ANALYSIS OF HYDROLOGIC SYSTEMS

by

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Thesis submitted to the Graduate Faculty of the

Virginia Polytechnic Institute

in partial fulfillment for the degree of

DOCTOR OF PHILOSOPHY

in

Civil Engineering

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January, 1968

Blacksburg, Virginia

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I. INTRODUCTION

Systems analysis, as used in this thesis, is essentially an empirical method of simplifying the determination of the physical parameters for a system in order to mathematically formulate the process. Extensive application and development of systems analysis is occurring in the process industries, both in analysis and design.

In any system, the output signal and the input signal may be related by a mathematical formulation, which is technically known as a transfer function. The transfer function is the ratio of the Laplace transform of the output function to the Laplace transform of the input function. If the transfer function of a system is known, the output may be easily calculated from given or assumed input. Therefore, finding the transfer function of a system is the main problem in analyzing that system. For simple systems, the transfer function may be derived theoretically by the physical characteristics of the system, but for complex systems, or a system whose physical relations are not surely known, theoretical formulation becomes impossible, and an experimental approach is called for. The use of analog and digital computers has made possible the application of systems analysis to physical systems that only a few years ago were impossible to analyze.

Surface water hydrology has been investigated by hydraulicians and hydrologists for many years. Many investigations of rainfall input and runoff output from drainage have been made, but there has not yet been developed a reliable method of surface runoff prediction over any time base interval for any drainage basin. The reason is that hydrologic systems are very complex, even in an artificial watershed. There are too many physical parameters and the relations between these parameters are not well enough known.

The purpose of this study is to apply systems analysis techniques to hydrology and examine the hydrologic runoff process in terms of fundamental systems analysis. In this study, the hydrologic system will be simplified. In the experimental work, only an impervious catchment will be investigated. The results could be used directly for the design of urban construction, such as parking lots, airports, etc. Ideally, through systems analysis, extensions of such results would apply to natural drainage systems as well as artificial ones.

The experimental catchments were made of plywood. Precipitation (input) was simulated by spray nozzles. The arrangement of nozzles was studied carefully to provide a fairly uniform rainfall. The discharge from the watershed, the output, was measured by means of a weighing tank and the output signals were amplified by an oscilloscope to an automatic recorder which provided accurate recording.

Data were analyzed by a pulse testing method. Bode diagrams were plotted which give information about the parameters in the transfer function.

The objectives of the present investigation can be summarized as follows:

1. Investigation of the relationship between rainfall (input) and runoff (output) for simple rectangular basins. The equation which describes this relationship will be determined.

2. If the equation found from (1) is other than a first order equation, the damping coefficient and the natural frequency of the system will be investigated.

3. Dead time or delay of the system will be investigated, and also the time constant, the gain (amplitude ratios) and the form of the transfer function will be determined.

4. The synthesis of other flows to provide a check on the method.

5. Consideration of the methods of similitude scaling in design.

The letter symbols used in this thesis are defined where they first appear and are assembled for convenience of reference in the Glossary.

II. REVIEW OF THE LITERATURE

In 1926, by using the principle of the conservation of linear momentum, Hinds (24) wrote an equation for spatially varied flow in a side channel spillway. Since then, a similar approach has been used as an analytical base for overland flow or surface runoff by many investigators. Favre (21) used a similar analysis, but considered the effect of lateral inflow and friction. Liggett (33) also did an analysis of unsteady flow with lateral inflow. Beij (6) studied the flow in a roof gutter. Keulegan (32) derived an equation of motion for overland flow in 1944, by using the concept of the conservation of momentum but considered the effect of variation in depth with time and also the effect of an initial flow. Frictional effect terms were included by Keulegan in his analysis. Izzard (30) did an experimental study of overland flow by applying Keulegan's equation of motion in the same year.

