PAPER NO. 70-236

AN OPERATIONAL WATERSHED MODEL: GENERAL CONSIDERATIONS, PURPOSES, AND PROGRESS

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For presentation at the 1970 Annual Meeting
AMERICAN SOCIETY OF AGRICULTURAL ENGINEERS

Leamington Hotel
Minneapolis, Minnesota
July 7-10, 1970

SUMMARY:

General considerations and purposes underlying the operational watershed model of the Central and Southern Florida Flood Control District are presented together with the progress of work under two separate pilot studies; one to simulate streamflow for extended periods and another to compute water surface elevations in the Kissimmee River Basin.

American Society of Agricultural Engineers
St. Joseph, Michigan 49085

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INTRODUCTION

In formulating solutions to complex water resources problems, which are subjected to legal, political and economic forces, consideration must be given insofar as practical to individual factors of many known hydrologic and meteorologic phenomena. It may be very difficult to draw an absolute line of demarcation establishing total independence between hydrology and meteorology but, Mitchell (7) states that, by assuming earth's surface as a dividing line, meteorology could be regarded to include those atmospheric phenomena which bring water to the earth's surface and hydrology would concern water after it reaches the earth's surface. Thus, the problems like changing habits, growing numbers, urbanization, and technological achievements of mankind are likely to alter our hydrologic patterns with time, but no substantial change in our meteorologic patterns could be expected over the centuries.

Only 0.025 percent (2) of the world's water is contained in surface lakes and stream channels, and it is this water that is either habitually in short supply or seasonably becomes a powerfully destructive flood. Associated with it are the man made problems which require making efforts so that water.may be timely available for the benefits of mankind. Inevitably, such efforts may not necessarily result into simple solutions, but the advent of computer has made it feasible to solve most of the computationally complex problems.

With these as background, the Central and Southern Florida Flood Control District has initiated a program for development of an "Operational Watershed Model" of a portion, Kissimmee River Basin, of the

District system. The Kissimmee River Basin system of reservoirs, channels and spillways (Figure 1) extend over approximately 3,000 square miles of the District's total area of 16,000 square miles. This portion of the District system was selected for development of an operational watershed model because system planning and design has been completed and major elements of the physical system are in existence. It is intended to present in this paper the general considerations, purposes, and progress of work carried out under this operational watershed model.

GENERAL CONSIDERATIONS

The main considerations in development of this model were: (a) the determination of the potential and practicality of mathematical modeling for operational water management and (b) the selection of components of the operational watershed model. Lindahl and Hamrick (6) have discussed the potential and practicality of mathematical modeling for operational water management in great detail. The components of the operational watershed model are illustrated in Figure 2.

The four principle components that would make up the District's operational watershed model are rainfall input model, physical system model, economic model for water allocation, and some constraints. The physical system model is further divided into two sub-components; one to simulate streamflow by utilizing information from rainfall input model and another to compute water surface elevations at control points by using simulated streamflow and set of gate operations as inputs. Using system states as one of the inputs to economic model, optimum allocation of water to different uses within the system may be made. Then the system states coupled with its economic consequences are to be evaluated. If the proposed long term general operating policy is accepted, it would then be used as a guide for short term policy execution. Otherwise, changes in the constraints have to be made accordingly.

It is very important to note that in developing long term operating policy the rainfall input to the system would be the values based upon historical records. However, in executing operational policy on short term (day to day) basis, it is quite likely that the rainfall input to the system would be the values based upon current occurrences of rainfall events. Thus, even without having useful rainfall input and economic models, the physical system model could provide day to day operating policies by using current rainfall occurrences and then allocation of water to different uses within the system could be made on the basis of either experience (judgment) and/or institutional constraints (regulation schedules, etc.).

PURPOSES

It is clearly expected that such a model, when fully developed and tested, will be a valuable tool for use in determining operating procedures and in guiding management of the District water resource system. Broadly speaking, the main purposes of this operational watershed model are the development of long term operating policies and their execution as close as practicable on a short term (day to day) basis. A close execution of long term policies on a day to day basis would depend primarily upon the values of input rainfall and constraints used. However, an operational watershed model of the nature presented in Figure 2 could be used for varieties of specific works, but some of major concern to the District at present are as follows:

1. To determine the runoff entering into the system from an occurrence of rainfall.
2. To determine available storage in the zone of aeration or release of water from soil reservoir into the stream.
3. To determine the water surface elevations particularly at the head and tail sides of the control structures within the system corresponding to a set of gate operations and runoff entering into the system.
4. To determine optimum allocation of water to different uses within the system.

