Applicability of Microcomputers for Managing Water Use in Small River Basins

by

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ABSTRACT

The task of managing water resources under the appropriative system of water rights in the Western United States normally becomes one of simply assuring that the legal priority is satisfied. Since irrigation is the primary use of water, to maximize availability in such a tightly constrained system requires the cooperation of users by increasing efficiency. To accomplish this, information on the best timing and amount of water application is required. As an aid to the local individual such as a watermaster or irrigation district manager in making decisions on distribution and providing information to water users on water availability, software has been developed to allow the necessary analysis. Principal data requirements are: legal information on water rights, effect of diversions on timing and rate of streamflow, and estimation of short term future water requirements. The microcomputer-based series of programs, consisting of a Water Rights and Water Use Data Management system and a Hydrologic Simulation System, were developed for the Apple IIe computer. The data management system provides information such as priority date, location and amount of each water right along with the type of crop, soil and irrigation method. These data are used in the simulation program which performs a field by field moisture balance and a river routing computation to evaluate the effects of the selected water distribution strategy. Both the soil moisture dynamics and river routing are described using simple, yet physically-based models, requiring a minimum of calibration and computation time. Tests of the

simulation system indicate the models are appropriate to this type of application. Based on the large amount of data and number of computations, the personal computer does not appear appropriate to this task; the more powerful microcomputer, including hard disks, would be more suitable due primarily to speed of operation and storage capability.

FOREWORD

The Water Resources Research Institute, located on the Oregon State University campus, serves the State of Oregon. The Institute fosters, encourages and facilitates water resources research and education involving all aspects of the quality and quantity of water available for beneficial use. The Institute administers and coordinates statewide and regional programs of multidisciplinary research in water and related land resources. The Institute provides a necessary communications and coordination link between the agencies of local, state and federal government, as well as the private sector, and the board research community at universities in the state on matters of water-related research. The Institute also coordinates the interdisciplinary program of graduate education in water resources at Oregon State University.

It is Institute policy to make available the results of significant water-related research conducted in Oregon's universities and colleges. The Institute neither endorses nor rejects the findings of the authors of such research. It does recommend careful consideration of the accumulated facts by those concerned with the solution of water-related problems.

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Much of the program development and testing was performed by Rod Allen as part of his Master's Thesis. Additional assistance was provided by Greg Jones and Dan Clark on development of the Data Management System, and by Theron Argraves in data reduction. The assistance of all these individuals was instrumental in the success of this work.

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CHAPTER I: INTRODUCTION

To manage the distribution and use of water within the legal and hydrologic systems of the Western United States is indeed a difficult task. Legally, the appropriative doctrine governs the use of water, requiring, in general, that priority be associated with the date of first application or use. Administered at the state level, this gives seniority to the historic early users. The amount allotted is generally restricted to that reasonably required for the proposed use. The climate of this region is such that irrigation is required for agriculture and has become the principal use of water. Hydrologically, the temporal distribution of water is out of phase with irrigation demands. In most situations, high flows occur in the late spring or early summer as a result of either winter rains or spring snowmelt. However, major water requirements occur in the mid to late summer months. In addition, there are many smaller river basins where storage facilities are either limited or nonexistent, making the users dependent on natural flows which are often insufficient during peak demand periods.

As a general objective, a state may wish to maximize the beneficial uses of its water. This may take the form of attempting to satisfy more of the existing irrigation water rights during low flow periods, thus increasing economic output. In addition to the consumptive use demands of irrigated agriculture, a new group of competing, nonconsumptive, demands have arisen over the last decade or so. These are instream uses of water for such purposes as maintenance of aquatic habitats and water quality. In many states, water rights have been filed for these uses. However, they are junior to the many existing rights, and therefore may not be satisfied during some of the more critical periods without providing storage facilities.

One means of mitigating the conflicts and thus maximizing the beneficial use is through improved efficiency by irrigation. If less water is used, then more will be left in the stream. In this case, efficiency is defined in terms of proper timing and amount of water use. This is difficult without the cooperation of the water users. However, there arepossible advantages, including improved crop yields, more efficient scheduling of irrigations relative to other tasks, decreased irrigation costs and better community cooperation. For irrigation districts, where control over the water is more centralized, it may be considerably easier to realize results of increased supplies from improved water use and scheduling.

Problems in Local Water Management

Those responsible for the day-to-day administration and management of water resources at the local level, such as a water master for the state, or the manager of an irrigation district, are faced with a formidable task. The manager must at least assure that the legal priorities are satisfied. For a small river basin, there may be as many as several thousand water rights and, in an irrigation district, several hundred members. Thus, a major requirement for more effective management is efficient record keeping in terms of storage and retrieval. As an example, a water master may wish to know how many water users with junior rights are located above an irrigator who is not receiving adequate flow in order of their priority date. Currently, this must be researched manually and can become complex if there are several upstream tributaries. In addition to the record keeping function, the manager often requires information on river travel times if water is to be released from storage in anticipation of downstream demand. This is often estimated empirically so that flow can be made available at approximately the time it is needed.

A function that would significantly enhance management capabilities is the estimation of the location and timing of future water demands. The ability to forecast when a user is likely to require water requires an accounting of soil moisture in response to crop consumptive use on a field by field basis. With this information, the manager can begin to advise the users on irrigation scheduling including suggesting rotations when available flows are low. In addition, demand forecasts provide information necessary for operation of any reservoirs in the system. Thus, the prediction of water demand could allow the manager to realistically evaluate future distribution and operation schemes, resulting in more efficient operation and use of the available supply.

In summary, there are three primary requirements for local water management: (1) more efficient record keeping, (2) streamflow routing to predicttravel time and (3) soil moisture accounting to forecast water demand. The integration of these three functions would allow the manager to advise for more efficient water use.

Project Objectives

The problem of improving water use efficiency to provide additional supplies and mitigate conflicting uses within small river basins has been identified, along with the major tasks and information requirements of the local water manager. The general objective of this project is to investigate how microcomputer technology can be developed and integrated into the day-to-day decision making and to begin the development and testing of such a system. The hypothesis is that the microcomputer provides an appropriate technology for application at this level of decision making due to a combination of its cost and computational capabilities and that it can serve as an economical tool in improving the efficiency of water use. To evaluate this hypothesis requires several specific tasks that have been undertaken throughout the course of this project. These are:

1. Develop the concept of a Water Management System Model which satisfies the needs of the local water manager;

2. Investigate microcomputer hardware in terms of storage capability and computational speed;

3. Investigate microcomputer software in terms of language availability and compatibility between machines;

4. Identify what information is required in the local water management process and develop a system to process these data;

5. Identify what properties the hydrologic model components must have to be consistent with the computer hardware;

6. Select and/or develop appropriate hydrologic models for use in the management system; and

7. Evaluate the performance of the computer and various system components using data from a specific study area.

CHAPTER II: SURVEY OF RELATED WORK

Much of the research related to agricultural water management has focused either on the operation and management in large river basins (e.g. Morel-Seytoux, 1979), often with extensive reservoir systems, or onthe agronomic and mechanical aspects of on-farm cropping, water deliveryand application systems. There has been limited attention to the requirements of the water manager whose responsibility may become aiding in irrigation scheduling on a small river basin or project level. In particular, there is no published work integrating water management duties through the use of microcomputer technology.

Even though no specific work has been reported covering the entire problem, there has been considerable work on various aspects of the problem and on related applications. As an aid to the conceptual development and design of microcomputer software, Hromadka et al. (1983) have presented numerous suggestions based on their experience to produce "humanized" computer programs. Particular emphasis is devoted to (a) the logic, to assure that it follows the usual thought processes of the user when solving the problem; (b) the input, to allow the user to see an entire "page"at a time and thus to first review the required data and then check the input, and (c) providing output in a useful tabular or graphical form. Prior to program development, the entire problem must be defined, including decision points and interactions between program elements.

