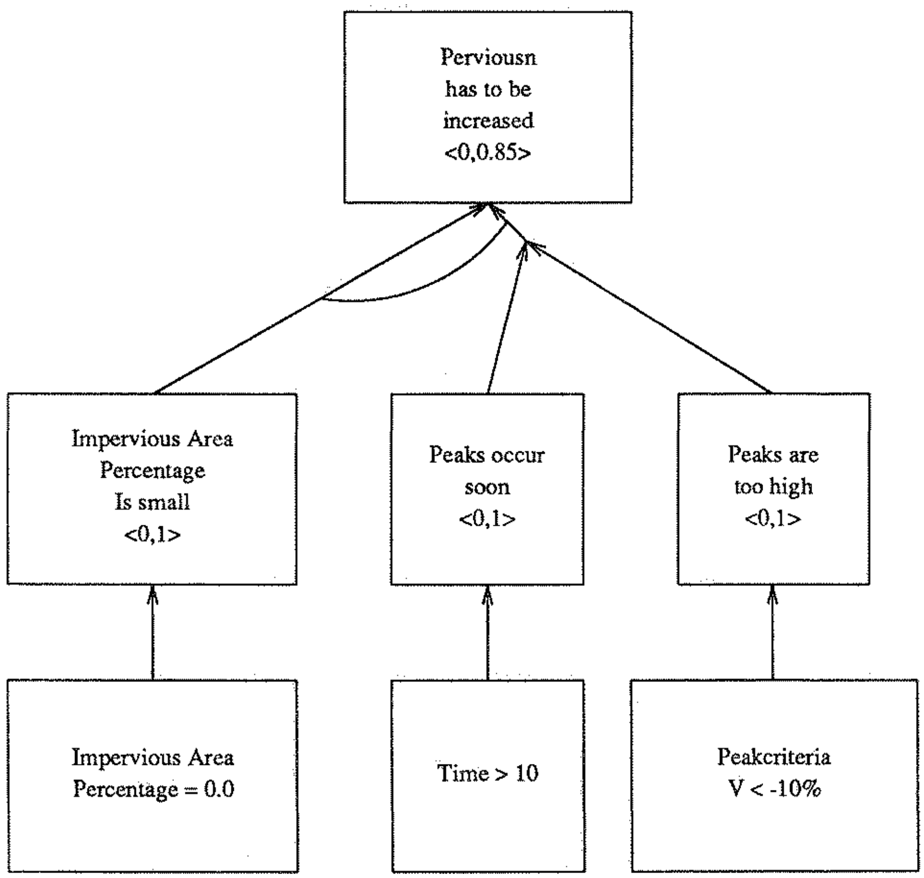

Figure A.11 Increase of the Manning's Coefficient for Pervious Area

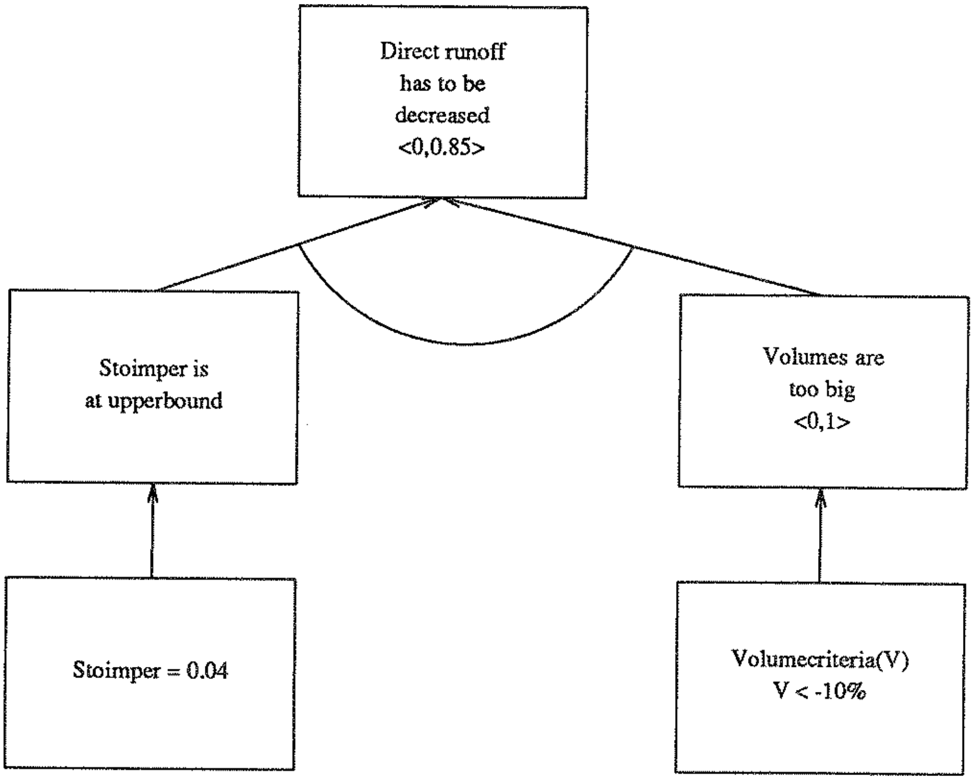

Figure A.12 Decrease of the Direct Runoff Percentage

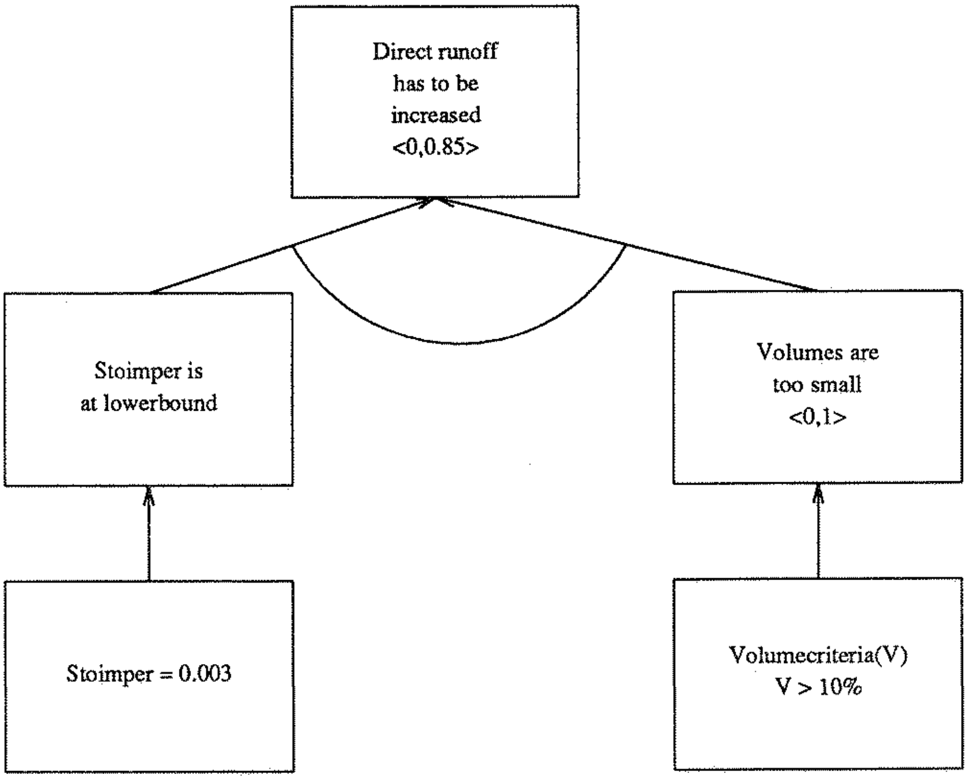

Figure A.13 Increase of the Direct Runoff Percentage

APPENDIX B

QUANTITY KNOWLEDGE BASE: The following program listing presents the quantity prototype knowledge base using the Knowledge Engineering System (KES) by Software A & E. This program was used to generate the sample user session presented as Appendix C.

```
constants:
   continuer: " ","Type ‘c’ to continue.".
   start again: " ","Type ‘nextcase’ to start again, or ‘stop’ to quit.".
   Swmmref: "Storm Water Management Model user’s manual".
%

text:
  The following text is used for a welcome banner to the system.
{welcome1:"   *******************************************************",
          "   *                                                     *",
          "   *                  PURDUE UNIVERSITY                  *",
          "   *             School of Civil Engineering             *",
          "   *  Department of Hydraulics and Systems Engineering   *",
          "   *                                                     *",
          "   *      #########################################      *",
          "   *      #                                       #      *",
          "   *      #               WELCOME                 #      *",
          "   *      #                  TO                   #      *",
          "   *      #                                       #      *",
          "   *      #               ESCALOS                 #      *",
          "   *      #                                       #      *",
          "   *      #  Expert Sys. for Calibration of SWMM  #      *",
          "   *      #                                       #      *",
          "   *      #########################################      *",
          "   *                                                     *",
          "   *      Copyright by Purdue University 1987.           *",
          "   *      All rights reserved.                           *",
          "   *******************************************************",
        "              Please Enter ’c’ To Continue                "}

{welcome2:"                                                          ",
          "**********************************************************",
          "*                                                        *",
          "*               ESCALOS HAS BEEN DEVELOPED               *",
          "*                                                        *",
          "*                         by                             *",
          "*                                                        *",
          "* Dr. Jacques W. Delleur  (Head of Hydr. and Sys. Eng.)  *",
          "* Dr. Mark H. Houck       (Professor of Water Res. Eng.) *",
          "* Dr. Jeff R. Wright      (Assoc. Professor of Sys. Eng.)*",
          "*                                                        *",
          "*                        and                             *",
          "*                                                        *",
          "* Ms. Claire Baffaut      (Research Associate)           *",
          "* Mr. Salah Benabdallah   (Research Assistant)           *",
          "* Mr. David Wood          (Research Assistant)           *",
          "*                                                        *",
          "**********************************************************",
          "                                                          ",
        "             Please Enter ’c’ To Continue :               "}

{welcome3:     "                                                     ",
               "*****************************************************",
               "*                                                   *",
               "*    Please Read All The Instructions Carefully.    *",
               "*                                                   *",
```

```
               "*    If You Need More Explanation of Any Input       *",
               "*    Variable, Just Enter 'e' at The Prompt.         *",
               "*                                                    *",
               "*    For Any Problems or Questions Please Call:      *",
               "*                                                    *",
               "*                  1-317-494-2171                    *",
               "*                                                    *",
               "*    ESCALOS is now ready to serve you. Good Luck.   *",
               "*                                                    *",
               "******************************************************",
               "                                                      ",
             "         Please Enter 'c' To Continue :            "}

{header:    "                                                         ",
            "                                                         ",
            "################=====   ESCALOS   =====################"}
%
attributes:
 INPUT ATTRIBUTES

         iqual: int.
         quantity: sgl(YES, NO)
   {question: "DID YOU ALREADY CALIBRATE QUANTITY FOR THIS PROBLEM ?"}.

         quality: sgl(YES, NO)
   {question: "DO YOU WANT TO CALIBRATE QUALITY ?"}.

         file: sgl(YES,NO)
   {question: "HAVE YOU PREVIOUSLY INPUT THE QUANTITY DATA ?"}.

         nucat: int
   {question: "WHAT IS THE NUMBER OF SUBCATCHMENTS ON YOUR SITE ?"}.

         nupipe: int
{question: "HOW MANY PIPES AND/OR GUTTER DO YOU WANT TO SIMULATE WITH ?"}.

           infmethod: sgl(Green_Ampt method
    {explain: "Green-Ampt method :                                        ",
              "The original equation was developped in 1911 and it       ",
            "was originally for infiltration with excess water at       ",
              "the surface at all time.  Mein and Larson showed how      ",
              "it could be adapted to a steady rainfall input and        ",
              "proposed a way in which the capillarity suction parameter ",
              "could be determined. In 1978, Chu showed the applicability ",
              "of the equation to unsteady rainfall. SWMM uses the equation",
              "by Mein and Larson. It is a two stage model. the first step ",
              "predicts the amount of water that will infiltrate in the  ",
              "ground before the surface becomes saturated.Then, the     ",
              "infiltration capacity is predicted.                       ",
              "reference: Storm Water Management Model user's manual     "},
                          Horton method
    {explain: "Horton method :                                            ",
              "Horton equation was developped in 1940. It predicts       ",
              "infiltration capacity as a exponential function of the time.",
              "                                                          ",
            "        Fp = Finf + (F0 - Finf) exp(-at)                  ",
              "                                                          ",
            "     Fp   : infiltration capacity into the soil          ",
            "     Finf : minimum or ultimate infiltration capacity    ",
            "     F0   : maximum or initial infiltration capacity     ",
            "     t    : time from the begining of storm              ",
            "     a    : decay coefficient                            ",
              "reference: Storm Water Management Model user's manual     "})
    {question: "DO YOU WANT TO SIMULATE INFILTRATION PROCESS WITH"}.

           infilm: int.
           area: real.
```

```
        char_length: real.
        overland_flow: real.
        impervious_area_percentage: real.
        prob1: real.
        slope: real.
        prob2: real.
        perviousn: real.
        imperviousn: real.
        stoimper: real.
        stoper: real.
        infmax: real.
        infmin: real.
        infreg: real.
        t: real.
        v: real.
        p: real.
        e: real.
        nosop: real.
        nosup: real.
        nosov: real.
        nosuv: real.

VARIABLES SUM OF ALL VARIABLES.
        tsuma :real.   Temporary sum of areas.
        suma :real.     of areas.
        tsuml : real.  Temporary sum of lengths.
        suml :real.     of lengths.
        tsumi : real.  Temporary sum of imperv. area. perc.
        sumi : real.    of imperv. area. perc.
        tsump1 : real. Temporary sum of prob. of imper. area. perc.
        sump1 : real.   of prob. of imper. area. perc.
        tsums : real.  Temporary sum of slopes.
        sums : real.    of slopes.
        tsump2 : real. Temporary sum of prob.
        sump2 : real.   of prob. of slopes.
        tsump : real.  Temporary sum of perviousn.
        sump : real.    of perviousn.
        tsumip : real. Temporary sum of imperviousn.
        sumip  : real.  of imperviousn.
        tsumst : real. Temporary sum of stoimper.
        sumst  : real.  of stoimper.
        tsumstp : real.Temporary sum of stoper.
        sumstp : real.  of stoper.
        tsumix : real. Temporary sum of infmax.
        sumix : real.   of infmax.
        tsumin : real. Temporary sum of infmin.
        sumin : real.   of infmin.
        tsumif : real. Temporary sum of infreg.
        sumif : real.  of infreg.

        operamenu: sgl( Char_length, Slope,
                        Impervious_area_percentage, Stoimper,
                        Stoper, Perviousn, Imperviousn,
                        Infmax, Infmin, Infreg)
     {question: " ","WHICH PARAMETER DO YOU WANT CHANGE ? "}.

         minchar_length: real
          {question: "Please Enter the Minimum Value of The Characteristic",
                     "Length of The Subcatchment (feet)."}.

         maxchar_length: real
          {question: "Please Enter the Maximum Value of The Characteristic",
                     "Length of The Subcatchment (feet)."}.

         minslope: real
        {question: "Please Enter the Minimum Value of The Slope (ft/ft)."}.
```

```
 maxslope: real
{question: "Please Enter the Maximum Value of The Slope (ft/ft)."}.

 minimp: real
 [constraint: minimp ge 0 and minimp le 100]
{question: "Please Enter the Minimum Value of The ",
           "Impervious Area Percentage."}.

 maximp: real
 [constraint: maximp ge 0 and maximp le 100 ]
{question: "Please Enter the Maximum Value of The ",
           "Impervious Area Percentage."}.

 minstoimper: real
{question: "Please Enter the Minimum Value of the Depression",
           "Storage for Impervious Area"}.

 maxstoimper: real
{question: "Please Enter the Maximum Value of the Depression",
           "Storage for Impervious Area"}.

 minstoper: real
{question: "Please Enter the Minimum Value of the Depression",
           "Storage for Pervious Area"}.

 maxstoper: real
{question: "Please Enter the Maximum Value of the Depression",
           "Storage for Pervious Area"}.

 minperviousn: real
{question: "Please Enter the Minimum Value of the Mannings",
           "Coefficients for Pervious Area"}.

 maxperviousn: real
{question: "Please Enter the Maximum Value of the Mannings",
           "Coefficients for Pervious Area"}.

 minimperviousn: real
{question: "Please Enter the Minimum Value of the Mannings",
           "Coefficients for Impervious Area"}.

 maximperviousn: real
{question: "Please Enter the Maximum Value of the Mannings",
           "Coefficients for Impervious Area"}.

 mininfmax: real
{question: "Please Enter the Minimum Value of the First",
           "Infiltration Parameter"}.

 maxinfmax: real
{question: "Please Enter the Maximum Value of the First",
           "Infiltration Parameter"}.

 mininfmin: real
{question: "Please Enter the Minimum Value of the Second",
           "Infiltration Parameter"}.

 maxinfmin: real
{question: "Please Enter the Maximum Value of the Second",
           "Infiltration Parameter"}.

 mininfreg: real
{question: "Please Enter the Minimum Value of the Third",
           "Infiltration Parameter"}.

 maxinfreg: real
{question: "Please Enter the Maximum Value of the Third",
```

```
                      "Infiltration Parameter"}.

        counter: int.    Counter for number of subcatchments
        temp: int.       Temporary for recursion in number of subcatchments
INFERRED ATTRIBUTES.

           action: mlt( char_length_has_to_be_increased,
                        char_length_has_to_be_decreased,
                        impervious_area_percentage_has_to_be_increased,
                        impervious_area_percentage_has_to_be_decreased,
                        stoimper_has_to_be_increased,
                        stoimper_has_to_be_decreased,
                        slope_has_to_be_increased,
                        slope_has_to_be_decreased,
                        direct_runoff_has_to_be_increased,
                        direct_runoff_has_to_be_decreased,
                        perviousn_has_to_be_increased,
                        perviousn_has_to_be_decreased,
                        calibration_is_done).

           scertanity: sgl( slope_is_uncertain).

           icertanity: sgl( impervious_area_percentage_is_uncertain).

           nump: sgl( noswop_lt noswup, noswop_gt noswup).

           numv: sgl( noswov_lt noswuv, noswov_gt noswuv).

           peaks: sgl( peaks_are_too_high, peaks_occur_soon,
                       peaks_are_too_low, peaks_occur_late,
                       peaks_simulation_is_obtained,
                       peaks_time_simulation_is_obtained).

           volumes: sgl( volumes_are_too_small, volumes_are_too_big,
                         volumes_simulation_is_obtained).

           justification: sgl(Yes,No)
       {question: "Would You Like To See The Supporting Sources :"}.
           criteria: sgl(Yes,No)
       {question: "Would You Like To See The Values of Criteria :"}.
%
 INPUTATTRIBUTES FOR SUBCATCHMENT RULES.

classes:
     subcatchments:
     attributes:


         idsubc: int
   [constraint: idsubc ge 1 and idsubc le 99]
   {question: "WHAT IS THE ID OF THE SUBCATCHEMENT ?"}.

         idpipe: int
   [constraint: idpipe ge 1 and idpipe le 999]
   {question: "WHAT IS THE ID DRAINING MANHOLE OR GUTTER/PIPE?"}
   {explain: "Integer between 1 and 999 used to identify the inlet,",
             "preferably different from the subcatchment."}.

         areac: real
   {question: "WHAT IS THE TOTAL AREA OF THE MODELIZED CATCHMENT (acres) ?"," "}
   {explain: " The total volume of runoff is dependant of the area",
             "of the catchment."}.

    char_lengthc: real
   {question: "WHAT IS YOUR ESTIMATION OF THE CHARACTERISTIC LENGTH ",
              "OF THE SUBCATCHMENT (feet) ? "}
   {explain: "The characteristic length of the subcatchment has an effect",
```

```
             "on the shape and on the storage. Smaller is the width, more",
             "water is stored and lesser will be peak."}.

          overland_flowc: real
   {question: "WHAT IS THE AVERAGE LENGTH OF OVERLAND FLOW? (IN CASE OF A",
              "RECTANGULAR SUBCATCHMENT IT IS HALF OF ITS PHYSICAL WIDTH.)"}
   {explain: "The caracteristic length of the catchment can be estimated",
             "with the quotient of its area by the average length of",
             "overland flow."}.

          impervious_area_percentagec: real
[constraint: impervious_area_percentagec ge 0 and impervious_area_percentagec
                le 100]
   {question: "WHAT IS THE PERCENTAGE OF IMPERVIOUSNESS ?"}
   {why: "Since the parameters such as depression storage or",
         "mannings coefficients are given for pervious and",
         "impervious areas we need to know the area of impervious",
         "surface."}.

         prob1c: real
         [constraint: prob1c ge 0 and prob1c le 1]
   {question: "WHAT IS YOUR CERTAINITY ABOUT THE PERCENTAGE ",
              "OF IMPERVIOUSNESS VALUE?"}.

           slopec: real
    {question: "WHAT IS THE AVERAGE SLOPE ALONG THE PATHWAY OF",
               "OVERLANDFLOW TO INLET LOCATIONS (ft/ft)?"}
    {explain: "The time of the peaks will depend on the slope. "}.

         prob2c: real
         [constraint: prob2c ge 0 and prob2c le 1]
   {question: "WHAT IS YOUR CERTAINITY ABOUT THE AVERAGE ",
              "SLOPE VALUE ?"}.

           perviousnc: real
    {question: "WHAT IS THE MANNINGS COEFFICIENTS FOR PERVIOUS AREA ?",
              "Proposed values:",
              "                  0.2 for light turf,",
              "                  0.3 for dense turf,",
              "                  0.4 for dense shrubbey and forest litter."}
    {explain: "This is a parameter whose time of peak depends on."," "}.

           imperviousnc: real
    {question: "WHAT IS THE MANNINGS COEFFICIENT FOR IMPERVIOUS AREA ?",
              "Proposed values:",
              "                  0.012 for smooth asphalt",
              "                  0.014 for asphalt or concrete",
              "                  0.03 for packed clay."}
    {explain: "This is a parameter whose time of peak depends on."," "}.

           stoimperc: real
    {question: "WHAT IS THE VALUE OF DEPRESSION STORAGE FOR IMPERVIOUS",
               "AREA ?","       [Proposed value: 0.018]"}.

           stoperc: real
    {question: "WHAT IS THE VALUE OF DEPRESSION STORAGE FOR PERVIOUS",
               "AREA ?","       [Proposed value: 0.03]"}.


           infmaxc: real.

           infmax0: real
    {question: "WHAT IS THE MAXIMUM INFILTRATION RATE (in/hr) ? For",
               "different single events, choose an average initial",
               "infiltration rate, it will depend on the moisture content",
               "and the type of soil.",
               "For more explanation type 'e'."}
```

```
  {explain: "Proposed values:",
             "1-Dry Soils with little or no vegetation:",
             "      group A : sandy soils : 5 in/hr    ",
             "      group B : loam soils  : 3 in/hr    ",
             "      group C : loam soils  : 3 in/hr    ",
             "      group D : clay soils  : 1 in/hr    ",
             " ",
             "2-Dry Soils with dense vegetation : multiply values",
             "                                    for dry soils by 2.",
             " ",
             "3-Moist Soils :",
             "  1- drained but not dried out : divide values for dry",
             "                                 soils by 3.",
             "  2- close to saturation : choose values close to minimum ",
             "                           infiltration.",
             "  3- soils who have partially dried out : divide values for",
             "                                          dry soils by 2."}.

         infmaxl: real
{question: "WHAT IS THE VALUE OF THE CAPILLARITY SUCTION (inches) ?",
           "Proposed Values:",
           "                 group A : sand        :  4 inches",
           "                 group B : sandy loam  :  8 inches",
           "                           silt loam   : 12 inches",
           "                           loam        :  8 inches",
           "                 group C : clay loam   : 10 inches",
           "                 group D : clay        :  7 inches"}.

         infminc: real.

         infmin0: real
 {question: "WHAT IS THE MINIMUM INFILTRATION RATE (in/hr)?",
            "Proposed Values :",
            "   soil group A (most pervious)  : between 0.45 and 0.30 in/hr",
            "   soil group B                  : between 0.30 and 0.15 in/hr",
            "   soil group C                  : between 0.15 and 0.05 in/hr",
            "   soil group D (most impervious): between 0.05 and 0.001 in/hr",
            " "}.

         infminl: real
 {question: "WHAT IS THE VALUE OF HYDRAULIC CONDUCTIVITY (in/hr) ?",
            "Proposed Values :",
            "   soil group A (most pervious)  : between 0.45 and 0.30 in/hr",
            "   soil group B                  : between 0.30 and 0.15 in/hr",
            "   soil group C                  : between 0.15 and 0.05 in/hr",
            "   soil group D (most impervious): between 0.05 and 0.001 in/hr",
            " "}.

         infregc: real.

         infreg0: real
 {question: "WHAT IS THE INFILTRATION DECAY RATE (1/sec) ?",
            "Proposed value: 0.00115",
            "[This means that the infiltration capacity will fall",
            "98% toward its minimum value during the first hour]"}.

         infregl: real
 {question: "WHAT IS THE VALUE OF THE MOISTURE DEFICIT ",
            "(volume air/volume voids) ? ",
            "Proposed Values:",
            "                 group A : sand        : 0.34",
            "                 group B : sandy loam",
            "                           silt loam   : 0.32",
            "                           loam",
            "                 group C : sandy clay loam",
            "                           clay loam   : 0.25",
            "                 group D : clay        : 0.21"}.
```

```
        %
endclass.
 GUTTER/PIPE INFORMATION.
    gutter_pipe:
    attributes:


        id_of_the_gutter_or_pipe: int
    {question: "WHAT IS THE ID OF THE GUTTER/PIPE ? "}
    {explain: "Integer used to identify the pipe, preferably different from",
              "the subcatchment id and inlet id"}.

        id_of_the_draining gutter_or_pipe_or_manhole: int
    {question: "WHAT IS THE ID OF THE DRAINING GUTTER/PIPE OR MANHOLE ?"}
    {explain: "Integer used to identify pipe or manhole where the water",
              "will flow into"}.

        shape: int
    {question: "WHAT IS THE SHAPE OF THE GUTTER/PIPE ?    ",
               "   1 : for gutter (trapezoidal channel)   ",
               "   2 : for circular pipes                 ",
               "   3 : for dummy gutter (inflow = outflow)"}.

        diameter: real.

        diameter1: real
     {question: "WHAT IS THE BOTTOM WIDTH OF THE CHANNEL (ft) ?"}.

        diameter2: real
     {question: "WHAT IS THE DIAMETER OF THE PIPE (ft) ?"}.

        length: real
    {question: "WHAT IS THE LENGTH OF THE GUTTER OR PIPE (ft) ?"}.

        slopep: real
    {question: "WHAT IS THE SLOPE OF THE GUTTER/PIPE (ft/ft) ?"}.

        left_side_slope: real
  {question: "WHAT IS THE SLOPE OF THE LEFT HAND-SIDE OF THE CHANNEL (ft/ft)?"}.

        right_side_slope: real
 {question: "WHAT IS THE SLOPE OF THE RIGHT HAND-SIDE OF THE CHANNEL (ft/ft)?"}.

        manning_coefficient: real
  {question: "WHAT IS THE MANNING COEFFICIENT OF THE GUTTER/PIPE ? "}.

        depth_when_flowing_full: real
  {question: "WHAT IS THE OF THE GUTTER WHEN FLOWING FULL (ft) ?"}.

   %
endclass.
%
externals:
             class: [program: "class"].
             clear: [program: "clear"].
             datafile: [program: "makefiles"].
             datainput: [program: "trans"].
             header: [program: "header"].
             model: [program: "swm"].
             operate: [program: "operate"].
             optimize: [program: "optimize"].
             qualityfile: [program: "kesr /x/swmm/QUAL/swmmqual"].
             remove1: [program:"rm transit1"].
             remove2: [program:"rm transit2"].

%
```

```
rules:


rule1: if
 P = peakcriteria
          p lt -10
       then
          peaks = peaks_are_too_high <1.0>.
       endif.

rule2: if
 T = timecriteria
          t gt 10
       then
          peaks = peaks_occur_soon <1.0>.
       endif.

rule char_length_has_to_be_decreased :
       if
          peaks = peaks_occur_soon or
          peaks = peaks_are_too_high
       then
          action = char_length_has_to_be_decreased <0.9>.
       endif.

rule4: if
 P = peakcriteria
          p gt 10
       then
          peaks = peaks_are_too_low <1.00>.
       endif.

rule5: if
 T = timecriteria
         t lt -10
      then
         peaks = peaks_occur late <1.0>.
      endif.

rule6: if
          peaks = peaks_are_too_low or
          peaks = peaks_occur late
       then
          action = char_length_has_to_be_increased <0.9>.
       endif.

rule7: if
             probl lt 0.9
        then
          icertanity = impervious_area_percentage_is_uncertain.
        endif.

rule8:   if
             prob2 lt 0.9
        then
          scertanity = slope_is_uncertain.
        endif.

rule9: if
 V = volumecriteria
          v gt 10
       then
          volumes = volumes_are_too_small <1.0>.
       endif.

rule10: if
          icertanity = impervious_area_percentage_is_uncertain and
```

```
          volumes = volumes_are_too_small
       then
        action = impervious_area_percentage_has_to_be_increased <0.95>.
       endif.

rule11: if
 v = volumecriteria
          v lt -10
        then
           volumes = volumes_are_too_big <1.0>.
        endif.

rule impervious_area_percentage_has_to_be_decreased :
        if
          icertanity = impervious_area_percentage_is_uncertain and
          volumes = volumes_are_too_big
        then
         action = impervious_area_percentage_has_to_be_decreased <0.95>.
        endif.

rule13: if
           volumes = volumes_are_too_small and
           stoimper gt 0.003
        then
           action = stoimper_has_to_be_decreased <0.85>.
        endif.

rule14: if
           volumes = volumes_are_too_big and
           stoimper lt 0.04
        then
           action = stoimper_has_to_be_increased <0.85>.
        endif.

rule15: if
           stoimper = 0.003 and
           volumes = volumes_are_too_small
        then
           action = direct_runoff_has_to_be_increased <0.85>.
        endif.

rule16: if
           stoimper = 0.04 and
           volumes = volumes_are_too_big
        then
           action = direct_runoff_has_to_be_decreased <0.85>.
        endif.

rule17: if
           scertanity = slope_is_uncertain and
           peaks = peaks_are_too_low or
           peaks = peaks_occur late
        then
           action = slope_has_to_be_increased <0.9>.
        endif.

rule slope_has_to_be_decreased :
        if
           scertanity = slope_is_uncertain and
           peaks = peaks_are_too_high or
           peaks = peaks_occur_soon
        then
           action = slope_has_to_be_decreased <0.9>.
        endif.

rule19: if
           impervious_area_percentage = 0 and
```

```
           peaks = peaks_are_too_high or
           peaks = peaks_occur_soon
        then
           action = perviousn_has_to_be_increased <0.75>.
        endif.

rule20: if
           impervious_area_percentage = 0 and
           peaks = peaks_are_too_low or
           peaks = peaks_occur late
        then
           action = perviousn_has_to_be_decreased <0.75>.
        endif.

rule21: if
           nosop lt (nosup-1)
        then
           nump = noswop_lt noswup <1.0>.
              noswop = number of storms with overpredicted peaks
              noswup = number of storms with underpredicted peaks
        endif.

rule22: if
           nosop gt (nosup+1)
        then
           nump = noswop_gt noswup <1.0>.
              noswop = number of storms with overpredicted peaks
              noswup = number of storms with underpredicted peaks
        endif.

rule23: if
           nosov lt (nosuv-1)
        then
           numv = noswov_lt noswuv <1.0>.
             noswov = number of storms with overpredicted volumes
             noswuv = number of storms with underpredicted volumes
        endif.

rule24: if
           nosov gt (nosuv+1)
        then
           numv = noswov_gt noswuv <1.0>.
             noswov = number of storms with overpredicted volumes
             noswuv = number of storms with underpredicted volumes
        endif.
rule25: if
           nump = noswop_lt noswup
              noswop = number of storms with overpredicted peaks
              noswup = number of storms with underpredicted peaks
        then
           action = char_length_has_to_be_increased <0.8>.
        endif.

rule26: if
           nump = noswop_gt noswup
              noswop = number of storms with overpredicted peaks
              noswup = number of storms with underpredicted peaks
        then
           action = char_length_has_to_be_decreased <0.8>.
        endif.

rule27: if
           numv = noswov_lt noswuv
             noswov = number of storms with overpredicted volumes
             noswuv = number of storms with underpredicted volumes
        then
           action = stoimper_has_to_be_decreased <0.9>.
```

```
        endif.

rule stoimper_has_to_be_increased :
        if
           numv = noswov_gt noswuv
              noswov = number of storms with overpredicted volumes
              noswuv = number of storms with underpredicted volumes
        then
           action = stoimper_has_to_be_increased <0.9>.
        endif.

rule29: if
           v ge -10 and v le 10
        then
           volumes = volumes_simulation is obtained.
        endif.

rule30: if
           p ge -10 and p le 10
        then
           peaks = peaks_simulation_is_obtained.
        endif.

rule31: if
           t ge -10 and t le 10
        then
           peaks = peaks_time_simulation_is_obtained.
        endif.

rule32: if
           volumes = volumes_simulation is obtained and
           peaks = peaks_simulation_is_obtained and
           peaks = peaks_time_simulation_is_obtained
        then
           action = calibration is done.
        endif.
%
actions:
display attach welcome1 of kb.
break.
run clear.
display attach welcome2 of kb.
break.
run clear.
display attach welcome3 of kb.
break.
run clear.
display attach header of kb.
obtain quantity.
    if quantity = NO
       then iqual = 0.
obtain file.
   if file = YES
      then read "data.quantity", nucat, nupipe, infilm,
          subcatchments, subcatchments(idsubc, idpipe, areac, char_lengthc,
          impervious_area_percentagec, slopec, perviousnc, imperviousnc,
          stoimperc, stoperc, infmaxc, infminc, infregc),
          suma, suml, sumi, sump1, sums, sump2, sump, sumip, sumst, sumstp,
          sumix, sumin, sumif,
          gutter_pipe, gutter_pipe(id_of_the_gutter_or_pipe,
          id_of_the_draining gutter_or_pipe_or_manhole,
          shape, diameter, length, slopep, left_side_slope,
          right_side_slope, manning_coefficient,
          depth_when_flowing_full).
*** WRITING THE DATA IN transit.quantity ********
         message file ="transit.quantity",
                combine(iqual),
```

```
                    combine(nucat),
                    combine(infilm),
                    combine(nupipe).
            forall x: subcatchments do
              message file ="transit.quantity",
                      combine(x>idsubc),
                      combine(x>idpipe),
                      combine(x>areac),
                      combine( x>char_lengthc),
                      combine(x>impervious_area_percentagec),
                      combine(x>slopec),
                      combine(x>imperviousnc),
                      combine(x>perviousnc),
                      combine(x>stoimperc),
                      combine(x>stoperc),
                      combine(x>infmaxc),
                      combine(x>infminc),
                      combine(x>infregc).
            endforall.

            forall x: gutter_pipe do
              message file = "transit.quantity",
                      combine(x>id_of_the_gutter_or_pipe),
                      combine(x>id_of_the_draining gutter_or_pipe_or_manhole),
                      combine(x>shape),
                      combine(x>diameter),
                      combine(x>length),
                      combine(x>slopep),
                      combine(x>left_side_slope),
                      combine(x>right_side_slope),
                      combine(x>manning_coefficient),
                      combine(x>depth_when_flowing_full).
            endforall.
        else
obtain nucat.
obtain nupipe.
message file = "classin",
        combine(nucat),
        combine(nupipe).
obtain infmethod.
  if infmethod = Horton method
     then infilm = 0.
  else
          infilm = 1.
  endif.
message file ="transit.quantity",
        combine(iqual),
        combine(nucat),
        combine(infilm),
        combine(nupipe).
message continuer.
break.
run clear.
suma = 0.
suml = 0.
sumi = 0.
sumpl = 0.
sums = 0.
sump2 = 0.
sump = 0.
sumip = 0.
sumst = 0.
sumstp = 0.
sumix = 0.
sumin = 0.
sumif = 0.
      run class.
```

```
      read "classout", subcatchments, gutter_pipe.
      write "subcat.no",subcatchments.
message " ","***** Please Enter The Data For Each Subcatchement *****"," ".
      forall x: subcatchments do
             obtain x>idsubc.
             obtain x>idpipe.
             obtain x>areac.
             tsuma = suma.
             erase suma.
             suma = tsuma + x>areac.
             erase tsuma.
             obtain x>char_lengthc.
                   if status(x>char_lengthc) = unknown
             then
               obtain x>overland_flowc.
               x>char_lengthc = x>areac/x>overland_flowc.
             endif.
                   tsuml = suml.
             erase suml.
             suml = tsuml + x>char_lengthc.
             erase tsuml.
                   obtain x>impervious_area_percentagec.
             tsumi = sumi.
             erase sumi.
             sumi = tsumi + x>impervious_area_percentagec.
             erase tsumi.
                   obtain x>problc.
             tsumpl = sumpl.
             erase sumpl.
             sumpl = tsumpl + x>problc.
             erase tsumpl.
                    obtain x>slopec.
             tsums = sums.
             erase sums.
             sums = tsums + x>slopec.
             erase tsums.
                    obtain x>prob2c.
             tsump2 = sump2.
             erase sump2.
             sump2 = tsump2 + x>prob2c.
             erase tsump2.

             obtain x>perviousnc.
             tsump = sump.
             erase sump.
             sump = tsump + x>perviousnc.
             erase tsump.
                     obtain x>imperviousnc.
             tsumip = sumip.
             erase sumip.
             sumip = tsumip + x>imperviousnc.
             erase tsumip.
                     obtain x>stoimperc.
             tsumst = sumst.
             erase sumst.
             sumst = tsumst + x>stoimperc.
             erase tsumst.
                    obtain x>stoperc.
             tsumstp = sumstp.
             erase sumstp.
             sumstp = tsumstp + x>stoperc.
             erase tsumstp.
                    if infmethod = Horton method
             then
                 obtain x>infmax0.
                 x>infmaxc = x>infmax0.
                 tsumix = sumix.
```

```
                 erase sumix.
                 sumix = tsumix + x>infmaxc.
                 erase tsumix.
                 obtain x>infmin0.
                 x>infminc = x>infmin0.
                 tsumin = sumin.
                 erase sumin.
                 sumin = tsumin + x>infminc.
                 erase tsumin.
                 obtain x>infreg0.
                 x>infregc = x>infreg0.
                 tsumif = sumif.
                 erase sumif.
                 sumif = tsumif + x>infregc.
                 erase tsumif.

             else
                 obtain x>infmax1.
                 x>infmaxc = x>infmax1.
                 tsumix = sumix.
                 erase sumix.
                 sumix = tsumix + x>infmaxc.
                 erase tsumix.
                 obtain x>infmin1.
                 x>infminc = x>infmin1.
                 tsumin = sumin.
                 erase sumin.
                 sumin = tsumin + x>infminc.
                 erase tsumin.
                 obtain x>infreg1.
                 x>infregc = x>infreg1.
                 tsumif = sumif.
                 erase sumif.
                 sumif = tsumif + x>infregc.
                 erase tsumif.
             endif.
message file = "transit.quantity",
          combine(x>idsubc),
          combine(x>idpipe),
          combine(x>areac),
          combine( x>char_lengthc),
          combine(x>impervious_area_percentagec),
          combine(x>slopec),
          combine(x>imperviousnc),
          combine(x>perviousnc),
          combine(x>stoimperc),
          combine(x>stoperc),
          combine(x>infmaxc),
          combine(x>infminc),
          combine(x>infregc).
          run clear.
        endforall.

message continuer.
break.
message " ","****** Please Enter The Data For Each Pipe ******"," ".
OBTAIN INFORMATION FOR GUTTER/PIPE.
     forall x: gutter_pipe do
        obtain x> id_of_the_gutter_or_pipe.
        obtain x>id_of_the_draining gutter_or_pipe_or_manhole.
        obtain x>shape.
          if x>shape = 1
          then obtain x>diameter1.
               x>diameter = x>diameter1.
               obtain x>length.
               obtain x>slopep.
               obtain x>left_side_slope.
```

```
                obtain x>right_side_slope.
                obtain x>manning_coefficient.
                obtain x>depth_when_flowing_full.
         endif.
            if x>shape = 2
           then obtain x>diameter2.
                x>diameter = x>diameter2.
                obtain x>length.
                obtain x>slopep.
                x>left_side_slope = 0.
                x>right_side_slope = 0.
                obtain x>manning_coefficient.
                x>depth_when_flowing_full = 0.
         endif.

         if x>shape = 3
           then x>diameter = 0.
                x>length = 0.
                x>slopep = 0.
                x>left_side_slope = 0.
                x>right_side_slope = 0.
                x>manning_coefficient = 0.
                x>depth_when_flowing_full = 0.
         endif.
 message file = "transit.quantity",
        combine(x>id_of_the_gutter_or_pipe),
        combine(x>id_of_the_draining gutter_or_pipe_or_manhole),
        combine(x>shape),
        combine(x>diameter),
        combine(x>length),
        combine(x>slopep),
        combine(x>left_side_slope),
        combine(x>right_side_slope),
        combine(x>manning_coefficient),
        combine(x>depth_when_flowing_full).
        run clear.
        endforall.
    endif.
  ******* WRITING THE QUANTITY DATA IN A FILE.
           write "data.quantity", nucat, nupipe, infilm,
           subcatchments, subcatchments(idsubc, idpipe, areac, char_lengthc,
           impervious_area_percentagec, slopec, perviousnc, imperviousnc,
           stoimperc, stoperc, infmaxc, infminc, infregc),
           suma, suml, sumi, sumpl, sums, sump2, sump, sumip, sumst, sumstp,
           sumix, sumin, sumif,
           gutter_pipe, gutter_pipe(id_of_the_gutter_or_pipe,
           id_of_the_draining gutter_or_pipe_or_manhole,
           shape, diameter, length, slopep, left_side_slope,
           right_side_slope, manning_coefficient,
           depth_when_flowing_full).
 COMPUTE THE AVERAGE VALUES OF ALL THE VARIABLES.
      area = suma/nucat.
      char_length = suml/nucat.
      impervious_area_percentage = sumi/nucat.
      probl = sumpl/nucat.
      slope = sums/nucat.
      prob2 = sump2/nucat.
      perviousn = sump/nucat.
      imperviousn = sumip/nucat.
      stoimper = sumst/nucat.
      stoper = sumstp/nucat.
      infmax = sumix/nucat.
      infmin = sumin/nucat.
      infreg = sumif/nucat.
 message continuer.
 break.
 message " ","****PLEASE ENTER THE DATA FOR SWMM.****"," ".
```

```
run datafile.
message continuer.
break.
message " ","  *** NOW SWMM PROGRAM IS RUNNING YOU MAY GO GET A DRINK ***"," ".
run model.
message " ","          /////// SWMM: TERMINATION CODE : SUCCESS !!!!!!!!"," ".
run datainput.
read "data", t, v, p, e, nosov, nosuv,nosop,nosup.
message continuer.
break.
obtain action.
     if action = calibration is done
        then message " ","*****************************"," ",
                     " ","======= GONGRATULATIONS ======="," ".
        endif.
display value of action.

 ************** JUSTIFY THE ACTION *************
            obtain justification.
            if justification = Yes
               then justify action.
            endif.

 ************ DISPLAY VALUES OF CRITERIA ***********
            obtain criteria.
            if criteria = Yes
              then message combine ("      Time Difference = ",t),
                           combine ("      Volume Difference = ",v),
                           combine ("      Peak Difference = ",p),
                           combine ("      Weighted Error = ",e).
              endif.

message continuer.
break.
  while action # calibration is done do
      obtain operamenu.
                run clear.
        if operamenu = Char_length
                 then obtain minchar_length.
                        obtain maxchar_length.
                        message file = "transit1",
                          combine ("char_length"),
                          combine (char_length),
                          combine (minchar_length),
                          combine (maxchar_length).
                          break.
                          run operate.
                          break.
                          erase char_length.
                          read "transit2",char_length.
                          run remove1.
                          run remove2.
                  endif.
                                    if operamenu = Slope
                  then obtain minslope.
                       obtain maxslope.
                       message file = "transit1",
                         combine ("slope"),
                         combine (slope),
                         combine (minslope),
                         combine (maxslope).
                         break.
                         run operate.
                         break.
                         erase slope.
                         read "transit2",slope.
                         run remove1.
```

```
      run remove2.
endif.
                   if operamenu = Impervious_area_percentage
then obtain minimp.
     obtain maximp.
     message file = "transit1",
       combine ("impervious_area_percentage"),
       combine (impervious_area_percentage),
       combine (minimp),
       combine (maximp).
       break.
       run operate.
       break.
       erase impervious_area_percentage.
       read "transit2",impervious_area_percentage.
       run remove1.
       run remove2.
  endif.
                     if operamenu = Stoimper or
    operamenu = Stoper or
    operamenu = Perviousn or
    operamenu = Imperviousn or
    operamenu = Infmax or
    operamenu = Infmin or
    operamenu = Infreg
 then obtain minstoimper.
      obtain maxstoimper.
      obtain minstoper.
      obtain maxstoper.
      obtain minperviousn.
      obtain maxperviousn.
      obtain minimperviousn.
      obtain maximperviousn.
      obtain mininfmax.
      obtain maxinfmax.
      obtain mininfmin.
      obtain maxinfmin.
      obtain mininfreg.
      obtain maxinfreg.
      message file = "transit1",
        combine ("imperviousn"),
        combine (imperviousn),
        combine (maximperviousn),
        combine (minimperviousn),
        combine ("perviousn"),
        combine (perviousn),
        combine (maxperviousn),
        combine (minperviousn),
        combine ("stoimper"),
        combine (stoimper),
        combine (maxstoimper),
        combine (minstoimper),
        combine ("stoper"),
        combine (stoper),
        combine (maxstoper),
        combine (minstoper),
        combine ("infmax"),
        combine (infmax),
        combine (maxinfmax),
        combine (mininfmax),
        combine ("infmin"),
        combine (infmin),
        combine (maxinfmin),
        combine (mininfmin),
        combine ("infreg"),
        combine (infreg),
        combine (maxinfreg),
```

```
                             combine (mininfreg).
                             break.
                             run optimize.
                             break.
                             erase imperviousn,perviousn,stoimper,
                             stoper,infmax,infmin,infreg.
                             read "transit2", imperviousn,perviousn,
                             stoimper,stoper,infmax,infmin,infreg.
                             run remove1.
                             run remove2.
                       endif.
                               erase operamenu.
                 erase action,scertanity,icertanity,nump,numv,peaks,volumes.
                 erase t, v, p, e, nosov, nosuv,nosop,nosup.
                 run datainput.
                 read "data", t, v, p, e, nosov, nosuv,nosop,nosup.
                 obtain action.
                       if action = calibration is done
                          then message " ","****************************"," ",
                                       " ","======= GONGRATULATIONS ======="," ".
                          endif.
                 display value of action.
 ************* JUSTIFY ACTION *****************
                 erase justification.
                 obtain justification.
                 if justification = Yes
                   then justify action.
                 endif.
 ************ DISPLAY VALUES OF CRITERIA ***********
             erase criteria.
             obtain criteria.
             if criteria = Yes
               then message combine ("        Time Difference = ",t),
                            combine ("        Volume Difference = ",v),
                            combine ("        Peak Difference = ",p),
                            combine ("        Weighted Error = ",e).
               endif.
              endwhile.
endif.
     if quantity = YES | NO
     then  obtain quality.
     if quality = YES
       then run qualityfile.
     endif.

     if quality = YES | NO
     then
message " "," ========== THANKS FOR USING ESCALOS =========="," ".
message start again.
endif.
endif.
%
```