PROGRESS OF WORK

The progress of work would depend primarily upon the number and capability of the persons involved in the work and the availability of necessary information to estimate the parameters for testing the model. A little progress has been made toward developing the rainfall input model. The economic model, which has received a matching fund under DI-14-31-0001-3069 Project No. B-005-FLA through the Office of Water Resources Research, is being developed in collaboration with the Agricultural Economics Department of the University of Florida, Gainesville, Florida. Therefore, the report on progress of work in this paper will be limited to physical system model only.

Under the physical system model, two separate sub-models were developed and tested. One sub-model was to simulate streamflow from an occurrence of rainfall and another sub-model was to compute water surface elevations, spatially and temporally, in the Kissimmee River Basin system of reservoirs, channels and spillways.

The details of the sub-model that is expected to simulate streamflow from an occurrence of rainfall are available in an in-house report (1). However, this is briefly outlined below.

The sub-model developed for simulating streamflow from a rainfall event was an amalgamation of the concepts and mathematical relationships developed by several research workers (3, 4, 5, 8, 9, 10, 11). Basically, this sub-model involved using mathematical relationships for determining four broad hydrologic activities. First, infiltration, entry of water into soil profile through soil surface. Second, to account for water losses due to evaporation, transpiration, and deep groundwater percolation. Third, the recovery of water into the stream channel from soil reservoir and overland flow. Fourth, routing the water from channel to watershed outlet. Mathematical relationships to represent infiltration, water loss, recovery, and routing are given below.

Infiltration: The volume of water that infiltrates into the soil profile is found out by evaluating infiltration equations at the beginning and end of the time interval. Infiltration equations are those given by Holtan (3), as

$$f = A(SA)^{1.4}, \quad SA \geq G \tag{1}$$

$$f = A(SA)^{1.4} + FC \quad SA < G \tag{2}$$

where f = capacity rate of infiltration,

A = surface penetration index,

SA = storage currently available in the soil reservoir, and

G = total amount of gravitational water that could exist in a soil profile of selected depth.

Water Loss: The water that reached the ground surface but never appeared at the watershed outlet is considered as water loss. Such loss of water in this model is accounted for under three categories. A sum of losses at any time under the three categories constitutes the total water loss (WL). The three categories are:

i) Evaporation loss: This is attributed to fluctuations in depth to water table and the rate of such a loss is assumed to never exceed the pan evaporation rate. An equation used to represent this is

$$E = C \left(1 - \frac{DWT}{DWTM}\right) \left(\frac{EP[NW]}{24}\right) (DT) \tag{3}$$

where E = evaporation loss (in),

C = a ratio of maximum evapotranspiration to maximum pan evaporation value = a constant,

DWT = depth to water table (in),

DWTM = maximum depth to water table at which DWT will cease to contribute toward the value of E (in),

EP = pan evaporation (in/day),

NW = number of the week,

DT = time increment (hr), and

24 = a factor to convert day into hour.

ii) Transpiration loss: This is attributed to existing vegetation and an equation to represent it is

$$T = C\ (GI\ [NW])\ \frac{EP[NW]}{24}\ (DT) \qquad (4)$$

where T = transpiration loss (in), and

GI = an over-all growth index for existing vegetation.

iii) Deep percolation loss: This is given by an equation

$$DPL = (FC)\ (DT) \qquad (5)$$

where DPL = deep percolation loss (in), and

FC = deep percolation rate (in/hr).

Recovery: The recovery of water into the stream channel is from two main scurces, one from sub-surface flow and another from overland flow. Mathematical relationships used to estimate the sub-surface discharge into the stream channel is that based upon the basic continuity equation and a storage-outflow curve developed from typical recessions. These equations are

$$2(DELF) - Q_1\ (DT) + 2S_1 = C4 \qquad (6)$$

$$2S_2 + Q_2\ (DT) = C5 \qquad (7)$$

where subscripts $_1$ and $_2$ represent the beginning and end of the time interval, and

DELF = volume of water that infiltrated during a DT,

Q = sub-surface discharge into the stream channel, and

S = total available storage in soil profile of selected depth.

The sub-surface discharge into the stream channel at the end of a time interval, Q_2, is accepted when absolute difference between C4 and C5 is within a tolerance limit of 0.01. Such a value of Q_2 in equation 7 is obtained by an iterative procedure. The details about the derivation and utilization of equations 6 and 7 together with an iterative procedure used to obtain the value of Q_2 in equation 7 can be found in (1).

The total storage available at any time (t+1) in any of the reservoirs of a soil profile is represented by

$$(S_i)_{t+1} = (S_i)_t + [(f_i^R - f_i^D) - Q_i - WL_t]\,(DT) \tag{8}$$

where i = reservoir number = 1, 2, ..., N

t = time

f_i^R = recharge rate to i^{th} reservoir,

f_i^D = downward depletion rate from i^{th} reservoir, and

Q_i = sub-surface discharge or lateral outflow into stream channel from the i^{th} reservoir.