Some of the functions of the water management system have been described by Sutter et al. (1983). In this case, the State of Idaho in conjunction with the U.S. Bureau of Reclamation (USBR) has developed a computerized model of the Upper Snake River system to aid in the accounting of natural flow and storage water. Included are the water rights and major diversions; but no soil moisture accounting or river routing are described. However, streamflow data are used on a real-time basis to operate the system.

Scheduling irrigation has been an interest of the USBR for many years. Termed the Water Management and Conservation (WMC) program (e.g. USBR, 1981), this activity has evolved from one purely of field measurements of soil moisture to a combination of measurements and accompanying soil water balance computations. A suite of programs are available for several minicomputers and microcomputers for this purpose (e.g. USBR, 1983). Typically, the crop coefficients necessary for use in these programs aredeveloped by extensive field measurements (McVay, 1983). Thus, several of the pieces of the problem have been addressed but have not been integrated. In addition, an intensive measurement scheme is an expensive undertaking and, for large areas, must be replaced by a reliable, computational model.

Modeling of the hydrologic system has been the subject of considerable research, both in the area of soil moisture dynamics and streamflow routing. In the description of soil moisture, much has been done with the numerical solution of the one dimensional partial differential equation governing soil water transportation (e.g. Remson et al., 1971).

This approach is quite computationally intensive and, although it provides detailed information, is not appropriate for repeated use in a management problem. Simplifications of the process have been proposed which provide an approximate solution to the problem. Dagan and Bressler (1983) have presented such approximations; however, they still require numerical (iterative) solutions and are thus also computationally burdensome. An important aspect of soil moisture dynamics is evapotranspiration (ET) since it is this process that accounts for the consumptive use. ET depends on the soil, plant and atmospheric conditions. It has been modeled in a very complex manner incorporating all of these aspects individually (Saxton et al., 1974) or in an empirical manner as a function of potential evapotranspiration and crop coefficients. This latter approach utilizes the crop coefficient information together with either pan evaporation or potential ET estimated from climatological variables (Jensen, 1973).

In contrast to point estimates of soil moisture, water balance in the upper soil zone have been developed for use in watershed models that reflect the lumped behavior of relatively large areas. These models are conceptual rather than physically based and the parameters do not necessarily represent the physical quantities but, rather the behavioral properties. Thus, they require calibration prior to use which has been found to be a difficult task (e.g. Sorooshian and Gupta, 1983). Although simple algebraic expressions such as these conceptual models are necessary for a management model, they should be physically based, have physically meaningful parameters, and require a minimum of calibration.

Streamflow routing has been studied in detail over the years. Weinmann and Laurenson (1979) review a number of approximate methods, concluding that they are completely adequate but that parameter estimation is important. The traditional hydrologic routing methods are computationally efficient and have been related to the hydraulics of the unsteady flow process by Cunge (1969), who has shown the significance of the parameters in the Muskingum routing equation in terms of variables of the physical system. In addition, Ponce and Yevjevich (1978) have extended the traditional Muskingum method to have variable parameters, thus allowing for a nonlinear effect with nearly equal computational efficiency. Thus, it appears that existing routing algorithms are available and need only to be formulated to fit the particular routing problem.

CHAPTER III: A WATER MANAGEMENT SYSTEM

To provide a tool which meets the needs of the local water manager requires the integration of several technologies. The microcomputer serves as the central component of the proposed system, due to recent advances in the technology which have made them powerful and yet relatively economical. They have therefore become appropriate for use in small-scale operations, particularly when tasks such as word processing and bookkeeping can also be incorporated. The microcomputer is the information processing unit which combines all of the relevant legal and hydrologic information, simulates the system and provides estimates of the outcome of various decisions. The philosophy is to allow the user to be the decision maker and use the computer to perform the data handling, synthesis and simulation.

System Structure

A natural structure for this computerized system seems to follow from a basic understanding of the major tasks to be performed. The major components are:

1. Water Rights and Water Use Data Management System;
2. Hydrologic Data Management System; and
3. Hydrologic Simulation System.

The Water Rights Data Management System (WRDMS) performs basic record keeping functions necessary for water distribution and provides information for system simulation. The Hydrologic Data Management System (HDMS) provides input necessary for system simulation in the form of climatological data and streamflow. This component is not dealt with here in that it is the subject of a subsequent project; however, this data file and management system are intended to provide continuously updated information as well as forecasts for use in the simulations.

Finally, the Hydrologic Simulation System contains models of the relevant hydrologic processes (soil moisture and streamflow) which allow the estimation of the 'state' of the system based on distribution strategies selected by the user. Analysis of the simulated streamflow then provides a basis for deciding if any of the requests for water must be denied and also how any reservoirs in the system should be operated.

System Operation

The integration of these system components through the microcomputer provides what can be called a Decision Support System (DSS) for local water management. Such a system provides the user with the ability to evaluate alternative strategies by simulating their impact. The two data management systems are used to provide information to the simulation program. The user then provides a water distribution scenario which is simulated, providing an estimate of its feasibility.

Assuming that forecast values of climatological data and inflows to the river system are available for the selected period (one to seven days), as well as the initial river flows and soil moisture values, the progress of a typical simulation for a given day is:

1. Read the forecast climatological data and compute potential ET;

2. Build a working file of all necessary physical and climatological data in order of priority, one record per water right;

3. Accept an estimate from the water manager of how many of the rights that need water are to be satisfied;

4. Read the working file, one record at a time, and update the soil moisture based on:

   a. If the soil moisture is depleted to the lower limit, assume an irrigation is required and refill the soil moisture to the field capacity;

   b. If no irrigation is required, compute the consumptive use during the day and decrease the soil moisture;

5. Accumulate the required diversions for irrigation by river reach;

6. Compute the flow rate at the end of each reach based on initial conditions, inflows and estimated diversions;

7. Output the flow rate and accumulated diversion information for each reach; and

8. Evaluate the results to see if more or less water is likely to actually be available and resimulate, if necessary.

Microcomputer Hardware

Even though the primary effort of this project is the development of supporting software, the microcomputer itself is a key element. The success and utility of the system depend on the ability of the machine to perform the data handling and computations within a reasonable length of time, probably on the order of a few minutes for a simulation. This, in turn, depends on the storage capacity of the computer and the speed of computation and access of peripheral data storage devices such as disk drives.

Although it is difficult to keep pace with the advances in microcomputers, at this time, a reasonable differentiation exists between those that are considered 'personal computers' (PC's), such as the Apple IIe and the IBM PC, and a more powerful class developed for commercial and scientific applications such as the IBM XT or the CROMEMCO systems. The difference in cost between these classes is on the order of 2 to 3 times, depending on peripheral devices, with the PC's priced in the $2,500 range. Typically, a PC has 64 to 128 kilobytes (KB) of memory while the more powerful models will have 256 KB or more. There may also be significant differences in the microprocessor, with the larger machines configured around a 16 bit microprocessor such as the 68000 used in the CROMEMCO system.

Since a significant amount of data handling and file manipulation in the form of reading and updating is required, a key element is the peripheral devices. Normally, data files are stored on either 5-1/4 or 8 inch floppy disks. For the case when an entire file cannot be read into the central memory of the computer, repeated access is required which can be quite time consuming. Two disk drives would normally be included in the price of a PC. A hard disk would provide data retrieval at a rate at least five times faster than the floppy disks. These units have storage on the order of 10 to 20 KB and are often used with the more powerful systems. They are also available for the PC's at a cost in the neighborhood of $2,000.

Since it is impossible to forecast the ultimate performance, an Apple IIe computer with two disk drives was selected for use in this project. This selection was based on the availability of equipment and the feeling that, if the system worked reasonably well on a small PC, any improvement in hardware would only enhance its performance. On the other hand, if the Apple IIe proved to be too slow or have inadequate memory, attention could be focused on the more powerful models in the future.