APPENDIX C

QUANTITY SCRIPT: The following script is a record of the user-computer interaction during a typical session using ESCALOS to address water quantity considerations. The input data for this example were taken from the Glen Ellyn watershed.

```
% kesr swmm

Knowledge Engineering System (KES), Release 2.3.
Copyright (C) 1986, Software Architecture & Engineering, Inc.
Loading the knowledge base "swmm.pkb".

        *********************************************************
        *                                                       *
        *                  PURDUE UNIVERSITY                    *
        *                                                       *
        *             School of Civil Engineering               *
        *                                                       *
        *  Department of Hydraulics and Systems Engineering     *
        *                                                       *
        *      ##########################################       *
        *      #                                        #       *
        *      #               WELCOME                  #       *
        *      #                  TO                    #       *
        *      #                                        #       *
        *      #               ESCALOS                  #       *
        *      #                                        #       *
        *      #  Expert Sys. for Calibration of SWMM   #       *
        *      #                                        #       *
        *      ##########################################       *
        *                                                       *
        *      Copyright by Purdue University 1987.             *
        *      All rights reserved.                             *
        *********************************************************

        Please Enter <RETURN> To Continue :

        ****************************************************************
        *                                                              *
        *               ESCALOS HAS BEEN DEVELOPED                     *
        *                                                              *
        *                         by                                   *
        *                                                              *
        *  Dr. Jacques W. Delleur   (Head of Hydr. and Sys. Eng.)      *
        *  Dr. Mark H. Houck        (Professor of Water Res. Eng.)     *
        *  Dr. Jeff R. Wright       (Assoc. Professor of Sys. Eng.)    *
        *                                                              *
        *                        and                                   *
        *                                                              *
        *  Ms. Claire Baffaut       (Research Associate)               *
        *  Mr. Salah Benabdallah    (Research Assistant)               *
        *  Mr. David Wood           (Research Assistant)               *
        *                                                              *
        ****************************************************************


        Please Enter <RETURN> To Continue :
```

```
    ****************************************************
    *                                                  *
    *    Please Read All The Instructions Carefully.   *
    *                                                  *
    *    If You Need More Explanation of Any Input     *
    *    Variable, Just Enter 'e' at The Prompt.       *
    *                                                  *
    *    For Any Problems or Questions Please Call:    *
    *                                                  *
    *                 1-317-494-2171                   *
    *                                                  *
    *      ESCALOS is now ready to serve you. Good Luck. *
    *                                                  *
    ****************************************************


    Please Enter <RETURN> To Continue :

    ################=====   ESCALOS   =====#################



DID YOU ALREADY CALIBRATE QUANTITY FOR THIS PROBLEM ?
        1. YES
        2. NO

=? 2


HAVE YOU PREVIOUSLY INPUT THE QUANTITY DATA ?
        1. YES
        2. NO

=? 2


WHAT IS THE NUMBER OF SUBCATCHMENTS ON YOUR SITE ?
(Enter a number)
=? 2


HOW MANY PIPES AND/OR GUTTER DO YOU WANT TO SIMULATE WITH ?
(Enter a number)
=? 3


DO YOU WANT TO SIMULATE INFILTRATION PROCESS WITH
        1. Green_Ampt method
        2. Horton method

=? explain 1
Green-Ampt method :
The original equation was developed in 1911 and it
was originally for infiltration with excess water at
the surface at all time.  Mein and Larson showed how
it could be adapted to a steady rainfall input and
proposed a way in which the cappillarity suction parameter
could be determined. In 1978, Chu showed the applicability
of the equation to unsteady rainfall. SWMM uses the equation
by Mein and Larson. It is a two stage model. the first step
predicts the amount of water that will infiltrate in the
ground before the surface becomes saturated.Then, the
infiltration capacity is predicted.
reference: Storm Water Management Model user's manual
```

```
Please reenter value:


DO YOU WANT TO SIMULATE INFILTRATION PROCESS WITH
        1. Green_Ampt method
        2. Horton method

=? explain 2
Horton method :
Horton equation was developed in 1940. It predicts
infiltration capacity as a exponential function of the time.

        Fp = Finf + (F0 - Finf) exp(-at)

     Fp   : infiltration capacity into the soil
     Finf : minimum or ultimate infiltration capacity
     F0   : maximum or initial infiltration capacity
     t    : time from the begining of storm
     a    : decay coefficient
reference: Storm Water Management Model user's manual

Please reenter value:


DO YOU WANT TO SIMULATE INFILTRATION PROCESS WITH
        1. Green_Ampt method
        2. Horton method

=? 1

Type 'c' to continue.

Ready for command: c

***** Please Enter The Data For Each Subcatchment *****


For subcatchment1 of class subcatchments:

WHAT IS THE ID OF THE SUBCATCHEMENT ?
   [constraint: idsubc ge 1
     and idsubc le 99 ]
(Enter a number)
=? 68

For subcatchment1 of class subcatchments:

WHAT IS THE ID DRAINING MANHOLE OR GUTTER/PIPE?
   [constraint: idpipe ge 1
     and idpipe le 999 ]
(Enter a number)
=? 1

For subcatchment1 of class subcatchments:

WHAT IS THE TOTAL AREA OF THE MODELIZED CATCHMENT (acres) ?

(Enter a number)
=? 255

For subcatchment1 of class subcatchments:

WHAT IS YOUR ESTIMATION OF THE CHARACTERISTIC LENGTH
OF THE SUBCATCHMENT (feet) ?
(Enter a number)
=? explain
The characteristic length of the subcatchment has an effect
```

```
on the shape and on the storage. Smaller is the width, more
water is stored and lesser will be peak.

Please reenter value:

For subcatchment1 of class subcatchments:

WHAT IS YOUR ESTIMATION OF THE CHARACTERISTIC LENGTH
OF THE SUBCATCHMENT (feet) ?
(Enter a number)
=? 4500

For subcatchment1 of class subcatchments:

WHAT IS THE PERCENTAGE OF IMPERVIOUSNESS ?
   [constraint: impervious_area_percentagec ge 0
     and impervious_area_percentagec le 100 ]
(Enter a number)
=? why

Since the parameters such as depression storage or
mannings coefficients are given for pervious and
impervious areas we need to know the area of impervious
surface.

Please reenter value:

For subcatchment1 of class subcatchments:

WHAT IS THE PERCENTAGE OF IMPERVIOUSNESS ?
   [constraint: impervious_area_percentagec ge 0
     and impervious_area_percentagec le 100 ]
(Enter a number)
=? 11.8

For subcatchment1 of class subcatchments:

WHAT IS YOUR CERTAINITY ABOUT THE PERCENTAGE
OF IMPERVIOUSNESS VALUE?
   [constraint: prob1c ge 0
     and prob1c le 1 ]
(Enter a number)
=? 0.7

For subcatchment1 of class subcatchments:

WHAT IS THE AVERAGE SLOPE ALONG THE PATHWAY OF
OVERLANDFLOW TO INLET LOCATIONS (ft/ft)?
(Enter a number)
=? 0.0087

For subcatchment1 of class subcatchments:

WHAT IS YOUR CERTAINITY ABOUT THE AVERAGE
SLOPE VALUE ?
   [constraint: prob2c ge 0
     and prob2c le 1 ]
(Enter a number)
=? 1.5

Error:  The value entered does not satisfy
        the constraint associated with attribute prob2c.


Please reenter value.
```

```
For subcatchment1 of class subcatchments:

WHAT IS YOUR CERTAINITY ABOUT THE AVERAGE
SLOPE VALUE ?
   [constraint: prob2c ge 0
     and prob2c le 1 ]
(Enter a number)
=? 0.5

For subcatchment1 of class subcatchments:

WHAT IS THE MANNINGS COEFFICIENTS FOR PERVIOUS AREA ?
Proposed values:
                 0.2 for light turf,
                 0.3 for dense turf,
                 0.4 for dense shrubbey and forest litter.
(Enter a number)
=? 0.25

For subcatchment1 of class subcatchments:

WHAT IS THE MANNINGS COEFFICIENT FOR IMPERVIOUS AREA ?
Proposed values:
                 0.012 for smooth asphalt
                 0.014 for asphalt or concrete
                 0.03 for packed clay.
(Enter a number)
=? 0.013

For subcatchment1 of class subcatchments:

WHAT IS THE VALUE OF DEPRESSION STORAGE FOR IMPERVIOUS
AREA ?
       [Proposed value: 0.018]
(Enter a number)
=? 0.045

For subcatchment1 of class subcatchments:

WHAT IS THE VALUE OF DEPRESSION STORAGE FOR PERVIOUS
AREA ?
       [Proposed value: 0.03]
(Enter a number)
=? 0.084

For subcatchment1 of class subcatchments:

WHAT IS THE VALUE OF THE CAPILLARITY SUCTION (inches) ?
Proposed Values:
                 group A : sand        :  4 inches
                 group B : sandy loam  :  8 inches
                           silt loam   : 12 inches
                           loam        :  8 inches
                 group C : clay loam   : 10 inches
                 group D : clay        :  7 inches
(Enter a number)
=? 10

For subcatchment1 of class subcatchments:

WHAT IS THE VALUE OF HYDRAULIC CONDUCTIVITY (in/hr) ?
Proposed Values :
   soil group A (most pervious)  : between 0.45 and 0.30 in/hr
   soil group B                  : between 0.30 and 0.15 in/hr
   soil group C                  : between 0.15 and 0.05 in/hr
   soil group D (most impervious): between 0.05 and 0.001 in/hr
```

```
 (Enter a number)
 =? 0.1

 For subcatchment1 of class subcatchments:

 WHAT IS THE VALUE OF THE MOISTURE DEFICIT
 (volume air/volume voids) ?
 Proposed Values:
                   group A : sand          : 0.34
                   group B : sandy loam
                             silt loam     : 0.32
                             loam
                   group C : sandy clay loam
                             clay loam     : 0.25
                   group D : clay          : 0.21
 (Enter a number)
 =? 0.25

 For subcatchment2 of class subcatchments:

 WHAT IS THE ID OF THE SUBCATCHEMENT ?
    [constraint: idsubc ge 1
      and idsubc le 99 ]
 (Enter a number)
 =? 69

 For subcatchment2 of class subcatchments:

 WHAT IS THE ID DRAINING MANHOLE OR GUTTER/PIPE?
    [constraint: idpipe ge 1
      and idpipe le 999 ]
 (Enter a number)
 =? 2

 For subcatchment2 of class subcatchments:

 WHAT IS THE TOTAL AREA OF THE MODELIZED CATCHMENT (acres) ?

 (Enter a number)
 =? 162

 For subcatchment2 of class subcatchments:

 WHAT IS YOUR ESTIMATION OF THE CHARACTERISTIC LENGTH
 OF THE SUBCATCHMENT (feet) ?
 (Enter a number)
 =? 5000

 For subcatchment2 of class subcatchments:

 WHAT IS THE PERCENTAGE OF IMPERVIOUSNESS ?
    [constraint: impervious_area_percentagec ge 0
      and impervious_area_percentagec le 100 ]
 (Enter a number)
 =? 30.9

 For subcatchment2 of class subcatchments:

 WHAT IS YOUR CERTAINITY ABOUT THE PERCENTAGE
 OF IMPERVIOUSNESS VALUE?
    [constraint: problc ge 0
      and problc le 1 ]
 (Enter a number)
 =? 0.7

 For subcatchment2 of class subcatchments:
```

```
WHAT IS THE AVERAGE SLOPE ALONG THE PATHWAY OF
OVERLANDFLOW TO INLET LOCATIONS (ft/ft)?
(Enter a number)
=? 0.0087

For subcatchment2 of class subcatchments:

WHAT IS YOUR CERTAINITY ABOUT THE AVERAGE
SLOPE VALUE ?
   [constraint: prob2c ge 0
     and prob2c le 1 ]
(Enter a number)
=? 0.7

For subcatchment2 of class subcatchments:

WHAT IS THE MANNINGS COEFFICIENTS FOR PERVIOUS AREA ?
Proposed values:
                 0.2 for light turf,
                 0.3 for dense turf,
                 0.4 for dense shrubbey and forest litter.
(Enter a number)
=? 0.25

For subcatchment2 of class subcatchments:

WHAT IS THE MANNINGS COEFFICIENT FOR IMPERVIOUS AREA ?
Proposed values:
                 0.012 for smooth asphalt
                 0.014 for asphalt or concrete
                 0.03 for packed clay.
(Enter a number)
=? 0.013

For subcatchment2 of class subcatchments:

WHAT IS THE VALUE OF DEPRESSION STORAGE FOR IMPERVIOUS
AREA ?
       [Proposed value: 0.018]
(Enter a number)
=? 0.045

For subcatchment2 of class subcatchments:

WHAT IS THE VALUE OF DEPRESSION STORAGE FOR PERVIOUS
AREA ?
       [Proposed value: 0.03]
(Enter a number)
=? 0.184

For subcatchment2 of class subcatchments:

WHAT IS THE VALUE OF THE CAPILLARITY SUCTION (inches) ?
Proposed Values:
                 group A : sand        :  4 inches
                 group B : sandy loam  :  8 inches
                           silt loam   : 12 inches
                           loam        :  8 inches
                 group C : clay loam   : 10 inches
                 group D : clay        :  7 inches
(Enter a number)
=? 10

For subcatchment2 of class subcatchments:

WHAT IS THE VALUE OF HYDRAULIC CONDUCTIVITY (in/hr) ?
Proposed Values :
```

```
    soil group A (most pervious)  : between 0.45 and 0.30 in/hr
    soil group B                  : between 0.30 and 0.15 in/hr
    soil group C                  : between 0.15 and 0.05 in/hr
    soil group D (most impervious): between 0.05 and 0.001 in/hr

 (Enter a number)
 =? 0.1

 For subcatchment2 of class subcatchments:

 WHAT IS THE VALUE OF THE MOISTURE DEFICIT
 (volume air/volume voids) ?
 Proposed Values:
                    group A : sand          : 0.34
                    group B : sandy loam
                              silt loam     : 0.32
                              loam
                    group C : sandy clay loam
                              clay loam     : 0.25
                    group D : clay          : 0.21
 (Enter a number)
 =? 0.25

 Type 'c' to continue.

 Ready for command: c

 ****** Please Enter The Data For Each Pipe ******


 For pipe1 of class gutter_pipe:

 WHAT IS THE ID OF THE GUTTER/PIPE ?
 (Enter a number)
 =? 1

 For pipe1 of class gutter_pipe:

 WHAT IS THE ID OF THE DRAINING GUTTER/PIPE OR MANHOLE ?
 (Enter a number)
 =? 2

 For pipe1 of class gutter_pipe:

 WHAT IS THE SHAPE OF THE GUTTER/PIPE ?
    1 : for gutter (trapezoidal channel)
    2 : for circular pipes
    3 : for dummy gutter (inflow = outflow)
 (Enter a number)
 =? 2

 For pipe1 of class gutter_pipe:

 WHAT IS THE DIAMETER OF THE PIPE (ft) ?
 (Enter a number)
 =? 4

 For pipe1 of class gutter_pipe:

 WHAT IS THE LENGTH OF THE GUTTER OR PIPE (ft) ?
 (Enter a number)
 =? 2550

 For pipe1 of class gutter_pipe:

 WHAT IS THE SLOPE OF THE GUTTER/PIPE (ft/ft) ?
 (Enter a number)
```

```
=? 0.0087

For pipe1 of class gutter_pipe:

WHAT IS THE MANNING COEFFICIENT OF THE GUTTER/PIPE ?
(Enter a number)
=? 0.018

For pipe2 of class gutter_pipe:

WHAT IS THE ID OF THE GUTTER/PIPE ?
(Enter a number)
=? 2

For pipe2 of class gutter_pipe:

WHAT IS THE ID OF THE DRAINING GUTTER/PIPE OR MANHOLE ?
(Enter a number)
=? 3

For pipe2 of class gutter_pipe:

WHAT IS THE SHAPE OF THE GUTTER/PIPE ?
   1 : for gutter (trapezoidal channel)
   2 : for circular pipes
   3 : for dummy gutter (inflow = outflow)
(Enter a number)
=? 2

For pipe2 of class gutter_pipe:

WHAT IS THE DIAMETER OF THE PIPE (ft) ?
(Enter a number)
=? 5

For pipe2 of class gutter_pipe:

WHAT IS THE LENGTH OF THE GUTTER OR PIPE (ft) ?
(Enter a number)
=? 600

For pipe2 of class gutter_pipe:

WHAT IS THE SLOPE OF THE GUTTER/PIPE (ft/ft) ?
(Enter a number)
=? 0.0087

For pipe2 of class gutter_pipe:

WHAT IS THE MANNING COEFFICIENT OF THE GUTTER/PIPE ?
(Enter a number)
=? 0.018

For pipe3 of class gutter_pipe:

WHAT IS THE ID OF THE GUTTER/PIPE ?
(Enter a number)
=? 3

For pipe3 of class gutter_pipe:

WHAT IS THE ID OF THE DRAINING GUTTER/PIPE OR MANHOLE ?
(Enter a number)
=? 4

For pipe3 of class gutter_pipe:
```

```
WHAT IS THE SHAPE OF THE GUTTER/PIPE ?
   1 : for gutter (trapezoidal channel)
   2 : for circular pipes
   3 : for dummy gutter (inflow = outflow)
(Enter a number)
=? 3

Type 'c' to continue.

Ready for command: c

****PLEASE ENTER THE DATA FOR SWMM.****

 How many hydrographs will you use for calibration?
3
 For storm event            1
 Do you want to enter rainfall and runoff data now (1)
 or is it already in some file (0)?
0
 For storm event            2
 Do you want to enter rainfall and runoff data now (1)
 or is it already in some file (0)?
0
 For storm event            3
 Do you want to enter rainfall and runoff data now (1)
 or is it already in some file (0)?
0

Type 'c' to continue.

Ready for command: c

  *** NOW SWMM PROGRAM IS RUNNING  ***


         /////// SWMM: TERMINATION CODE : SUCCESS !!!!!!!!


Type 'c' to continue.

Ready for command: c
  impervious_area_percentage_has_to_be_decreased <0.95>
  stoimper_has_to_be_increased <0.90>
  slope_has_to_be_decreased <0.90>
  char_length_has_to_be_decreased <0.90>



Would You Like To See The Supporting Sources :
        1. Yes
        2. No

=? 1

action = impervious_area_percentage_has_to_be_decreased

Reasons for belief:
     rule: rule impervious_area_percentage_has_to_be_decreased

Would you like to see the supporting knowledge sources? (y/n) y

Name: rule impervious_area_percentage_has_to_be_decreased
Is: Production Rule


        if
          icertanty = impervious_area_percentage_is_uncertain and
```

```
          volumes = volumes_are_too_big
        then
         action = impervious_area_percentage_has_to_be_decreased <0.95>.
        endif.

Enter <RETURN> to continue:


action = stoimper_has_to_be_increased

Reasons for belief:
     rule: rule stoimper_has_to_be_increased

Would you like to see the supporting knowledge sources? (y/n) n


action = slope_has_to_be_decreased

Reasons for belief:
     rule: rule slope_has_to_be_decreased

Would you like to see the supporting knowledge sources? (y/n) n


action = char_length_has_to_be_decreased

Reasons for belief:
     rule: rule char_length_has_to_be_decreased

Would you like to see the supporting knowledge sources? (y/n) y

Name: rule char_length_has_to_be_decreased
Is: Production Rule


       if
          peaks = peaks_occur_soon or
          peaks = peaks_are_too_high
       then
          action = char_length_has_to_be_decreased <0.9>.
       endif.

Enter <RETURN> to continue:




Would You Like To See The Values of Criteria :
        1. Yes
        2. No

=? 1
      Time Difference = -5.1999998
      Volume Difference = -49.800003
      Peak Difference = -41.899994
      Weighted Error = 27.800003

Type 'c' to continue.

Ready for command: c


WHICH PARAMETER DO YOU WANT CHANGE ?
        1. Char_length
        2. Slope
```

```
        3. Impervious_area_percentage
        4. Stoimper
        5. Stoper
        6. Perviousn
        7. Imperviousn
        8. Infmax
        9. Infmin
       10. Infreg

=? 3


Please Enter the Minimum Value of The
Impervious Area Percentage.
   [constraint: minimp ge 0
     and minimp le 100 ]
(Enter a number)
=? 15


Please Enter the Maximum Value of The
Impervious Area Percentage.
   [constraint: maximp ge 0
     and maximp le 100 ]
(Enter a number)
=? 40

Ready for command: c
 previous volume criteria :  -49.80000
   1.489600       -49.80000
   2.844074       -27.48579
 forecast criteria :  -27.48579
 ratio of new to old values :  0.8099999
 peakcriteria =  -27.98697      volume criteria =  -22.03777
 new value is  0.8099999
 imper<<

Ready for command: c
  impervious_area_percentage_has_to_be_decreased <0.95>
  slope_has_to_be_decreased <0.90>
  char_length_has_to_be_decreased <0.90>



Would You Like To See The Supporting Sources :
        1. Yes
        2. No

=? 2


Would You Like To See The Values of Criteria :
        1. Yes
        2. No

=? 1
      Time Difference = -5.1999998
      Volume Difference = -22
      Peak Difference = -28
      Weighted Error = 18.699997



WHICH PARAMETER DO YOU WANT CHANGE ?
        1. Char_length
        2. Slope
        3. Impervious_area_percentage
```

```
        4. Stoimper
        5. Stoper
        6. Perviousn
        7. Imperviousn
        8. Infmax
        9. Infmin
       10. Infreg

=? 3

Ready for command: c
 previous volume criteria :  -22.00000
   3.314285      -22.00000
 forecast criteria :  -22.00000
 ratio of new to old values :  0.8999999
 peakcriteria =  0.1035452     volume criteria =   9.793013
 new value is  0.4782968
 imper<<

Ready for command: c

****************************


======= GONGRATULATIONS =======

  calibration is done <1.00>



Would You Like To See The Supporting Sources :
        1. Yes
        2. No

=? 1

action = calibration is done

Reasons for belief:
     rule: rule32

Would you like to see the supporting knowledge sources? (y/n) n





Would You Like To See The Values of Criteria :
        1. Yes
        2. No

=? 1
      Time Difference = -3.5
      Volume Difference = 9.8000002
      Peak Difference = 0.10000002
      Weighted Error = 15.6


DO YOU WANT TO CALIBRATE QUALITY ?
        1. YES
        2. NO

=? 2

 ========== THANKS FOR USING ESCALOS ==========
```

```
Type 'nextcase' to start again, or 'stop' to quit.

Ready for command: s

KES - Copyright (C) 1986, Software Architecture & Engineering, Inc.
```