An overland flow contribution to the stream channel is estimated by an equation of the form

$$OF = P - f,\ VD = VDM,\ P>f \qquad (9)$$

where OF = overland flow,

P = precipitation,

VD = amount of water currently in surface depression storage, and

VDM = maximum volume of surface depression storage.

Routing: To obtain a time distribution of water at the watershed outlet, routing was done by Nash's (9) equation which assumed the existence of linear equal reservoirs. Nash's (9) equation is

$$U(o,t) = \frac{1}{K(N-1)!}\left(\frac{t}{K}\right)^{N-1} e^{-t/k} \qquad (10)$$

where t = time,

N = number of reservoirs = 1, 2, ..., N,

K = a time constant, and

e = naperian base.

The details about estimation of parameters involved in equations presented here are also available in (1).

This sub-model was tested on Taylor Creek which is 100 square miles in area, discharges into Lake Okeechobee, and is located north and west of Okeechobee, Florida. The streamflow records were simulated for two extended periods by using this sub-model, one from October 1 through November 15, 1956 (46 days) and another from March 15 through July 4, 1959 (127 days). A graphical comparison of historical and simulated records for these two periods are presented in Figures 3 and 4.

The sub-model that is expected to compute water surface elevations at control points in the District's system is based upon the principle of gradually varied flow and its detail was presented by Sinha (12). Its feasibility for application is clearly demonstrated by the simulated mean daily water surface elevation for a period of two years on the tail side of one typical gated spillway (Structure 59) and on the head side of another gated spillway (Structure 61). Graphical comparisons of recorded and simulated values are presented in Figures 5, 6, and 7.

The results presented in Figures 3 through 7 indicate that the simulated values, obtained separately under two sub-models, approximate very well the recorded values. Therefore, recommendations were made for the collection of necessary data so that the physical system model could be tested on the entire upper chain of the Kissimmee River Basin. The upper chain of the Kissimmee River Basin has been already delineated into several sub-basins and computations of parameter values required in the two sub-models are essentially complete. The two sub-models are in the process of being combined to produce information of the nature presented in Figure 8.

SUMMARY AND REMARKS

General considerations, purposes, and progress of work carried out under an Operational Watershed Model of the Central and Southern Florida Flood Conrol District is presented. The major considerations given before initiating this project were the potential and practicality of mathematical modeling and the components that would make up an operational watershed model. The purposes of the District's operational watershed model, when fully developed and tested, are to help determine operating procedures and to guide management of its water resource system. Considerable progress has been made in developing the physical system model which consists of two sub-models. One sub-model is to simulate streamflow from an occurrence of rainfall. The mathematical relationships representing the various processes of rainfall-runoff phenomenon have been presented in a brief outline of this sub-model. The other sub-model is to compute water surface elevations in the Kissimmee River Basin system of reservoirs, channels and spillways. The details about this sub-model are available elsewhere.

The two sub-models developed under the physical system model have been found to be satisfactory and the promising results obtained thereunder led to a decision to extend them over the entire upper chain of the Kissimmee River Basin. The necessary data has been collected and the computations of parameter values required in the two sub-models are almost complete. The work is in progress to combine the two sub-models for producing information of the nature presented in Figure 8.

REFERENCES

1. An in-house report to W. V. Storch, Director, Engineering Department. 1968. A Watershed Model for Simulating Streamflow.

2. Campbell, J. C. 1969. Man, and streamflow modification. Paper No. 69-216, presented at the American Society of Agricultural Engineers Meeting, Purdue University, Lafayette, Indiana, June 22-25.

3. Holtan, H. N. 1961. A concept for infiltration estimates in watershed engineering. U. S. Dept. Agr. ARS 41-51.

4. Holtan, H. N. and N. R. Creitz. 1967. Influence of soils, vegetation, and geomorphology on elements of the flood hydrograph. Symposium on floods and their computation. Leningrad, Russia.

5. Jamieson, D. G. and C. R. Amerman. Quick-return subsurface flow. Unpublished manuscript. U. S.Dept. Agr. ARS.

6. Lindahl, L. E. and R. L. Hamrick. 1970. The Potential and Practicality of Watershed Models in Operational Water Management. Paper presented at ASCE National Water Resources Engineering Meeting at Memphis, Tennessee, January 26-30.

7. Mitchell, Jr., John T. 1970. A Perspective on the Use of Operation Rules. Paper presented at the ASCE National Water Resources Meeting, Memphis, Tennessee, January 26-30.