Programming Language

After selection of the computer, the programming language must be selected. Most of the PC's and all of the more powerful computers have compilers for BASIC, FORTRAN and PASCAL. Upon inspection, it appears that there are many different versions of BASIC, with nearly each machinehaving a slight variation. For many years, FORTRAN has been the standard language for scientific computing. In addition to this, it is, in general, completely standardized, the newest version being FORTRAN 77. After considering the transferability of the code between machines, FORTRAN was selected as the programming language to minimize the incompatibility. In any transfer between computers, changes in file handling, job control and possibly input and output (I/O) statements may be required. However, it was felt that FORTRAN would minimize changes in the simulation code.

CHAPTER IV: DATA MANAGEMENT SYSTEM

One of the major problems faced by the local water manager is data and information handling. Ultimately, any local water management system must be equipped with a versatile data base management system as a means of both storing and retrieving these significant volumes of information. Such a system would allow searches of the list of water users to provide listings by such indicators as location or priority date, and, in the case of an irrigation district, may provide a base for annual assessments. The development of such a program is, however, more in the realm of computer science and is somewhat outside the scope of this project. The immediate objective for this work, in terms of data management, is to develop software capable of building, maintaining and using data relevant to the system simulation. To accomplish this required first the identification of relevant data and, second, the development of necessary software.

Data Requirements

The information necessary for a simulation includes a combination of legal and physical data for each water right. These data must allow the identification of the priority for water use, the location of the diversion and application, the amount of water allowed, and the amount required. Priority of use depends simply on the date attached to each water right based on the "first in time, first in right" principle. In addition, the permit number may also be of interest to the manager.

Along with the priority date, there are restrictions on use in terms of location of diversion and application, flow rate, and volume (in the Oregon system), all of which are specified in the water right permit. The water must be diverted from the river and used at the location indicated at a rate not to exceed that specified. Finally, the acreage of the particular field is also included.

Determination of the amount of water required must be based on a soil moisture balance, in the case of irrigation. This requires some knowledge of soil properties and crop type, which, along with the acreage, dictate the water requirements and rate of depletion of soil moisture. An additional consideration is the method of irrigation, which determines the efficiency of use and, thus, the amount of application.

For any small river basin or irrigation district, there will be a relatively small number of individual soils, crops and irrigation methods. Water balance computations require several soil properties which are generally related to the soil type, e.g. that assigned by the Soil Conservation Service (SCS) during a soil survey. Rather than maintain several parameters in the water rights and water use data file, each soil is identified by a single number code which is then translated into the respective soil properties in building a working file for use in the simulation. A similar approach is taken for the crop and irrigation method, each being given a code which is translated into crop consumptive use coefficients, root zone depths and irrigation efficiencies prior to simulation.

Water Rights and Water Use File

The contents of one record of the water rights and water use file are given in Table 1, including the name of each data field, the variable type, its length and the range of values allowed.

Table 1

Water Rights and Water Use
Data File Contents

Field Name	Variable Type	Field Length	Range of Values	Units
Priority Number	Integer	4	0-9999	-
Diversion Reach	Integer	3	0-999	-
Return Reach	Integer	3	0-999	-
Flow Rate Allowed	Real	6	0-999.99	cfs
Volume Allowed	Integer	5	0-32767	ac-ft
Permit Number	Character	8	0-9999999	-
Priority Date	Character	8	0-19831231	-
Type of Use Code	Integer	1	0-9	-
Irrigation Method	Integer	1	0-9	-
Crop Code	Integer	2	0-99	-
Soil Code	Integer	2	0-99	-
Acreage	Integer	4	0-9999	acres
Soil Moisture	Real	4	0-1.00	-
Year to Date Use	Integer	5	0-32767	-
Zone Code	Integer	1	0-9	-

Since there is one record for each water right or water user, the entire file would contain as many records as there were individual rights.

There are several fields not directly discussed previously that have been included for completeness. A code for the type of use has been included to allow for the possibility of water uses other than irrigation, such as for municipal or industrial purposes. A zone code inthe last field is used to identify in which climatic zone a water right is located. Since use may be spread over reasonably large areas and climatic factors such as precipitation or temperature may differ, this code has been included to indicate which climatic data should be used inpotential ET and soil moisture computations.

A brief flow chart of the program for creation and manipulation of the water rights and water use data file is given in Figure 1.

The system startup file loads Program HDRV1, the overall driving routine, and displays the first screen, a credit to the authors. It is followed by a request for the current date. The date is a four digit integer stored in the header of each file.

After the date is accepted, the HDRV1 system proceeds with the following question:

Shall We:

1. Update or Adjust Files?
2. Input Projection Data?
3. Run Analysis of Watershed?

Please choose a number ...

This is the first of several responses required. The valid answer

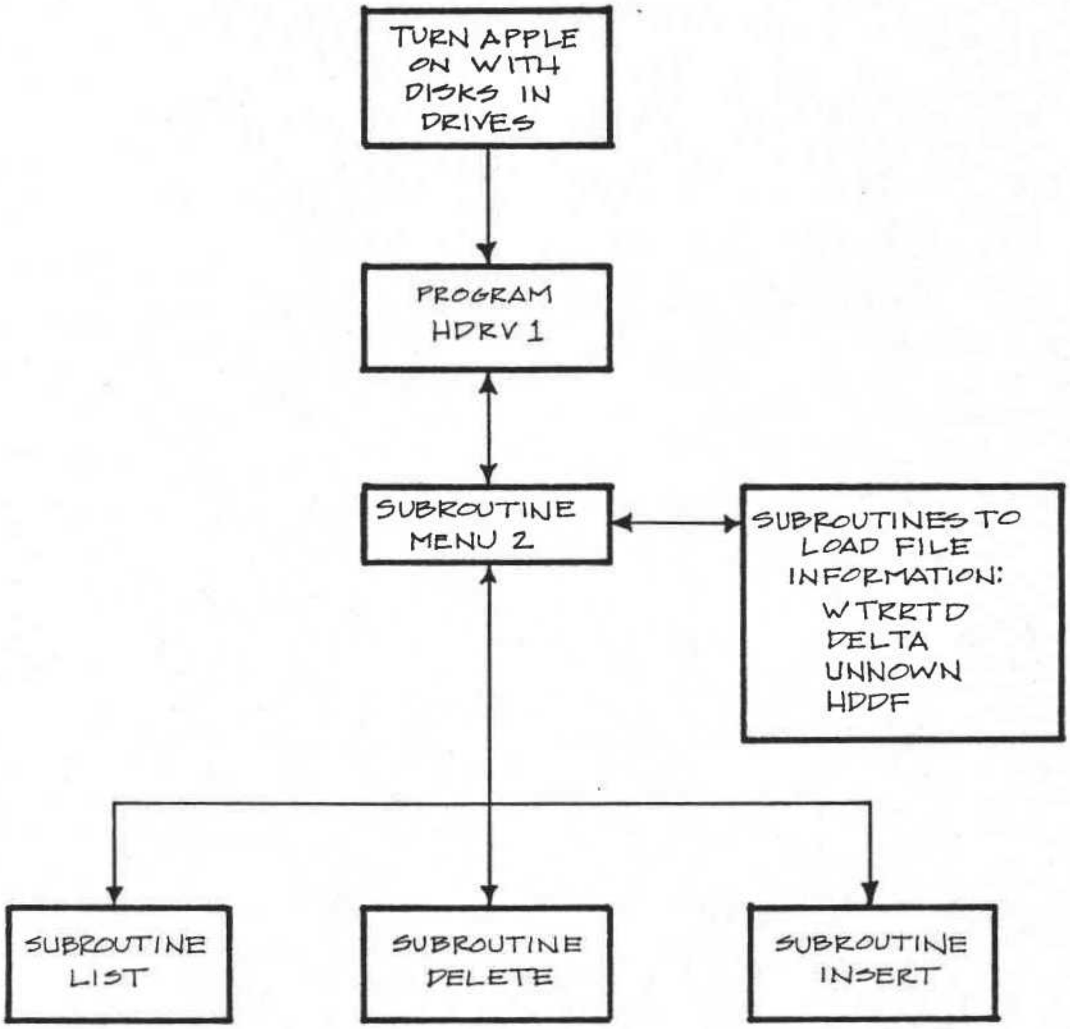

FIGURE 1

General Flow Chart for the Water Rights and Water Use Data Management System to this question is an integer from 1 to 3, so the program will ask again if given any other response.