APPENDIX D

QUALITY KNOWLEDGE BASE: The following program listing presents the quality prototype knowledge base using the Knowledge Engineering System (KES) by Software A & E. This program was used to generate the sample user session presented as Appendix E.

```
constants:
      welcome:

" ",
" WELCOME TO THE QUALITY PORTION OF THE SWMM EXPERT SYSTEM",
" ",
" ".

      what_next:
" ", "Type 'c' to continue, 'n' for nextcase, 's' to stop".

      swmm_run:" ",
"####################################################################",
" ",
" The Storm Watershed Management Model has now been activated based ",
" on the data you have entered. ",
" ",
"####################################################################",
" ".

      newswmm_run:" ",
"####################################################################",
" ",
" The Storm Watershed Management Model has now been activated based ",
" on the updated data.  ",
" ",
"####################################################################",
" ".

      calibration: " ",
"**********    Calibration is not done, you     **********",
"**********    must follow these directions.    **********",
" ".

%

patterns:
      mg_per_liter: "mg/l".
      other_per_liter: other [alternatives: "MPN/l","meq/l"].
      other_conc_units: unit [alternatives: "pH","JTU","PCU","oC"].
%

attributes:

 INPUT attributes

      data_prompt: truth
            {question: "Do you want to skip entering data?"}.

      no_of_poll: int
            [constraint: no_of_poll ge 1 and no_of_poll le 10]
            {question: "Please enter the number of pollutants to be simulated.",
"Type 'explain' for an explanation."}
            {explain:
"Up to ten quality constituents may be simulated.  The number and ",
"choice of constituents to be simulated must reflect the user's ",
```

```
"needs, potential for treatment and receiving water impacts, etc.",
"Almost any constituent measured by common laboratory or field tests",
"can be included, up to a total of ten."}.

      no_of_landuse: int
            [constraint: no_of_landuse ge 1 and no_of_landuse le 5]
            {question: "Please enter the number of land uses existing in the watershe
                         "Type 'explain' for an explanation."}
            {explain: "Up to five user supplied land uses may be entered to",
 "characterize different subcatchments.",
                        "Examples are:",
                        "   Single-family residential, ",
                  "   Multi-family residential, ",
                  "   Commercial,             ",
                  "   Industrial, ",
                  "   Undeveloped/Park. "}.

      eros_sim: truth
            {question: "Is erosion to be simulated?"}.

      eros_code: int.

      landuse_flag: sgl (yes, no).

      cab_vol: real
            {question:
"Please enter the average storage volume of existing individual catchbasins.",
"Type 'explain' for an explanation"}
                {explain:
"The purpose of the deep well or sump of a catchbasin is to",
"trap solids by sedimentation prior to stormwater entry into",
"the sewer.  This distinguishes catchbasins from stormwater ",
"inlets.  The volume of the sump varies considerably with ",
"design, ranging from 2.8 to 78 cubic feet.  The volume is ",
"typically reduced by a large quantity of solids trapped in ",
"the sump, often by more than 50 percent."}.

      ss_eff: real
            {question:
 "Please enter the street sweeping efficiency for dust and dirt.",
 "Type 'explain' for an explanation."}
            {explain:
 "Street cleaning is performed in most urban areas for control of",
 "solids and trash deposited along street gutters. Typical removal",
 "efficiencies for Total Solids (Vacuum Cleaner) are the following: ",
 " ",
 "Small Load (20-200 lb/curb mile TS): 31% ",
 "Med. Load (200-1,000 lb/curb mile TS): 37%",
 "Large Load (1,000-10,000 lb/curb mile TS): 48%",
 " ",
 "Efficiencies increase slightly with no. of passes by street cleaner."}.
      justification: truth
            {question: "Would you like to see the supporting rules?"}.

      calib_done: sgl(calibration is done,
                      calibration is not done).

%

classes:

 EROSION class

   erosion:
     attributes:

     subc_no: int
```

```
           {question: "Please enter the number of the subcatchment ."}.

     subc_area: real
           {question: "Please enter the area of the subcatchment."}.

     flow_dist: real
           {question: "Please enter the flow distance for the subcatchment."}.

     soil_fac: real
           {question: "Please enter the soil factor 'K' for the subcatchment."}.

     crop_mngmt: real
           {question: "Please enter the cropping management factor 'C' for the subca

     contr_prac: real
           {question: "Please enter the control practice factor 'P' for the subcatch

     %
     endclass.

POLLUTANT CLASS
   pollutant:
The following are input attributes for the class POLLUTANT

     attributes:
       poll_name: str
       {question: "Please enter the pollutant name.",
                "Enter a string, no more than 8 characters."}.

       unit_abbr: str
       {question: "Please enter the unit abbreviation.",
                "For example: mg/l, MPN/l, pH, etc.",
                "No more than 8 characters."}.

       typ_units: int.

       buildup_meth: sgl (power linear,
                      exponential,
                      Michaelis Menton,
                      fract dust dirt buildup,
                      constant load)
       {question: "Please indicate which buildup method you would like to use,",
                "for the particular pollutant. Type 'explain' for an explanation"}
       {explain:
 "For each of the five methods an explanation of the procedure to ",
 "determine dust and dirt buildup is given. t represents time in days.",
 "power-linear:",
 "         equation =>  dd buildup = buildup coefficient * (t ** buildup power).",
 "   Linear buildup is a power function with power = 1.0",
 "exponential:  ",
 "   equation => dd buildup = buildup limit * (1 - e**(-buildup power * t)).",
 "   The exponent is the familiar exponential decay constant. It may",
 "   be obtained from the slope of a semi-log plot of buildup vs. time.",
 "Michaelis-Menton:  ",
 "   equation => dd buildup = buildup limit * t/(buildup coefficient + t).",
 "   The coefficient for dust and dirt buildup has the interpretation",
 "   of the halftime constant, that is, the time at which buildup is ",
 "   half the maximum value.",
 "fraction of dust and dirt buildup:",
 "   Buildup is computed as a fraction of dust and dirt.  The rate of",
 "   buildup will depend upon the fraction for a given land use.",
 "constant load:",
 "   Buildup load is entered by the user for each constituent",
 "   for each subcatchment. ",
 " "," "}.

       bmeth_code: int.
```

```
i
lp parameters
d
        func_dep: sgl (gutter length, area, constant)
            {question: "Please indicate the functional dependence of dust and dirt bu
                      "Type 'explain' for an explanation."}
            {explain:
" ",
"If the buildup is a function of gutter length, gutter length can",
"be estimated by two methods: ",
"1) Gutter Length (100ft) = twice the total length of streets.",
"2) Gutter Length (100ft) = area * (413 - 353 * (0.839**population density))/100.",
"The buildup can also be a function of the total land area or it",
"can be constant"}.


        funcdep_code: int.

        build_lim: real
            {question: "Please enter the buildup limit.",
                          "Type 'explain' for an explanation"}
            {explain:
"If no buildup limit is desired, enter a large number such as 100,000"}.

        build_exp: real
            {question: "Please enter the buildup exponent.",
                          "Type 'explain' for an explanation"}
            {explain: "A typical range is from 0-1 for linear,",
                    "no exponent for Michaelis Menton and  ",
                    "0-5 for exponential "}.

        build_coeff: real
            {question: "Please enter the buildup coefficient."}.

        build_coeff4: real.

        build_coeff5: real.

        washoff_calc: sgl (power exponential, rating curve by buildup eqn no limit,
                            rating curve by buildup eqn with limit)
            {question: "Please indicate the type of washoff calculation.",
                    "Type 'explain' for an explanation."}
            {explain:
"Washoff calculations may be computed via a power-exponential function",
"or they may be avoided and load rates computed for each subcatchment",
"at each time step by a rating curve method; each method is described.",
"The rating curve can also be used where the maximum amount that can be",
"removed is the amount built up prior to the storm.",
" power exponential:",
"     -POFF(t) = d PSHED/dt = -RCOEFX * r**WASHPO * PSHED ",
"     where => POFF = constituent load washed off at time, t,",
"                     quantity per sec. (eg. mg/sec)",
"             PSHED = quantity of constituent available for washoff",
"                     at time, t, (eg. mg).",
"             RCOEFFX = washoff coefficient ",
"             r = runoff rate, in/hr. ",
" rating curve: ",
"     POFF = RCOEFF * WFLOW**WASHPO.",
"     where => WFLOW = subcatchment runoff, cfs.",
"             RCOEF = coefficient that includes correct units conversion.",
"             WASHPO = exponent.",
" ",
" ",
" ",
" "}.

        washoff_code: int.
```

```
      washoff_coeff: real
          {question: "Please enter the washoff equation coefficient."}.

      washoff_pow: real
          {question: "Please enter the exponent of the washoff equation."}.

      rc_corr: real.

      catchb_conc: real
          {question: "Please enter the initial concentration of pollutant in the ca
          "Type 'explain' if unsure"}
          {explain:" ",
"Values are typically in the following range for 4 pollutants",
"COD       153  -  143,000",
"BOD5        5  -    15,00",
"Total N   0.5  -       33",
"Total P        <  0.2    "}.

      prec_conc: real
          {question: "Please enter the concentration of pollutant in precipitation.
              "Type 'explain' if unsure"}
          {explain: " ",
"Typical ranges for the following constituents are: ",
" ",
"acidity, (pH)            3 -  6",
"BOD5, mg/l               1 - 13",
"COD, mg/l                9 - 16",
"TOC, mg/l                  few ",
"Total Solids, mg/l      18 - 24",
"Susp. Solids, mg/l       2 - 13",
"Turbidity, JTU           4 -  7",
"Organic N, mg/l       0.05 - 1.0",
"Total N, mg/l          0.2 - 1.5",
"Pesticides, ug/l           few",
"Lead ug/l               30 - 70",
"Heavy Metals ug/l          few"}.

        ss_eff: real
          {question: "Please enter the street sweeping efficiency.",
              "Type 'explain' if unsure"}
          {explain:
"The following are proposed removal efficiencies",
"for Vaccuum Street Cleaners (1 pass) :",
"                  Small Loads       Med. Loads     Large Loads   ",
"Total Solids          .31           .37               .48       ",
"BOD5                  .24           .29            .38   ",
"COD                   .16           .21               .33       ",
"KN                   .26            .31               .43       ",
"PO4                   .8            .12               .20       ",
"Pesticides            .33           .40               .57       ",
"Cd                   .23            .30               .45       ",
"Sr                   .27            .34               .44       ",
"Cu                   .30            .36               .49       ",
"Ni                   .37            .43               .55       ",
"Cr                   .34            .42               .53       ",
"Zn                   .34            .41               .55       ",
"Mn                    .37           .45               .58       ",
"Pb                   .40            .49               .62       ",
"Fe                   .40            .59               .63   ",
"Small, Med and Large represent 20-200, 200-1000, 1000-10000",
"lb/curb-mile of total solids respectively.  If Street Cleaner ",
"makes more than one pass, removal efficiency increases slightly"}.


    bfract_lu1: real
          {question: "Please enter the percent of dust and dirt buildup for land us
```

```
      bfract_lu2: real
            {question: "Please enter the percent of dust and dirt buildup for land us


      bfract_lu3: real
            {question: "Please enter the percent of dust and dirt buildup for land us


      bfract_lu4: real
            {question: "Please enter the percent of dust and dirt buildup for land us


      bfract_lu5: real
            {question: "Please enter the percent of dust and dirt buildup for land us

 INFERRED attributes.

      buil_load: real.
      storm_load: real.
      percent: real.
      load_diff: real.

      swmm_action: mlt (storm loads are too small,
                    storm loads are too big).

      swmm_action1: mlt(buildup load has to be decreased,
                    buildup load has to be increased).


      user_action: mlt (buildup limit has to be increased,
                    buildup limit has to be decreased,
                    buildup coefficient has to be increased,
                    buildup coefficient has to be decreased,
                    subcatchment loads have to be increased,
                    subcatchment loads have to be decreased,
                    buildup exponent has to be increased,
                    buildup exponent has to be decreased,
                    washoff coefficient has to be increased,
                    washoff coefficient has to be decreased,
                    calibration is done).

 Variables representing calibration changes after each iteration

      new_blim: real.
      new_bcoeff: real.
      new_bexp: real.
      new_wcoeff: real.

 Variable representing the parameter user desires to change.

      par_chng: sgl (buildup limit,
                  buildup coefficient,
                  buildup exponent,
                  washoff coefficient)
      {question:
"Which parameter would you like to change based",
"on the expert system diagnosis?"}.


   %
   endclass.

 LAND USE class

    land_use:
      attributes:
```

```
      name: str.

      buil_eqn: sgl (power linear, exponential, Michaelis Menton)
            {question: "Please indicate the type of buildup equation for dust and dir
            {explain:
  "For each of the three methods an explanation of the procedure to ",
  "determine dust and dirt buildup is given. t represents time in days.",
  "power-linear:",
  "         equation =>  dd buildup = buildup coefficient * (t ** buildup power).",
  "   Linear buildup is a power function with power = 1.0",
  "exponential:  ",
  "   equation => dd buildup = buildup limit * (1 - e**(-buildup power * t)).",
  "   The exponent is the familiar exponential decay constant. It may",
  "   be obtained from the slope of a semi-log plot of buildup vs. time.",
  "Michaelis-Menton:  ",
  "   equation => dd buildup = buildup limit * t/(buildup coefficient + t).",
  "   The coefficient for dust and dirt buildup has the interpretation",
  "   of the halftime constant, that is, the time at which buildup is ",
  "   half the maximum value."}.


      buil_code: int.

      func_dep: sgl (gutter length, area, constant)
            {question: "Please indicate the functional dependence of buildup paramete
                {explain:
"If the buildup is a function of gutter length, gutter length can",
"be estimated by two methods: ",
"1) Gutter Length (100ft) = twice the total length of streets.",
"2) Gutter Length (100ft) = area * (413 - 353 * (0.839**population density))/100.",
"The buildup can also be a function of the total land area or it",
"can be constant"}.


      funcdep_code: int.

      buil_lim: real
            {question: "Please enter the buildup quantity limit."}.

      power: real
            {question: "Please enter the buildup equation power."}.


      coeff: real
            {question: "Please enter the buildup equation coefficient."}.

      ss_int: real
            {question: "Please enter the street sweeping cleaning interval in days.",
"Very often 15-30 days in most cities."}.

      ss_avfac: real
            {question: "Please enter the street sweeping availability factor.",
"Type 'explain' for an explanation"}
            {explain:
"The availability factor is intended to account for the fraction of",
"the catchments area that is actually sweepable.  This is usually a ",
"function of the number of cars parked along the sides of streets, ",
"which will depend on the population density."}.

       %
       endclass.

 SUBCATCHMENT Class

       subcatchments:
      attributes:
```

```
      subc_no: int
            {question: "Please enter the subcatchment number."}.

        subc_luse: int
            [constraint: subc_luse ge 1 and subc_luse le 5]
            {question: "Please enter the land use for the subcatchment."}.

      no_catba: int
            {question: "How many catchbasins are there in the subcatchment?",
                           "Type 'explain' for an explanation"}
            {explain:
 "Catchbasins are treated as a reservoir of constituents in each",
 "subcatchment available to be flushed out during a storm. The number",
 "of catchbasins in a subcatchment is ususally a function of the area"}.

      curb_ln: real
            {question: "Please enter the total curb length within the subcatchment (p
                     "Type 'explain' for an explanation."}
            {explain:
"1) Gutter Length (100ft) = twice the total length of streets.",
"2) Gutter Length (100ft) = area * (413 - 353 * (0.839**population density))/100."}.

      init_load1: real
            {question: "Please enter the initial load for pollutant1."}.
      init_load2: real
            {question: "Please enter the initial load for pollutant2."}.
      init_load3: real
            {question: "Please enter the initial load for pollutant3."}.
      init_load4: real
            {question: "Please enter the initial load for pollutant4."}.
      init_load5: real
            {question: "Please enter the initial load for pollutant5."}.
      init_load6: real
            {question: "Please enter the initial load for pollutant6."}.
      init_load7: real
            {question: "Please enter the initial load for pollutant7."}.
      init_load8: real
            {question: "Please enter the initial load for pollutant8."}.
      init_load9: real
            {question: "Please enter the initial load for pollutant9."}.
      init_load10: real
            {question: "Please enter the initial load for pollutant10."}.
      %
      endclass.

%

externals:

      clear:  [program: "clear"].
      remove1: [program: "rm transit.qual pollin"].
      remove2: [program: "rm transit1"].
      create: [program: "makefiles"].
      swmm: [program: "/x/yug/CLAIRE/EXPERT/run"].
      new_swmm: [program: "operqual"].
      poll_dumnames: [program: "poll"].

%

rules:


      rule1 to assign pollutant buildup method code:
      P:pollutant
      if P>buildup_meth = fract dust dirt buildup then
      P>bmeth_code = 0.
      endif.
```

```
rule2 to assign pollutant buildup method code:
P:pollutant
if P>buildup_meth = power linear then
P>bmeth_code = 1.
endif.

rule3 to assign pollutant buildup method code:
P:pollutant
if P>buildup_meth = exponential then
P>bmeth_code = 2.
endif.

rule4 to assign pollutant buildup method code:
P:pollutant
if P>buildup_meth = Michaelis Menton then
P>bmeth_code = 3.
endif.

rule5 to assign pollutant buildup method code:
P:pollutant
if P>buildup_meth = constant load then
P>bmeth_code = 4.
endif.

rule1 to assign pollutant washoff code:
P:pollutant
if P>washoff_calc = power exponential then
  P>washoff_code = 0.
endif.

rule2 to assign pollutant washoff code:
P:pollutant
if P>washoff_calc = rating curve by buildup eqn no limit then
  P>washoff_code = 1.
  endif.

rule3 to assign pollutant washoff code:
P:pollutant
if P>washoff_calc = rating curve by buildup eqn with limit then
  P>washoff_code = 2.
  endif.

rule1 to assign pollutant functional dependence:
P:pollutant
if P>func_dep = gutter length then P>funcdep_code = 0.
endif.

rule2 to assign pollutant functional dependence:
P:pollutant
if P>func_dep = area then P>funcdep_code = 1.
endif.

rule3 to assign pollutant functional dependence:
P:pollutant
if P>func_dep = constant then P>funcdep_code = 2.
endif.

rule1 to assign land use buildup code:
L:land_use
if L>buil_eqn = power linear then L>buil_code = 0.
endif.


rule2 to assign land use buildup code:
L:land_use
if L>buil_eqn = exponential then L>buil_code = 1.
```

```
    endif.

    rule3 to assign land use buildup code:
    L:land_use
    if L>buil_eqn = Michaelis Menton then L>buil_code = 2.
    endif.

    rule1 to assign land use functional dependence code:
    L:land_use
    if L>func_dep = gutter length then L>funcdep_code = 0.
    endif.

    rule2 to assign land use functional dependence code:
    L:land_use
    if L>func_dep = area then L>funcdep_code = 1.
    endif.

    rule3 to assign land use functional dependence code:
    L:land_use
    if L>func_dep = constant then L>funcdep_code = 2.
    endif.

    rule1 to assign erosion code:
    if eros_sim = true then eros_code = 1.
    endif.

    rule2 to assign erosion code:
    if eros_sim = false then eros_code = 0.
    endif.

Calibration rules:

    Calibration rule1:
    P:pollutant
    if P>load_diff ge 0.25 then
    P>swmm_action = storm loads are too small <1.0>.
    endif.

    Calibration rule2:
    P:pollutant
    if P>load_diff le -0.25 then
    P>swmm_action = storm loads are too big <1.0>.
    endif.

    Calibration rule3:
    P:pollutant
    if P>user_action # calibration is done then
    calib_done = calibration is not done.
    endif.

    Calibration rule4:
    P:pollutant
    if P>user_action = calibration is done then
    calib_done = calibration is done.
    endif.

    Calibration rule5:
    P:pollutant
    if P>swmm_action = storm loads are too small and
       status (P>build_lim) = unknown or
       P>buil_load le (0.9*P>build_lim) then
       P>swmm_action1 = buildup load has to be increased <0.85>.
    endif.

    Calibration rule6:
    P:pollutant
    if P>swmm_action = storm loads are too big and
```

```
        status (P>build_lim) = unknown or
        P>buil_load le (0.9*P>build_lim) then
        P>swmm_action1 = buildup load has to be decreased <0.85>.
      endif.
```

Rules that determine the action the user should take in order o calibrate the model.

```
      User Action rule1:
        P:pollutant
      if P>load_diff le 0.25 and
           P>load_diff ge -0.25 then
         P>user_action = calibration is done.
        endif.

      User Action rule2:
      P:pollutant
      if P>swmm_action = storm loads are too small and
        status (P>build_lim) # unknown and
        P>buil_load gt (0.9*P>build_lim) then
        P>user_action = buildup limit has to be increased <0.9>.
      endif.

      User Action rule3:
      P:pollutant
      if P>swmm_action = storm loads are too big and
          status (P>build_lim) # unknown and
        P>buil_load gt (0.9*P>build_lim) then
        P>user_action = buildup limit has to be decreased <0.7>.
      endif.

      User Action rule4:
      P:pollutant
      if P>swmm_action = storm loads are too big and
        P>buildup_meth = Michaelis Menton and
        P>build_coeff lt 1 then
        P>user_action = buildup limit has to be decreased <0.8>.
      endif.

      User Action rule5:
      P:pollutant
      if P>swmm_action = storm loads are too small and
        P>buildup_meth = Michaelis Menton and
        P>build_coeff lt 1 then
        P>user_action = buildup limit has to be increased <0.7>.
      endif.

      User Action rule6:
      P:pollutant
      if P>swmm_action1 = buildup load has to be increased and
        P>buildup_meth = power linear then
        P>user_action = buildup coefficient has to be increased <0.8>.
      endif.

      User Action rule7:
      P:pollutant
      if P>swmm_action1 = buildup load has to be decreased and
        P>buildup_meth = power linear then
        P>user_action = buildup coefficient has to be decreased <0.8>.
      endif.

      User Action rule8:
      P:pollutant
      if P>swmm_action1 = buildup load has to be increased and
        P>buildup_meth = Michaelis Menton and
        P>build_coeff ge 1.0 then
        P>user_action = buildup coefficient has to be decreased <0.8>.
```

```
endif.

User Action rule9:
P:pollutant
if P>swmm_action1 = buildup load has to be decreased and
  P>buildup_meth = Michaelis Menton and
  P>build_coeff ge 1.0 then
  P>user_action = buildup coefficient has to be increased <0.8>.
endif.

User Action rule10:
P:pollutant
if P>swmm_action = storm loads are too big and
  P>buildup_meth = constant load then
  P>user_action = subcatchment loads have to be decreased <0.8>.
endif.

User Action rule11:
P:pollutant
if P>swmm_action = storm loads are too small and
  P>buildup_meth = constant load then
  P>user_action = subcatchment loads have to be increased <0.8>.
endif.

User Action rule12:
P:pollutant
if P>swmm_action1 = buildup load has to be increased and
  P>buildup_meth = exponential then
  P>user_action = buildup exponent has to be increased <0.8>.
endif.

User Action rule13:
P:pollutant
if P>swmm_action1 = buildup load has to be decreased and
  P>buildup_meth = exponential then
  P>user_action = buildup exponent has to be decreased <0.8>.
endif.

User Action rule14:
P:pollutant
if P>swmm_action = storm loads are too small and
  P>washoff_coeff lt 5 then
  P>user_action = washoff coefficient has to be increased <0.8>.
endif.

User Action rule15:
P:pollutant
if P>swmm_action = storm loads are too big and
  P>washoff_coeff gt 0 then
  P>user_action = washoff coefficient has to be decreased <0.8>.
endif.
```