8. Musgrave, G. D. 1955. How much water enters the soil. Agriculture Yearbook, pp 151-159.

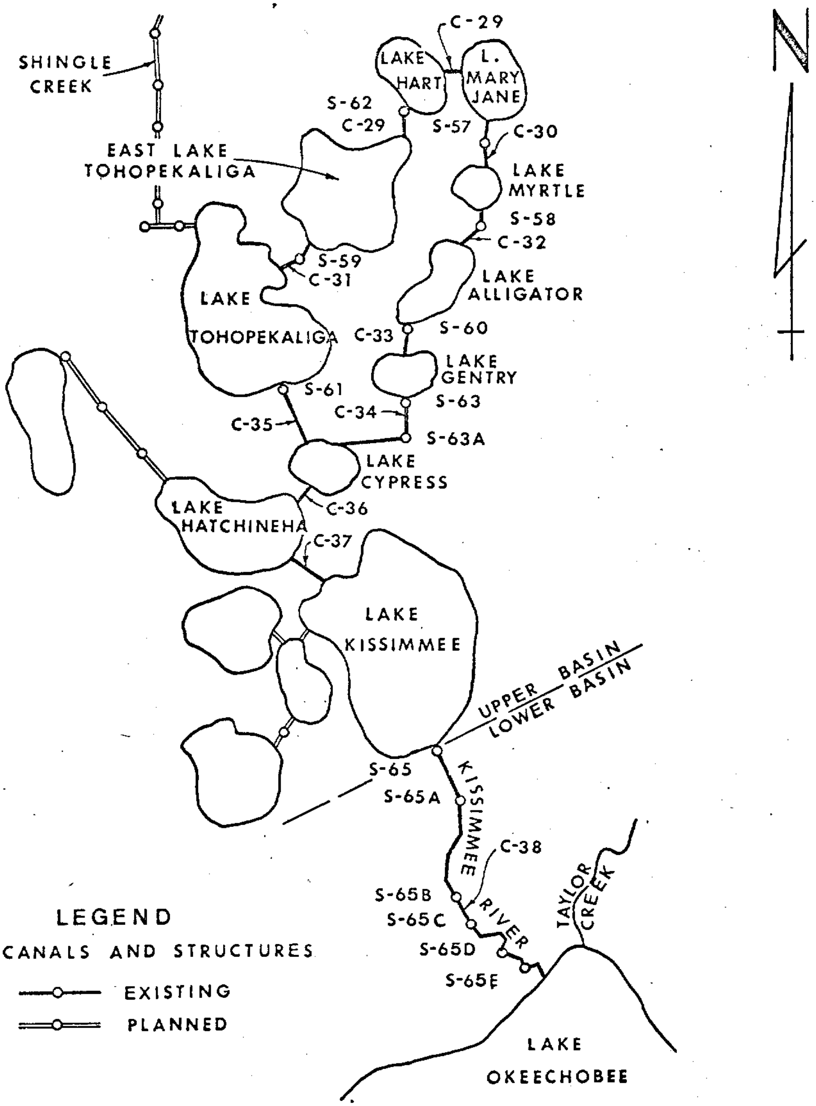
9. Nash, J. E. 1957. The form of the instantaneous unit hydrograph. Intn'l. Assoc. of Scientific Hydrology. Assemblee Generale de Toronto, Tome III, pp 114-121.

10. Onstad, C. A. and D. G. Jamieson. Subsurface flow regimes of a hydrologic watershed model. Unpublished manuscript. U. S. Dept. Agr. ARS.