The update and adjust data option allows for the change of information in any of the data files. Files such as hydrologic data, routing coefficients, return flow data, and water right information may need to be adjusted periodically at frequencies currently unknown.

Choosing option one (update or adjust files) will advance the program into a group of subroutines driven by Program Menu2.

After choosing option one, the screen clears and fills with a new menu, referred to as Menu2:

```
Choose the file to manipulate from those below

1. Water Right File (WTRRTD)
2. The Delta File (DELTA)
3. The File of Unknown Returns (UNKNOWN)
4. Hydrologic Data File (HDDF)
5. The End.

Please choose a number now ...
```

The DELTA file contains data used in streamflow routing and the UNKNOWN file is meant to contain data on return flows in the river system as a result of inefficient irrigation.

An acceptable response to the menu prompt is an integer between 1 and 5. A response of 5 returns the user back to the power-up menu. Any other response leads to a third menu which allows manipulation of the chosen data file. The display is:

What are we doing to this file ...

1. A Listing
2. Inserting Records
3. Deleting Records
4. Exit

Please choose a number now ...

An integer between 1 and 4 is a valid response. Choosing 1 puts the user into a listing subroutine, choosing 2 leads the user into the insert routine, and choosing 3 leads to the delete subroutine. Choosing option 4 takes the user back to Menu2 for a change of file or an exit back to Menu1.

CHAPTER V: HYDROLOGIC SIMULATION SYSTEM

Model Requirements

To provide the manager with estimates of water demand for a system where irrigation is the primary use requires an accounting of the soil moisture. This dictates the irrigation scheduling as well as the effectsof diversions on the river flowrate. Soil moisture computations must beundertaken on a field by field basis corresponding to the various water users. Thus, there may be from several hundred to several thousand computations for each simulation time period. This, of course, requires an efficient computational scheme. In addition, it poses serious practical problems if calibration is required, due to the large number of sites, which is in contrast to the lumped approach of most watershed models. Thus, a model of soil moisture dynamics must be sought that is simple and has parameters that reflect physical soil properties.

Routing of streamflow can be accomplished on the basis of river reaches. These may be defined based on homogeneous physical properties, such as width, slope or roughness, at convenient measurement points or atlocations where major tributaries enter the system. The selection of hydrologic routing requires that each reach be viewed in a 'lumped' manner. Thus, all diversions and return flows within each reach can be accumulated for a given time period (day). The routing algorithm then requires flow at selected convenient locations as output from each routing computation for use by the manager.

The microcomputer is at present inherently slower than the more powerful mainframe. Thus, the hydrologic simulation models must be computationally efficient in order to minimize run time for a simulation. However, the process models must also describe the system in a realistic manner if useful results are to be obtained. These competing goals of simplicity and accuracy guide the search and development of hydrologic model components.

Soil Moisture Dynamics

As indicated previously, past efforts to model the dynamics of soil moisture have involved either computationally intensive and inefficient models or conceptually based descriptions suitable for large, heterogeneous areas. Neither of these types of models was sufficient for the purposes of this work. To accomodate the requirement of this particular application, a simplified, physically based model has been developed based on the principle of volume conservation in the root zone and an assumed soil moisture profile shape. The sharp wetting front model was selected as an approximation to the distribution of soil moisture, as shown in Figure 2. This assumes a uniform initial soil moisture θ_i, and a 'piston' shaped soil moisture profile at the end of an irrigation or rainfall event with moisture equal to θ_u above the wetting front and θ_i below the wetting front. The continuity equation for soil moisture after an irrigation or rainfall can then be written as:

$$\frac{d\theta}{dt} = -q(\theta) - ET(\theta) \qquad (1)$$

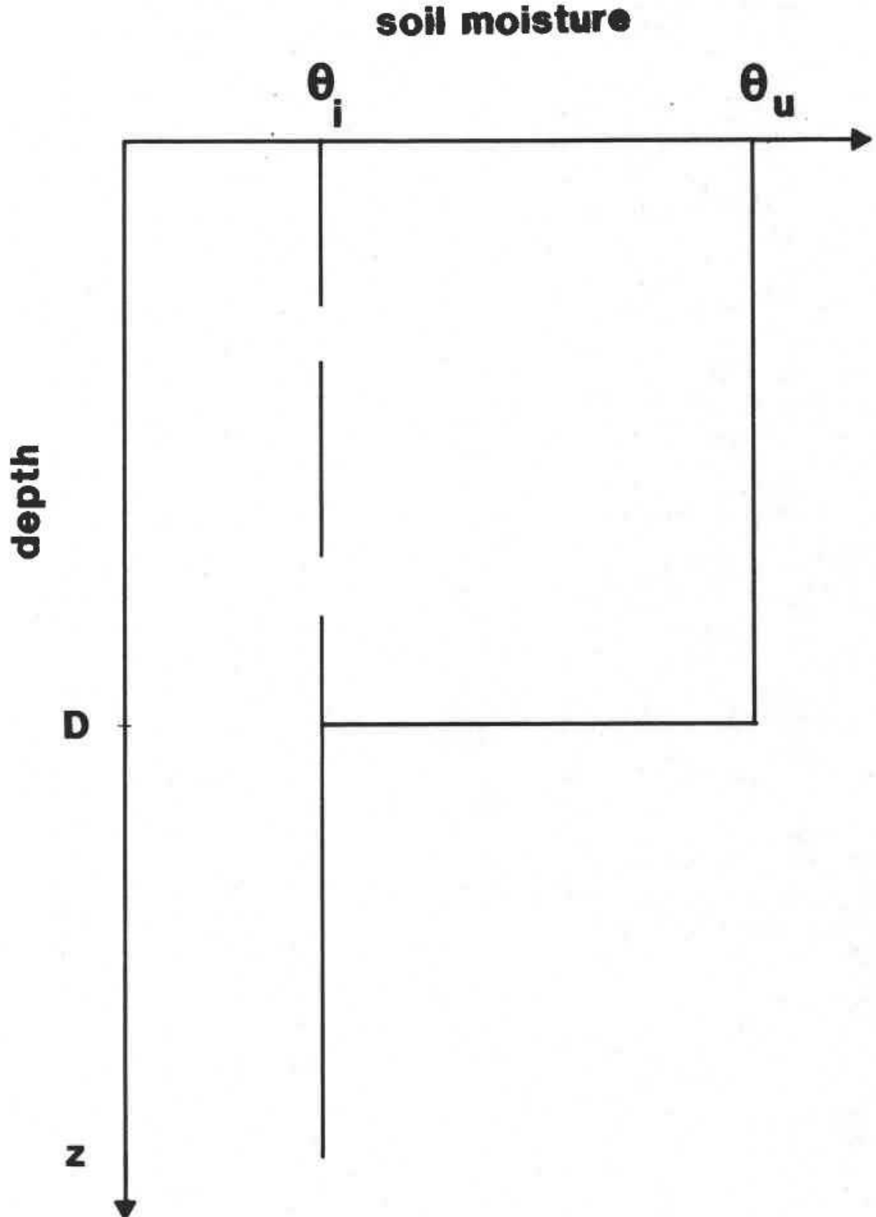

FIGURE 2

Sharp Wetting Front Model for Soil Moisture Simulation where θ is the volumetric water content per bulk volume of soil

$q(\theta)$ is the drainage rate, e.g. in./day

$ET(\theta)$ is the evapotranspiration rate, e.g. in./day

Assuming the profile remains as a sharp front allows it to be tracked to determine when the front reaches the base of the root zone.