Rules to adjust parameters in order to calibrate the model

```
rule1 to adjust buildup limit:
P:pollutant
if P>user_action = buildup limit has to be increased then
    P>new_blim = P>build_lim + (0.1*P>build_lim).
endif.

rule2 to adjust buildup limit:
P:pollutant
if P>user_action = buildup limit has to be decreased then
    P>new_blim = P>build_lim - (0.1*P>build_lim).
endif.

rule1 to adjust buildup coefficient:
```

```
      P:pollutant
      if P>user_action = buildup coefficient has to be increased then
          P>new_bcoeff = P>build_coeff + (0.1*P>build_coeff).
      endif.

      rule2 to adjust buildup coefficient:
      P:pollutant
      if P>user_action = buildup coefficient has to be decreased then
          P>new_bcoeff = P>build_coeff - (0.1*P>build_coeff).
      endif.

      rule1 to adjust buildup exponent:
      P:pollutant
      if P>user_action = buildup exponent has to be increased then
          P>new_bexp = P>build_exp + (0.1*P>build_exp).
      endif.

      rule2 to adjust buildup exponent:
      P:pollutant
      if P>user_action = buildup exponent has to be decreased then
          P>new_bexp = P>build_exp - (0.1*P>build_exp).
      endif.

      rule1 to adjust washoff coefficient:
      P:pollutant
      if P>user_action = washoff coefficient has to be increased then
          P>new_wcoeff = P>washoff_coeff + (0.1*P>washoff_coeff).
      endif.

      rule2 to adjust washoff coefficient:
      P:pollutant
      if P>user_action = washoff coefficient has to be decreased then
          P>new_wcoeff = P>washoff_coeff - (0.1*P>washoff_coeff).
      endif.
%
actions:

landuse_flag = no.
run removel.
message welcome.
obtain data_prompt.
if data_prompt = true then
  read "infile", eros_sim, no_of_poll, no_of_landuse, eros_code,
      cab_vol, ss_eff.
  read "pfile", pollutant, pollutant(poll_name, buildup_meth,
      washoff_calc, washoff_coeff, washoff_pow, func_dep, unit_abbr,
      typ_units, build_lim, build_exp, build_coeff, catchb_conc,
      prec_conc, ss_eff).
  read "lfile", land_use, land_use(name, buil_eqn, func_dep, buil_lim,
       power, coeff, ss_int, ss_avfac).
  read "sfile", subcatchments, subcatchments(subc_luse, no_catba,
      curb_ln).
endif.
if eros_sim = true then
  message " ",
  "Erosion of suspended solids is simulated using the",
  "Universal Soil Loss Equation.  Information is needed",
  "pertaining to each subcatchment that is subject to",
  "erosion computations.  These subcatchments will be ",
  "contained in the class 'EROSION'.",
  " ",
  "Enter a dummy name for each subcatchment for which",
  "erosion is to be simulated (e.g. sub1,sub2,...,subn).".
  forall E:erosion do
    obtain E>subc_no.
    obtain E>subc_area.
    obtain E>flow_dist.
```

```
    obtain E>soil_fac.
    obtain E>crop_mngmt.
    obtain E>contr_prac.
  endforall.
endif.
if data_prompt = false then
message file = "pollin", no_of_poll.
run poll_dumnames.
read "pollout", pollutant.
endif.
message file = "transit.qual",
      no_of_poll, no_of_landuse, eros_code.
message " ",
"Information pertaining to each pollutant simulated by",
"SWMM (up to 10) is contained in the class 'POLLUTANT'.",
"Each pollutant simulated will be represented in the ",
"class by the dummy names:  p01,p02,...,p10.",
" ".
forall P:pollutant do
  obtain P>poll_name.
  if P>buildup_meth = power linear or
     P>buildup_meth = exponential or
     P>buildup_meth = Michaelis Menton then
    P>build_coeff4 = 0.
    P>build_coeff5 = 0.
  endif.
  if P>washoff_calc = power exponential then
   obtain P>washoff_coeff.
   obtain P>washoff_pow.
  else
   P>washoff_coeff = 0.
   P>washoff_pow = 0.
  endif.
  if landuse_flag = no and
    P>buildup_meth = fract dust dirt buildup then
    erase landuse_flag.
    landuse_flag = yes.
  endif.
  obtain P>poll_name.
  obtain P>unit_abbr.
  if match (mg_per_liter,P>unit_abbr) = true then
    P>typ_units = 0.
  endif.
  if match (other_per_liter,P>unit_abbr) = true then
    P>typ_units = 1.
  endif.
  if match (other_conc_units,P>unit_abbr) = true then
    P>typ_units = 2.
  endif.
  message file = "transit.qual",
      P>poll_name, P>unit_abbr, P>typ_units, P>bmeth_code,
      P>washoff_code, P>funcdep_code.
  if P>buildup_meth = power linear or
     P>buildup_meth = exponential or
     P>buildup_meth = Michaelis Menton then
        message file = "transit.qual",
        P>build_lim, P>build_exp, P>build_coeff, P>build_coeff4,
      P>build_coeff5.
  endif.
  if P>buildup_meth = fract dust dirt buildup then
        message file = "transit",
      P>bfract_lu1, P>bfract_lu2, P>bfract_lu3, P>bfract_lu4,
      P>bfract_lu5.
  endif.
  if P>buildup_meth = constant load then
        P>build_lim = 0.
        P>build_exp = 0.
```

```
        P>build_coeff = 0.
      P>build_coeff4 = 0.
      P>build_coeff5 = 0.
        message file = "transit.qual",
        P>build_lim, P>build_exp, P>build_coeff, P>build_coeff4,
      P>build_coeff5.
  endif.
  message file = "transit.qual",
        P>washoff_pow, P>washoff_coeff,
        P>catchb_conc, P>prec_conc, P>ss_eff.
endforall.
message " ",
"The class 'LAND USE' will contain information",
"pertaining to each of the land uses existing in ",
"the watershed (no more than 5).",
"Please specify the names of the land uses using",
"strings no longer than 8 characters.",
" ".
if data_prompt = false then
forall L:land_use do
  L>name = L.
  if landuse_flag = yes then
  if L>buil_eqn = power linear then
    obtain L>buil_lim.
    obtain L>power.
    obtain L>coeff.
    endif.
  if L>buil_eqn = exponential then
    obtain L>buil_lim.
    obtain L>power.
    L>coeff = 0.
    endif.
  if L>buil_eqn = Michaelis Menton then
    obtain L>buil_lim.
    L>power = 0.
    obtain L>coeff.
    endif.
  else
    L>buil_lim = 0.
    L>power = 0.
    L>coeff = 0.
    L>funcdep_code = 0.
    L>buil_code = 0.
  endif.
endforall.
endif.
forall L:land_use do
  message file = "transit.qual",
      L>name, L>buil_code, L>funcdep_code, L>buil_lim, L>power,
      L>coeff, L>ss_int, L>ss_avfac.
endforall.
message file = "transit.qual", cab_vol, ss_eff.
if data_prompt = false then
read "/x/swmm/QUANTITY/subcat.no", subcatchments.
endif.
forall S:subcatchments do
    message " ", "The Land Uses specified earlier in numeric order are the following:
  forall L:land_use do
   display value of L>name.
  endforall.
  message file = "transit.qual",
      S>subc_luse, S>no_catba, S>curb_ln.
    S>init_load1 = 0.
    S>init_load2 = 0.
    S>init_load3 = 0.
    S>init_load4 = 0.
    S>init_load5 = 0.
```

```
     S>init_load6 = 0.
     S>init_load7 = 0.
     S>init_load8 = 0.
     S>init_load9 = 0.
     S>init_load10 = 0.
       if no_of_poll ge 1 and
         pollutant:p01>buildup_meth = constant load then
         erase S>init_load1.
         obtain S>init_load1.
         endif.
       if no_of_poll ge 2 and
         pollutant:p02>buildup_meth = constant load then
         erase S>init_load2.
         obtain S>init_load2.
         endif.
       if no_of_poll ge 3 and
         pollutant:p03>buildup_meth = constant load then
         erase S>init_load3.
         obtain S>init_load3.
         endif.
       if no_of_poll ge 4 and
         pollutant:p04>buildup_meth = constant load then
         erase S>init_load4.
         obtain S>init_load4.
         endif.
       if no_of_poll ge 5 and
         pollutant:p05>buildup_meth = constant load then
         erase S>init_load5.
         obtain S>init_load5.
         endif.
       if no_of_poll ge 6 and
         pollutant:p06>buildup_meth = constant load then
         erase S>init_load6.
         obtain S>init_load6.
         endif.
       if no_of_poll ge 7 and
         pollutant:p07>buildup_meth = constant load then
         erase S>init_load7.
         obtain S>init_load7.
         endif.
       if no_of_poll ge 8 and
         pollutant:p08>buildup_meth = constant load then
         erase S>init_load8.
         obtain S>init_load8.
         endif.
       if no_of_poll ge 9 and
         pollutant:p09>buildup_meth = constant load then
         erase S>init_load9.
         obtain S>init_load9.
         endif.
       if no_of_poll ge 10 and
         pollutant:p10>buildup_meth = constant load then
         erase S>init_load10.
         obtain S>init_load10.
         endif.
  message file = "transit.qual",
      S>init_load1, S>init_load2, S>init_load3, S>init_load4, S>init_load5,
      S>init_load6, S>init_load7, S>init_load8, S>init_load9, S>init_load10.
endforall.
run create.
forall P:pollutant do
if P>washoff_calc # power exponential then
  read "transit2", P>washoff_coeff, P>washoff_pow, P>rc_corr.
endif.
endforall.
message swmm_run.
run swmm.
```

```
message " ",
 "###########  The results of SWMM have been obtained.   ##########",
 "###########  If necessary, the Expert System will      ##########",
 "###########  determine steps required for calibration  ##########",
 "###########  of the model.                             ##########",
" ".
message what_next.
break.
read "result", pollutant, pollutant(buil_load, storm_load, percent,
                     load_diff).
obtain calib_done.
while calib_done = calibration is not done do
message calibration.
forall P:pollutant do
obtain P>user_action.
message " ",  combine("For pollutant ",P>poll_name," : ").
display value of P>user_action.
obtain justification.
if justification = true then
  justify P>user_action.
endif.
erase justification.
endforall.
forall P:pollutant do
if P>user_action # calibration is done then
message  " ",
    combine ("*** Reminder --> ",P," is pollutant ",P>poll_name,"."),
    combine ("*** Reminder --> Expert System Diagnosis Is The Following: ").
    display value of P>user_action.
obtain P>par_chng.
if P>par_chng = buildup limit then
  message file = "transit1",P,combine("qfact1"),P>new_blim.
  message combine("*** Pollutant ",P>poll_name,": buildup limit modified from ",P>bui
  erase P>build_lim.
  P>build_lim = P>new_blim.
  erase P>new_blim.
endif.
if P>par_chng = buildup exponent then
  message file = "transit1",P,combine("qfact2"),P>new_bexp.
  message combine("*** Pollutant ",P>poll_name,": buildup exponent modified from ",P>
  erase P>build_exp.
  P>build_exp = P>new_bexp.
  erase P>new_bexp.
endif.
if P>par_chng = buildup coefficient then
  message file = "transit1",P,combine("qfact3"),P>new_bcoeff.
  message combine("*** Pollutant ",P>poll_name,": buildup coefficient modified from "
  erase P>build_coeff.
  P>build_coeff = P>new_bcoeff.
  erase P>new_bcoeff.
endif.
if P>par_chng = washoff coefficient then
  message file = "transit1",P,combine("rcoeff"),P>new_wcoeff.
  message combine("*** Pollutant ",P>poll_name,": washoff coefficient modified from "
  erase P>washoff_coeff.
  P>washoff_coeff = P>new_wcoeff.
  erase P>new_wcoeff.
endif.
else
  message file = "transit1",P.
endif.
endforall.
message file = "transit1", combine("%").
message what_next.
break.
message newswmm_run.
run new_swmm.
```

```
run remove2.
forall P:pollutant do
erase P>buil_load, P>storm_load, P>percent, P>load_diff,
      P>user_action, P>par_chng, P>swmm_action, P>swmm_action1.
endforall.
read "result", pollutant, pollutant(buil_load, storm_load, percent,
                     load_diff).
erase calib_done.
obtain calib_done.
endwhile.
message " ",
"******  All pollutants simulated in the QUALITY segment of the  ******",
"******  Storm Watershed Management Model are now calibrated.    ******".
message " ",
 "*** Final Values of Key Calibration Parameters ***".
forall P:pollutant do
message " ".
message combine("For pollutant ",P>poll_name," : ").
message combine("Buildup Limit is ",P>build_lim).
message combine("Buildup Power is ",P>build_exp).
message combine("Buildup Coefficient is ",P>build_coeff).
message combine("Washoff Coefficient is ",P>washoff_coeff).
message combine("Load Difference is ",P>load_diff).
endforall.
message " ",
 "***  Note:                                                        ***",
 "***  Load Difference = (Meas. load - Pred. load)/Meas. load   ***".
%
```

APPENDIX E

QUALITY SCRIPT: The following script is a record of the user-computer interaction during a typical session using ESCALOS to address watar quality. The input data for this example were taken from the Glen Ellyn watershed.

```
% kesr qual

Knowledge Engineering System (KES), Release 2.3.
Copyright (C) 1986, Software Architecture & Engineering, Inc.
Loading the knowledge base "qual.pkb".

 WELCOME TO THE QUALITY PORTION OF THE SWMM EXPERT SYSTEM


Do you want to skip entering data?
        1. true
        2. false
=? 2


Is erosion to be simulated?
        1. true
        2. false
=? 2


Please enter the number of pollutants to be simulated.
Type 'explain' for an explanation.
   [constraint: no_of_poll ge 1
     and no_of_poll le 10 ]
(Enter a number)
=? e
Up to ten quality constituents may be simulated.  The number and
choice of constituents to be simulated must reflect the user's
needs, potential for treatment and receiving water impacts, etc.
Almost any constituent measured by common laboratory or field tests
can be included, up to a total of ten.

Please reenter value:


Please enter the number of pollutants to be simulated.
Type 'explain' for an explanation.
   [constraint: no_of_poll ge 1
     and no_of_poll le 10 ]
(Enter a number)
=? 2


Please enter the number of land uses existing in the watershed.
Type 'explain' for an explanation.
   [constraint: no_of_landuse ge 1
     and no_of_landuse le 5 ]
(Enter a number)
=? e
Up to five user supplied land uses may be entered to
characterize different subcatchments.
Examples are:
        Single-family residential,
        Multi-family residential,
```

```
         Commercial,
         Industrial,
         Undeveloped/Park.

 Please reenter value:


 Please enter the number of land uses existing in the watershed.
 Type 'explain' for an explanation.
    [constraint: no_of_landuse ge 1
      and no_of_landuse le 5 ]
 (Enter a number)
 =? 1

 Information pertaining to each pollutant simulated by
 SWMM (up to 10) is contained in the class 'POLLUTANT'.
 Each pollutant simulated will be represented in the
 class by the dummy names:  p01,p02,...,p10.


 For p01 of class pollutant:

 Please enter the pollutant name.
 Enter a string, no more than 8 characters.
 (Enter a string)
 =? COD

 For p01 of class pollutant:

 Please indicate which buildup method you would like to use,
 for the particular pollutant. Type 'explain' for an explanation
         1. power linear
         2. exponential
         3. Michaelis Menton
         4. fract dust dirt buildup
         5. constant load

 =? e
 For each of the five methods an explanation of the procedure to
 determine dust and dirt buildup is given. t represents time in days.
 power-linear:
         equation =>  dd buildup = buildup coefficient * (t ** buildup power).
         Linear buildup is a power function with power = 1.0
 exponential:
         equation => dd buildup = buildup limit * (1 - e**(-buildup power * t)).
         The exponent is the familiar exponential decay constant. It may
         be obtained from the slope of a semi-log plot of buildup vs. time.
 Michaelis-Menton:
         equation => dd buildup = buildup limit * t/(buildup coefficient + t).
         The coefficient for dust and dirt buildup has the interpretation
         of the halftime constant, that is, the time at which buildup is
         half the maximum value.
 fraction of dust and dirt buildup:
         Buildup is computed as a fraction of dust and dirt.  The rate of
         buildup will depend upon the fraction for a given land use.
 constant load:
         Buildup load is entered by the user for each constituent
         for each subcatchment.



 Enter <RETURN> to continue, 'q' then <RETURN> to quit:



 Please reenter value:
```

```
For p01 of class pollutant:

Please indicate which buildup method you would like to use,
for the particular pollutant. Type 'explain' for an explanation
        1. power linear
        2. exponential
        3. Michaelis Menton
        4. fract dust dirt buildup
        5. constant load

=? 1

For p01 of class pollutant:

Please indicate the type of washoff calculation.
Type 'explain' for an explanation.
        1. power exponential
        2. rating curve by buildup eqn no limit
        3. rating curve by buildup eqn with limit

=? e
Washoff calculations may be computed via a power-exponential function
or they may be avoided and load rates computed for each subcatchment
at each time step by a rating curve method; each method is described.
The rating curve can also be used where the maximum amount that can be
removed is the amount built up prior to the storm.
 power exponential:
        -POFF(t) = d PSHED/dt = -RCOEFX * r**WASHPO * PSHED
        where => POFF = constituent load washed off at time, t,
                       quantity per sec. (eg. mg/sec)
                 PSHED = quantity of constituent available for washoff
                         at time, t, (eg. mg).
                 RCOEFFX = washoff coefficient
                 r = runoff rate, in/hr.
 rating curve:
        POFF = RCOEFF * WFLOW**WASHPO.
        where => WFLOW = subcatchment runoff, cfs.
                 RCOEF = coefficient that includes correct units conversion.
                 WASHPO = exponent.


Enter <RETURN> to continue, 'q' then <RETURN> to quit:



Please reenter value:

For p01 of class pollutant:

Please indicate the type of washoff calculation.
Type 'explain' for an explanation.
        1. power exponential
        2. rating curve by buildup eqn no limit
        3. rating curve by buildup eqn with limit

=? 1

For p01 of class pollutant:

Please enter the washoff equation coefficient.
(Enter a number)
=? 4.0

For p01 of class pollutant:

Please enter the exponent of the washoff equation.
(Enter a number)
```

```
=? 1.0

For p01 of class pollutant:

Please enter the unit abbreviation.
For example: mg/l, MPN/l, pH, etc.
No more than 8 characters.
(Enter a string)
=? mg/l

For p01 of class pollutant:

Please indicate the functional dependence of dust and dirt buildup.
Type 'explain' for an explanation.
        1. gutter length
        2. area
        3. constant

=? e

If the buildup is a function of gutter length, gutter length can
be estimated by two methods:
1) Gutter Length (100ft) = twice the total length of streets.
2) Gutter Length (100ft) = area * (413 - 353 * (0.839**population density))/100.
The buildup can also be a function of the total land area or it
can be constant

Please reenter value:

For p01 of class pollutant:

Please indicate the functional dependence of dust and dirt buildup.
Type 'explain' for an explanation.
        1. gutter length
        2. area
        3. constant

=? 1

For p01 of class pollutant:

Please enter the buildup limit.
Type 'explain' for an explanation
(Enter a number)
=? e
If no buildup limit is desired, enter a large number such as 100,000

Please reenter value:

For p01 of class pollutant:

Please enter the buildup limit.
Type 'explain' for an explanation
(Enter a number)
=? 10000

For p01 of class pollutant:

Please enter the buildup exponent.
Type 'explain' for an explanation
(Enter a number)
=? e
A typical range is from 0-1 for linear,
no exponent for Michaelis Menton and
0-5 for exponential

Please reenter value:
```

```
For p01 of class pollutant:

Please enter the buildup exponent.
Type 'explain' for an explanation
(Enter a number)
=? 1.0

For p01 of class pollutant:

Please enter the buildup coefficient.
(Enter a number)
=? 9.0

For p01 of class pollutant:

Please enter the initial concentration of pollutant in the catchbasin.
Type 'explain' if unsure
(Enter a number)
=? e

Values are typically in the following range for 4 pollutants
COD       153  -  143,000
BOD5        5  -    15,00
Total N   0.5  -       33
Total P        <  0.2

Please reenter value:

For p01 of class pollutant:

Please enter the initial concentration of pollutant in the catchbasin.
Type 'explain' if unsure
(Enter a number)
=? 600

For p01 of class pollutant:

Please enter the concentration of pollutant in precipitation.
Type 'explain' if unsure
(Enter a number)
=? e

Typical ranges for the following constituents are:

acidity, (pH)           3 -  6
BOD5, mg/l              1 - 13
COD, mg/l               9 - 16
TOC, mg/l                 few
Total Solids, mg/l     18 - 24
Susp. Solids, mg/l      2 - 13
Turbidity, JTU          4 -  7
Organic N, mg/l       0.05 - 1.0
Total N, mg/l          0.2 - 1.5
Pesticides, ug/l          few
Lead ug/l               30 - 70
Heavy Metals ug/l         few

Please reenter value:

For p01 of class pollutant:

Please enter the concentration of pollutant in precipitation.
Type 'explain' if unsure
(Enter a number)
=? 0.11

For p01 of class pollutant:
```

```
Please enter the street sweeping efficiency.
Type 'explain' if unsure
(Enter a number)
=? e
The following are proposed removal efficiencies
for Vaccuum Street Cleaners (1 pass) :
                      Small Loads         Med. Loads       Large Loads
Total Solids                 .31                 .37               .48
BOD5                         .24                 .29               .38
COD                          .16                 .21               .33
KN                           .26                 .31               .43
PO4                          .8                  .12               .20
Pesticides                   .33                 .40               .57
Cd                           .23                 .30               .45
Sr                           .27                 .34               .44
Cu                           .30                 .36               .49
Ni                           .37                 .43               .55
Cr                           .34                 .42               .53
Zn                           .34                 .41               .55
Mn                           .37                 .45               .58
Pb                           .40                 .49               .62
Fe                           .40                 .59               .63
Small, Med and Large represent 20-200, 200-1000, 1000-10000
lb/curb-mile of total solids respectively.  If Street Cleaner
makes more than one pass, removal efficiency increases slightly

Please reenter value:

For p01 of class pollutant:

Please enter the street sweeping efficiency.
Type 'explain' if unsure
(Enter a number)
=? 0.27

For p02 of class pollutant:

Please enter the pollutant name.
Enter a string, no more than 8 characters.
(Enter a string)
=? SUS.SOL

For p02 of class pollutant:

Please indicate which buildup method you would like to use,
for the particular pollutant. Type 'explain' for an explanation
          1. power linear
          2. exponential
          3. Michaelis Menton
          4. fract dust dirt buildup
          5. constant load

=? 1

For p02 of class pollutant:

Please indicate the type of washoff calculation.
Type 'explain' for an explanation.
          1. power exponential
          2. rating curve by buildup eqn no limit
          3. rating curve by buildup eqn with limit

=? 1

For p02 of class pollutant:

Please enter the washoff equation coefficient.
```

```
(Enter a number)
=? 5.5

For p02 of class pollutant:

Please enter the exponent of the washoff equation.
(Enter a number)
=? 1.0

For p02 of class pollutant:

Please enter the unit abbreviation.
For example: mg/l, MPN/l, pH, etc.
No more than 8 characters.
(Enter a string)
=? mg/l

For p02 of class pollutant:

Please indicate the functional dependence of dust and dirt buildup.
Type 'explain' for an explanation.
        1. gutter length
        2. area
        3. constant

=? 1

For p02 of class pollutant:

Please enter the buildup limit.
Type 'explain' for an explanation
(Enter a number)
=? 10000

For p02 of class pollutant:

Please enter the buildup exponent.
Type 'explain' for an explanation
(Enter a number)
=? 1.0

For p02 of class pollutant:

Please enter the buildup coefficient.
(Enter a number)
=? 15.5

For p02 of class pollutant:

Please enter the initial concentration of pollutant in the catchbasin.
Type 'explain' if unsure
(Enter a number)
=? 345

For p02 of class pollutant:

Please enter the concentration of pollutant in precipitation.
Type 'explain' if unsure
(Enter a number)
=? 0.9

For p02 of class pollutant:

Please enter the street sweeping efficiency.
Type 'explain' if unsure
(Enter a number)
=? 0.37
```

```
The class 'LAND USE' will contain information
pertaining to each of the land uses existing in
the watershed (no more than 5).
Please specify the names of the land uses using
strings no longer than 8 characters.


List the members of class land_use

=? residential

For residential of class land_use:

Please enter the street sweeping cleaning interval in days.
Very often 15-30 days in most cities.
(Enter a number)
=? 15

For residential of class land_use:

Please enter the street sweeping availability factor.
Type 'explain' for an explanation
(Enter a number)
=? e
The availability factor is intended to account for the fraction of
the catchments area that is actually sweepable.  This is usually a
function of the number of cars parked along the sides of streets,
which will depend on the population density.

Please reenter value:

For residential of class land_use:

Please enter the street sweeping availability factor.
Type 'explain' for an explanation
(Enter a number)
=? 0.6


Please enter the average storage volume of existing individual catchbasins.
Type 'explain' for an explanation
(Enter a number)
=? e
The purpose of the deep well or sump of a catchbasin is to
trap solids by sedimentation prior to stormwater entry into
the sewer.  This distinguishes catchbasins from stormwater
inlets.  The volume of the sump varies considerably with
design, ranging from 2.8 to 78 cubic feet.  The volume is
typically reduced by a large quantity of solids trapped in
the sump, often by more than 50 percent.

Please reenter value:


Please enter the average storage volume of existing individual catchbasins.
Type 'explain' for an explanation
(Enter a number)
=? 27.0


Please enter the street sweeping efficiency for dust and dirt.
Type 'explain' for an explanation.
(Enter a number)
=? e
Street cleaning is performed in most urban areas for control of
solids and trash deposited along street gutters. Typical removal
```

```
efficiencies for Total Solids (Vacuum Cleaner) are the following:

Small Load (20-200 lb/curb mile TS): 31%
Med. Load (200-1,000 lb/curb mile TS): 37%
Large Load (1,000-10,000 lb/curb mile TS): 48%

Efficiencies increase slightly with no. of passes by street cleaner.

Please reenter value:


Please enter the street sweeping efficiency for dust and dirt.
Type 'explain' for an explanation.
(Enter a number)
=? 0.65

The Land Uses specified earlier in numeric order are the following:

  "residential"


For subcatchment1 of class subcatchments:

Please enter the land use for the subcatchment.
   [constraint: subc_luse ge 1
     and subc_luse le 5 ]
(Enter a number)
=? 1

For subcatchment1 of class subcatchments:

How many catchbasins are there in the subcatchment?
Type 'explain' for an explanation
(Enter a number)
=? e
Catchbasins are treated as a reservoir of constituents in each
subcatchment available to be flushed out during a storm. The number
of catchbasins in a subcatchment is ususally a function of the area

Please reenter value:

For subcatchment1 of class subcatchments:

How many catchbasins are there in the subcatchment?
Type 'explain' for an explanation
(Enter a number)
=? 73

For subcatchment1 of class subcatchments:

Please enter the total curb length within the subcatchment (per 100 ft).
Type 'explain' for an explanation.
(Enter a number)
=? e
1) Gutter Length (100ft) = twice the total length of streets.
2) Gutter Length (100ft) = area * (413 - 353 * (0.839**population density))/100.

Please reenter value:

For subcatchment1 of class subcatchments:

Please enter the total curb length within the subcatchment (per 100 ft).
Type 'explain' for an explanation.
(Enter a number)
=? 14

The Land Uses specified earlier in numeric order are the following:
```

```
   "residential"


 For subcatchment2 of class subcatchments:

 Please enter the land use for the subcatchment.
    [constraint: subc_luse ge 1
      and subc_luse le 5 ]
 (Enter a number)
 =? 1

 For subcatchment2 of class subcatchments:

 How many catchbasins are there in the subcatchment?
 Type 'explain' for an explanation
 (Enter a number)
 =? 46

 For subcatchment2 of class subcatchments:

 Please enter the total curb length within the subcatchment (per 100 ft).
 Type 'explain' for an explanation.
 (Enter a number)
 =? 27
  How many hydrographs will you use for calibration?
 3
  Are the loads of pollutants for each storm
  and each pollutant already estimated (1=y/0=n)?
 1
  For storm event           1
  Do you want to enter rainfall and runoff data now (1)
  or is it already in some file (0)?
 0
  For storm event           1
  Do you want to enter quality data now (1)
  or is it already in this same file (0)?
 0
  For storm event           2
  Do you want to enter rainfall and runoff data now (1)
  or is it already in some file (0)?
 0
  For storm event           2
  Do you want to enter quality data now (1)
  or is it already in this same file (0)?
 0
  For storm event           3
  Do you want to enter rainfall and runoff data now (1)
  or is it already in some file (0)?
 0
  For storm event           3
  Do you want to enter quality data now (1)
  or is it already in this same file (0)?
 0

#####################################################################

 The Storm Watershed Management Model has now been activated based
 on the data you have entered.

#####################################################################


###########  The results of SWMM have been obtained.   ##########
###########  If necessary, the Expert System will      ##########
###########  determine steps required for calibration  ##########
###########  of the model.                             ##########
```

```
Type 'c' to continue, 'n' for nextcase, 's' to stop

Ready for command: c

**********    Calibration is not done, you     **********
**********    must follow these directions.    **********


For pollutant COD :
  washoff coefficient has to be increased <0.80>
  buildup coefficient has to be increased <0.68>



Would you like to see the supporting rules?
        1. true
        2. false
=? 1

user_action = washoff coefficient has to be increased

Reasons for belief:
     rule: User Action rule14

Would you like to see the supporting knowledge sources? (y/n) y

Name: User Action rule14
Is: Production Rule


        P:pollutant
        if P>swmm_action = storm loads are too small and
          P>washoff_coeff lt 5 then
          P>user_action = washoff coefficient has to be increased <0.8>.
        endif.

Enter <RETURN> to continue:


user_action = buildup coefficient has to be increased

Reasons for belief:
     rule: User Action rule6

Would you like to see the supporting knowledge sources? (y/n) y

Name: User Action rule6
Is: Production Rule


        P:pollutant
        if P>swmm_action1 = buildup load has to be increased and
          P>buildup_meth = power linear then
          P>user_action = buildup coefficient has to be increased <0.8>.
        endif.

Enter <RETURN> to continue:



For pollutant SUS.SOL :
  buildup coefficient has to be increased <0.68>
```

```
Would you like to see the supporting rules?
        1. true
        2. false
=? 1

user_action = buildup coefficient has to be increased

Reasons for belief:
     rule: User Action rule6

Would you like to see the supporting knowledge sources? (y/n) y

Name: User Action rule6
Is: Production Rule


        P:pollutant
        if P>swmm_action1 = buildup load has to be increased and
          P>buildup_meth = power linear then
          P>user_action = buildup coefficient has to be increased <0.8>.
        endif.

Enter <RETURN> to continue:



*** Reminder --> p01 is pollutant COD.
*** Reminder --> Expert System Diagnosis Is The Following:
  washoff coefficient has to be increased <0.80>
  buildup coefficient has to be increased <0.68>


For p01 of class pollutant:

Which parameter would you like to change based
on the expert system diagnosis?
        1. buildup limit
        2. buildup coefficient
        3. buildup exponent
        4. washoff coefficient

=? 4
*** Pollutant COD: washoff coefficient modified from 4 to 4.4000006 ***

*** Reminder --> p02 is pollutant SUS.SOL.
*** Reminder --> Expert System Diagnosis Is The Following:
  buildup coefficient has to be increased <0.68>


For p02 of class pollutant:

Which parameter would you like to change based
on the expert system diagnosis?
        1. buildup limit
        2. buildup coefficient
        3. buildup exponent
        4. washoff coefficient

=? 2
*** Pollutant SUS.SOL: buildup coefficient modified from 15.5 to 17.050003 ***

Type 'c' to continue, 'n' for nextcase, 's' to stop

Ready for command: c

####################################################################
```

```
 The Storm Watershed Management Model has now been activated based
 on the updated data.

####################################################################

**********    Calibration is not done, you     **********
**********    must follow these directions.    **********


For pollutant COD :
  washoff coefficient has to be increased <0.80>
  buildup coefficient has to be increased <0.68>



Would you like to see the supporting rules?
        1. true
        2. false
=? 2

For pollutant SUS.SOL :
  buildup coefficient has to be increased <0.68>



Would you like to see the supporting rules?
        1. true
        2. false
=? 2

*** Reminder --> p01 is pollutant COD.
*** Reminder --> Expert System Diagnosis Is The Following:
  washoff coefficient has to be increased <0.80>
  buildup coefficient has to be increased <0.68>


For p01 of class pollutant:

Which parameter would you like to change based
on the expert system diagnosis?
        1. buildup limit
        2. buildup coefficient
        3. buildup exponent
        4. washoff coefficient

=? 2
*** Pollutant COD: buildup coefficient modified from 9 to 9.9000006 ***

*** Reminder --> p02 is pollutant SUS.SOL.
*** Reminder --> Expert System Diagnosis Is The Following:
  buildup coefficient has to be increased <0.68>


For p02 of class pollutant:

Which parameter would you like to change based
on the expert system diagnosis?
        1. buildup limit
        2. buildup coefficient
        3. buildup exponent
        4. washoff coefficient

=? 2
*** Pollutant SUS.SOL: buildup coefficient modified from 17.050003 to 18.755005 ***
```

```
Type 'c' to continue, 'n' for nextcase, 's' to stop

Ready for command: c

####################################################################

 The Storm Watershed Management Model has now been activated based
 on the updated data.

####################################################################


*****  All pollutants simulated in the QUALITY segment of the  *****
*****  Storm Watershed Management Model are now calibrated.    *****

*** Final Values of Key Calibration Parameters ***

For pollutant COD :
Buildup Limit is 10000
Buildup Power is 1
Buildup Coefficient is 9.9000006
Washoff Coefficient is 4.4000006
Load Difference is 0.22799999

For pollutant SUS.SOL :
Buildup Limit is 10000
Buildup Power is 1
Buildup Coefficient is 18.755005
Washoff Coefficient is 5.5
Load Difference is 0.20599997

***  Note:                                                 ***
***  Load Difference = (Meas. load - Pred. load)/Meas. load   ***

Ready for command: s

KES - Copyright (C) 1986, Software Architecture & Engineering, Inc.
% exit
```