In 1932, Sherman (43) introduced his almost universally accepted concept of the unit hydrograph or unit-graph, which is defined as a hydrograph of surface runoff resulting from one-inch of rainfall excess input uniformly distributed areally over the catchment during a given period of time. However, the general theoretical basis for the unit hydrograph method was completed in 1959 by Dooge (18). This analysis showed that an ideal linear catchment can be represented by the combination of a linear reservoir and a linear channel. The proposed general equation of the instantaneous unit hydrograph was:

$$u(0,t) = \frac{V_0}{A} \int_0^{A(t)} \frac{\delta(t-\tau)}{\pi(1+K_i D)} \; i \; dA$$

where u(0, t) = ordinate of the instantaneous unit hydrograph

Vo = volume of runoff

A = area of catchment

(0) = Dirac-delta function

K_1, K_2,... K_3 = storage delay time

i(A) = the ratio of local rainfall intensity to the average rainfall intensity over the catchment

t = time elapsed

τ = translation time

D = differential operator

π is the product of similar terms to be taken. Dooge also suggested that any catchment suitable for unit hydrograph analysis can be represented by an equivalent ideal linear catchment. One year later, Nash (37), using British catchments, developed a linear model technique, by which a two-parameter instantaneous unit hydrograph (IUH) could be solved numerically from surface runoff and rainfall excess data for a given basin; where the instantaneous unit hydrograph is defined as the direct surface runoff hydrograph at the basin outlet when a unit rainfall excess is instantaneously applied uniformly over the entire basin.

Horton (26), in 1935, derived an equation for runoff by assuming that flow rate is proportional to the second power of the depth. This relation could be used to solve for runoff rate directly in terms of rain intensity, time, and a constant depending in part upon surface roughness. He (27) also made some experimental studies. Many experiments have been made following Horton's analysis which generally tried to determine the constants for his equation for different basin conditions. Such experiments were made by Ree (40), Robertson, Turner, Ree and Crow (41), McCool, Geinn, Ree and Garton (34), Izzard (31) and Izzard and Augustine (29). The problem is that Horton's assumption does not hold for every watershed.

Mitchell (35), in 1948, studied 58 Illinois watersheds and concluded that the delay time for the unit hydrographs could be predicted by the empirical relationship

$$t = 1.05\ A^{0.6}$$

where A is area of the catchment and with values between 10 to 1400 square miles. Obviously, no theoretical basis exists for this formula.

Chow (10), modifying the differential equation for spatially varied steady flow by adding an acceleration effect, published a differential equation for overland flow in terms of discharge, slope, friction losses, momentum and

and acceleration. The solution of the equation may be obtained by step methods or by numerical integration. Chow (11, 12) also presented some methods for hydrologic determination of flows and for design of drainage structures. The Report of The Committee on Runoff (13) stated that "a small watershed is very sensitive to high intensity rainfalls of short durations and to land use"; also, it stated that "overland flow rather than channel flow is a dominating factor affecting the peak runoff, whereas a large watershed has pronounced effects from channel storage to suppress such sensitivities."

O'Donnell (38) assumed that catchment behavior is linear. He presented a method, by harmonic analysis, of finding the IUH of a catchment directly from a set of surface runoff and rainfall excess data. Wu (48) presented a design method for small watersheds in 1963, by using an instantaneous hydrograph. Derivation included a dimensionless hydrograph which was determined by the time to peak and the storage coefficients. The gamma function was used to indicate the shape of the hydrograph. Viessman (47) presented a method for determining the hydrology of small impervious areas based on the assumption that the impervious area functions as a linear reservoir.

It is well known that catchment behavior, in reality, is nonlinear, but only recently have investigations related both to theoretical and empirical analysis been made. Amorocho (3) and Amorocho and Orlob (5) have carried out some studies, both theoretical and experimental, using general nonlinear analysis techniques applied to catchment problems. Amorocho and Hart (4) presented a general review of current methodologies in hydrologic research which gives a clear exposition of systems analysis and synthesis as applied both to linear and nonlinear systems. Crawford and Linsley (16) developed a nonlinear model of watershed behavior using the digital computer. They tried to use this model to represent the whole of the land phase of the hydrologic cycle. More recently, Dawdy and O'Donnell (17) have presented a mathematical model simulating the hydrologic cycle. They predicted that the digital computer and mathematical models should gain wide use in hydrologic simulation. Amerman (2) has tried using unit source watershed (which is referred to as a subdivision of a complex watershed and is physically homogeneous, i.e. it has same characteristics) data to predict runoff from a complex watershed. Results indicated that it is inadequate. Singh (44) proposed a nonlinear Instantaneous Unit Hydrograph theory from different storms over a given drainage basin in terms of physically significant parameters and a functional parameter which related to time. Recently, by using the technique of nonlinear least squares procedure, a TVA study (46) presented a program for the digital computer to evaluate the parameters of a water yield model.