Drainage is modeled assuming that capillairy effects are negligible. In this event, the drainage rate is simply the unsaturated hydraulic conductivity, $K(\theta)$, so :

$$q(\theta) = K(\theta) \tag{2}$$

The hydraulic conductivity is a function of the soil type and soil moisture and can be approximated by a function of the form (Corey, 1977)

$$K(\theta) = \begin{cases} 0 \text{ , for } \theta<\theta_{fc} \\ K_s\left(\dfrac{\theta-\theta_{fc}}{\theta_s-\theta_{fc}}\right)^n \text{, for } \theta_{fc}<\theta<\theta_s \end{cases} \tag{3}$$

where K_s is the hydraulic conductivity of natural saturation, e.g. in./day

θ_{fc} is the soil moisture at field capacity (drainage by gravity stops at this point),

θ_s is the soil moisture of natural saturation, and

n is an empirical exponent

This is shown graphically in Figure 3. For analytical purposes, it is necessary to approximate this as a linear function as shown in Figure 3, where K_1 is the selected maximum hydraulic conductivity.

Evapotranspiration is also modeled as a simple, piecewise function of soil moisture (Yaron et al. 1973) as shown in Figure 4 and given as:

$$ET(\theta) = \begin{cases} ET_p, & \theta > \theta_{fc} \\ ET\left(\frac{\theta - \theta_{wp}}{\theta_{fc} - \theta_{wp}}\right), & \text{if } \theta_{wp} < \theta < \theta_{fc} \end{cases} \quad (4)$$

where ET_p is the potential rate of evapotranspiration for a reference crop, and

θ_{wp} is the soil moisture at the permanent wetting point.

Actual evapotranspiration is a function of the crop type, so that

$$AET = K_c ET(\theta) \quad (5)$$

where AET is the actual evapotranspiration, and

K_c is the crop coefficient.

The potential rate of evapotranspiration can be computed from any number of equations, such as the expression developed by Jensen and Haise (e.g. Saxon and McGuinness, 1982):

$$ET_p = (0.025T + 0.078)R_s \quad (6)$$

where T is the mean daily temperature, celsius, and

R_s is the solar radiation (cm/day).

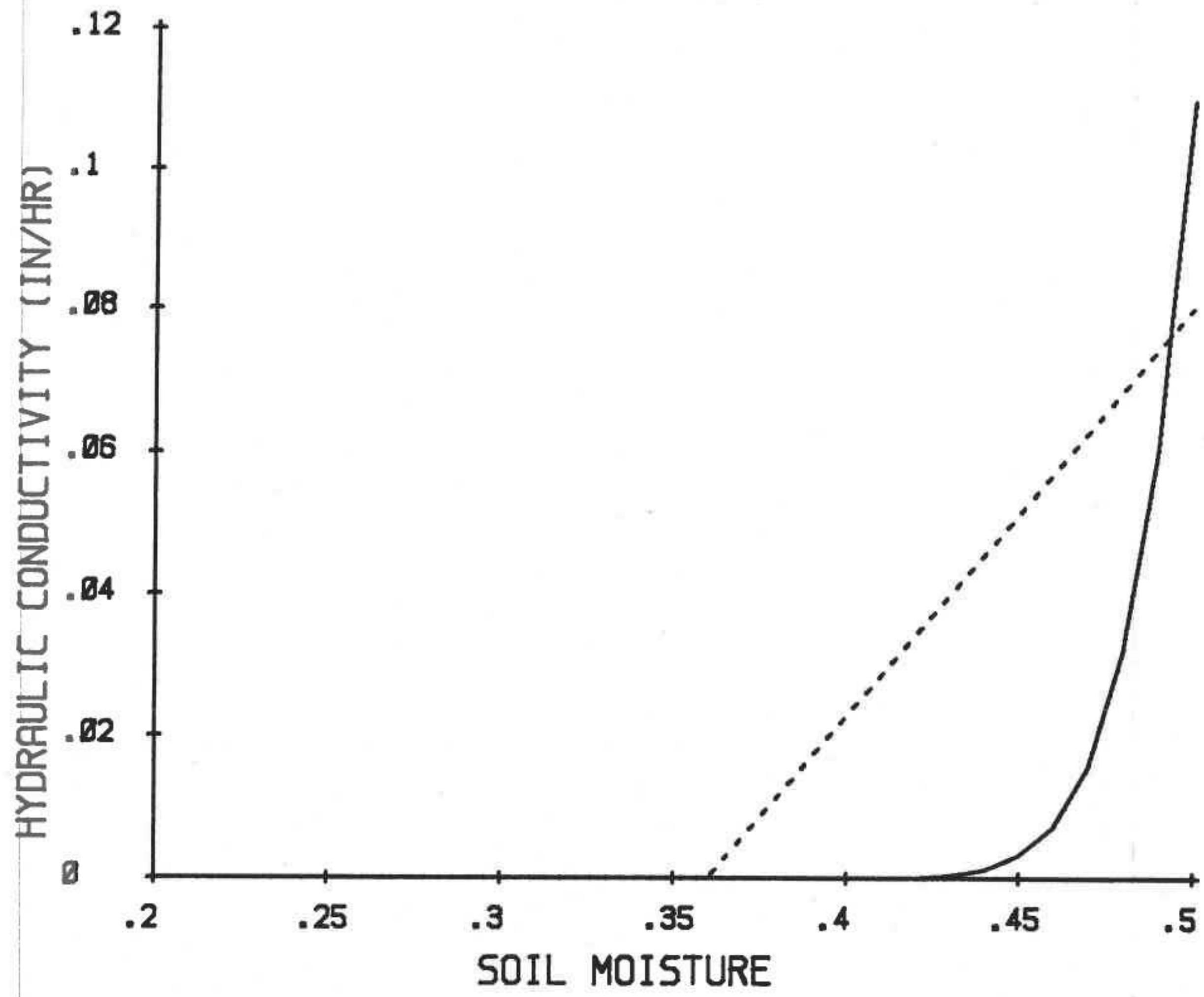

FIGURE 3

Unsaturated Hydraulic Conductivity as a Function of Soil Moisture.
Solid line indicates actual behavior; dashed line shows linear approximation.