Water Resources Research Center
Lilly Hall of Life Sciences
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West Lafayette, Indiana 47907

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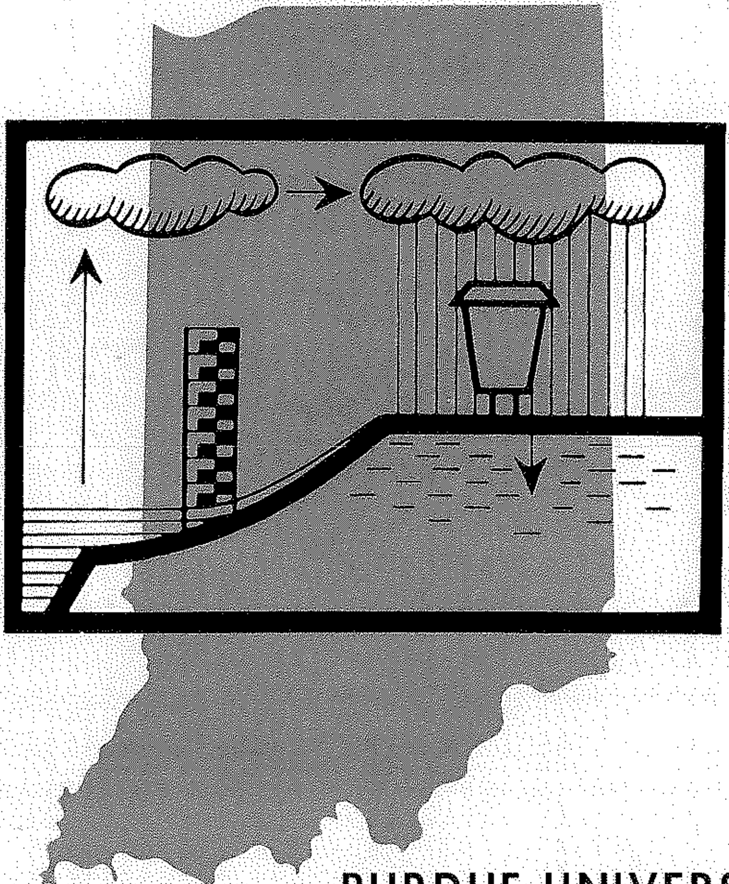
TECHNICAL REPORT NUMBER 181

MEASUREMENT OF RECHARGE RATES THROUGH AN UNSATURATED GLACIAL TILL BY TRITIUM ANALYSES



by

Douglas P. Daniels
Steven J. Fritz
Darrell I. Leap

June 1989

PURDUE UNIVERSITY
WATER RESOURCES RESEARCH CENTER
WEST LAFAYETTE, INDIANA

Technical Report Number 181

Measurement of Recharge Rates Through an Unsaturated Glacial Till by Tritium Analyses

by

Douglas P. Daniels, Steven J. Fritz, and Darrell I. Leap

Project Number: G1561-03

Submitted to:

U.S.Geological Survey
United States Department of the Interior
Reston, VA 22092

"The activities on which this report is based were financed in part by the Department of the Interior, U.S. Geological Survey through the Purdue University Water Resources Research Center."

Water Resources Research Center
Purdue University, West Lafayette, IN 47907

---June 1989---

FINAL TECHNICAL COMPLETION REPORT

Period of Investigation: 7/1/88 to 6/30/89

Project Number: G1561-03

Grant Agreement Number: 14-08-0001-G1561

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ABSTRACT

Measurement of the penetration depth of bomb-derived tritium is a relatively simple, yet effective method for measuring the average annual recharge rate through the vadose zone. The tritium profile obtained in core BN-1, located on the upland till plain near West Lafayette, Indiana, showed a definite low-high-low signal at depth, indicating the position of recharge water derived from 1963/64 precipitation. The recharge rate calculated using the depth of penetration of the 1963/64 peak, as well as by comparing the amount of tritium held in the vadose zone with that available for recharge since 1963/64, is 36 mm/yr (1.4 in/yr). This is in reasonable agreement with Arihood's (1982) estimate of 51 to 114 mm/yr (2 to 4.5 in/yr) for tills, based on his numerical groundwater-flow model. Two other cores, located on a slope topographically lower than BN-1, showed no definite reversal in tritium concentration. This is probably due to lateral flow components at these locations.

INTRODUCTION

In order to use the hydrologic equation in groundwater studies, several parameters need to be known. One of the more important of these parameters is the infiltration rate of water into the vadose zone. This parameter is needed for determining the ground-water budget of an area, and for assessing the migration rates of fluids through near-surface sediments toward the saturated zone. Recharge rate is often estimated, and the methods used to estimate this quantity may be grouped under indirect methods and direct methods.

Indirect methods do not actually measure water recharge rates. Instead, measurements are made of areal ground-water discharge (i.e. at base stream flow), as well as precipitation, evapotranspiration, and runoff. This information is then used in a numerical groundwater-flow model to obtain an estimate of recharge rate. Indirect methods have the advantage of being simple, requiring few, if any, sophisticated instruments. Often, data already collected by other organizations (for instance, precipitation data from a weather bureau) may be used. However, such estimates may suffer from measurement inaccuracies, calculation errors, or the assumptions used.

Direct methods measure the actual rate at which water moves through the porous medium. These schemes employ devices (such as infiltrometers, lysimeters, and tensiometers) as well as tracer techniques to measure water movement beneath the surface. Infiltrometers estimate the infiltration rate under ponded conditions by measuring the rate of water-level decrease in a cylinder installed in the ground. However, lateral divergence of flow beneath the device can lead to erroneous estimates. A lysimeter is a soil-filled device in which the water added or lost during the time of measurement is determined gravimetrically. Use of a lysimeter requires reproducing actual soil conditions in the device, which may be difficult to obtain in practice. Tensiometers monitor changes in water content at various soil depths of an initially saturated profile. The surface of the area needs to be covered with a plastic sheet in order to minimize evapotranspiration. This technique is generally used only in relatively wet profiles.

Problems are associated with these direct-measurement methods. All three devices disturb the soil in the measured area. Moreover, measurements are usually taken only for short periods of time, and the results extrapolated to longer times. Finally, the devices require manpower to install, monitor, and maintain. The manpower requirement also adds cost to the investigation.

In hydrogeologic studies, tracer techniques are typically used to determine a groundwater's velocity, flow direction, or dispersive pattern. Artificial tracers, such as dyes, may be added. Natural tracers, such as tritium, carbon-14, and chlorine-36, are added through precipitation events. An "ideal tracer" in groundwater studies is a substance that behaves in the system exactly as the material being traced, but has one property which distinguishes it from the material being traced which is easily and accurately detected and measured.

Certain isotopes are excellent candidates for ideal tracers. Tritium, a radioactive form of hydrogen occurring in water, is one of these candidates. The activity of this isotope is reported in Tritium Units (TU), where 1 TU is the ratio of one atom of tritium to 10^{18} atoms of stable hydrogen (protium and deuterium). One TU is also equal to 3.2 picoCuries per kilogram of water (Fontes, 1980), where 1 Curie is equivalent to 3.7×10^{10} disintegrations per second. The half-life of tritium is 12.43 years (Mann et al., 1982).

Prior to above-ground thermonuclear testing, the background level of tritium in precipitation was on the order of 5-20 TU (Kaufman and Libby, 1954; Fontes, 1983). According to Freeze and Cherry (1979), groundwater recharged before 1953 can be expected to have tritium activities between 2 and 4 TU. During the late 1950's and early 1960's, thermonuclear tests introduced large amounts of tritium (as well as other isotopes) into the atmosphere. The activity of tritium in precipitation during and shortly after this period was several orders of magnitude higher than prior to the nuclear tests. The elevated tritium activities (relative to pre-bomb levels) may be easily distinguished in subsurface waters. As such, tritium has been used as a tracer in both the saturated zone and the vadose zone. It should be added here that, due to tritium's short half-life, the elevated tritium activities of the mid-1960's precipitation will become more difficult to trace in groundwater systems as this isotope decays and becomes diluted with water having little or no tritium.

Previous Studies

A number of investigators have used tritium to study water movement in the saturated zone. The great number of such studies is likely due to the fact that sufficient water for analysis can be easily extracted from a relatively narrow zone. Also, since domestic and municipal wells are screened in the saturated zone, such wells are convenient sources of water for study. Finally, most groundwater hydrologists are trained in the processes and mechanics of saturated flow, and therefore are most comfortable with such studies.

Fewer tritium studies exist for the vadose zone. This is surprising, considering that recharge waters must traverse the vadose zone before entering the saturated zone. The lack of such studies is due to the difficulty in extracting a sufficient volume of water from a narrow soil horizon for detailed studies. At the same time, methods for extracting water from unsaturated sediments may lead to isotopic fractionation, which will cause erroneous results. Lastly, the physics of unsaturated flow is not as simple as that of saturated flow, and many investigators lack sufficient knowledge of these processes. Results obtained by previous investigators who have used bomb tritium in the vadose zone are summarized below.

Smith et al. (1970) compared the tritium profiles of a high permeability chalk section and a low permeability clay section in southern England. The authors concluded that the downward movement of the tritium front occurred mainly by intergranular seepage, with some flow through crack systems.

Andersen and Sevel (1974) studied the tritium profile in a sand-and-gravel outwash unit in Denmark. Four profiles were obtained over a period of six years, allowing the authors to follow the progress of the tritium front. These profiles indicate that recharge occurred essentially by displacement flow ("slug flow"), in which a given year's recharge water displaces all previously recharged water downward by an amount equal to that year's recharge. They also concluded that dispersive processes operate on the waters, serving to smear out the originally sharp tritium peak.

Dincer et al. (1974) studied the movement of bomb-tritium through sand dunes in Saudi Arabia. Understandably, recharge in this arid area is difficult to estimate using precipitation-evaporation balance methods. They observed a low-high-low signal of tritium concentration with depth, indicating progressive downward movement of a tritium front. Because this front was presumed to correspond with the peak levels of tritium in 1963/64 precipitation, they could estimate the rate of water movement through the dunes. Their findings indicated that more moisture was recharging through the dunes than was previously estimated.

At the Hanford site near Richland, Washington, Isaacson et al. (1974) used the depth of penetration of bomb tritium to assess the vadose-zone water movement at a low-level nuclear waste site. Holes were drilled 90 m into the vadose zone, and the tritium profile was measured. They found no tritium in the vadose-zone below about 5 m; however, detectable tritium was found in the saturated zone below 94 m, suggesting that tritium was recharging by some other means in addition to intergranular flow. Although the Hanford site is located in an arid region, the results of this study are useful to others in assessing the suitability of storing hazardous materials in vadose-zone sediments.

Allison and Hughes (1978) used tritium (as well as chloride in rainfall) to estimate recharge in a portion of the Gambier Plain, South Australia. A total of sixteen sampled profiles, representing ten different hydrologic units, were obtained. The local recharge rates were found to vary by a factor of five (50 to 250 mm/yr) among the different units, as might be expected for different soil types.

Verhagen et al. (1979) compared the depth of penetra-tion of bomb tritium in sands in the Kalahari Thirstland (South Africa) at two different periods. They observed that between 1962 and 1974, a period of average precipitation relative to years when these records were kept, the peak had reached depths of 4 to 6 meters. Between 1974 and 1978, a period of higher than normal precipitation, the peak had moved to depths of 16 to 23 meters. This illustrates the effect that varying precipitation can have on the measured recharge rate if there was no change in hydraulic conductivity with depth.

Hendry (1983) studied an area in the semi-arid prairie of southern Alberta, Canada. The sediments at this site are composed of clayey till which is overlain by about three meters of lacustrine silts and clays. The highest tritium activities were found in the lacustrine sediments, indicating a low recharge rate. However, two zones of lower activity were found in the underlying till, separated by zones of essentially dead water (no measurable tritium). Hendry interpreted the presence of these zones as due to migration of tritium through near-surface fractures.

Purpose

In Indiana, as well as the Midwest, many aquifers are overlain by glacial tills. Since recharge to the aquifers occurs through these tills, knowledge of the recharge rate is important in determining local and regional water budgets. Using tritium to measure this rate is an excellent direct method which can be used to corroborate estimates based on other methods (for instance, groundwater-flow models). As such, this study uses the depth of penetration of the bomb-tritium front to measure the recharge rate in the upland till plain near West Lafayette, Indiana. Due to the heterogeneous nature of tills, various physical, chemical, and mineralogical properties are also measured and compared to the tritium profile, in order to evaluate any correlation between these properties and movement of the tritium front.

Acknowledgements

Kenneth Sheeringa, Purdue Agronomy Department, provided printouts of climatological data recorded at the Purdue Agronomy Farm. David Mengel, Purdue Agronomy Department and Soil Erosion Lab, provided assistance in determining the cation exchange capacities of samples. Wanda Curtis typed the tables, and Giovanni Soto drafted the figures. The authors thank these people for their assistance on this project.

We especially wish to thank the staff at the Environmental Isotope Lab at the University of Waterloo. This includes Bob Drimmie, Rick Heemskirk, Jean Johnson, and Mary Ellen Patton.

GEOGRAPHY

Location

The study area lies in northwestern Tippecanoe County, Indiana, as shown in Fig. 1. The actual site is located in the NE/4 of section 14, T. 23 N., R. 5 W., and was once the site of one of Purdue University's poultry farms. This location is about 4 km (2.5 mi) west of West Lafayette.

Physiography

Tippecanoe County lies within the Tipton Till Plain of Indiana (Malott, 1922), which is a part of the Central Lowlands Province. Much of the county is till plain which lies at an average elevation of approximately 213 m (700 ft) above mean sea level.

The study site is located on top of a small knoll, whose highest elevation is about 211 m (692 ft) (Fig. 2). This knoll is bounded on the northwest and the south by intermittent streams which are a maximum of 7.5 m (25 ft) lower than the top of the hill. The stream to the south drains Blackbird Pond, a shallow depression covering about 4.5 acres. This stream flows to the west out of the pond. It is of interest to note that this pond had completely dried up during the summer of 1988. According to local inhabitants, the complete drying of this pond is a rare

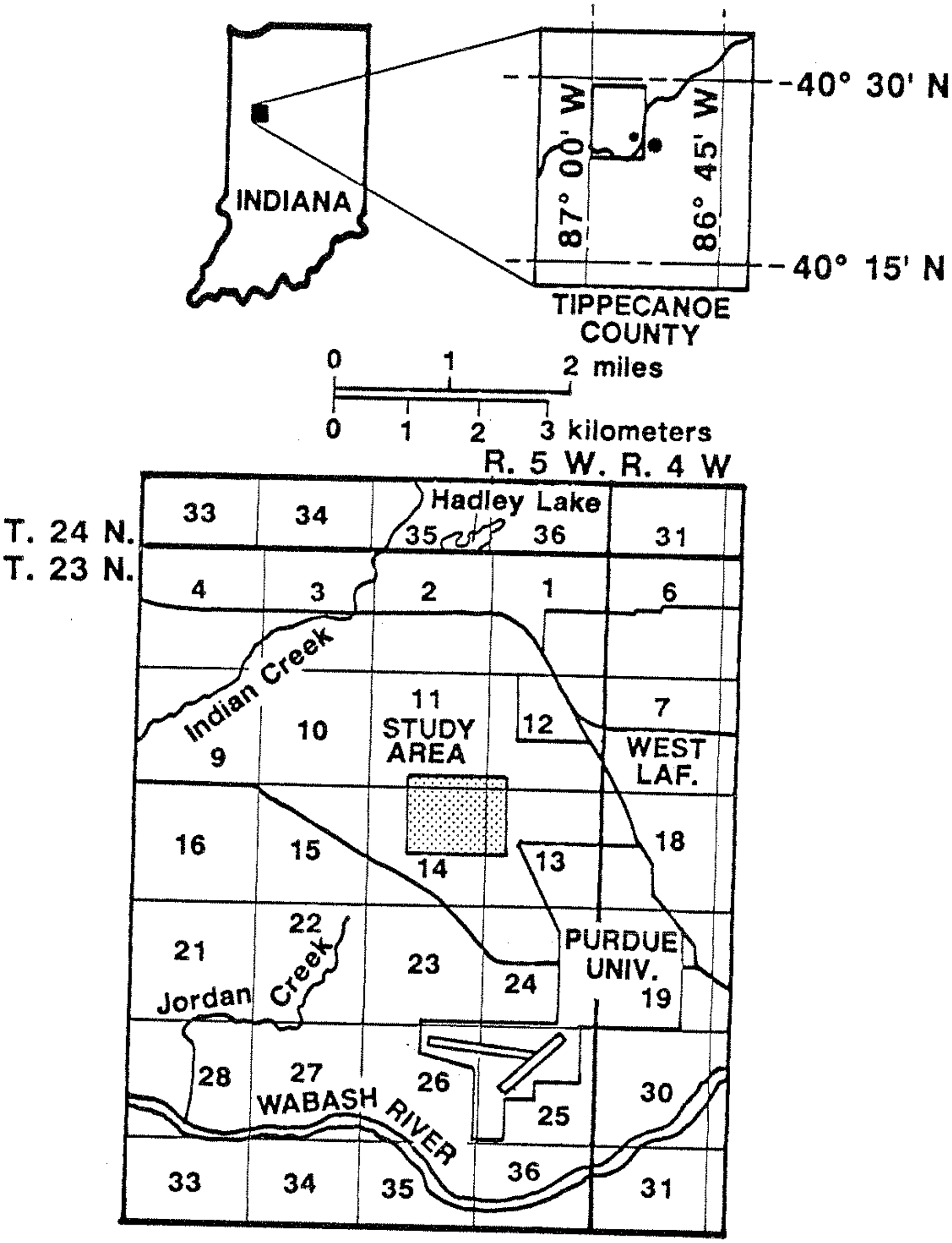

Figure 1 General location of study area.

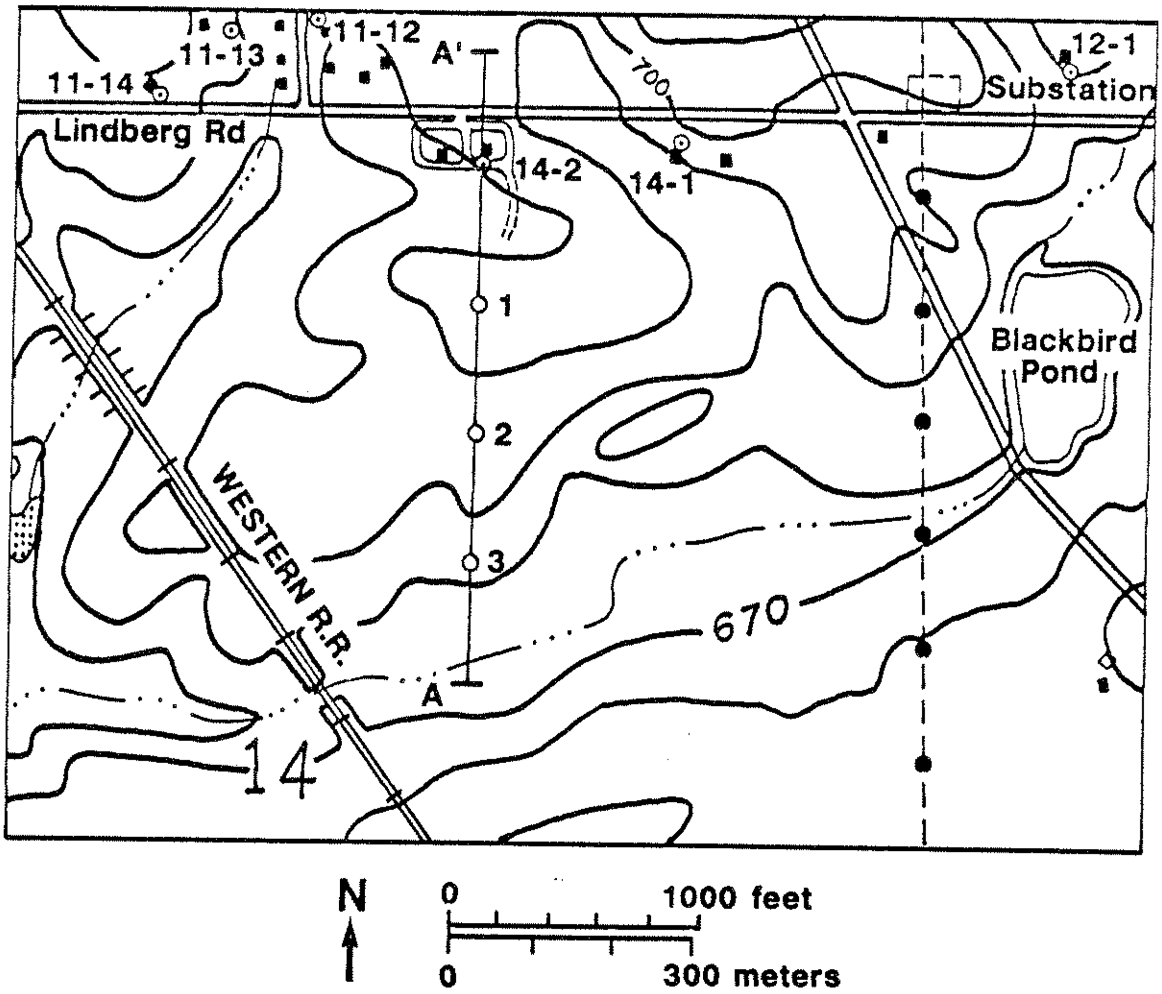

Figure 2 Detailed map of study area from enlargement of Lafayette West (Indiana) quadrangle, U.S. Geological Survey (1986). Cores BN-1, BN-2, and BN-3 are denoted on cross-sectional line A-A′ as 1, 2, and 3 (respectively).

event.

Climate

The climate of Tippecanoe County is continental, humid, and temperate, with warm humid summers and moderately cold winters (Ulrich, 1959). Based on data covering the period 1880-1987, the average summer temperature is 22.7° C (72.8° F), and the average winter temperature is -2.4° C (27.6° F). The average annual precipitation is 959 mm (37.75 in), with most of this (291 mm or 11.46 in) occurring during the months of June-August, and the least (174 mm or 6.87 in) during the months of December-February. Based on pan evaporation measurements taken at the Purdue Agronomy Farm (starting in 1956), the average monthly evaporation during the months of April-October (139 mm or 5.46 in) exceeds the average monthly precipitation for the same period (94 mm or 3.71 in).

GEOLOGY

Bedrock Geology

Tippecanoe County is located structurally on the southwest flank of the Cincinnati Arch. Paleozoic rocks along this flank dip southwest into the Illinois Basin at about 4 m/km (20 ft/mi). The principle bedrock units in the county, based on the regional bedrock geology map of Wayne, et al. (1966), include the Devonian New Albany Shale (a black, organic-rich shale), and the Mississippian Borden Group (argillaceous siltstones, shales, and interbedded limestones).

The present topography of the bedrock surface was caused by erosion during the late Tertiary to early Pleistocene (Thornbury, 1958). This erosion caused the development of a number of valleys cut into relatively flat bedrock uplands. The maximum relief on this surface in Tippecanoe County is about 150 m (500 ft) (Maarouf and Melhorn, 1975). Later glaciation covered this eroded surface with deposits of glacial, fluvial, eolian, and lacustrine origin.

Glacial Geology

During the Pleistocene epoch, several ice sheets advanced over Tippecanoe County (Maarouf and Melhorn, 1975; Pavey, 1983; and Kenega, 1987). Each advance left a covering of till. Sands and gravels were deposited along major glacial-drainage lines during periods of ice retreat, with the thickest of these units being deposited in the pre-existing valleys. As the climate warmed during the Holocene period, the final deglaciation occurred. Winds transported sands and silts, resulting in the deposition of a thin layer of loess over most of the county (Maarouf and Melhorn, 1975). Some depressions in the till uplands filled with water, forming lakes in which lacustrine sediments were deposited. Fluvial processes deposited sediments along the major drainageways.

Tills of Wisconsinan, Illinoian, and possibly Kansan age underlie the study area. Interglacial deposits of Sangamonian and Yarmouthian ages may also be found. Maarouf (1975) described the glacial stratigraphy in a well located in the NW/4, NE/4, NW/4, section 14, T. 23 N., R. 5 W. (610 m or 2000 ft west of the study site) as consisting of 27 m (90 ft) of Wisconsinan clays, 11 m (35 ft) of Illinoian clay and sand, 1.2 m (4 ft) of Yarmouthian sand and gravel, and 14 m (45 ft) of pre-Illinoian clay, sand, and gravel. The thicker sand and gravel units within the section tend to form the major aquifers throughout the county, and are often overlain or intercalated with tills.

METHODOLOGY

Site Selection

Selection of the study site was influenced by several factors, the most important being a location on the upland till plain, since the till plain covers the majority of Tippecanoe County. Moreover, results obtained on the till plain can be compared to estimates made by Arihood (1982). Also, the selected site had to be topographically as flat as possible, and preferably unforested. A site with low relief is preferrable so that runoff is minimal. Farmed areas were avoided due to the effects that plowing can have on the near-surface regime. One final consideration of importance was that the site be located on Purdue-owned acreage to insure access.

In order to assess the subsurface stratigraphy of candidate areas, water-well drillers logs were examined. These were used to determine relative thickness and location of till, and sand and gravel units. The logs were often of limited use due to the qualitative descriptions and lack of stratigraphic detail; however, they were the only source of subsurface information available.

The principle coring location was located on top of a small knoll. Two additional borings were added along a transect line from the knoll to the intermittant stream south of the hill (Fig. 2). These two additional holes served to evaluate the lateral component of flow in a down-slope direction. Assumed here is that the direction of lateral flow in the vadose zone toward these lower-elevation holes would be perpendicular to the elevation contours, and that water percolating through the soil at the top of the knoll would have no horizontal component of flow.

Sample Collection

Three 9 meter (30 ft) deep holes were drilled by Professional Service Industries, Inc., of West Lafayette, on October 26, 1988. This depth was selected based on results published in the literature for other vadose-zone studies. Each profile was sampled by continuous coring using a 1.5-inch I.D. split-spoon sampler. Sampling by three-inch O.D., thin-wall tubes was tried at several intervals, but this effort was abandoned because of difficulty in pushing the tubes into the till. Each core was 0.61 m (2 ft) long.

Because evaporation of water from the sediment will enrich the residual soil water in tritium, precautions were taken to prevent this. As the cores were extracted, they were either sealed in glass jars or wrapped in aluminum foil. The few thin-wall tube samples were capped with plastic end-caps, which were then wrapped with duct tape.

Each core was labelled immediately as to hole number and depth interval.

One half of each core was retained for physical, chemical, and mineralogical analyses. The other half was stored for twelve days at 4° C, after which they were driven to the Environmental Isotope Laboratory at the University of Waterloo in Ontario, Canada. The water extraction process and tritium analyses were performed by technicians at the isotope lab.

Water Extraction and Tritium Analysis

Water extraction

Water for tritium analysis was extracted from the samples by azeotropic distillation with toluene (Hendry, 1983). This extraction method was used because it insures complete recovery of the water in the soil, thus obviating any isotopic fractionation caused by incomplete extraction. In this process, the sample is placed in a boiling flask, and covered with toluene. Next, the flask is connected to a condenser and distillation trap. The toluene is then brought to a boil using a heating mantle. The gaseous toluene-water mixture is condensed in the condenser, and collected in the distillation trap. Water, being denser than toluene, sinks to the bottom of the trap, and is then drained off via a stopcock located at the base. The toluene refluxes back into the boiling flask. All traces of toluene are removed from the collected water by pouring melted paraffin on top of the water, capping the vial, then warming the system. The toluene dissoves in the paraffin, which then remains in the paraffin when the vial is cooled.