Grace and Eagleson (22) published an analysis of modeling of a catchment behavior. The partial differential momentum and continuity equations were used in deriving similarity relations. These criteria govern the experimental phases of this research.

Allison (1), in 1967, in his "Review of Small Basin Runoff Prediction Methods," concluded that there is no simple, accurate and universally applicable method of predicting storm runoff. That is why this research was attempted.

III. LABORATORY EQUIPMENT

The experimental phases of this study were performed in the hydraulics laboratory of the Virginia Polytechnic Institute. The equipment and apparatus used in this study included water supply, test basins, rainfall simulator, weighing tank and recorder, and equipment for measuring the discharge, slope of the basin, and time.

Water Supply

Water flow to the experiment site is through a closed pumping system. Water is pumped to a head tank which is approximately 40 feet above the rainfall simulator pipe lines, then back down through a six-inch main pipe line with several regulating valves to provide quantity control. The pumping system is set with an automatic control to provide a constant head. The rainfall simulator system was connected to the main pipe by means of three-inch pipe, as shown in Figure 3-1.

Rainfall Simulator

Rainfall was simulated by spray nozzles. Two types of nozzles were selected to give different rainfall intensities. Nozzle type 1 produced larger drops and a wetted area that was approximately square and about eight feet on each side with fairly uniform distribution. Single nozzle mounting was used for low rainfall intensity, while double