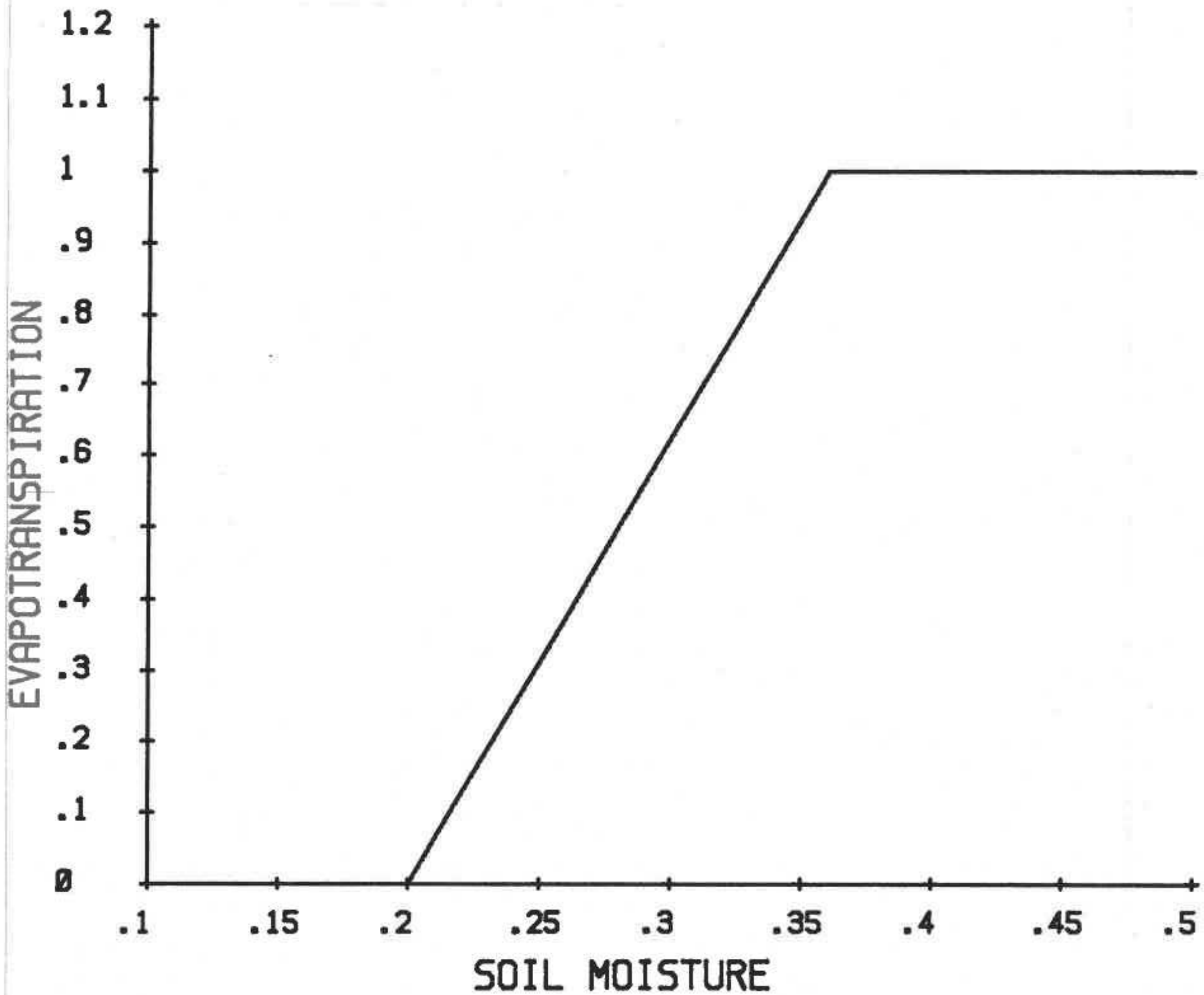

FIGURE 4

Assumed Behavior for Evapotranspiration as a Function of Soil Moisture

The solution of the continuity equation for soil moisture results in two expressions, one describing redistribution and drainage, the other ET when soil moisture is less than the field capacity. For redistribution, ET is ignored for the time until the wetting front reaches the base of the root zone, a relatively short period for many soils. For the case when the cumulative infiltration, due to irrigation and rainfall, F, is sufficient to fill the soil moisture deficit, i.e., $F > (\theta_{fc}-\theta_i)D$, redistribution will occur as:

$$\theta(t) = \theta_{fc} + (\theta_u-\theta_{fc}) \exp(-K_1(\theta_u-\theta_{fc})t/F), \text{ for } 0<t<t_D$$

$$\theta_{fc} + ((\theta_D-\theta_{fc}) + (\theta_s-\theta_{fc})ET_p/K_1) \exp(-K_1 t((\theta_s-\theta_{fc}))$$

$$-(\theta_s-\theta_{fc})ET_p/K_1 \text{ , for } t>t_D \tag{7}$$

where t_D is the time from the end of the irrigation or rainfall when the wetting front reaches base of the root zone, and

Q_D is the moisture content at $t = t_D$,

$$Q_D = \frac{F}{D} + \theta_i. \tag{8}$$

For the situation when $F < (\theta_{fc}-\theta_i)D$, no drainage out of the root zone occurs and the soil moisture is assumed to be uniformly distributed within the root zone at a value of $\theta = \theta_i + F/D$. Although this does not provide the proper spatial distribution, total water in the root zone and the computed ET are the same as if a 'step' profile were assumed.

In equation (7) all parameters except K_1 are physically based. For the simulation model presented here, daily time steps were used. This part of the dynamics proved to be unimportant, as it occurs in times much less than this. In addition, with efficient irrigation methods such assprinklers, there is limited drainage out of the root zone, since applications closely approximate the soil moisture deficit. Thus, attention has been focused on the ET process of soil moisture depletion.

For the ET phase, the soil moisture is computed by solving the continuity equation with no drainage, leading to:

$$\theta(t) = \theta_{wp} + (\theta_i - \theta_{wp}) \exp\left(-ET_p t/(\theta_{fc} - \theta_{wp})\right) \tag{9}$$

where θ_i is the uniform initial soil water content at the beginning of the computation period, where $\theta_i < \theta_{fc}$.

The soil moisture simulation is accomplished by applying the above equation to each field that is not being irrigated, with t equal to 24 hours. Thus the soil water content at the end of the period results. It is important to note that the soil moisture asymptotically approaches the wilting point but efficient operation normally requires irrigation at some critical value above θ_{wp}.

Although it is difficult to validate such equations, limited data are available for such purposes where the USBR has initiated a WMC program. This is the case in the Tualatin River Basin in Northwestern Oregon. Using soil moisture, precipitation, temperature and solar radiation data provided by the Tualatin Valley Irrigation District (TVID) and soil properties estimated from the Washington County, Oregon Soil Survey

(Soil Conservation Service, 1982), a test of the ET phase of the soil moisture model was undertaken. The soil properties, as estimated from the Soil Survey, are provided in Table 2 along with the crop coefficient for pasture (McVay, 1984, personal communication). The field was in full cover by the time data were available. ET_p was computed based on the Jensen and Haise equation. The results of this simulation for the June to September period are presented in Figure 5. Agreement with observed soil moisture is quite good, considering that there was no calibration. Also, point values of precipitation, temperature and solar radiation for a location some distance from the field were used in the computation.

TABLE 2

Soil Properties and Crop Consumptive Use Coefficient for Field Application of Soil Moisture Model

Property	Symbol	Value
Field capacity	θ_{fc}	0.35
Available water	$\theta_{fc}-\theta_{wp}$	0.20
Wilting point	θ_{wp}	0.15
Crop coefficient	K_c	0.85