Tritium Analysis

The tritium activity of the water sample is obtained using a liquid scintillation technique. Each time an atom of tritium decays to helium-3, the ejected beta particle strikes the dissolved scintillation compound to create a pulse of light. The light pulses are recorded by a photomultipier tube and amplifier.

Two basic techniques are used for preparing the sample for tritium analysis: direct counting and electrolytic tritium enrichment. The main differences between the two methods involve the amount of water required for analysis, the pretreatment of the water sample, and the precision of the measured activities. The descriptions below are paraphrased from an unpublished methods manual of the Environmental Isotope Laboratory (EIL), University of Waterloo.

Direct counting is the simplest of the two methods, and requires a minimum of only 10 ml of water. The main drawback is the precision, which may be as high as ±10 TU. Sample preparation involves an initial distillation, under a moderate vacuum, to remove any dissolved chemical contaminants. Eight ml of this distillate are mixed with 15 ml of Canberra-Packard Pico-fluor LLT (scintillator compound) in standard, low-background polyethylene scintillation vials. The vials are then stored in a vial box covered with aluminum foil in the dark for at least 15 hours prior to counting.

The electrolytic tritium enrichment method is more accurate than the direct method, with precision as low as ±0.8 TU. However, more than 250 ml of water are needed for this method. Lesser amounts can be diluted to the required volume by dilution with "dead" water (< 1 TU), but precision suffers (R. Drimmie, pers. comm., 1988). The method makes use of the property of fractionation, in which water molecules containing only protium ("normal" hydrogen) will preferentially decompose by electrolysis, resulting in a concentration of tritium- and deuterium-bearing water. It has been estimated that this enrichment process retains about 85% of the tritium.

Prior to enrichment, the water sample undergoes an initial distillation. Then, 250 g of this distillate are added to the electrolysis vessel along with 1 gram of reagent-grade sodium peroxide. Electrolysis is performed using a current of 6 amps for 113 hours, after which about 15 ml of a sodium hydroxide solution remain (in which the tritium is concentrated). The water is drawn off via a vacuum distillation technique. This tritium-enriched water is then prepared for scintillation counting as described above.

Counting is performed using either a Packard 1550 or a Packard 4530 liquid scintillation counter. Both counters are adjusted for low-level counting.

To determine background corrections associated with the solution matrix, two reagents are treated and counted in the same manner as the water samples. The first reagent is a tritium standard solution, prepared by diluting NBS-4361 with "dead" water. The second reagent is a "background water," or tritium blank, in which a sample of "dead" water is prepared in exactly the same manner as the samples and standards. This reagent allows removal of signal introduced by reagents, background radioactivity, and machine noise. A sample of deionized water, as drawn from the tap, is also used to check the low-level efficiency of the system. The tritium activities of this water have dropped over the past ten years according to the 12.43-year half life of tritium from about 60 TU to 35 TU. Also, an unenriched standard and background sample are counted for calculation purposes.

The numbers reported in the tritium analyses are determined in the following manner. Direct counting results are calculated using

$$TU = (CPM - BKG)*TF, \tag{1}$$

where TU = the reported tritium activity (TU),

CPM = average counts per minute for sample,

BKG = average counts per minute for background, and TF = correction factor related to the amount of sample.

Calculation of enriched samples is more complicated. First, an enrichment factor "E" is calculated by taking the ratio of the counting rates (corrected for background) of the enriched standard to original standard :

$$E = CPM_{enr}/CPM_{std}. \qquad (2)$$

The activity of the original sample is then calculated by dividing the activity of the electrolyzed concentrate by E:

$$TU_{spl} = TU_{elec}/E. \qquad (3)$$

Error values (ERR) represent one sigma unit, meaning there is a 67% probability that the reported value is within ±ERR of the actual value. This quantity is calculated as

$$ERR = TU*[(CPM + 2BKG)]/CPM, \qquad (4)$$

where CPM and BKG are defined above.

Physical Analyses

Water Content

The gravimetric water content of each sample was obtained by first weighing a portion of the sample. The sample was broken into smaller pieces (to facilitate complete drying), and then dried overnight at 110° C under vacuum. After cooling, the sample was reweighed. The weight loss after drying represents the amount of water in the sample. The gravimetric water content is then calculated by dividing the weight loss by the weight of the dry sample. The result is reported as grams of water per gram of dry sample. The weight of the dry sample is used because it is a constant compared to the water, which may vary (especially in the vadose zone). The gravimetric water content may be related to the volumetric water content by converting the mass of water present and the mass of the sample to volumes, using the density of water and the dry bulk density of the sample.

A saturated water content was also estimated by fully saturating the dried sample, reweighing to determine the amount of water gained, and dividing this number by the dry weight of the sample. This number can then be compared to the actual water content in order to assess the relative level of saturation for the sample.

Porosity

Total porosity was measured using a water-displacement scheme. The dried sample was first weighed, then tightly wrapped in a preweighed piece of aluminum foil. The total volume was determined by displacing an equal volume of water; sample volume was then calculated by subtracting the volume due to the aluminum foil. The volume of void space was determined by saturating the sample in a preweighed beaker of water. This allowed two void space determinations to be made: The first was obtained by the weight gain exhibited by the sample after saturation. The second obtained by the weight lost from the original volume of water. The weight values were then converted to volume based on the density of water at room temperature.

Effective porosity was determined by taking the saturated sample, placing it in a closed vessel under an atmosphere of 100% relative humidity for two days. This time period was arbitrarily selected, since complete gravity drainage may take up to one year (Fetter, 1980).

Dry bulk density was calculated using information recorded in the porosity determinations.

Grain Size

Grain size analysis was performed using the hydrometer method. A weighed sample of oven-dried material was disaggregated, mixed with a measured volume of dispersant (sodium hexametaphosphate), mixed in a commercial blender, and allowed to settle overnight (to be sure of dispersion). The next morning, the slurry was placed into a one-liter sedimentation cylinder, and filled with deionized water. The slurry was agitated briefly by stirring with a long glass rod. A control cylinder, filled with deionized water and the same volume of dispersant, was prepared for correcting the hydrometer readings. One minute prior to time zero, the cylinder was capped, then agitated by repeatedly inverting the cylinder. At time zero, agitation was stopped, the cylinder uncapped, and then left undisturbed, except for insertion of the hydrometer. Readings of the amount of sediment still in suspension were taken at 1 minute, 2 minutes, 8 minutes, 30 minutes, and 2 hours. Only total clay fraction was determined. After the 2 hour reading, the material in the sedimentation cylinder was washed through a 74-micron sieve. The retained fraction was dried, weighed, then passed through a nest of standard sieves to obtain the sand and gravel fractions (the gravel fraction is that portion retained on the 2-mm sieve). The silt fraction was obtained by subtracting the sand/gravel and clay fractions from unity.

Data collected by these methods were reduced for gravel (greater than 2 mm), sand (2 mm to 0.074 mm), silt (0.074mm to 0.0039 mm), and clay (less than 0.0039 mm) percents, cumulative percents, and mean grain size.

Hydraulic Conductivity

The saturated hydraulic conductivities of selected samples from hole BN-1 were measured using a Soiltest permeameter (model K-605), assembled in the falling-head configuration, as described by Fetter (1980). The sample was mixed with deionized water to form a thick slurry, which was then added to the sample chamber. The total sample was compressed using a tamping device to dislodge any air bubbles which might have been trapped. Length of the sample was measured after assembling the device. Water was allowed to flow through the sample for several hours in order to establish a relatively constant flow. The buret was then filled with deionized water, and the date, time, and height of the water column above the outlet port recorded. The date, time, head, and flow volume were recorded at several times throughout each test. Typically, it took two days to complete a measurement on a plug whose length of 5 cm was representative of samples in these tests.

Chemical Analyses

Organic Content

Herein, the organic content is defined as that portion of the organic material which is oxidizable by treatment with 30 weight-percent hydrogen peroxide. The procedure involved reacting a weighed sample with hydrogen peroxide until the reaction ceased. The sample was then dried and reweighed. The weight loss represents the fraction oxidized by the peroxide treatment.

Sediment-Water Extracts

The chemistry of soil-water in each sampled interval was assumed to be reflected by the chemistry of water extracts from the core sample. Approximately 25 grams of air-dried sample was weighed into an Erlenmeyer flask, after which a weighed amount of deionized water (about 100 grams) was added. The suspension was then stirred under open-air conditions. The suspension was allowed to settle for 2 days, after which the supernatant liquid was filtered off. The pH of the filtered solution was measured using an Orion Research model 901 Ionalyzer equipped with pH electrodes. Alkalinity was determined titrimetrically. Anions (Cl^-, NO_3^-, and SO_4^{-2}) were determined using a Dionex 4000i ion chromatograph. Cations (Na^+, K^+, Ca^{+2}, and Mg^{+2}) were analyzed using a Varian SpectrAA-20 atomic absorption spectrometer. In order to give some sense of normalization to the analyses, the concentrations are reported as milliequivalents per 100 grams sample of dry sample.

Cation Exchange Capacity

The cation exchange capacity of selected samples was determined by the soil erosion laboratory at the Purdue Agronomy Department.

Exchangeable cations were determined by the ammonium acetate method (Thomas, 1982). Five grams of <2 mm air-dried soil are placed in a 50 ml centrifuge tube, and mixed with 25 ml 1-**N** ammonium acetate. After shaking for 30 minutes, the suspension is centrifuged at 2000 rpm for 10 minutes. The supernatant liquid is transferred to a 50 ml volumetric flask. The above procedure is repeated with an additional 25 ml of reagent. The final solution is brought to 50 ml with 1-**N** ammonium acetate. The cations are then analyzed by atomic absorption spectrometry. It should be noted that calcium determined by this method is questionable when the soil contains free $CaCO_3$ or gypsum.

Exchangeable acidity is acidity from: 1) hydrolysis of partially hydrolyzed and nonexchangeable Al; 2) weakly acidic groups (e.g. on organic matter); 3) H^+ ions from the hydrolysis of exchangeable Al; and/or 4) exchangeable H^+. The first two reactions are probably the most important (Thomas, 1982). The acidity is determined using the barium chloride-triethanolamine method (Thomas, 1982). Ten grams of sample are added to 25 ml of a buffer solution containing 61.07 g/l $BaCl_2 \cdot 2H_2O$ and 29.8 g/l triethanolamine, adjusted to pH 8.2. After one hour, this is transferred to a 5.5 cm diameter Buchner funnel fitted with Whatman no. 42 filter paper, and 75 ml more of the buffer solution added. After this solution has filtered, 100 ml of a replacement solution (61.07 g/l $BaCl_2 \cdot 2H_2O$, with 0.4 ml buffer solution per liter) is added to the funnel and collected with the previous filtrate. Two drops of 0.1% bromocresol green aqueous solution, and 10 drops of a mixed indicator (1.250 g methyl red and 0.825 g methylene blue in one liter of 90% ethanol) are added. This solution is then titrated to the endpoint (in the range green to purple) with a standardized HCl solution.

Mineralogical Analyses

Matrix Calcite-Dolomite Content

The weight-percent of calcite and dolomite present in the matrix, or mud fraction (less than 0.062 mm), was determined using a Chittick apparatus, as described by Dreimanis (1962). It should be noted that this method assumes that these carbonates are present as pure calcite and pure dolomite.

Magnesium Content of Calcite

The magnesium content of the calcite in the mud fraction was determined for several intervals in hole BN-1. A small amount of sample was treated with about 2 ml. of 0.1 **N** HCl. This was then diluted, and the resulting solution filtered. The concentration of calcium and magnesium in the solution was analyzed by atomic absorption spectrometry, and the results converted to number of moles of calcium and number of moles of magnesium. The ratio of each cation to the total moles of calcium and magnesium allows estimation of the magnesium content of the calcite.

Mineralogy

Mineralogical determinations were performed on the very-fine sand fraction (0.074 to 0.125 mm) of the sample. A portion of the sand was weighed out, and the "heavy" minerals (S.G. greater than 2.85) separated using bromoform. The heavy mineral fraction was weighed, and the magnetite and ilmenite separated by passing a hand magnet over the fraction. The amount of magnetite and ilmenite (reported as magnetite) was determined by weight loss from the heavy fraction. The remaining fraction was not further divided as to amounts of the various minerals present; although the fractions were observed under a binocular microscope in order to ascertain the major minerals present.

The fraction less dense than bromoform was also weighed, and then treated to remove the carbonates. This was done in two steps in order to determine the proportions of calcite and dolomite. Calcite was determined after treatment with 0.1 **N** HCl, and dolomite after treatment with 6 **N** HCl. The relative proportions of quartz, potassium feldspar, and plagioclase in the remaining sample were determined by staining techniques (Gross and Moran, 1970). First, the grains were etched with concentrated hydrofluoric acid. After rinsing, the etched grains were treated with a concentrated sodium cobaltinitrite solution, washed, then treated with a dilute solution of amaranth dye. This treatment stained the potassium feldspars yellow and the plagioclase pink-to-purple, while leaving the quartz and chert grains white. Proportions were determined by counting several hundred grains under a binocular microscope.

RESULTS

Physical Properties

Results of the analyses are tabulated in Tables 1-3, and selected results are plotted versus depth in Figs. 3-5.

Figure 6 shows the site's near-surface stratigraphy as interpreted from the three borings as well as from the driller's log for the water well at the old poultry farm. Color of the dry sediment in the cores ranges from pale yellow (2.5 Y 7/4) to yellow (10 YR 7/6) above 5 m (16 ft), to light gray (10 YR 7/1) below 5 m (16 ft). A zone of mottled yellow-to-light gray sediment, about 0.5 m (1.5 ft) thick, is present at the boundary of the two zones. The color change is interpreted to represent an oxidation boundary. Visually, the samples appeared to be silt- to clay-rich till, containing several thin sand streaks. At a depth of about 7 m (24 ft) in BN-1 and BN-2, a relatively coarse-grained, wet sand was encountered. In BN-3, a coarse sand zone was not encountered until about 8 m (27 ft), and in this hole was found to be highly gravelly and dry. Thus, while at approximately the same depth below the surface, the wet sand in BN-1 and BN-2 likely pinches out before reaching BN-3. A thin sand was also reported on the driller's log for water well 14-2, and is interpreted as being correlative

Table 1a. Physical properties for core BN-1. In this and succeeding tables, N.D. denotes not determined.

Interval Depth (ft. below surface)	Gravimetric Water (g/100g)	Saturated Wtr. Cont. (g/100g)	Total Porosity (%)	Effective Porosity (%)	Dry Bulk Density gram per cc	Grain Size Distribution (%)				Mean Grain Size (ϕ units)	Log (Kv) (cm/sec)
						Gravel	Sand	Silt	Clay		
3 to 4	24.40	26.60	44.10	9.50	1.66						-6.00
6 to 7	8.70	26.46	51.50	12.20	1.85	4.05	37.91	33.70	23.57	5.05	-5.92
7 to 8	11.67	25.18	50.30	14.20	1.96	4.73	31.68	38.24	25.35	5.35	
9 to 10	19.01	24.12	46.80	13.30	1.90	6.18	39.81	36.29	17.72	4.43	
10 to 11	6.49	N.D.				4.69	48.32	31.74	15.25	4.37	-6.20
11 to 12	7.19	12.50	23.30		1.87	4.16	70.28	15.28	10.27	3.07	
12 to 13	9.48	19.54	40.00	25.40	2.04	7.05	37.48	32.00	23.47	4.87	
13 to 14	9.23	19.92	38.10	9.50	2.04	6.38	40.66	30.36	22.60	4.66	
15 to 16	11.52	20.15	38.20	9.40	1.83	7.13	51.61	22.27	18.99	4.15	-6.50
17 to 18	7.47	12.56	28.40	4.00	2.18	6.90	40.68	33.17	19.25	4.52	
19 to 20	7.94	20.49	42.80	19.40	1.97	9.96	39.17	33.05	17.82	4.15	
22 to 23	9.23	22.78	37.30	10.80	1.66	5.34	38.32	33.12	23.21	5.10	-6.50
25 to 26	18.29	N.D.				0.67	74.97	17.60	6.77	3.25	
27 to 28	17.54	N.D.				2.08	53.56	36.63	7.73	3.97	
28 to 29	18.27	N.D.				2.61	68.53	20.15	8.71	3.50	
29 to 30	10.04	21.09	45.50	22.30	1.97	7.40	56.48	23.39	12.73	3.29	-6.11

Table 1b. Mineralogical composition and cation exchange capacity (CEC) vs. depth for core BN-1.

Depth (ft below surface)	Organic Content (weight %)	Mineralogy of 0.074-0.125 mm fraction (%)							Carbonate Content of mud fraction (% by wt.)		CEC (meq/100g)					
		(grain % after other separations)			(weight %)											
		Qtz	Kspar	Plag	Calc.	Dolo.	Heavies	Fe_3O_4	Calcite	Dolo	Ca	Mg	Na	K	acid	Total
6 to 7	0.93	92.80	0.30	6.90	2.87	2.49	7.03	0.28	4.60	10.80	17.00	2.80	0.109	0.20	0.00	20.11
7 to 8	1.91	99.05	0.32	0.63	4.92	16.91	2.12	0.24	7.10	15.40						
9 to 10	0.00	99.01	0.33	0.66	6.20	14.15	3.18	0.24	7.80	18.50	16.00	1.07	0.035	0.12	0.00	17.22
10 to 11	0.03	97.90	1.50	0.60	4.94	13.96	4.94	0.20	8.60	19.00						
11 to 12	0.18	99.38	tr	0.62	8.66	14.31	6.67	0.52	7.80	19.60						
12 to 13	0.26	100	tr	tr	7.90	13.04	3.36	0.24	10.50	16.80	16.00	0.99	0.048	0.10	0.00	17.14
13 to 14	0.03	99.61	tr	0.39	7.13	12.13	4.57	0.34	10.50	15.70						
15 to 16	0.23	94.00	4.29	1.71	7.88	11.84	4.02	0.33	10.40	20.10	14.50	1.07	0.035	0.06	0.00	15.67
17 to 18	0.57	98.62	0.59	0.79	3.63	17.09	3.79	0.34	9.20	19.40						
19 to 20	0.59	97.80	1.50	0.70	4.71	17.15	3.93	0.30	9.60	19.50	12.50	1.15	0.026	0.13	0.20	14.00
22 to 23	0.00	99.67	tr	0.33	6.31	12.45	4.60	0.31	7.80	20.80	17.00	1.56	0.074	0.20	0.00	18.84
25 to 26	0.39	97.80	1.40	0.80	5.01	17.88	4.10	0.22	7.60	27.00						
27to 28	0.46	99.57	tr	0.43	6.02	16.88	3.06	0.14	7.60	27.30	11.50	0.74	0.013	0.06	0.00	12.32
28 to 29	0.42	99.50	tr	0.50	3.74	19.87	5.19	0.21	8.40	25.60						
29 to 30	0.46	95.60	3.70	0.70	3.95	19.08	3.99	0.27	10.80	21.60	12.00	0.82	0.013	0.13	0.98	13.95

Table 1c. Chemistry of soil-water extracts for core BN-1. Concentrations are related to 100 grams of air-dried sediment.

Depth (ft)	pH	Cations (meq/100g)				Anions (meq/100g)			
		Ca^{+2}	Mg^{+2}	K^+	Na^+	Alk (as HCO_3^-)	Cl^-	NO_3^-	$SO_4^=$
6 to 7	7.57	0.37	0.2	0.06	0.14	0.57	0.08	-	0.09
7 to 8	7.58	0.45	0.13	0.06	0.08	0.57	0.05	-	0.06
9 to 10	7.7	0.25	0.06	0.03	0.04	0.32	0.01	-	0.01
11 to 12	7.71	0.26	0.06	0.03	0.04	0.28	0.05	-	0.03
12 to 13	7.69	0.24	0.04	0.03	0.05	0.26	0.04	-	0.03
13 to 14	7.98	0.38	0.07	0.03	0.06	0.32	0.14	0.01	0.06
15 to 16	7.62	0.24	0.09	0.03	0.05	0.26	0.05	-	0.03
17 to 18	7.53	0.91	0.18	0.05	0.05	0.19	0.04	-	0.94
19 to 20	7.62	0.78	0.24	0.05	0.04	0.27	0.05	-	0.56
22 to 23	7.64	0.85	0.27	0.06	0.06	0.25	0.06	-	0.92
25 to 26	7.49	0.52	0.15	0.04	0.02	0.34	0.03	-	0.35
28 to 29	7.27	0.44	0.14	0.04	0.02	0.27	0.03	-	0.33
29 to 30	7.99	0.61	0.2	0.08	0.03	0.59	0.02	-	0.27

Table 2a. Physical properties for core BN-2.

Interval Depth (ft. below surface)	Gravimetric Water (g/100g)	Saturated Wtr. Cont. (g/100g)	Total Porosity (%)	Effective Porosity (%)	Dry Bulk Density (g/cm^3)	Grain Size Distribution (%)				Mean Grain Size (ϕ units)
						Gravel	Sand	Silt	Clay	
4 to 5	7.52	17.77	35.00	9.90	1.97					
5 to 6	6.45					8.89	35.00	35.84	20.27	4.55
6 to 7	7.63	19.62	37.60	14.10	1.96	4.40	38.40	35.03	22.17	4.97
9 to 10	6.55					1.06	50.00	39.47	9.47	4.15
10 to 11	8.39		54.50	52.70	1.56	1.59	38.46	45.32	14.63	4.82
11 to 12	8.24	17.05	34.60	9.40	2.06					
12 to 13	9.67					2.70	33.60	42.66	21.04	5.15
13 to 14	6.59					7.98	49.39	22.94	19.69	3.73
14 to 15	8.82	19.25	36.90	7.60	1.97	5.21	33.66	39.48	21.65	5.10
16 to 17	9.86	20.44	39.40	17.20	1.87	8.50	34.36	35.01	22.13	4.83
17 to18	9.37									
19 to 20	15.21	21.02	32.50	15.70	1.78	3.95	61.33	14.06	19.97	4.25
20 to 21	16.90					8.72	68.60	11.96	9.92	2.73
21 to 22	9.36	11.16	18.50	5.90	2.01	16.14	53.29	15.56	15.01	2.78
23 to 24	11.12					9.8	60.01	17.79	12.4	2.9
24 to 25	11.59					9.68	51.1	23.24	15.94	3.42
25 to 26	12.05	15.14	25.9	12.1	1.87	10.4	68.49	10.63	10.64	2.4
26 to 27	11.07	14.69	31	7.6	2.03	8.73	45.38	27.05	18.65	3.97

Table 2b. Mineralogical composition and cation exchange capacity (CEC) vs. depth for core BN-2.

Depth (ft below surface)	Organic Content weight %)	Mineralogy of 0.074-0.125 mm fraction (%) (grain % after other separations)			(weight %)				Carbonate Content of mud fraction (% by wt.)		CEC (meq/100g)					
		Qtz	Kspar	Plag	Calc.	Dolo.	Heavies	Fe_3O_4	Calcite	Dolo	Ca	Mg	Na	K	acid	Total
5 to 6	0.00	90.73	8.28	0.99	5.13	14.06	3.43	0.22	7.20	18.00						
6 to 7	0.29	98.56	0.80	0.64	4.98	14.17	2.80	0.14	8.90	18.40	15.50	1.73	0.061	0.10	0.00	17.39
9 to 10	0.08	99.25	0.25	0.50	5.07	13.06	2.01	0.10	6.80	23.30						
10 to 11	0.00	94.03	4.42	1.55	6.50	11.22	2.62	0.07	4.80	23.40	13.00	0.99	0.030	0.05	0.00	14.07
12 to 13	0.28	99.80	0.10	0.10	6.00	14.35	2.11	0.13	5.60	20.80						
13 to 14	0.17	99.50	tr	0.50	5.18	16.67	2.60	0.26	5.20	16.20						
14 to 15		96.15	3.10	0.75	5.11	15.00	2.50	0.13	5.80	19.90						
16 to 17		100	tr	tr	4.57	17.62	2.89	0.14	9.20	19.60	13.00	1.15	0.030	0.13	0.98	15.29
17 to 18									(6.80)	(19.40)						
19 to 20	0.11	99.14	0.34	0.52	4.09	19.20	4.09	0.37	6.20	19.90						
20 to 21	0.07	92.38	6.98	0.64	3.98	18.20	3.36	0.34	5.70	20.40						
21 to 22	0.08	98.25	0.29	1.46	3.83	22.58	3.93	0.26	5.70	19.20	13.00	1.32	0.052	0.12	0.98	15.47
23 to 24	0.31	97.09	2.62	0.29	3.45	20.84	3.59	0.25	6.20	19.80						
24 to 25	0.83	96.15	2.20	1.65	3.24	18.36	4.07	0.23	6.60	22.20	12.00	1.15	0.022	0.12	0.59	13.88
25 to 26	0.17	91.01	8.04	0.95	3.22	20.05	4.85	0.42	9.20	21.30						
26 to 27		97.69	0.99	1.32	4.70	18.96	3.93	0.21	7.60	20.20	13.50	1.32	0.030	0.15	0.79	15.79

Table 2c. Chemistry of soil-water extracts for core BN-2. Concentrations are related to 100 grams of air-dried sediment.

Depth		Cations (meq/100g)				Anions (meq/100g)			
(ft)	pH	Ca^{+2}	Mg^{+2}	K^+	Na^+	Alk (as HCO_3^-)	Cl^-	NO_3^-	$SO_4^=$
6 to 7	7.99	0.38	0.15	0.03	0.07	0.39	0.14	-	0.07
9 to 10	7.93	0.26	0.09	0.03	0.04	0.32	0.03	-	0.02
10 to 11	7.85	0.32	0.08	0.02	0.05	0.33	0.05	0.01	0.03
13 to 14	7.78	0.28	0.11	0.03	0.06	0.39	0.02	-	0.03
16 to 17	7.64	0.55	0.27	0.07	0.05	0.48	0.02	-	0.38
19 to 20	7.71	0.57	0.19	0.06	0.03	0.29	0.03	-	0.46
21 to 22	7.53	0.69	0.35	0.05	0.04	0.3	0.02	-	0.85
23 to 24	7.63	0.58	0.28	0.06	0.04	0.32	0.03	-	0.57
25 to 26	7.67	0.49	0.2	0.06	0.04	0.36	0.02	-	0.34

Table 3a. Physical properties for core BN-3.

Interval Depth (ft. below surface)	Gravimetric Water (g/100g)	Saturated Wtr. Cont. (g/100g)	Total Porosity (%)	Effective Porosity (%)	Dry Bulk Density (g/cm^3)	Grain Size Distribution (%)				Mean Grain Size (ϕunits)
						Gravel	Sand	Silt	Clay	
2 to 3	13.9	24.19	39.5	7	1.6	0.43	13.71	57.48	28.38	6.53
3 to 4	7.29					5.29	39.41	32.67	22.63	4.9
4 to 5	10.46	17.66	36.6	6.6	2.02	0.6	11.72	50.62	37.06	6.95
6 to 7	10.41	22.98	43	8.9	1.94	3.66	33.31	36.99	26.04	5.47
7 to 8	7.99					4.15	36.8	40.5	18.55	4.88
8 to 9	9.63	30.03	50.2	18.2	1.64	5.09	29.87	38.93	25.99	5.5
10 to 11	8.95	17.49	36.6	7.5	2.07	3.2	35.2	36.16	25.44	5.3
12 to 13	9.73	19.12	38.4	11	1.99	2.6	30.71	37.34	29.35	5.8
14 to 15	9.26	16.02	35.1	4.7	2.09	11.99	30.67	32.91	24.43	4.77
16 to 17	9.14	20.81	41.8	14.9	1.94	3.51	36.7	33.16	26.63	5.3
18 to 19	9.43	19.98	41.7	11.1	2.03	6.11	32.82	33	28.07	5.47
20 to 21	9.34	16.84	35	1.9	2.18	5.08	27.26	38.41	29.25	5.68
22 to 23	9.4	20.42	40.5	10.4	2.14	8.06	28.62	35.39	27.93	5.37
24 to 25	11.9	19.6	35.3	9.4	2.04	4.58	29.46	37.32	28.64	5.63
27 to 28	2.64					44.24	38.3	9.73	7.73	0.4
28 to 29	9.21	19.06	35.42	7.6	1.91	13.72	38.7	23.46	24.12	3.83
29 to 30	4.31					12.52	69.62	9.7	8.77	1.77

Table 3b. Mineralogical composition and cation exchange capacity (CEC) vs. depth for core BN-3.

Depth (ft below surface)	Organic Content (weight %)	Mineralogy of 0.074-0.125 mm fraction (%) (grain % after other separations)					(weight %)		Carbonate Content of mud fraction (% of wt.)		CEC (meq/100g)					
		Qtz	Kspar	Plag	Calc.	Dolo.	Heavies	Fe_3O_4	Calcite	Dolo	Ca	Mg	Na	K	acid	Total
2 to 3	2.18	99.01	0.66	0.33	3.42	3.35	4.76	0.13	0.30	1.20						
3 to 4	0.00	97.56	0.70	1.74	1.06	1.68	11.65	2.21								
4 to 5	1.06	96.23	3.35	0.42	6.55	5.74	3.78	0.12	0.00	6.10	15.00	2.80	0.078	0.22	0.98	19.08
6 to 7	0.00	97.12	1.44	1.44	2.79	8.72	3.05	0.19	0.00	8.00						
7 to 8	0.00	96.53	3.18	0.29	3.22	17.40	2.91	0.18	5.00	16.80						
8 to 9	0.00	93.28	5.60	1.12	5.22	13.57	3.26	0.19	5.10	13.90	16.50	2.06	0.070	0.18	0.00	18.81
10 to 11	0.64	93.25	5.70	1.05	3.90	18.20	2.76	0.18	6.40	16.80	16.00	1.48	0.039	0.17	0.00	17.69
12 to 13	0.58	95.89	2.90	1.21	7.11	15.20	3.01	0.25	9.10	14.40						
14 to 15	0.54	94.88	4.69	0.43	3.91	18.98	4.08	0.24	7.20	17.80	15.50	1.65	0.039	0.23	0.59	18.00
16 to 17	1.34	95.80	2.40	1.80	4.71	19.47	4.08	0.29	4.70	17.20	15.50	1.40	0.022	0.22	0.59	17.73
18 to 19	1.35	96.18	2.97	0.85	4.57	19.24	3.73	0.23	7.40	17.10	13.50	1.32	0.017	0.23	0.79	15.85
20 to 21	0.00	94.28	5.05	0.67	5.99	18.31	3.05	0.21	8.00	17.20						
22 to 23	1.25	96.47	2.89	0.64	4.05	19.92	3.02	0.19	7.20	17.60	15.00	1.40	0.017	0.24	0.59	17.25
24 to 25	0.33	94.56	4.26	1.18	6.92	16.92	3.32	0.32	7.70	17.40						
27 to 28	0.52	97.44	2.05	0.51	4.68	42.54	3.29	0.21								
28 to 29	0.58															
29 to 30	0.51	97.99	1.15	0.86	10.98	24.10	4.09	0.27	7.30	23.90	7.00	1.07	0.013	0.12	0.79	8.98

Table 3c. Chemistry of soil-water extracts for core BN-3. Concentrations are related to 100 grams of air-dried sediment.