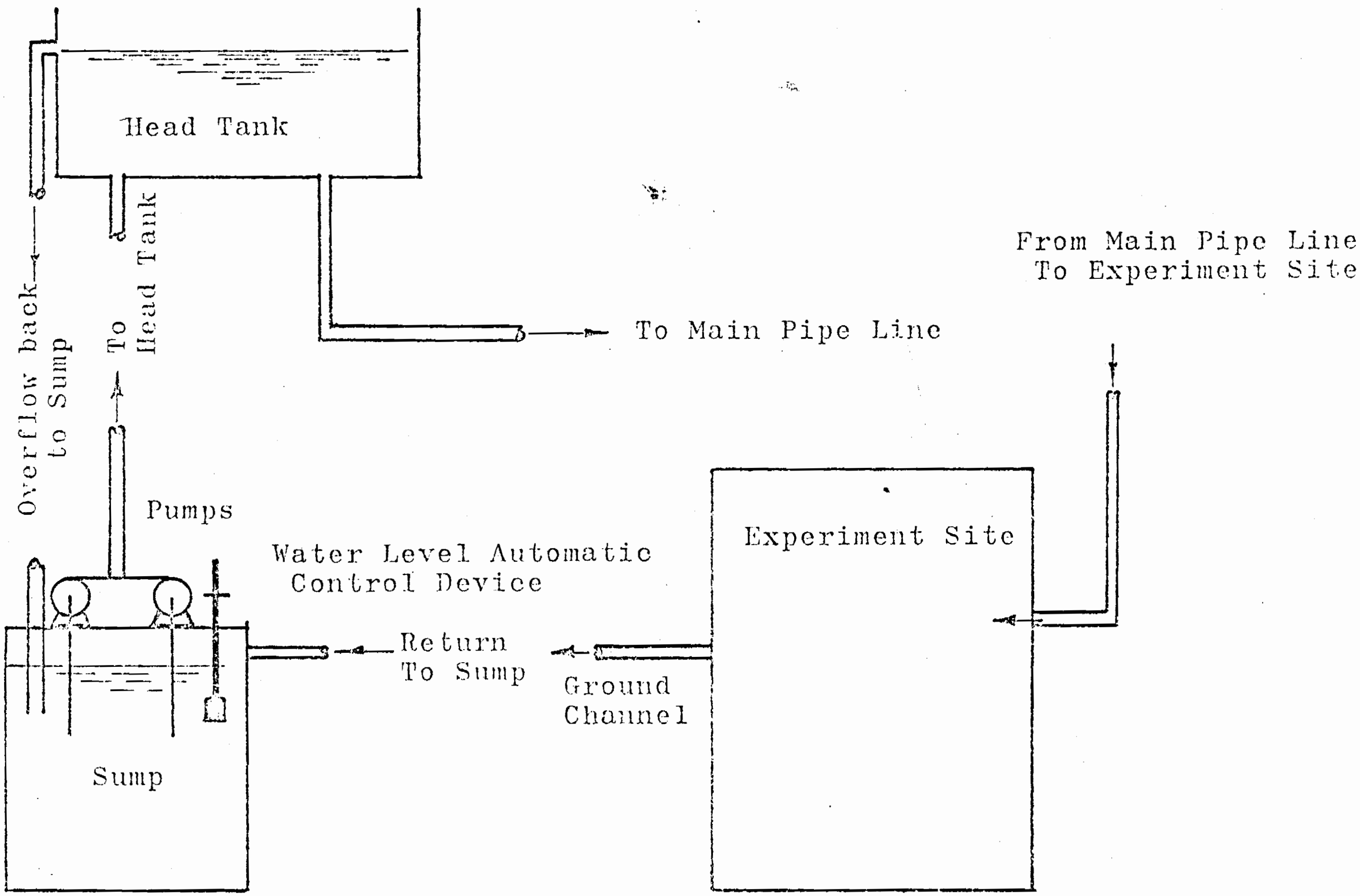

Figure 3-1. Sketch of Water Supply System.

mounting was used for higher intensity. These nozzles provided adjustable spray direction.

In this study, the nozzles were mounted about two feet apart on the side of the basin. The direction of the spray was adjusted to about 50° upward with the horizontal. This was found to be the best position to provide uniform rainfall on the basin.

Nozzle type 2 produced smaller drops and a rectangular shaped wetted area of about 1 ft by 4 ft. To attain fairly uniform rainfall distribution, 18 nozzles were used which were mounted on two one-inch pipe lines seven inches apart. The one-inch pipe lines were fixed on a frame three feet apart and were about nine feet above the catchment. The spray direction was vertically downward.

Three quick-opening valves were used to provide positive control of rainfall duration, as shown in Figure 3-2.

Catchment

Three rectangular catchments were used. All catchments were made of plywood with adjustable slope from 0° to 8° in the longitudinal direction. Type I and type II were plane basins of 4 ft by 6 ft and 2.66 ft by 4 ft respectively. Type III was a catchment not only with adjustable longitudinal slope, but also with 3° transverse slope from both sides to the middle of the basin. All types of basins had an outlet in the middle of the longitudinal end. Type I and type III had an outlet of four inches and type II had an outlet of 2.66 inches.