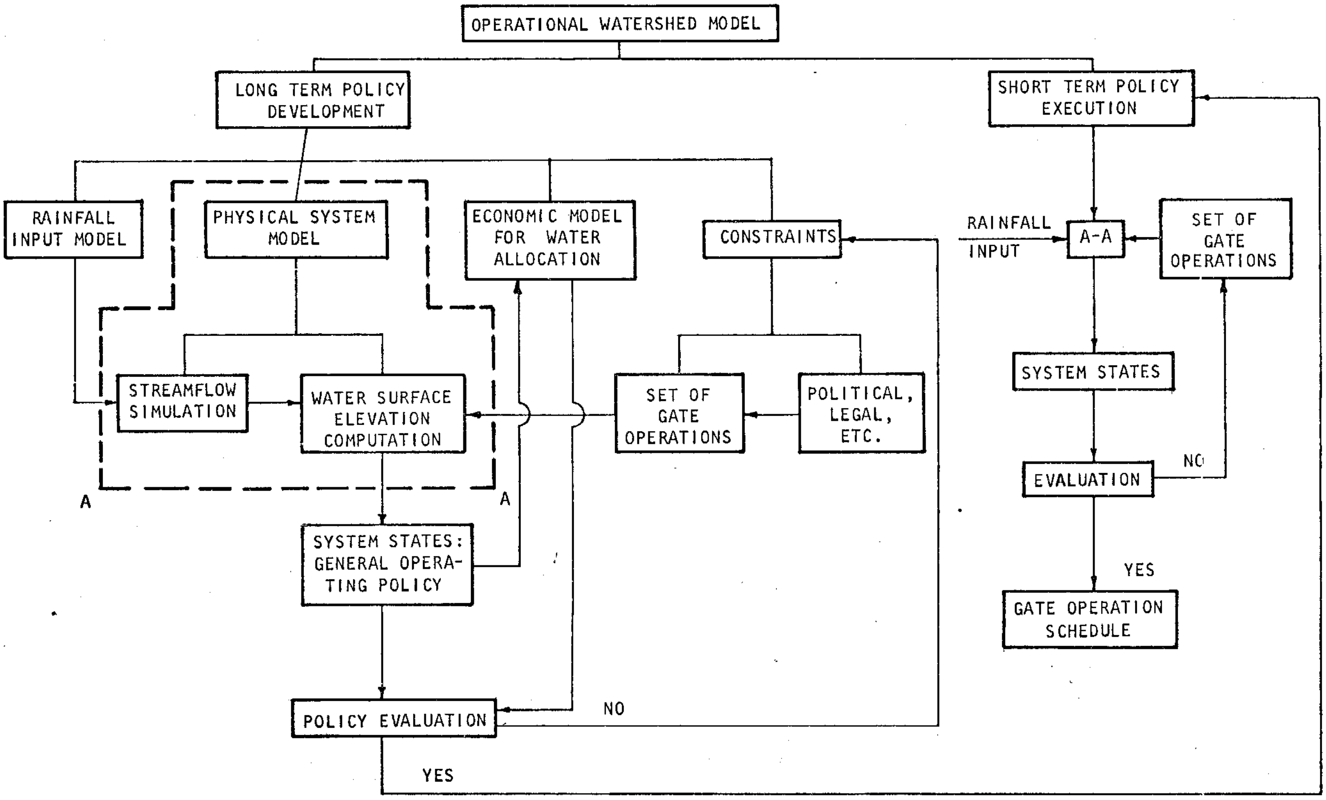
11. Singh, K. P. 1964. Non-linear instantaneous unit-hydrograph theory. Am. Soc. Civil Engr. Jour. Hydr. Div. Vol. 90 , HY2, pp 313-317.

12. Sinha, L. K. 1970. An Operational Watershed Model: Step-1B; Regulation of Water Levels in the Kissimmee River Basin. Accepted for publication in Water Resources Bulletin, April.