Depth (ft)	pH	Cations (meq/100g)				Anions (meq/100g)			
		Ca^{+2}	Mg^{+2}	K^+	Na^+	Alk (as HCO_3^-)	Cl^-	NO_3^-	$SO_4^=$
2 to 3	7.57	0.68	0.23	0.22	0.22	1.2	0.074	-	0.12
3 to 4	8.1	0.15	0.13	0.01	0.14	0.85	0.11	-	0.18
4 to 5	7.4	0.59	0.33	0.05	0.21	1.17	0.14	-	0.16
6 to 7	6.85	0.28	0.19	0.04	0.24	0.67	0.1	-	0.11
8 to 9	7.98	0.41	0.22	0.03	0.13	0.47	0.16	0	0.17
10 to 11	7.99	0.37	0.11	0.04	0.09	0.45	0.1	0.04	0.07
12 to 13	8.01	0.25	0.12	0.04	0.07	0.45	0.01	0.01	0.04
14 to 15	7.89	0.69	0.3	0.07	0.1	0.76	0.05	-	0.35
16 to 17	7.67	1.07	0.39	0.08	0.04	0.22	0.01	-	1.4
18 to 19	7.74	0.78	0.27	0.1	0.05	0.38	0.02	-	0.9
20 to 21	7.69	0.83	0.37	0.11	0.04	0.31	0.02	-	1.14
22 to 23	7.75	0.85	0.34	0.1	0.04	0.28	0.02	-	1.12
24 to 25	7.87	0.7	0.28	0.1	0.04	0.35	0.16	-	0.82
29 to 30	7.82	1.1	0.53	0.07	0.06	0.31	0.02	-	1.5

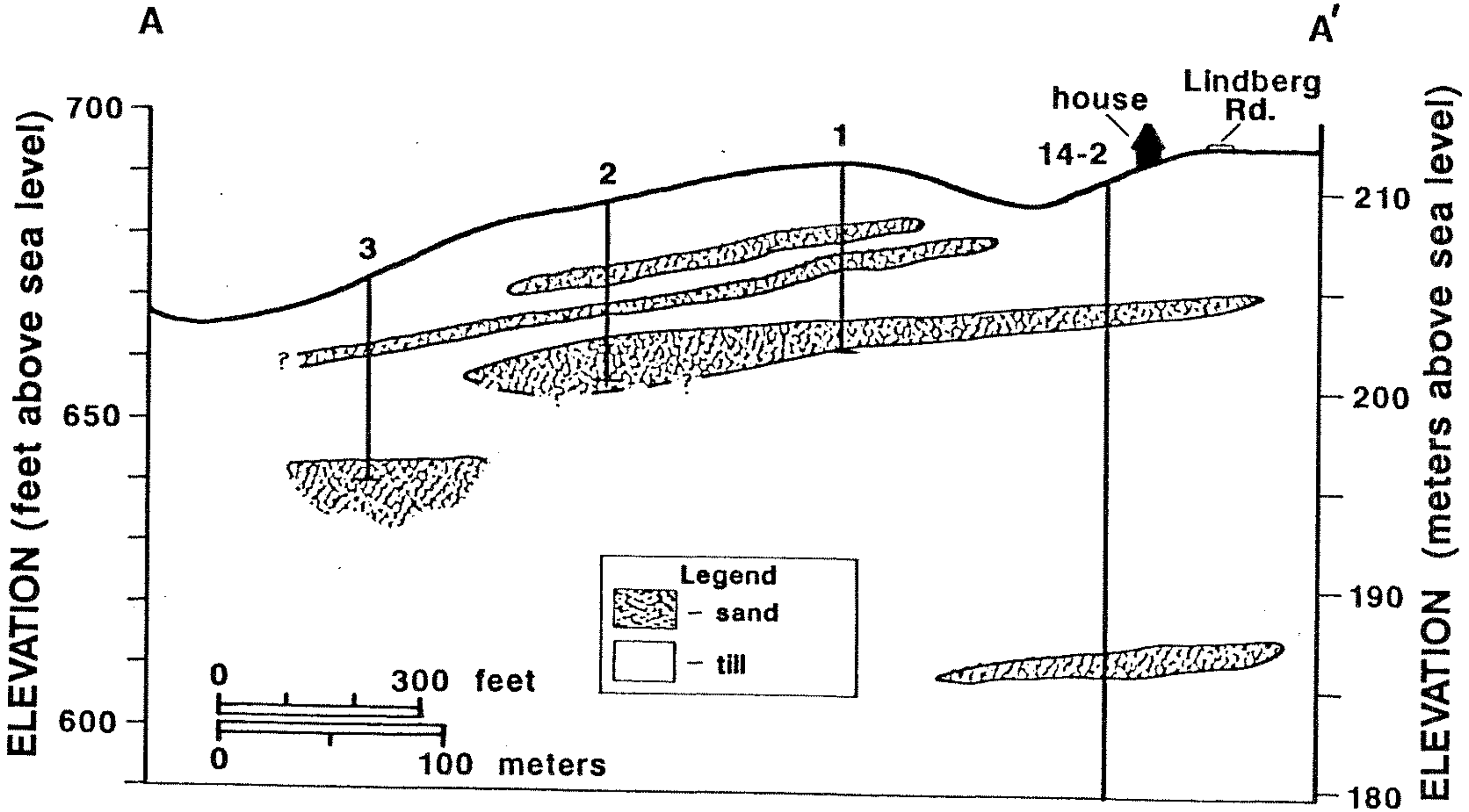

Figure 6 Subsurface stratigraphy along A-A′ (see Fig. 2 for location). Vertical enhancement = 30.9. Water well 14-2 is 69.2 m (227 ft) deep.

with the wet sand zone; however, it is not known whether this sand was wet or not.

Grain size is more variable with depth in BN-1 and BN-2 than in BN-3. All three holes, however, show a coarsening with depth, as evidenced by the plots of mean grain size (Figs. 3, 4, and 5). Using the U.S. Department of Agriculture (1951) textural classification, the sediments range from silty clay loam near the surface, grading into loam and finally to sandy loam.

The average grain-size data compare favorably with the average grain-size distribution for the Earl Park member of the Trafalgar Formation. Pavey (1983) reported the grain size distribution for this till unit as : 45.5±7.6% sand, 35.6±6.8% silt, and 19.0±5.8% clay. The average distribution in the brown-colored zone is 38.5% sand, 38.4% silt, and 23.1% clay, while the distribution in the gray-colored zone is 54.4% sand, 26.6% silt, and 19.0% clay.

Porosity (both total and effective) and water content are also variable in BN-1 and BN-2, but less variable in BN-3. The more constant values of total and effective porosity with depth in BN-3 are most likely a function of this core's grain sorting, as compared to the other two holes. The water content in BN-3 may also be influenced by seepage from runoff from Blackbird Pond.

Organic content of the sediments overall averaged 0.56% by weight. Individual values may be low as several samples (7 out of 44) showed a slight weight gain (average 1.10% by weight) after the hydrogen peroxide treatment. This may be partially due to oxidation of iron minerals. A test using the >2 mm fraction from one of the deeper sand zones showed, after treatment with hydrogen peroxide, a weight gain of 0.33%, as well as production of a precipitate of ferric hydroxide. Two other reactions were noted during the determination of organic content. First, many samples showed numerous fine, golden-colored mica flakes after treatment. These were produced by the action of the hydrogen peroxide on larger biotite crystals, as confirmed by reacting hand-picked biotite flakes with the reagent. The second reaction involved the sediments from the gray-colored zone. After treatment, a number of small white crystals were noted on the surface of the dried sample. Based on outward morphology, as well as other chemical data, these were identified as gypsum.

Figure 3 shows that the saturated hydraulic conductivities in BN-1 show a slight decrease between 4 and 7 m (13 and 23 ft). Values of this parameter vary between $10^{-5.9}$ and $10^{-6.5}$ cm/sec. However, these are saturated conductivities, and as such they are probably not representative of the true conductivities in the section. Also, the method used to determine the conductivities precluded testing the effects of fractures upon this parameter. Although fractures were not observed in the three cores, they are common features in glacial sediments.

Mineralogy

The mineralogy of the fine sand fractions showed no obvious pattern with depth. The grains are comprised predominantly of quartz, followed by dolomite and calcite. Potassium feldspar and plagioclase make up a variable (though generally small) fraction of the sediment. The heavy-mineral fraction is made up primarily of hornblende, garnet, and magnetite/ilmenite, with minor amounts of rutile, zircon, and epidote. Small amounts of pyrite were noted in the fractions from the gray-colored samples.

Measurement of the carbonate content of the mud fraction showed a depletion of calcite and dolomite in the shallow depths (<2 m or 6 ft). This is interpreted to represent a leached zone, in which soil water rich in CO_2 (derived from decaying organic matter) dissolves the carbonates as water moves vertically downward. This is consistent with what is found in glacial sediments by Reardon et al. (1980). Below this depth, the carbonate content is fairly constant, averaging 8% by weight calcite and 19% by weight dolomite. This further supports the identification of the till as the Earl Park member, as Pavey (1983) reports the average carbonate content as $9.9 \pm 2.4\%$ calcite and $19.4 \pm 1.9\%$ dolomite.

The magnesium content of calcite in the mud fraction was determined at several levels in BN-1 (4 samples from the oxidized zone and 4 from the unoxidized zone). The Ca:Mg ratio is 0.74:0.26.

Water-Extract Chemistry

Solute chemistry of water extracted from the cores showed chloride and sodium levels decreasing with depth. This is especially noticeable in BN-3. Higher concentrations of chloride can be attributed to both road salt and chloride-bearing fertilizers such as KCl. Meltwater from road salt is particularly applicable to BN-3 because this location is near a stream bed draining Blackbird Pond (Fig. 2).

A surprising result is the large increase in sulfate with depth. This increase occurs in the unoxidized zone, where sulfate concentrations range from 0.271 to 1.500 meq per 100 g dry soil. Sulfate could be derived from two sources: dissolution of gypsum/anhydrite, or pyrite oxidation. Although pyrite is found in glacial sediments, neither gypsum nor anhydrite have been reported in local surficial sediments.

Magnesium also shows an increase in concentration with depth. This is likely due to dolomite dissolution. Potassium shows a slight increase with depth, and probably represents the presence of non-leached clays with depth.

The total CEC decreases slightly with depth, indicating a lesser ability to exchange or sorb cations at depth. This trend roughly correlates with the percent clay present in the sediment. Since the shallower depths have higher percentages of clay, the higher CEC values tend to occur in the shallow zones. This assumes the clay mineralogy does not change with depth.

Total CEC can be used as an indicator of clay mineralogy (Buol et al., 1980). Applying their deterministic criteria to the CEC data, the presence of illite or chlorite, and possibly kaolinite, is suggested. Kenega (1987) reported the clay mineralogy of Earl Park till as averaging 78% illite, 16% chlorite+kaolinite, and 6% expandables.

Tritium Analyses

Results of the tritium analyses are tabulated in Table 4, and plotted in Fig. 7. Due to the low water contents of the samples, the majority of the 0.61 m (2 ft) intervals yielded only enough water for the direct counting method. However, all intervals had detectable tritium, indicating that these zones have had contact with post-1952 water.

The profile for BN-1 shows fairly constant tritium activities of between 25 and 40 TU to a depth of 6.5 m (21 ft). The tritium activity increases between 6.5 and 8.5 m (21 and 28 ft), after which the activity decreases. This low-high-low pattern indicates the location of the bomb-derived tritium. The high value of 78.9 TU at about 7 m (23 ft) is interpreted to represent the tritium input by

Table 4. Tritium content in samples (TU). Figures in parentheses indicate ±analytical uncertainties. Bold type indicates enriched sample.

Interval below surface, m (ft)	BN-1	BN-2	BN-3
2-4	**24.8(1.8)**	**24.9(1.8)**	25 (8)
4-6	**25.1(1.8)**	-	20 (8)
5-6	-	44 (8)	-
6-8	21 (8)	29 (8)	29 (8)
8-10	23 (8)	42 (8)	26 (8)
10-12	24 (8)	43 (8)	53 (8)
12-14	19 (8)	-	42 (8)
13-14	-	42 (8)	-
14-16	29 (8)	-	-
15-16	-	48 (8)	41 (8)
16-18	39 (8)	50 (8)	37 (8)
18-20	31 (8)	37 (8)	33 (8)
20-22	**39.8(1.7)**	58 (8)	**35.1(2.4)**
22-24	**78.9(5.3)**	-	**41.1(2.8)**
23-24	-	**64(5.0)**	-
24-26	61 (8)	48 (8)	**33.9(2.3)**
26-27	-	63 (8)	-
26-28	62 (8)	-	31 (8)
28-30	33 (8)	-	37 (8)

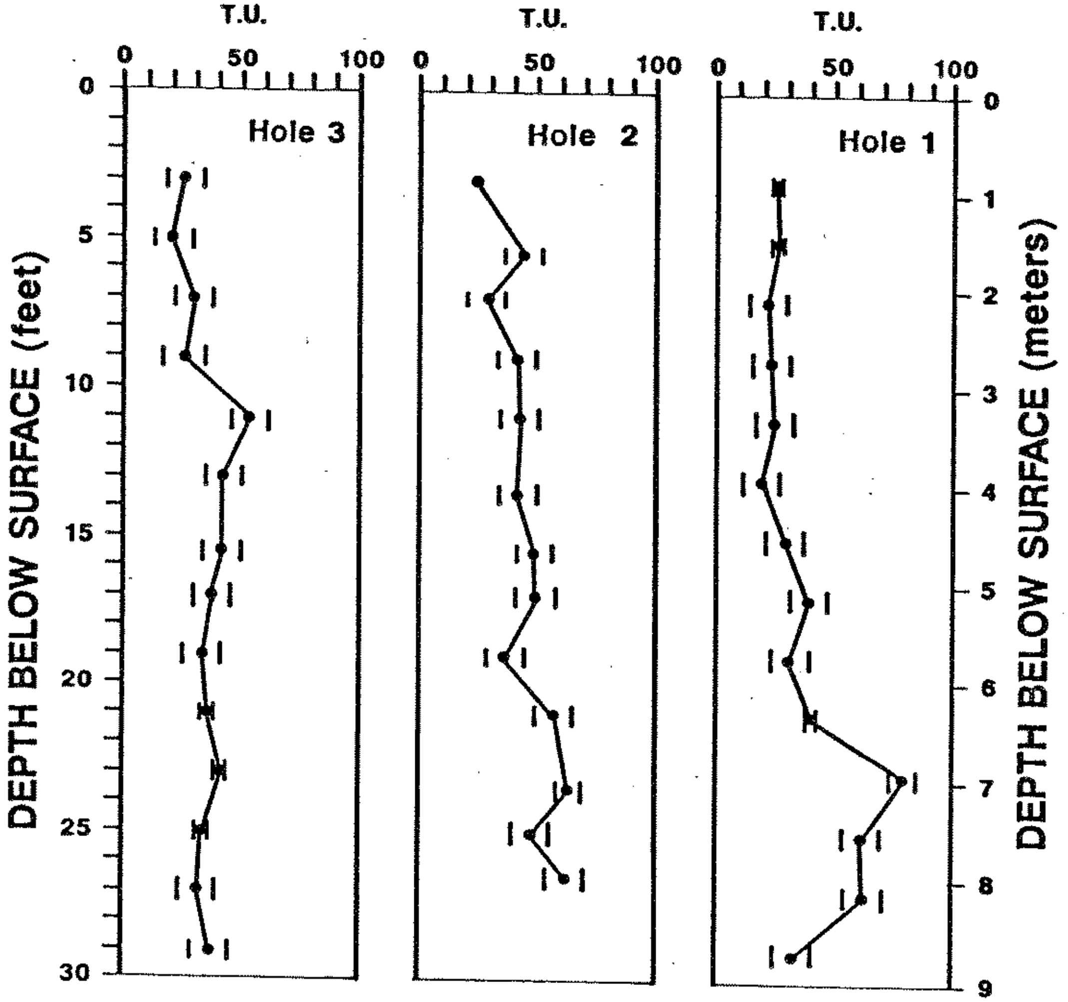

Figure 7 Tritium profiles vs. depth. Short vertical bars represent analytical uncertainties.

the peak of tritium activity in the atmosphere corresponding to 1963/64 rainfall. If this is true then the lower values just below this zone then represent the tritium input by rainfall prior to 1963/64.

Relative to the well-defined geometry of core BN-1's low-high-low tritium signature with depth, profiles BN-2 and BN-3 are more "smeared out"; hence, the geometric form of their curves are less definitive than BN-1 in delineating the position of the 1963/64 peak. The reversal in tritium activities may be indicated in BN-2 between 6 and 8.5 m (20 and 27 ft). However, due to problems in retrieving samples below 8 m (27 ft), it cannot be shown definitively that the reversal back to a low signal is occurring here. The smeared appearance of the profile is attributed to a lateral component of flow through the vadose zone.

The profile for BN-3 is less interpretable than BN-1 or BN-2. Below 3 m (10 ft), the tritium activites show an almost constant level of 35 TU, with a "kick" of 53 TU at 3.3 m (11 ft). Two explanations are proferred for this core's profile. First, the peak levels of tritium may have already passed below the total depth of the hole. Second, runoff from Blackbird Pond may have affected the tritium content of the recharging waters by dilution with water of lower activity. Since it is not known how the tritium content of the pond has varied over the past 30 years, this possibility cannot be pursued.

DISCUSSION

Due to its location at the top of a relatively flat knoll, BN-1 is most useful for estimating the recharge rate of vertically infiltrating water. This location lies on top of a localized groundwater divide. As such, percolating water has little horizontal component (Knott and Olimpio, 1986; Delcore and Larsen, 1987). Before discussing the tritium profile in this hole, however, it is desirable to have a knowledge of the tritium activities in precipitation since 1952 (the advent of above-ground thermonuclear testing).

Source of Tritium

Tritium is produced naturally in the upper atmosphere by spallation reactions whereby cosmic-ray neutrons interact with nitrogen atoms to form tritium and carbon:

$$^{14}N_7 + n \text{ ---> } {}^3H + {}^{12}C_6 \text{ (Faure, 1986).} \qquad (5)$$

Once produced, tritium is quickly oxidized to form tritiated water, or HTO. Estimates of steady-state production of tritium, as well as a few actual measurements of activites in precipitation prior to 1952, indicate that the natural background activity in precipitation should be less than about 20 TU (Fontes, 1980; Gat, 1980).

Since the advent of above-ground thermonuclear testing, anthropogenic tritium has dominated over natural tritium in precipitation. The majority of this input occurred during the late 1950's and early 1960's, during which tritium activities in precipitation as high as 3000 TU were recorded (Fontes, 1980). The tritium introduced by these tests was dispersed globally by atmospheric circulation, and slowly washed out in precipitation. The concentration of tritium in precipitation has been monitored globally by the International Atomic Energy Agency. The most complete record of tritium in precipitation in North America is that for Ottawa, Canada, where measurements began in 1953.

Tritium Input Function

Previous studies have shown that the tritium profile as measured at a particular location is often similar in shape to the time history of tritium in precipitation, corrected for radioactive decay. Thus, the tritium concentration in soil moisture will be a function of the tritium concentration of individual precipitation events, the amount of that precipitation which is available for recharge, the decay rate of tritium, and the residence time of the tritium in the soil zone.

The IAEA publishes results of measurements of tritium in precipitation for the world. The nearest location at which tritium concentrations in precipitation have been monitored is the Chicago area. The Chicago data is reported in IAEA (1969, 1970, 1971, 1973, 1975, 1976, 1981, and 1986). Tritium monitoring was performed at Chicago only during the period 1962-1978. To obtain a more complete record, the Chicago data was compared to the Ottawa data for the same period (Fig 8). By plotting the Ottawa data versus the Chicago data on a log-log plot (Fig. 9), it can be seen that there is nearly a 1:1 correlation. Thus, a regression equation relating tritium in Chicago and Ottawa precipitation was calculated and used to obtain Chicago values for those years which were not monitored. The equation derived for this purpose is

$$\log_{10}(TU_{Chi}) = 0.95\log_{10}(TU_{Ott}) + 0.01, \qquad (6)$$

where TU_{Chi} = the tritium activity of Chicago precipitation,

and TU_{Ott} = the tritium activity of Ottawa precipitation.

Inspection of Fig. 8 shows several noteworthy features. The most obvious is the peak activity during 1963, the acme of thermonuclear testing. The second feature to note is the secondary peak during 1958, another year with a high level of thermonuclear testing. Finally, after the 1963 peak, tritium activities in precipitation have decreased to their present levels of about 40 TU (weighted mean annual activity).

The monthly mean tritium activities in Chicago precipitation were corrected for radioactive decay from the time of precipitation to the time of sampling (October 1988)

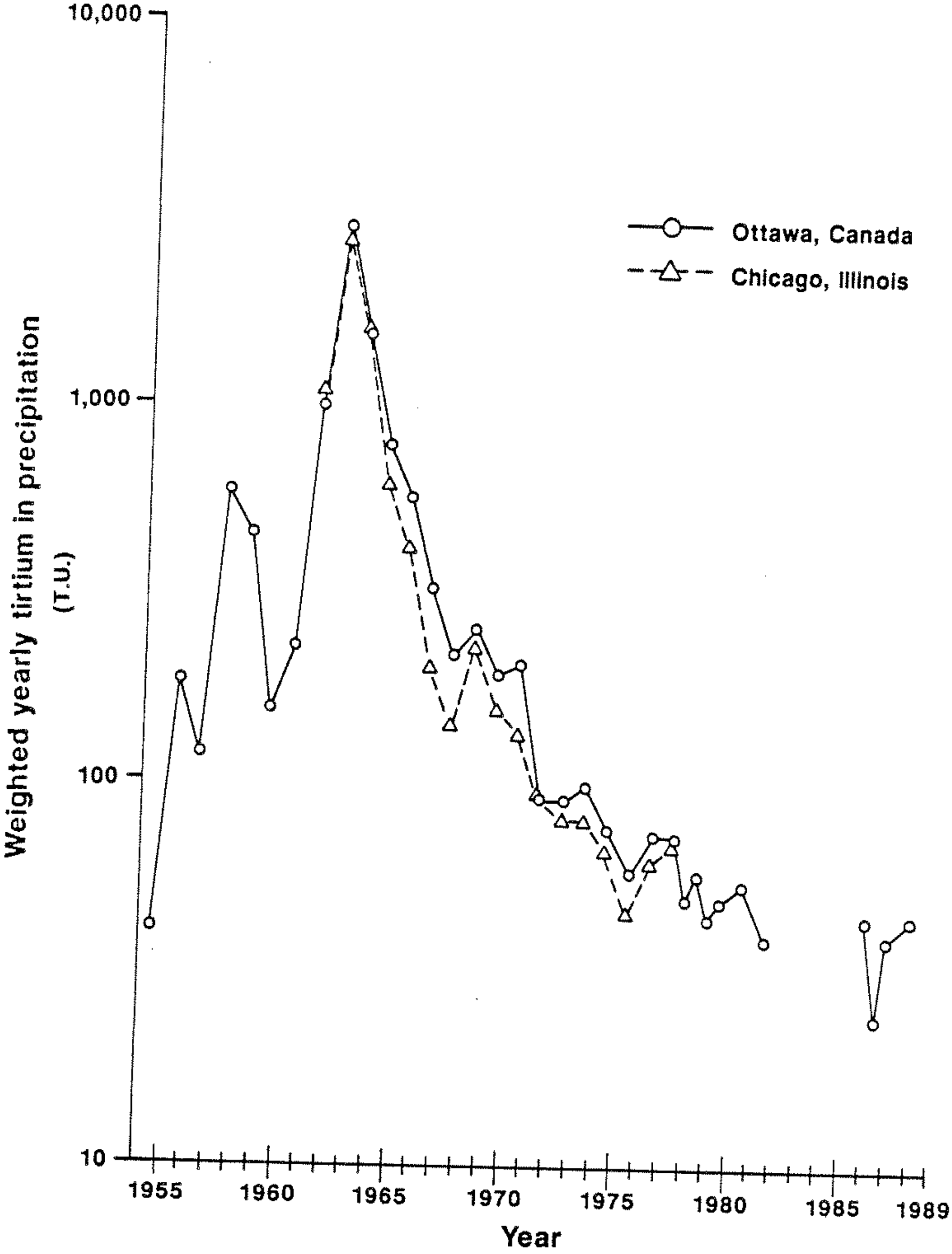

Figure 8 Tritium activity in precipitation at Ottawa, Canada, and Chicago, Illinois. Activities have not been corrected for radioactive decay.

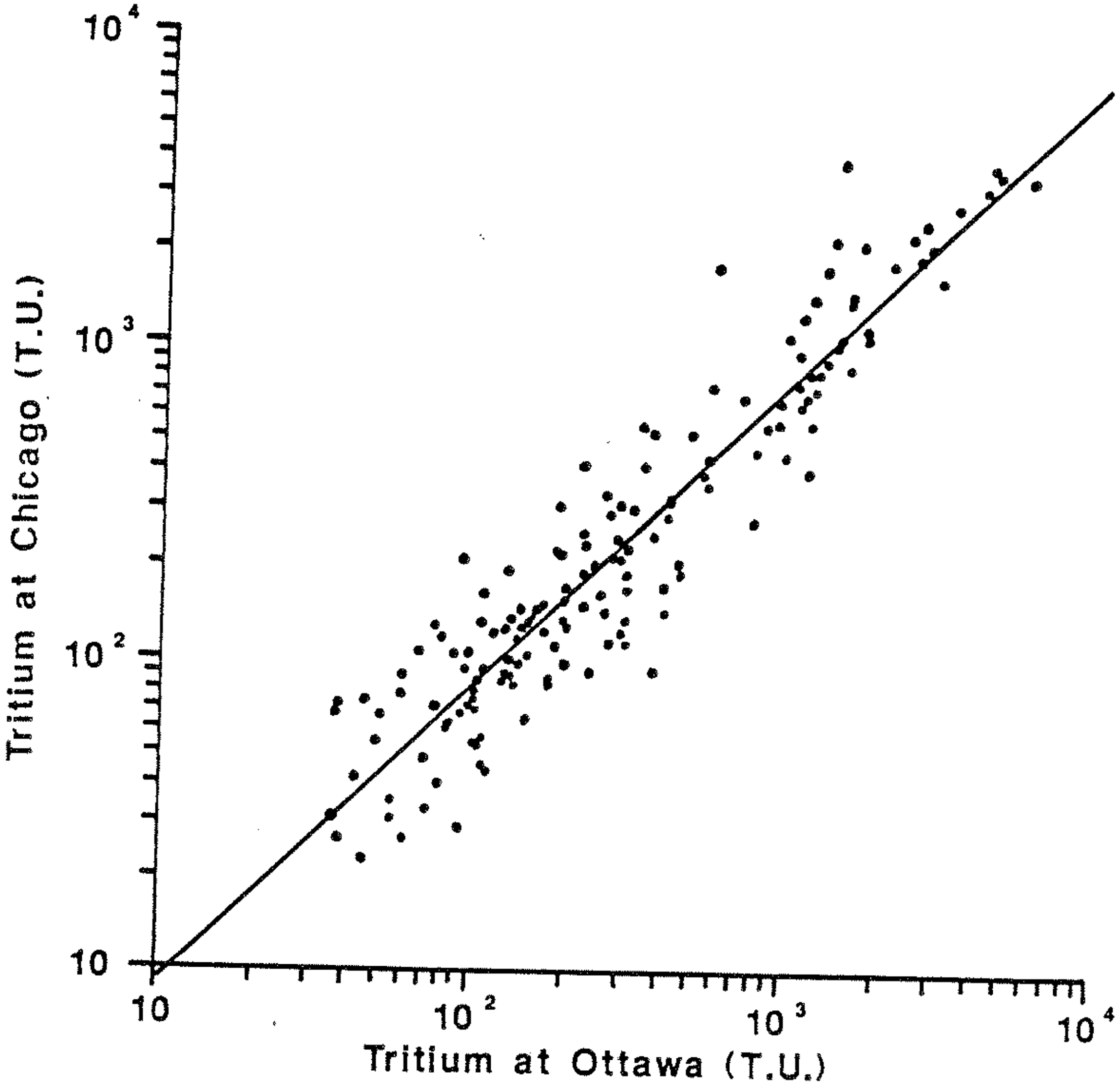

Figure 9 Log-log plot of tritium in Ottawa precipitation vs. tritium in Chicago precipitation for the period 1962-1978.

using

$$T = T_0 \exp(-\lambda t), \tag{7}$$

where T_0 = the measured activity in precipitation (TU),
T = the activity at the time of sampling (TU),
t = the time interval from the month of precipitation to the month of sampling (yrs),
and λ = the decay constant for tritium = 0.05576/yr.

The amount of rainfall available for recharge is a function of the amount of precipitation, evapotranspiration, and runoff. Runoff at the study site was not measured, due to the limited time available for this study. Also, during the study period the region was experiencing a drought, and so any measurements would have been suspect. However, Marie and Davis (1974) reported average monthly runoff values at Logansport, 48 km (30 mi) northeast of West Lafayette, for the period 1953-1967. The reported average monthly values were converted to percent of monthly average precipitation at Logansport; these percents were then used to correct the monthly precipitation values at the study site for runoff. Information on precipitation and pan evaporation were obtained from measurements at the Purdue Agronomy Farm, located 4.5 km (2.8 mi) northwest of the sampling site. The pan evaporation measurements were used as an estimate for evapotranspiration.

Previous investigators have assumed that little, if any, of the precipitation which falls during the summer months is available for recharge (e.g. Zimmerman et al., 1967; Allison and Hughes, 1978; Reardon et al., 1980). Examination of the precipitation and pan evaporation measurements from the Purdue Agronomy Farm would seem to support this, since the average monthly evaporation during the months April-October (139 mm or 5.46 in) exceeds the average monthly precipitation for the same period (94 mm or 3.71 in). However, these measurements are total monthly values. If the spring and summer rains occur as relatively heavy events (Ulrich, 1959), then some of this water may quickly infiltrate to depths where evapotranspiration effects are negligible.

Grabczak et al. (1984) addressed this problem by using the seasonal variations of ^{18}O and ^{2}H in precipitation with respect to the isotopic composition of shallow groundwater. The shallow groundwater is assumed to show the mean isotopic content of infiltrating water, and thus represents a mixture of two waters whose end-members are winter precipitation and summer precipitation. The method was tested at two sites near Cracow, Poland, where the stable isotope data indicated that summer infiltration comprised about 50% of the total infiltration. This estimate agreed with estimates based on conventional hydrologic data, but is in sharp contrast to the assumption of no summer infiltration.