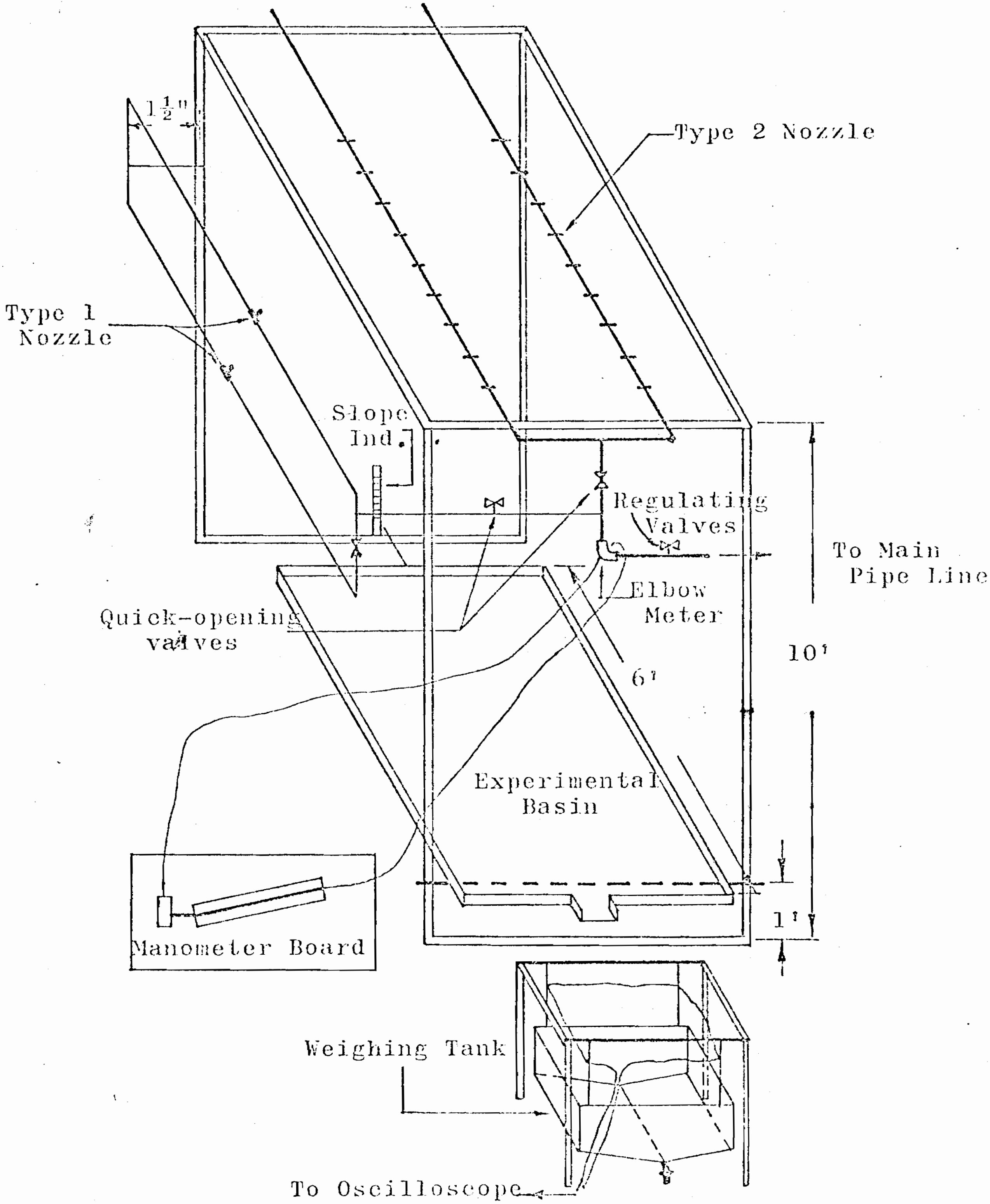

Figure 3-2. Sketch of Experimental Basin and Measurement Devices.

Outflow Measurement

A weighing tank was used with an oscilloscope and a recorder for measuring the outflow. The weighing tank was a rectangular tank with triangular bottom. It was hung on a frame by four metal bars and with a valve at the bottom for releasing water. On each of the bars were two SR-4 strain gages, one on each side of the bar, cemented on the bar at the same position to provide a measurement of the tension stress in the bar caused by the weight of water only. The eight strain gages were connected in series, then connected to an oscilloscope which was used to amplify the output signal to the recorder to provide more accurate recording. Also one extra bar cemented with two strain gages was used as a temperature reference in order to reduce the effect of changing temperature at the basin site. All strain gages were carefully cemented and waterproofed and all wire connections were carefully soldered. The reading from the recorder was calibrated before it was used.

Measurement of Discharge

The discharge was obtained from reading an inclined manometer which was connected to an elbow-meter. The elbow-meter had been previously calibrated by standard weighing methods.

Measurement of Slope

The slope could be obtained from reading of an indicator, which was carefully calibrated by a cathetometer. The cathetometer consists of a level, a one meter high steel stand and a base having three small legs. The level rides on the steel stand and can be moved up and down conveniently. The stand can be rotated to any horizontal angle. The basin bed slope was computed from the difference of heights on the scale read directly by the level.

IV. THEORETICAL CONSIDERATIONS

Under field conditions, a hydrologic system is extremely complex and is immune to analytical treatment or description. Even in an experimental treatment it is impossible to get completely accurate results. In this study, simplifications were introduced which permitted experimentation. These simplifying conditions and assumptions were:

1. The applied input (rainfall) was uniformly distributed areally over the entire experimental basin, and was of constant intensity.

2. The flow was two-dimensional and the surface was impervious, i.e. there was no infiltration.

3. The slope of the catchment was uniform and the downstream end effects and surface tension effects could be neglected.

4. The surface was relatively wide so that hydraulic radius and depth were approximately equal.

5. Roll wave effects, if any, were neglected.

6. Evaporation was neglected.

7. The momentum correction factor, β, for model and for prototype was assumed equal. This assumption was made because the velocity regime was unknown in the disturbed flow region.