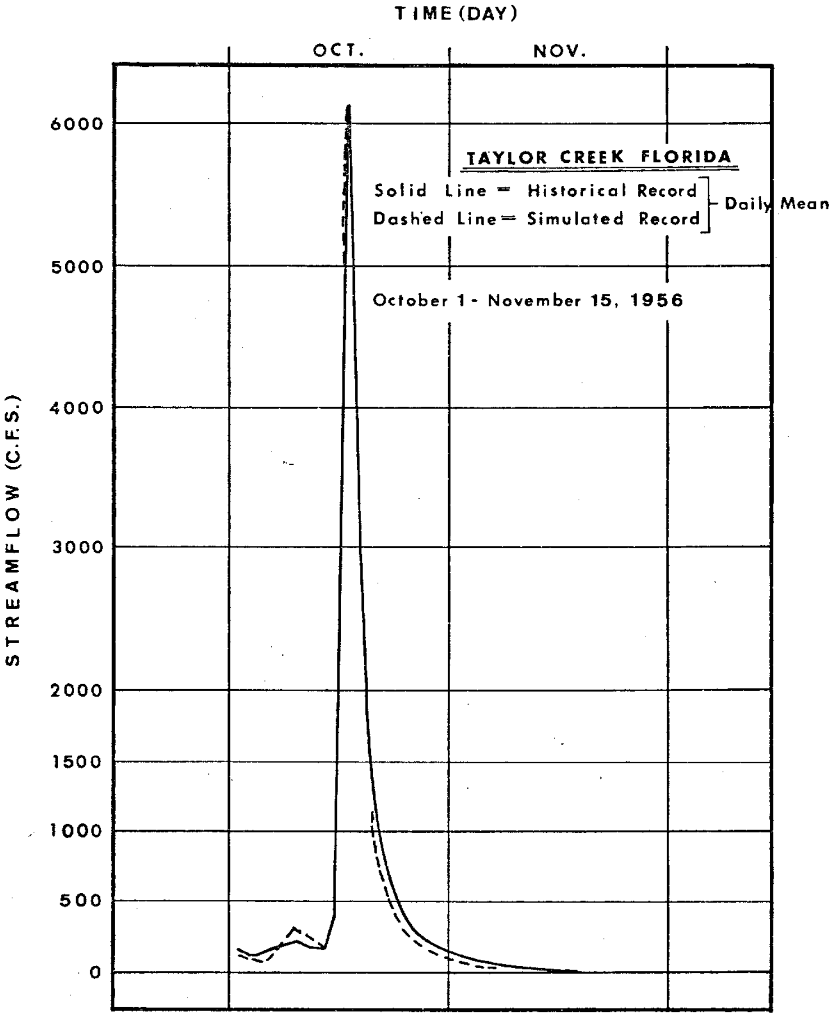
FIGURES



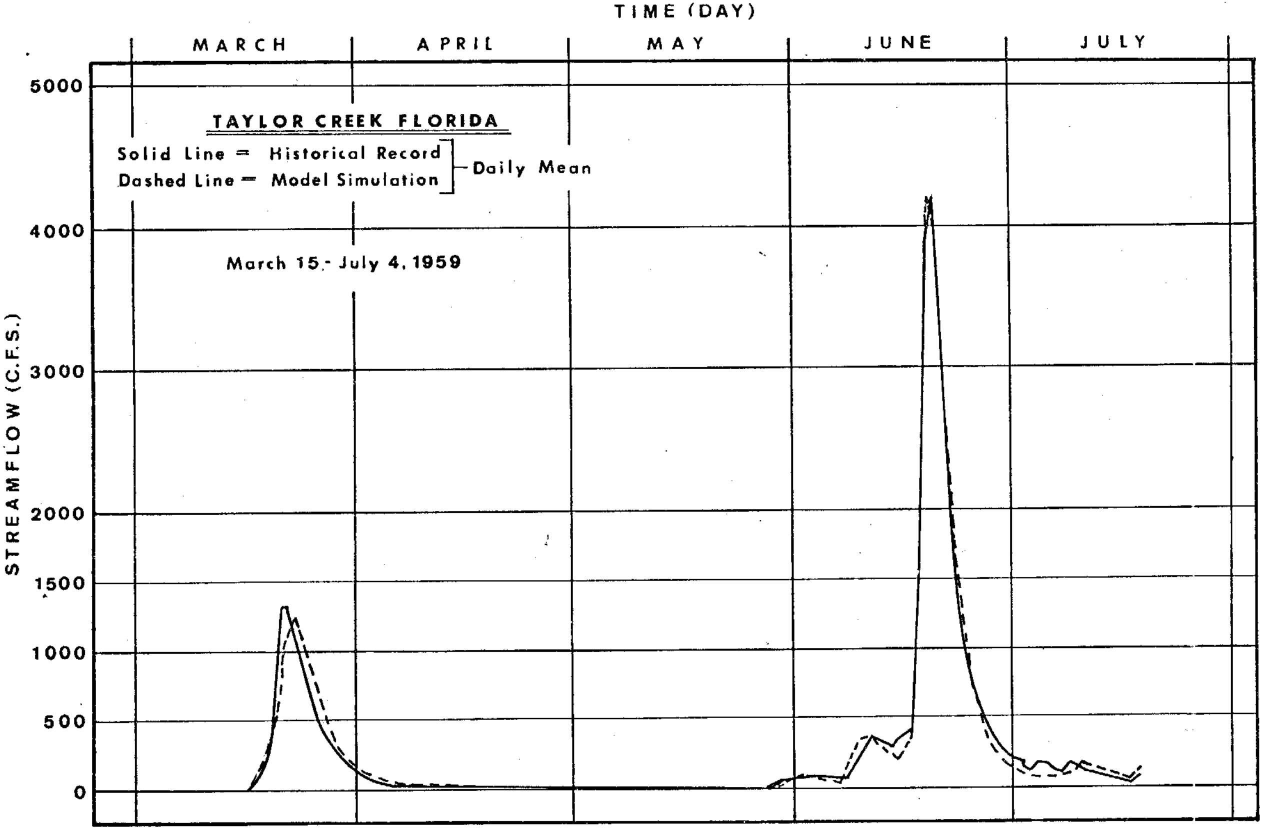
KISSIMMEE RIVER BASIN



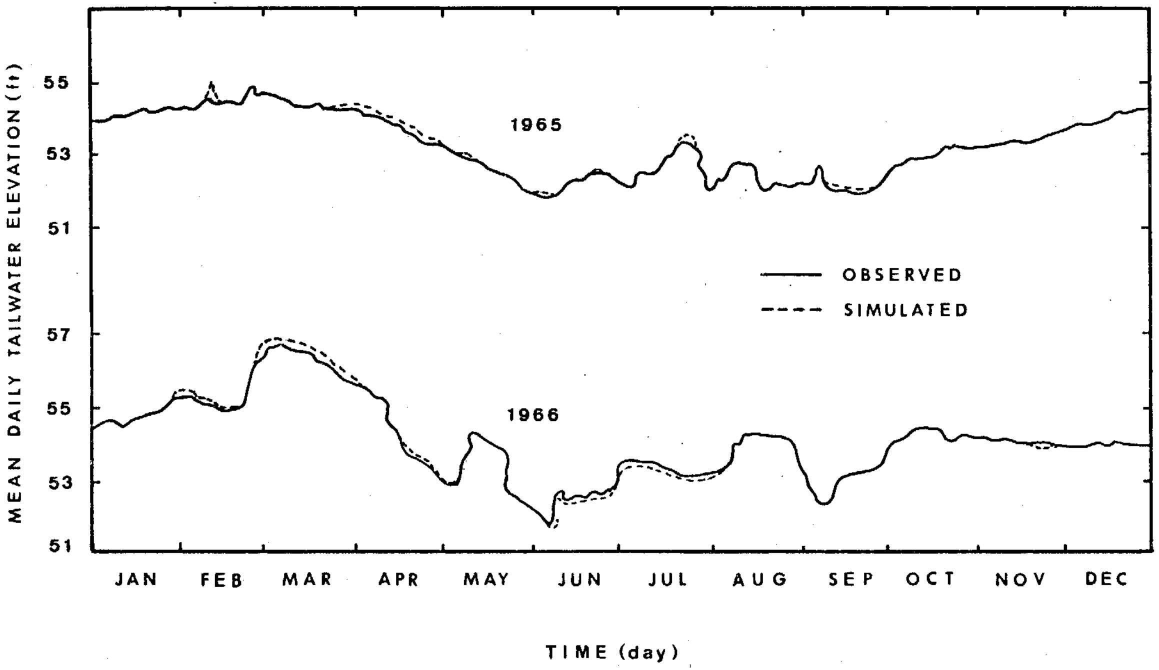
SCHEMATIC OPERATIONAL WATERSHED MODEL



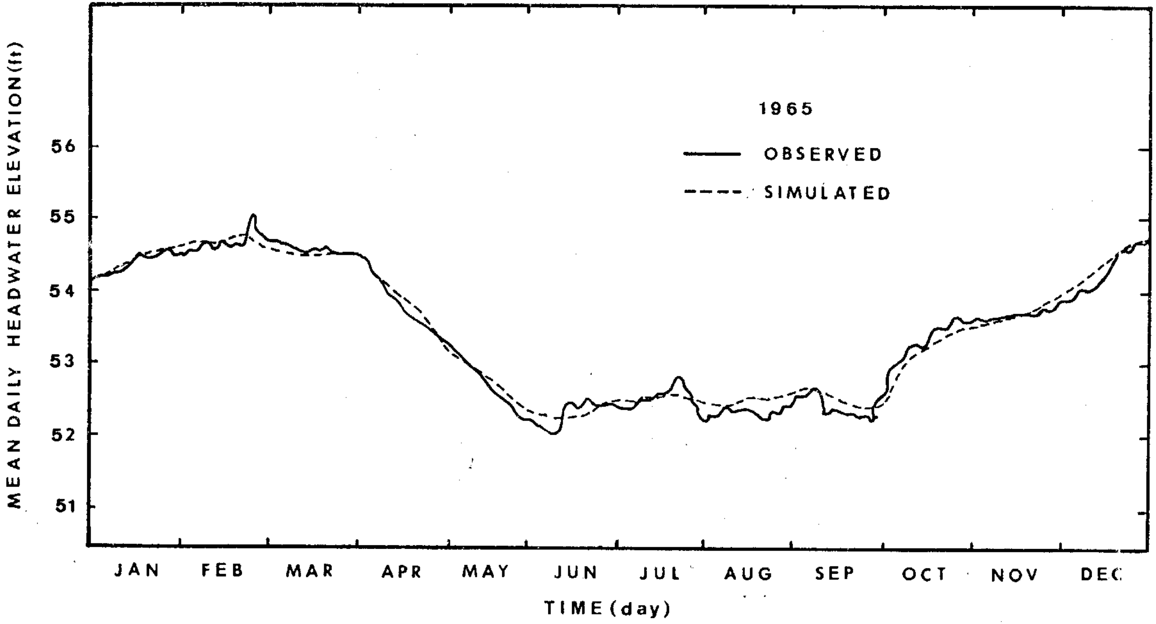