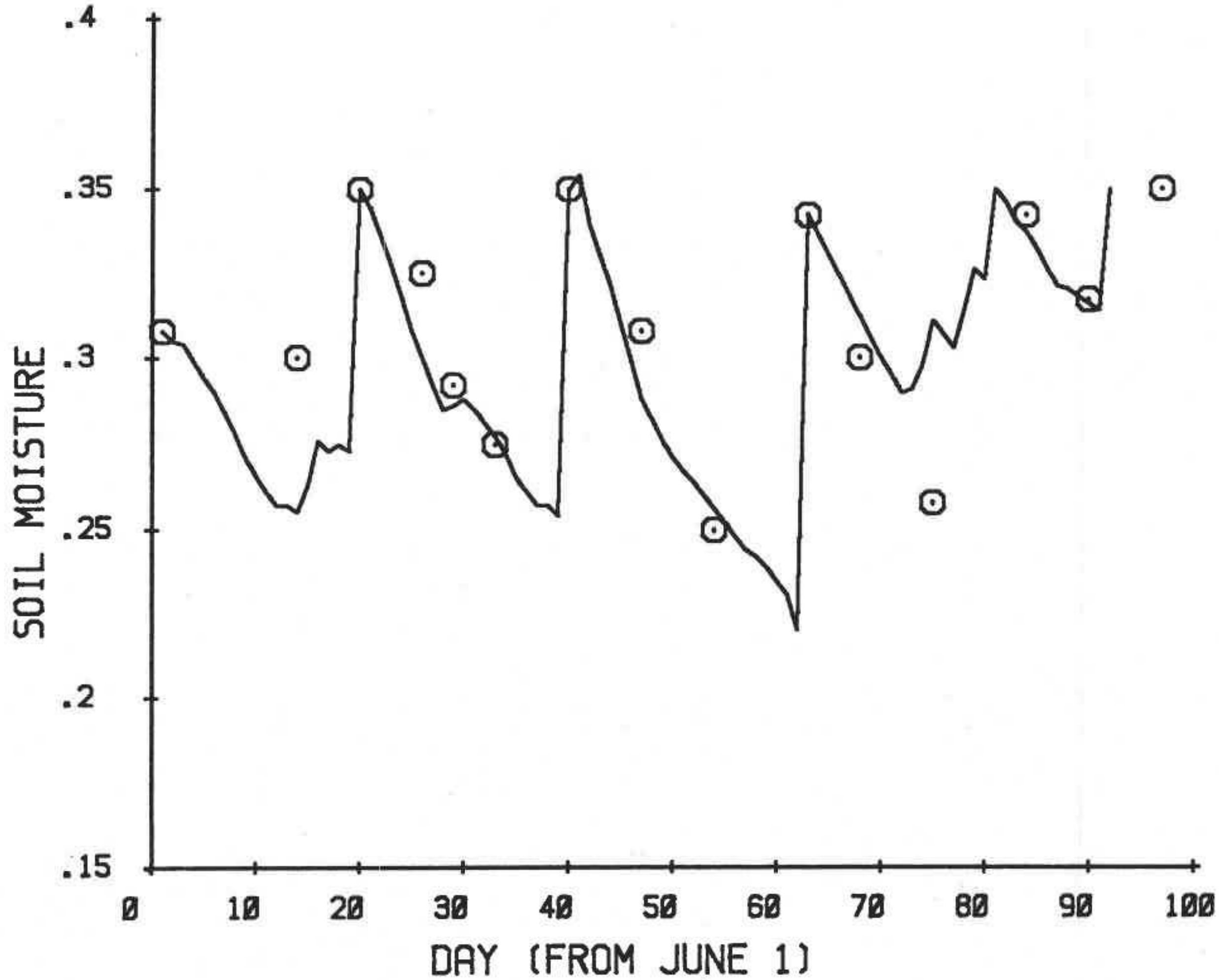

FIGURE 5

Comparison of Simulated and Observed Soil Moisture

Streamflow Routing

Similar to the soil moisture dynamics, streamflow routing must be efficiently described for use on microcomputers. In this case, a hydrologic routing model was selected: a special case of the classical Muskingum method (e.g. Viessman et. al. 1977 p. 232). However, Cunge (1969) has shown the correspondence between the Muskingum routing method and the diffusive wave approximation of the St. Venant equations. Further, Ponce et al. (1978) and Weinmann and Lawrenson (1979) demonstrate that this is an adequate approximation for most practical river routing problems.

The basis of this method is the storage equation:

$$\frac{dS}{dt} = I - Q \tag{10}$$

where S is storage in the river reach
Q is outflow from the reach, in cfs
I is inflow into the reach, in cfs

and an equation relating storage to inflow and outflow

$$S = K(xI + (1-x)Q) \tag{11}$$

where K and x are parameters

Cunge has shown that

$$x = \frac{1}{2}\left(1-\frac{Q}{B\Delta x c S_f}\right) \tag{12}$$

and $$K = \frac{\Delta x}{c} \tag{13}$$

where Q is a reference flowrate,

B is a the width of the river,

Δx is the reach length,

c is the wave celerity, and

S_f is the friction slope of the stream (often approximated as the bed slope).

The celerity or speed of movement of the flood wave can be approximated as the slope of the discharge-stage relationship in the neighborhood of the referenced discharge. A further simplification can be made if the parameter x is set equal to zero. This gives a linear reservoir approximation and provides guidance in selecting a representative reach length (Ponce, 1980), given by

$$\Delta x = \frac{Q}{BcS_f} \tag{14}$$

This approximation is used to describe the physical process of streamflow routing by assuming that the river system acts as a cascade of linear reservoirs with reach lengths, Δx, and storage constants, K. The model is a hydrologic one but is based on parameters that can be estimated in terms of physically realistic variables. Computationally, the problem was formulated in state space notation with the state variables being the flow at intermediate locations on the river. This allows efficient, recursive computation of future flows based on the equation

$$\underline{Q}(t) = \Phi\ \underline{Q}(0) + \Lambda\ \underline{I}(t)$$

where $\underline{Q}(t)$ is the vector of flows at various intermediate locations in the basin,

$\underline{Q}(0)$ is the vector of initial conditions,

Φ is the transition matrix,

Λ is the matrix relating the inflows to flow at selected locations, and

$\underline{I}(t)$ is the vector of inflows, diversions and return flows in the various reaches.

To apply the routing model requires dividing the river into a number of reaches. Each reach is then modeled as a single linear reservoir. Thus, the entire river system is represented as a cascade of linear reservoirs, each with a different storage constant, K, reflecting the hydraulics of the reach. This conceptualization of the system allows the state transition matrix, Φ , representing the response of the river to the initial flow conditions, and the matrix relating inflow and outflow, Λ , to be derived analytically in the usual state-space fashion for a linear, ordinary differential equation (e.g. Wiberg, 1971).

To evaluate the routing procedure, an isolated storm in the Tualatin River basin that occurred in September 1974 was selected. During that period there was limited diversion, due to both the precipitation and time of year. In addition, most of the tributary streams were gaged at that time. A convenient number of reaches was selected, based on the location of existing and possible future measuring stations. Thus, most were at bridges crossing the river or at major confluences. The selected locations are given in Table 3, based on the river mile and location at the downstream end of each reach.

TABLE 3

Location of River Reaches for Application of the Routing Algorithm to the Tualatin River Basin

Reach	River Mile	Location	Comments
1	33.3	Farmington Bridge	Farmington Gaging Station
2	38.5	Rood Bridge	TVID Gaging Station
3	44.4	Unnamed Bridge	
4	51.5	Golf Course Bridge	
5	55.4	Unnamed Bridge	Future TVID Gaging Station in future
6	58.9	Dilley Bridge	USGS Dilley Gaging Station
7	4.0	Scoggins Creek at confluence with Tualatin River	
8	63.8	Tualatin River above Scoggins Creek	

In equation (14) a criterion for reach length of the linear reservoir approximation to theoretically equal the diffusive wave routing procedure was given. For the Tualatin River Basin, representative parameter values are given in Table 4. A comparison of the reach lengths, Δx, from the equation and those selected (see Table 3) reveals that the chosen locations are greater than the computed distances. This disparity can be handled by modeling each reach as a cascade of linear reservoirs. However this would require a significant increase in the number of locations where streamflow would have to be computed in order

TABLE 4

Typical Parameter Values for the Tualatin River Basin

Parameter	Symbol	Value	
		Upper reaches	Lower reaches
Slope	S_f	0.00063	0.0001
Width	B	20 ft.	120 ft.
Representative Discharge	Q	100 cfs	160 cfs
Wave Celerity	c	1.83 ft./s.	1.83 ft./s.
Reach Length	Δx	4340 ft.	7308 ft.
Storage Constant	K	0.66 hr.	1.1 hr.

for the system to have minimum number of state variables. This, in turn, increases the dimension of the transition and input response matrices and thus requires computer storage and computation time.

Alternatively, the full Muskingum equation could be used. This approach leads to a much more conceptually difficult problem. To explain briefly, the output of a 'Muskingum' reach is affected not only by the inflow but also by the derivative of the inflow, which makes state space formulation much more difficult and not nearly as intuitive. Thus, at this stage the linear reservoir approximation is preferred.

To overcome these difficulties, each of the reaches was modeled as an 'equivalent' linear reservoir. That is, the response of each reach to a given inflow was the same as if the inflow were routed through the required number of cascaded reservoirs. Based on this, the coefficients for the appropriate values for the transition and input response matrices, Φ and Λ respectively, were obtained. The results are given in Tables 5 and 6. These matrices may be interpreted to determine the outflow of a given reach due to the flow in all other reaches at the beginning of the day (Table 5) and any inflow (return flow or tributary) or outflow (diversion) from any of the upstream reaches (Table 6). All blank spaces are zero. In the case of a return flow or inflow, I(t) is positive and for a diversion it is negative.