Similarity Considerations

From a theoretical point of view, the similarity of model to prototype should be determined from the momentum and continuity equations, since these two equations govern two-dimensional overland flow, which is the initial phase of surface runoff. According to Grace and Eagleson's analysis (22) the similarity criteria are:

$$R_r = \left(L_r \frac{\sin^3 \theta_m}{\sin^3 \theta_p} \frac{\cos^7 \theta_p}{\cos^7 \theta_m} \right)^{\frac{1}{2}} \xi \qquad (4\text{-}1)$$

in which $\xi = (1 - F_p/R_p)$ (4-2)

$$Y_r = L_r \frac{\sin \theta_m}{\sin \theta_p} \frac{\cos^2 \theta_p}{\cos^2 \theta_m} \qquad (4\text{-}3)$$

and $$U_r = \left(L_r \frac{\sin \theta_m}{\sin \theta_p} \frac{\cos^3 \theta_p}{\cos^3 \theta_m} \right)^{\frac{1}{2}} \qquad (4\text{-}4)$$

In addition $$c_{f_r} = \frac{\sin \theta_m}{\sin \theta_p} \frac{\cos \theta_m}{\cos \theta_p} \qquad (4\text{-}5)$$

and $$t_r = \frac{L_r}{U_r} \frac{\cos \theta_p}{\cos \theta_m} = \left(L_r \frac{\tan \theta_p}{\tan \theta_m} \right)^{\frac{1}{2}} \qquad (4\text{-}6)$$

where F_p is the prototype infiltration intensity. (In this study, by assumption 2, $F_p = 0$. So $\xi = 1$)

R_r is the rainfall intensity ratio, model to prototype.

R_p is the rainfall intensity in prototype.

L_r is the ratio of a horizontal reference length in the model to prototype.

θ_m and θ_p are the average basin slopes in model and prototype, respectively.

Y_r is the model to prototype depth ratio.

U_r is the model to prototype velocity ratio.

c_{f_r} is the ratio of friction coefficients, model to prototype.

t_r is the time ratio, model to prototype.

Dynamic Analysis

Dynamic systems analysis obtains a mathematical description of a system by analyzing the response of that system to an applied disturbance or forcing function. The general types of forcing functions are step, pulse, impulse, ramp, sinusoidal and random. Here, only four types of generally used forcing functions will be described.

1. A step function, or step input, is an instantaneous shift from one level to another. Mathematically, a step input of magnitude A is defined as

$$X(t) = A\ U(t) \qquad (4\text{-}7)$$

where U(t) is the unit function and is defined as

$$U(t) = \begin{bmatrix} 0, & t < 0 \\ 1, & t \geqslant 0 \end{bmatrix} \tag{4-8}$$

2. The pulse input is a sudden surge with a return to the pre-surge intensity level. Mathematically, a pulse input of magnitude A can be expressed as

$$X(t) = A(U(t) - U(t - t_1)) \tag{4-9}$$

where $U(t - t_1)$ is also a unit function which is defined as

$$U(t - t_1) = \begin{bmatrix} 0, & t < t_1 \\ 1, & t \geqslant t_1 \end{bmatrix} \tag{4-10}$$

3. The impulse function may be obtained by letting $(t - t_1) \rightarrow 0$ in the pulse function, i.e. the duration being very short.

4. Periodic changes are variations in intensity that repeat within a fixed period of time. The periodic input may be represented by any mathematical periodic function with the restraint that the function is equal to zero when time t is less than 0. For example:

$$X(t) = \begin{bmatrix} 0, & t < 0 \\ A \operatorname{Sin} \omega t, & t \geqslant 0 \end{bmatrix} \tag{4-11}$$

where A is the amplitude and ω is the radian frequency.

Dynamic testing using pulse or step changes is called transient response analysis, while the use of periodic changes is called frequency response analysis. The impulse is different from the pulse in that the duration is not long enough for complete response. The action of a natural watershed is similar. Figure 4-1 illustrates some typical responses for these inputs in first order systems.

Terminology

Some of the basic terms used in systems analysis follow:

The ratio of the output amplitude to the input amplitude is called gain or magnitude ratio. The inverse of a gain is called attenuation. The difference of time when input waves and output waves come to the same level is called phase shift. If the output wave is before the input wave, the output is said to lead the input. When the output wave is at a later time than the input wave, the output is said to lag the input. Phase shift is commonly measured in angular degrees, and called the phase angle. Phase angle is negative for phase lag and positive for phase lead. Gain is governed by the transfer function, and the phase shift determines the timing.