SIMULATED AND RECORDED STREAMFLOW FOR 46 DAYS



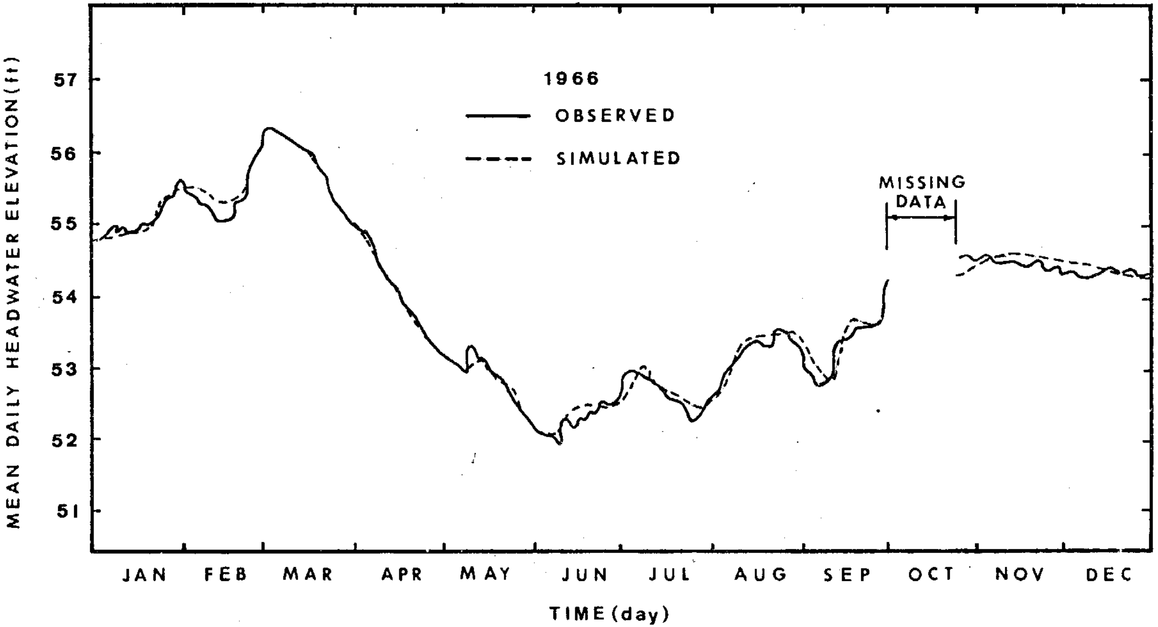
SIMULATED AND RECORDED STREAMFLOW FOR 127 DAYS



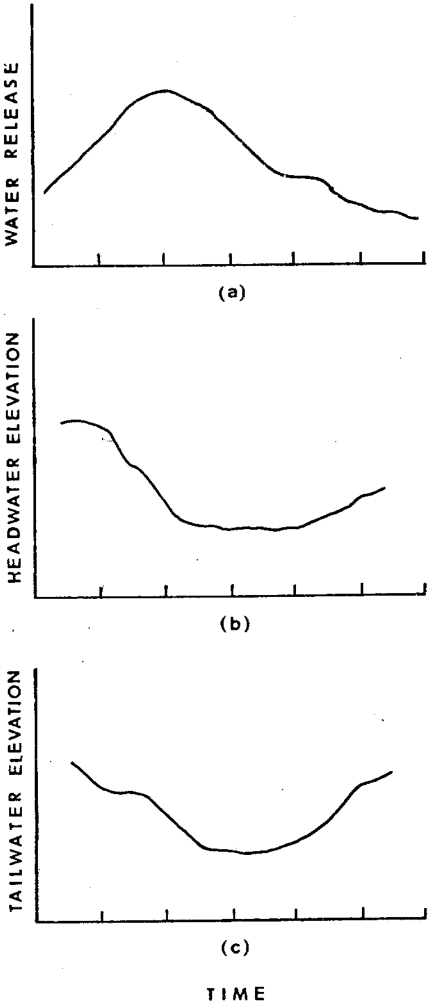
SIMULATED AND OBSERVED MEAN DAILY TAILWATER ELEVATION AT STRUCTURE 59



SIMULATED AND OBSERVED MEAN DAILY HEADWATER ELEVATION AT STRUCTURE 61



SIMULATED AND OBSERVED MEAN DAILY HEADWATER ELEVATION AT STRUCTURE 61



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