TABLE 5

Values of the Transition Matrix, Φ , for the Tualatin River Basin

0.008	0.036	0.137	0.0885	0.100	0.024	0.090	0.105
	0.007	0.068	0.0526	0.070	0.017	0.074	0.107
		0.024	0.0218	0.035	0.009	0.044	0.069
			0.0004	0.003	0.001	0.007	0.015
				0.0002	0.0001	0.001	0.004
					0.0	0.0	0.001
						0.0	0.0
							0.0

TABLE 6

Values of the Input Response Matrix, Λ , for the Tualatin River Basin

0.992	0.956	0.819	0.731	0.630	0.607	0.517	0.483
	0.993	0.925	0.872	0.802	0.785	0.711	0.677
		0.976	0.954	0.919	0.911	0.867	0.842
			0.999	0.997	0.996	0.990	0.982
				1.000	1.000	0.999	0.996
					1.000	1.000	0.999
						1.000	0.0
							1.000

Results of the application of this method to the September 1974 storm are shown in Figure 6. Agreement with observed flow is good. It should be noted that no calibration of the model was undertaken; parameters were based solely on the methods proposed by Cunge and the equivalent linear reservoir concept. The streamflow routing then requires only two matrix multiplications, given the intial flow conditions (results from the previous computation) and the accumulated diversions and inflow to each reach.

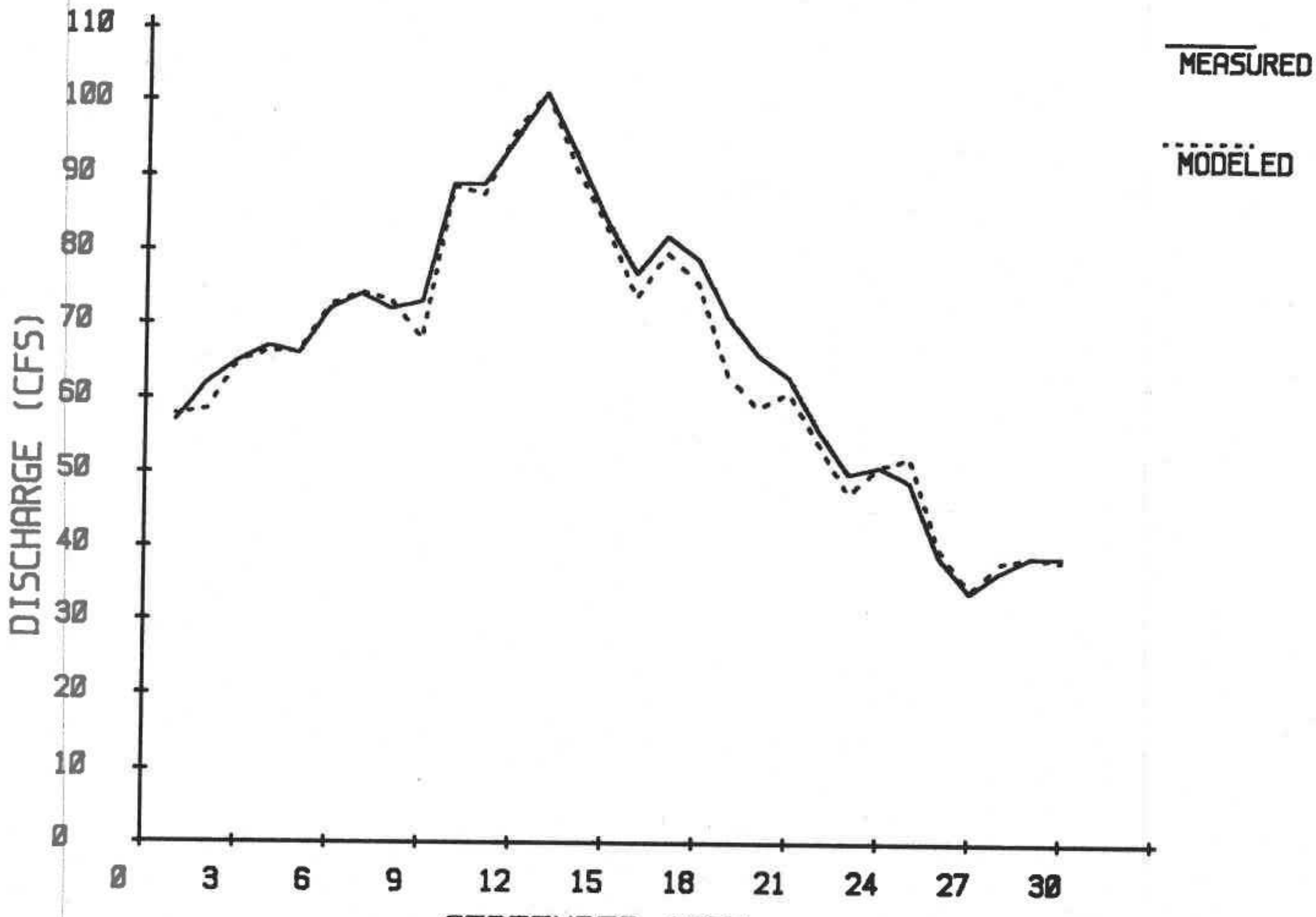

FIGURE 6

Comparison of Simulated and Observed Streamflow for the Tualatin River at Farmington Bridge

CHAPTER VI: EVALUATION

Summary of the System

Having identified possible gains in water availability through increased irrigation efficiency, a microcomputer based system has been proposed to guide water users in irrigation scheduling through the local water manager. The system is composed of a Data Management System for storing and handling data on water rights and water use and a simulation model for estimating irrigation requirements and the resulting river flows. A hydrologic data system for obtaining and storing real time data as well as providing forecast information is the subject of future research. A simplified, physically based model was developed and tested for the soil moisture accounting. The resulting equations were algebraic expressions with parameters describing physical soil properties. They are computationally efficient and were applied without calibration. A hydrologic routing scheme was used in a state space formulation to evaluate the time variation of streamflow at selected locations within the river system. The Data Management and Hydrologic Simulation Systems have been programmed on an Apple IIe in the FORTRAN language.

Evaluation of the Data Management System

The program developed for storage and manipulation of water rights and water use data provides the necessary function of interfacing with the hydrologic simulation system. It is a well written, well documented program that is quite "user friendly". As a result of the user oriented nature, there are some inefficiencies and redundancies to prevent inadvertent loss of information. This, then, affects the speed of editing data records.

Although the system works well for the particular purpose intended, it is not a complete data base management (DBM) system that is useful for tasks other than providing the specific information required for simulations. Thus, it does not meet the general need for record keeping. A true DBM system would be a very valuable addition to the overall program but these are difficult to develop. There are, however, a number of commercially available programs that may be suitable for interfacing with the simulation model.

Evaluation of the Hydrologic Models

The two components of the Hydrologic simulation system, soil moisture and river routing, have been tested and shown to reproduce observed data quite well with no calibration for the conditions tested. In addition, they are simple and therefore computationally efficient. In the application of the models to the Tualatin River Basin, the effects of groundwater and return flow were not incorporated, since they have minimal impact in this situation. In a more general case, these components must also be included.

Overall Evaluation

The components of the local Water Management System that have been developed seem to be adequate to the task and appropriate to the microcomputer technology. The microcomputer itself, in form of a PC, appears to be somewhat deficient in terms of both storage and speed of operation. Many of these problems could be overcome by the addition of a hard disk storage unit to the system. Particular problems of requiring several disks to store the necessary programs and data require either additional disk drives or special programming and repeated changing of disks. Thus, the hard disk is an attractive alternative. It also appears as if the PC may not be appropriate if other tasks are to be combined with the water management activities or if multiple users are anticipated. Thus, the more advanced microcomputers are suggested for consideration as being more appropriate to the task.

The simulation program components have shown very encouraging results. The soil moisture model needs to be tested under a broad range of crop and soil types before accepting the hypothesis that it can be used without calibration. The routing routine may require implementation of the full Muskingum approach to more realistically represent the river system. However, the present approach appears quite adequate.

The addition of the hydrologic data base is paramount to producing an operating system. Since this is the focus of current and future work, an evaluation of the true operational nature of the system must be postponed awaiting this phase. However, the overall approach appears sound, as do the components developed to date.

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