A convenient way of demonstrating the relationships between frequency and gain and between frequency and phase angle is the "Bode diagram" which is a plot of gain and phase angle with respect to frequency on semi-log or log-log paper, depending on the unit of gain. The ordinate, when plotted on semi-log paper, is the gain in decibels which is 20 times the logarithm of the magnitude ratio. The Bode plot is a very important tool in systems analysis.

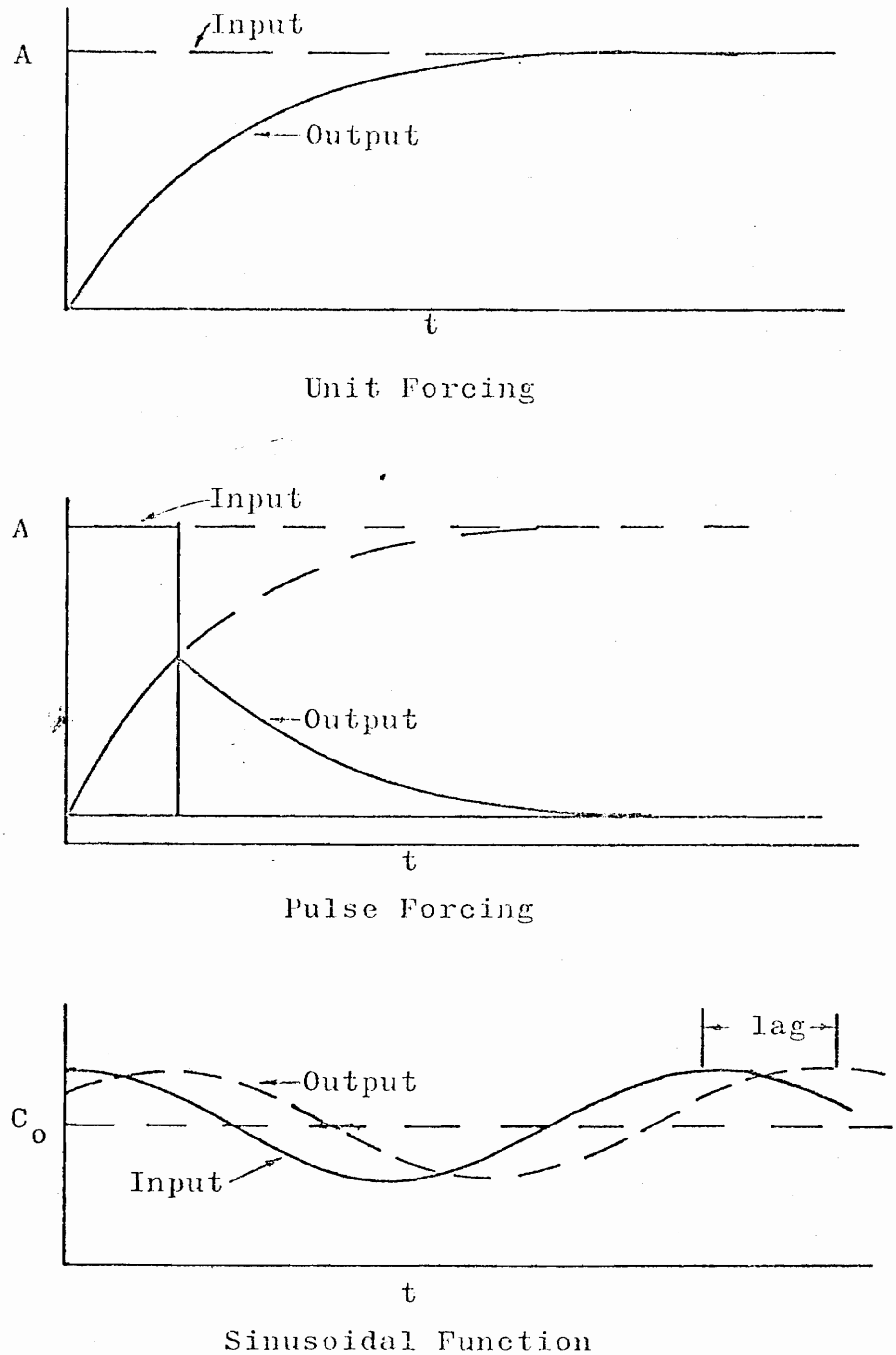

Figure 4-1. Typical Relationship Between Input and Output for Different Input Functions for First Order Systems.