According to Grabczak et al. (1984), the weighted mean tritium content of a given year's recharge can be represent-as

$$c' = \frac{[\alpha_{sm}\Sigma\,(P_i c_i)_{sm} + \alpha_{wn}\Sigma\,(P_i c_i)_{wn}]}{[\alpha_{sm}\Sigma P_{sm} + \alpha_{wn}\Sigma P_{wn}]} \qquad (8)$$

where c' = the weighted mean tritium content of a year's recharge (TU),

c = the measured monthly tritium activity of each month's precipitation (corrected for decay) (TU),

P = the monthly precipitation amounts (mm),

and α = a coefficient representing the fraction of precipitation available for recharge (assumed constant for a given season).

Subscripts sm and wn represent summer (April through September) and winter (October through March), respectively. Although both α_{sm} and α_{wn} can vary between 0 and 1, most investigators have assumed $\alpha_{sm} = 0$ and $\alpha_{wn} = 1$. In other words, only winter precipitation is assumed contributing to recharge.

The form of equation 8 can also be used for stable isotope data. In this case, the equation is written:

$$\delta G = \frac{\alpha_{sm}\Sigma(P\delta R)_{sm} + \alpha_{wn}\Sigma(P\delta R)_{wn}}{\alpha_{sm}\Sigma P_{sm} + \alpha_{wn}\Sigma P_{wn}}\ , \qquad (9)$$

where δG = the mean stable isotope content of the groundwater,

and δR = the weighted mean stable isotope content of summer or winter precipitation.

These are expressed in traditional delta notation as per mil differences relative to some standard.

Only a limited record exists for the stable isotope content of local precipitation. However, the mean isotope content of groundwater represents recharge over a much longer time interval. Thus, equation 9 (as well as succeeding equations using stable isotopes) should be regarded as approximations.

It is difficult to obtain estimates for α_{sm} and α_{wn} separately. A simplification can be made by dividing both the numerator and denominator of the right-hand sides of equations 8 and 9 by α_{wn}, and defining α as the ratio of the summer infiltration coefficient to the winter infiltration coefficient: α_{sm}/α_{wn}.

The long-term mean stable isotope content $\delta\overline{R}$ of summer or winter precipitation can be represented as:

$$\delta\overline{R} = \frac{\Sigma P\delta R}{\Sigma P} . \qquad (10)$$

The summations are carried out over all the summer or winter months for which stable isotope data in precipitation are available. For example, if stable isotope data are available for the years a, b, and c, then $\Sigma(P\delta R)_{sm}$ is formed using the summer precipitation and δR values for years a, b, and c, and ΣP using the summer precipitation for those same years.

Equation 10, along with the definition of α, may be inserted into equation 9 to obtain:

$$\delta G = \frac{\alpha\delta\overline{R}_{sm}\Sigma P_{sm} + \delta\overline{R}_{wn}\Sigma P_{wn}}{\alpha\Sigma P_{sm} + \Sigma P_{wn}} . \qquad (11)$$

Solving for α:

$$\alpha = \frac{(\overline{\delta R}_{wn} - \delta G)\Sigma P_{wn}}{(\delta G - \delta R_{sm})\Sigma P_{sm}}. \tag{12}$$

This coefficient may assume any value greater than or equal to 0. A value of α equal to zero implies either that $\Sigma P_{wn} = 0$ or that $\delta\bar{R}_{wn} = \delta G$. The first possibility of no winter precipitation is unlikely. The second possibility implies that the stable isotope content of the groundwater is equal to the long-term mean stable isotope content of winter precipitation. This is reasonable since $\alpha = \alpha_{sm}/\alpha_{wn} = 0$ means that there is no summer infiltration.

Equation 8 takes into account variations of precipitation within each year. However, year-to-year differences in precipitation may lead to errors if the years of maximum tritium content in precipitation were unusually wet or dry. Therefore, the yearly mean tritium contents calculated by equation 8 are weighted by the yearly amount of infiltrating water:

$$c_{inp} = (I/\bar{I})c' \tag{13}$$

where c_{inp} = the weighted mean tritium content for a given year (TU),

c' = the tritium content calculated from equation 8 (TU),

I = the amount of recharging water in a given year (mm),

and $\bar{I}$ = the mean yearly recharge (mm) = $\Sigma I/n$ (n = the number of years over which the input function calculated).

The amount of water I recharging in a given year may be denoted as the sum of summer infiltration and winter infiltration:

$$I = I_{sm} + I_{wn} \tag{14}$$

$$= \alpha_{sm}\Sigma P_{sm} + \alpha_{wn}\Sigma P_{wn} \tag{15}$$

$$= \alpha\Sigma P_{sm} + \Sigma P_{wn}. \tag{16}$$

The long-term average infiltration $\overline{I}$ over n years is then

$$\overline{I} = \overline{I}_{sm} + \overline{I}_{wn} \tag{17}$$

$$= (\alpha\Sigma P_{sm} + \Sigma P_{wn})/n \tag{18}$$

Inserting equations 17 and 18 into equation 11 and rearranging yields:

$$\overline{I}_{sm}/\overline{I} = \frac{(\delta\overline{R}_{wn} - \delta G)}{(\delta R_{wn} - \delta R_{sm})} . \tag{19}$$

Equation 19 estimates the ratio of mean summer infiltration to mean total infiltration using the stable isotope content of groundwater, and of summer and winter precipitation.

The stable isotope content of the vadose-zone moisture was not measured in this study. However, Harvey (1989, pers. comm.) reported the $\delta^{18}O$ and $\delta^{2}H$ values of the deeper groundwaters in the West Lafayette area. He reports values of $\delta^{18}O$ ranging from - 7.78 to -6.17 $^{o}/oo$, with an average of -7.31 $^{o}/oo$. Deuterium ranges from -56.1 to -48.1 $^{o}/oo$, with an average of -52.8 $^{o}/oo$. Both isotopes are reported relative to SMOW. Assuming that these deeper waters have the same mean stable isotope content as the recharge water in the vadose zone, then the method of Grabczak et al.

(1984) may be used to produce a more accurate tritium input function by incorporating summer infiltration.

Using equation 12, along with the stable isotope data of Harvey (1989, pers. comm.) for the groundwater, stable isotope data for Chicago precipitation (for the period 1962 to 1975), and West Lafayette precipitation (for the same period), the value of α may be determined. Thus, using the $\delta^{18}O$ data

$$\alpha = \frac{[-8.98 - (-7.31)]^{o}/oo}{[-7.31 - (-4.19)]^{o}/oo} \; \frac{4390 \text{ mm}}{8040 \text{ mm}} = 0.292,$$

and for the $\delta^{2}H$ data,

$$\alpha = \frac{[-62.4 - (-52.8)]^{o}/oo}{[-52.8 - (-34.0)]^{o}/oo} \; \frac{4390 \text{ mm}}{8040 \text{ mm}} = 0.2771.$$

An average of these two alpha values, 0.284, was used in equation 8 to calculate each year's weighted mean tritium concentration in the recharging water. These values were then further weighted using equation 13. Summing the weighted mean tritium contents thus calculated over the period 1963 to 1988 indicates that the input tritium content for the study site was 1380 TU.

Inserting the stable isotope data into equation 19, the ratio $\overline{I}_{sm}/\overline{I}$ is found to be

$$\overline{I}_{sm}/\overline{I} = \frac{[-8.98 - (-7.31)]^{o}/oo}{[-8.98 - (-4.19)]^{o}/oo} = 0.349$$

using the $\delta^{18}O$ data, and

$$\overline{I}_{sm}/\overline{I} = \frac{[-62.4 - (-52.8)]^{o}/oo}{[-62.4 - (-34.0)]^{o}/oo} = 0.337$$

using the δ^2H data. The average I_{sm}/I is equal to 0.343. This implies that about 34.3% of the mean total infiltration is due to summer infiltration. Provided all assumptions are correct, then this indicates that more infiltration occurs during summer than previous investigators have assumed. This is reasonable since at least some of the spring/summer precipitation occurs as heavy downpours. An intense rain would force some of the infiltrating water to a depth at which evapotranspiration would have a lesser effect.

Calculation of Recharge Rate

Use of the tritium profile in BN-1 to calculate the recharge rate assumes that flow is vertical. It is further assumed that the water infiltrates by slug-flow in which a given year's recharge displaces downward all previous years' recharge. Slug-flow movement of water through the vadose zone has been demonstrated by several investigators (e.g. Andersen and Sevel,1974; Allison and Hughes, 1978; and Reardon et al., 1980). A comparison of slug-flow input with an actual tritium profile, modified from Andersen and Sevel (1974), is shown in Figure 10. Their slug-flow model assumed recharge during the winter only, and that the tritium content of the downward-moving slug of water was equal to the weighted mean activity of that winter's precipitation. This slug then displaces downward all previously recharged water.

The shapes of the two curves in Fig. 10 are similar,

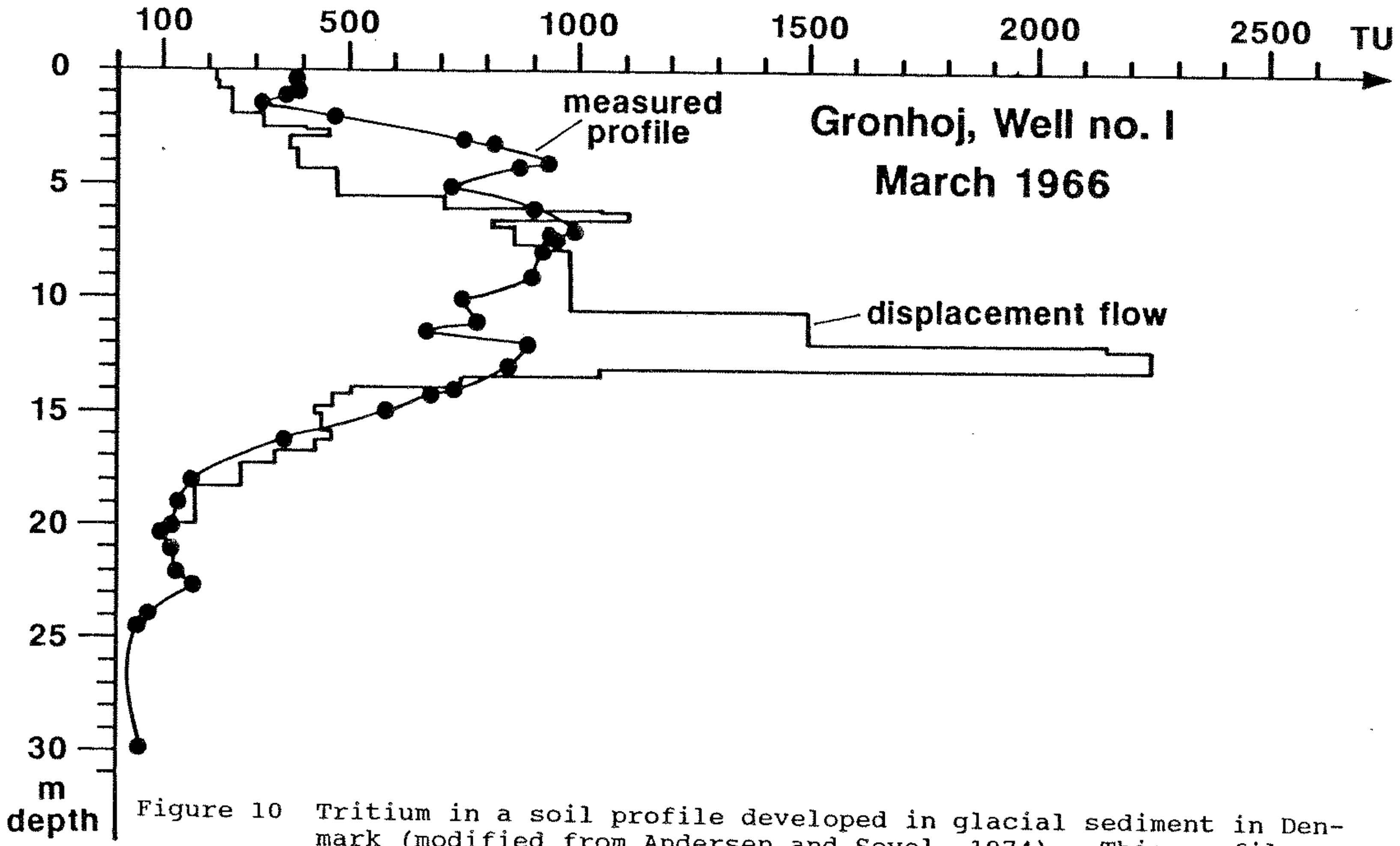

Figure 10 Tritium in a soil profile developed in glacial sediment in Denmark (modified from Andersen and Sevel, 1974). This profile shows the downward movement of the 1963/64 peak of the bomb-tritium pulse through the vadose zone. Also shown is the profile calculated using a displacement flow model, where each year's recharge (precipitation minus evaporation) displaces downward all previous recharge.

showing elevated activities at shallow depths, and a sharp decrease in activities at depths containing waters recharged prior to the advent of above-ground thermonuclear testing. The most obvious difference is that the large peak associated with the 1963/64 input is not seen on the slug-flow curve. This discrepancy was explained by the Andersen and Sevel to be a result of dispersion smearing out the input.

A slug-flow curve was similarly generated for BN-1. Estimates of recharge were obtained by subtracting monthly pan-evaporation measurements from monthly precipitation amounts (both of which were recorded at the Purdue Agronomy Farm). When the evaporation exceeded precipitation, the recharge for that month was set equal to zero. The recharge estimate was further modified by subtracting runoff estimates, obtained by multiplying each month's precipitation value by the average monthly runoff fraction. The percentage of precipitation attributed to runoff was calculated from data given in Marie and Davis (1974). The profile generated using only precipitation-minus-evaporation is shown in Fig. 11, and the profile further modified by runoff is shown in Fig. 12.

The slug-flow profile using only precipitation and evaporation (Fig. 11) shows several similarities to the actual profile in BN-1. A zone of relatively high tritium activites appears at depth in both, occurring between 7.0 and 9.0 m (23 and 29.5 ft) on the slug-flow model versus 6.7 an 8.5 m (22 and 28 ft) on the actual profile. Above

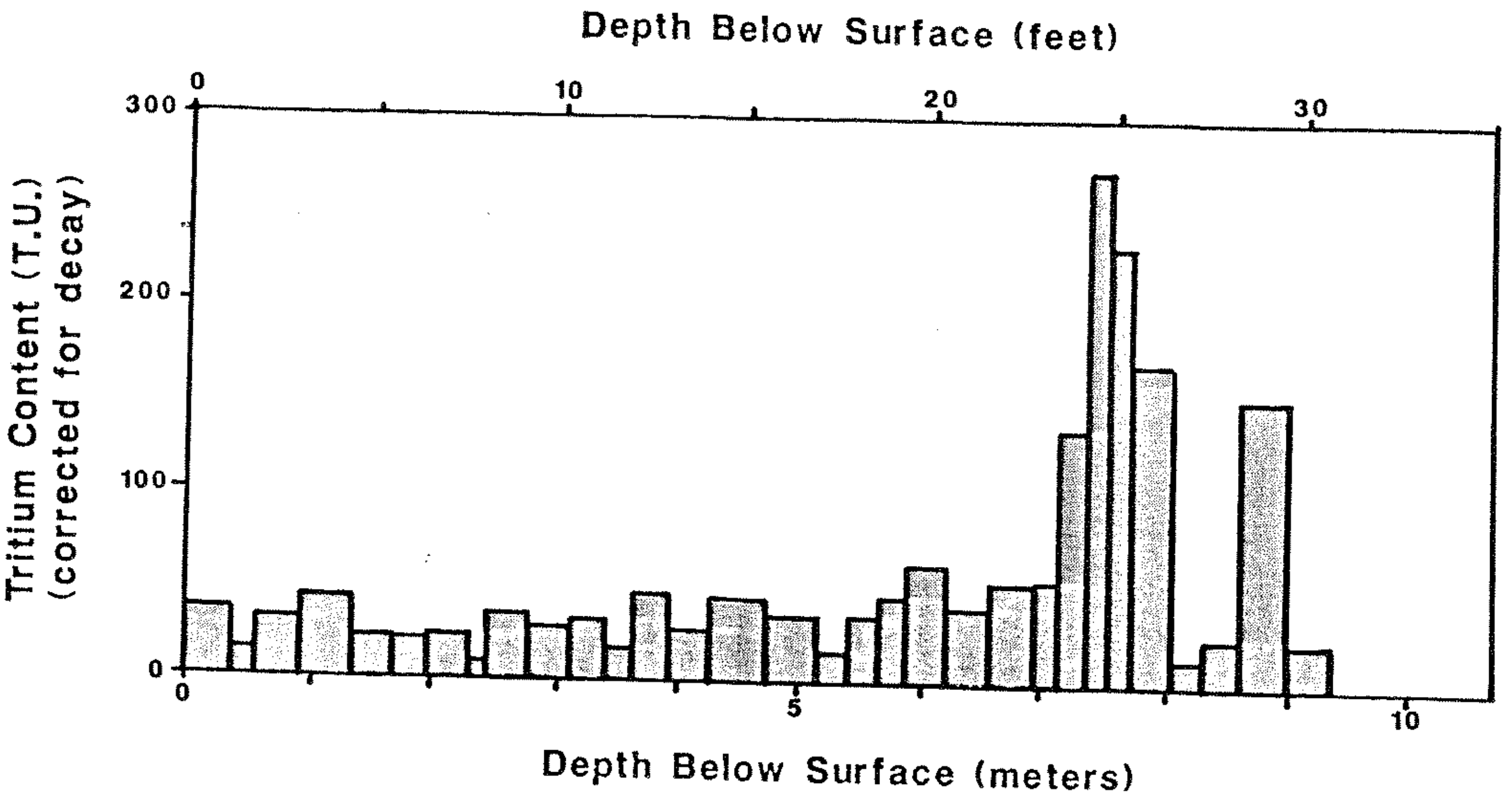

Figure 11 Tritium profile for slug-flow model, where each year's recharge is determined as that year's precipitation minus the same year's evapotranspiration. The latter's values are obtained from pan-evaporation records at Purdue's Agronomy Farm, located 4.5 km (2.8 mi) northwest of the sampling site.

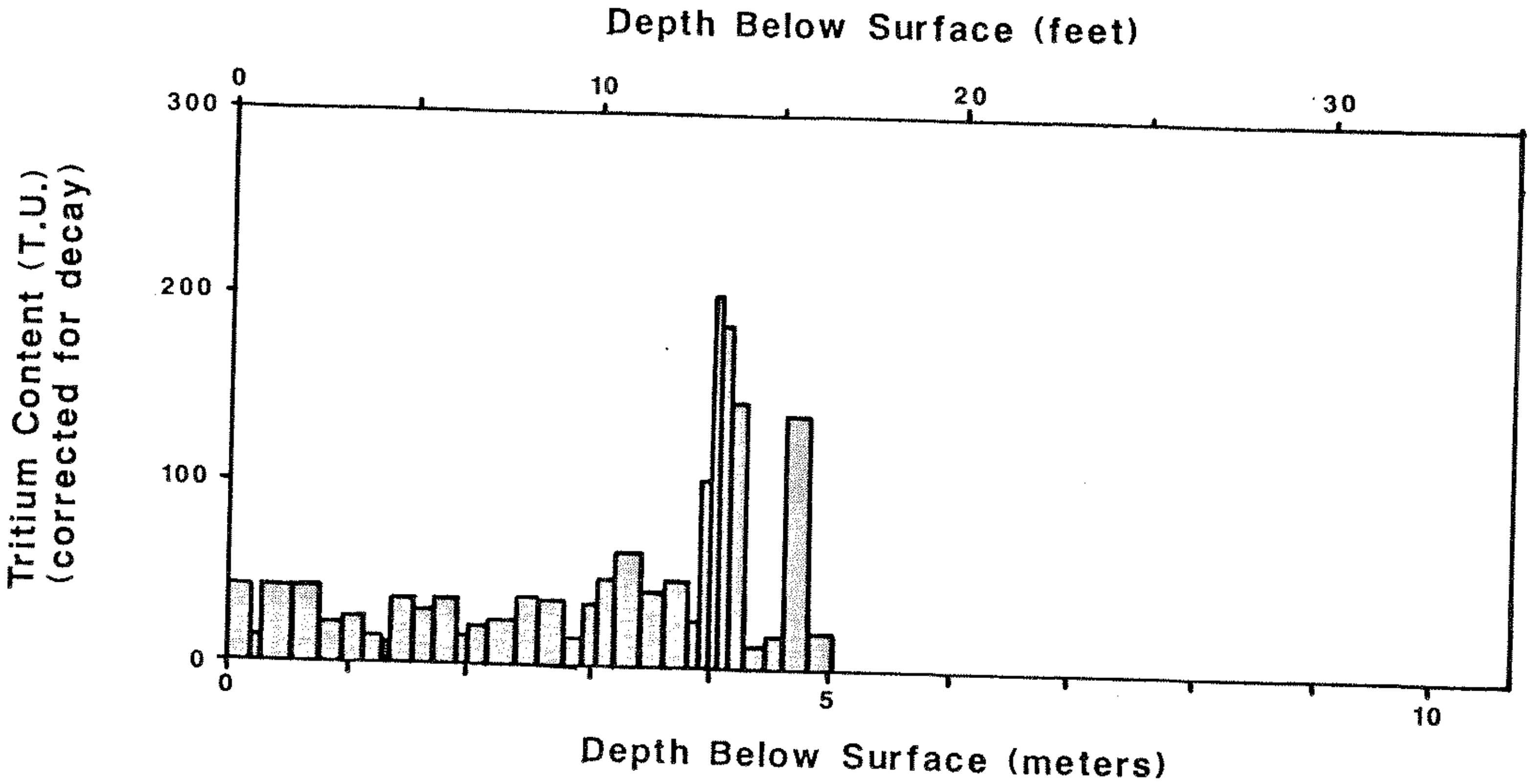

Figure 12 Tritium profile for slug-flow model, calculated as for Fig. 11, but modified by subtracting runoff estimates. The runoff estimates were calculated by multiplying each month's precipitation by a fractional value determined from data given in Marie and Davis (1974).

this zone, both the calculated and actual profiles show low activities, averaging 25-30 TU. The 1963/64 peak occurs between 7.3 and 7.6 m (24 and 25 ft) on the model, whereas the peak activity on the actual profile (assumed to represent the 1963/64 peak) occurs between 6.7 and 7.3 m (22 and 24 ft). Differences between the predicted depths and the actual depths could be due to incorrect estimates of evapotranspiration, the coarseness of the sampling interval used, and/or the lack of a runoff correction. The difference in the peak tritium concentrations may be due to dispersion processes in the vadose zone. A numerical model to test this hypothesis could not be run prior to the end of this study.

The slug-flow model modified by runoff estimates (Fig. 12) also appears similar to the profile in BN-1. However, the depths of the zone of elevated activities is much shallower on this model. Obviously, runoff estimates used to generate this model were too high. In fact, the close fit of the actual data with Fig. 11 implies that there is little-to-no runoff at BN-1. This is not surprising as the estimates were based on regional monthly average runoffs as measured at gaging stations, and thus do not accurately represent runoff at the study site. It should also be noted that the peak activity, while still higher than the actual profile, is lower than in the previous model. This indicates that runoff may be an important factor in explaining the low activities seen in BN-3.

The depth of the 1963/64 peak can be used to calculate the average annual recharge rate if it can be assumed that there are no long-term increases or decreases in groundwater levels. Data given by Bathala et al. (1976) support this assumption for the West Lafayette area. Thus, the average annual recharge should be in balance with the average annual discharge to streams, ponds, etc., and the average annual recharge rate $\bar{R}$ can be calculated as

$$\bar{R} = n_e Z/T, \tag{20}$$

where n_e = the effective porosity of the column,
Z = the depth of the 1963/64 peak below the surface (meters or feet),
and T = the time between 1963/64 and sampling, in years.

Using an average effective porosity of 13% for BN-1, a depth to the 1963/64 peak of 7.0 m (23 ft) (the depth of the highest tritium activity), and a transit time of 25 years, the average annual recharge rate is found to be 3.6 cm/yr (1.4 inches/year).

Several possible sources of error are associated with this method of calculating the recharge rate. The coarse sample interval limits the accuracy with which the depth to the 1963/64 peak can be located. The depth used for the above calculation represents the center of the interval in which the highest tritium activity was found. Also, the value used for the average effective porosity may be in error. Of course, this parameter is difficult to measure accurately because of the arbitrary drying time chosen for the samples. Finally, this method assumes that water being discharged is immediately replaced by recharge water from the vadose zone. This is probably the weakest assumption in this method. The validity of this assumption could possibly be checked with measurements of the pressure head vs. depth in the vadose zone. However, such measurements were not taken as part of this study.

A second method for calculating the average annual recharge rate compares the amount of tritium held in the vadose-zone moisture to the amount available in precipitaion between the time of sampling and the years corresponding to peak levels of tritium in the atmosphere (1963/64). The amount of tritium T_V (in TU-m or TU-ft) added to the vadose zone over this time period is

$$T_V = \int_0^D T_Z \theta_Z dz, \qquad (21)$$

where T_Z = the tritium content of the soil-water at depth z (TU),

D = the depth of the 1963/64 tritium peak beneath the soil surface (m or ft),

and θ_Z = the volumetric water content at depth z.

The amount of tritium T_{inp} which would have been added to the profile is calculated using equations 8 and 13. In this case, the estimated input from summer infiltration is included. The mean annual recharge rate is then given by

$$\overline{R} = T_V/T_{inp}. \qquad (22)$$

Evaluation of equation 17 for depths shallower than the presumed 1963/64 peak in BN-1 yields a vadose-zone tritium content of 48.5 TU-m (159. TU-ft). Along with the previously calculated T_{inp} of 1380 TU, this translates to an average annual recharge rate of 35 mm/yr (1.4 in/yr).

Sources of error associated with this method include the obvious problem of not having site-specific information on the history of tritium activities in West Lafayette precipitation. This problem is common to the majority of studies using the penetration of bomb-tritium. However, considering the correlation between the tritium contents of precipitation at Ottawa and Chicago, which are separated by about 980 km (615 mi), this is not as critical as other error sources. Errors in determining the water content throughout the profile can affect the calculation of the total tritium held in the soil profile. More accurate determinations can be had by using neutron-logging methods in the boreholes (provided such logs are properly calibrated). Finally, the precision with which the tritium activity of the extracted water is measured will affect the calculated result. The direct counting method used with the majority of the samples had an analytical uncertainty of ±8 TU. This uncertainty alone gives a range of recharge rate of 29 to 41 mm/yr (1.1 to 1.6 in/yr).

Comparison to Previous Estimates

The recharge rates calculated by the above two methods may be compared to previous estimates for recharge through tills. Arihood (1982) used a numerical groundwater-flow model in the White River basin of Indiana. Input to the model included estimates of the recharge rate through the tills covering the study area. The model then calculated groundwater discharge to streams, as well as water levels in the study area. These values were then compared to the actual groundwater discharge and groundwater levels. Arihood found that a range of recharge rates through the till of 51 to 114 mm/yr (2 to 4.5 in/yr) gave the best results.

Based on the results of this numerical model, it might be expected that recharge rates through the tills near West Lafayette would fall in the range of 51 to 114 mm/yr (2 to 4.5 in/yr). The calculated values of 36 mm/yr and 35 mm/yr are lower than Arihood's estimates. However, the agreement is good, considering that the model estimates represent an average recharge rate over a large region as opposed to the measured recharge rate encompassing a very localized area. Also, assumptions and simplifications used in the numerical model may require that higher recharge estimates be input in order to agree with the actual measured quantities. Measurement of the recharge rate at a number of other sites on the till plain using the bomb-tritium method would allow a better analysis on the validity of Arihood's estimate because a greater number of samples could be analyzed and compared statistically.

CONCLUSIONS

Measurement of the depth of penetration of bomb-derived tritium is an effective method for determining the actual recharge rate through the vadose zone. The tritium profile obtained in core BN-1 from the upland till plain near West Lafayette showed a definite low-high-low signal at depth, indicating the position of recharge water derived from 1963/64 precipitation. This depth yields an average recharge rate of 36 mm/yr (1.4 in/yr), which is in reasonable agreement with Arihood's (1982) estimate of 51 to 114 mm/yr (2 to 4.5 in/yr) for tills. Two other cores, topographically lower than BN-1, showed no definite reversal in their tritium profiles. Since lateral flow components were expected along the slope, this result was not surprising.

Grain size distributions for the sampled intervals were variable, but showed an overall coarsening with depth in all three cores. This might suggest that the tritium profile is a function of grain-size distribution with depth. However, there was no correlation between tritium content and grain size. Higher tritium contents were neither limited to the coarser-grained intervals nor to the finer-grained intervals.

The coarsening with depth might also suggest higher hydraulic conductivities with depth, allowing somewhat faster flow as the water moves vertically downward. However, the saturated permeabilities measured in BN-1 decrease with depth, indicating the opposite. Measurement of in-situ permeabilities would be desirable in order to investigate how the grain-size distribution affects the rate of movement.

Chemically, and possibly mineralogically, the most interesting results are the high sulfate concentrations obtained in the soil-water extracts. The possible presence of gypsum or anhydrite in the till was unexpected. However, the presence of gypsum should not be surprising, in that pyrite in the till can be oxidized in the presence of calcite to produce gypsum. More work should be done to determine whether or not either of these minerals are actually present in the till, and if so, what are their distribution. The presence of gypsum in the vadose zone would help explain the sulfate content of groundwater samples.

While the recharge rate determined in this study is useful to investigators concerned with determining local and regional water budgets, or with hazardous materials buried in the vadose zone, it must be emphasized that it represents the recharge rate for a given site. Other sites should be tested to determine whether or not this recharge rate is a reasonable estimate for the whole till plain.

Future studies using bomb-tritium in the vadose zone should consider the following factors:

1) Accurate effective porosities for the profiles are needed if the recharge rate is to be determined the depth of penetration of the 1963/64 recharge and the travel time.
2) To determine recharge rate using the total tritium held in the profile, knowledge of the water content of the profile, as well as the distribution of the water in the profile, is needed. This is best obtained by logging the cored hole with a calibrated neutron probe, as this method gives the in-situ water profile with a small vertical sample interval.
3) Factors 1 and 2 require a small vertical sampling interval in order to accurately isolate the 1963/64 peak. For vadose-zone sediments, this implies large diameter cores of short length (which will depend on the actual water content). Commonly available coring devices are limited to diameters of about 7.6 cm (3 in), requiring longer samples to obtain sufficient water for analysis. Shorter samples could be taken if several closely-spaced holes are drilled. However, the drilling of several cores adds cost.
4) The likelihood of extracting only small volumes of water from the sediments suggests using enrichment schemes such as the conversion of the water to ethane, followed by direct gas counting (Knott and Olimpio, 1986). Such methods would allow higher

precision using smaller volumes of water. They might also allow sampling of smaller intervals. Again, these methods are likely to add cost.

5) The cores need to be deep enough to define the entire profile. The actual depth required is somewhat arbitrary, as every site will be different.

6) Downward vertical movement of the water should be demonstrated at the study site. Locating the sampling site on a localized groundwater divide is one way to insure this. However, it is preferable to determine that downward movement exists year-round in order to assess whether periods of net upward movement of water in the vadose zone exist.

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