For a first order system, the Bode diagram has two straight portions. The two asymptotes meet at the "corner frequency", which is the frequency corresponding to the reciprocal of the time constant. The phase angle at the corner frequency is 45°. The time constant is a parameter that has the dimension of time. For a first order system, the time constant is equal to the elapsed time when the output has completed 63.2 per cent of its response. The time constant is a parameter which determines the speed of the reaction of a system when a disturbance is applied. A typical first order system Bode diagram is shown in Figure 4-2. Two types of Bode diagrams for second order systems will be introduced here. One is a combination of two first order systems (a system with two time constants and two corner frequencies or two first order systems in series.) Another type is a true second order system, as shown in Figure 4-3. The peak response for the second type of system occurs at the critical response frequency, or natural frequency, which is related to the time constant. The height of the peak depends on the damping coefficient of the system. A plot of the template which shows the relationship between natural frequency and the damping coefficients is shown in Figure 4-4.

Dead time, transportation lag or distance-velocity lag or delay, is a waiting period between input change and the

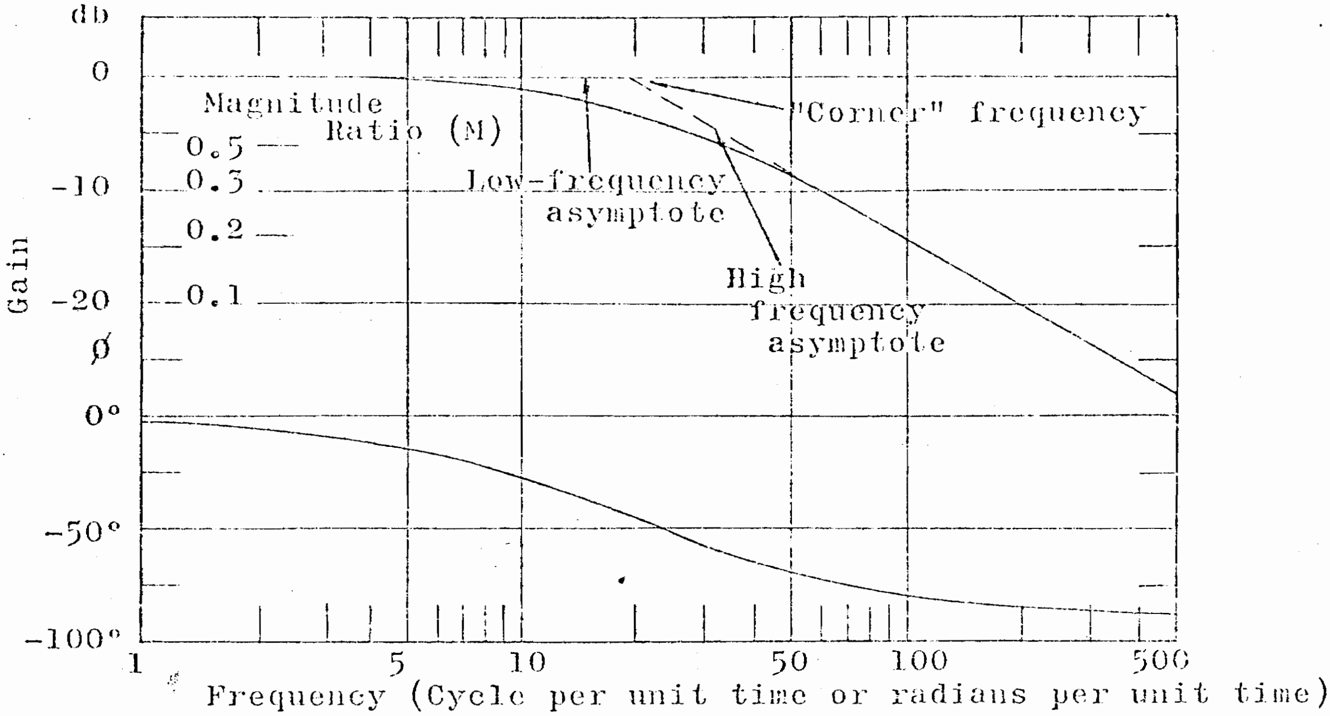

Figure 4-2. Typical Bode Diagram for First Order System.

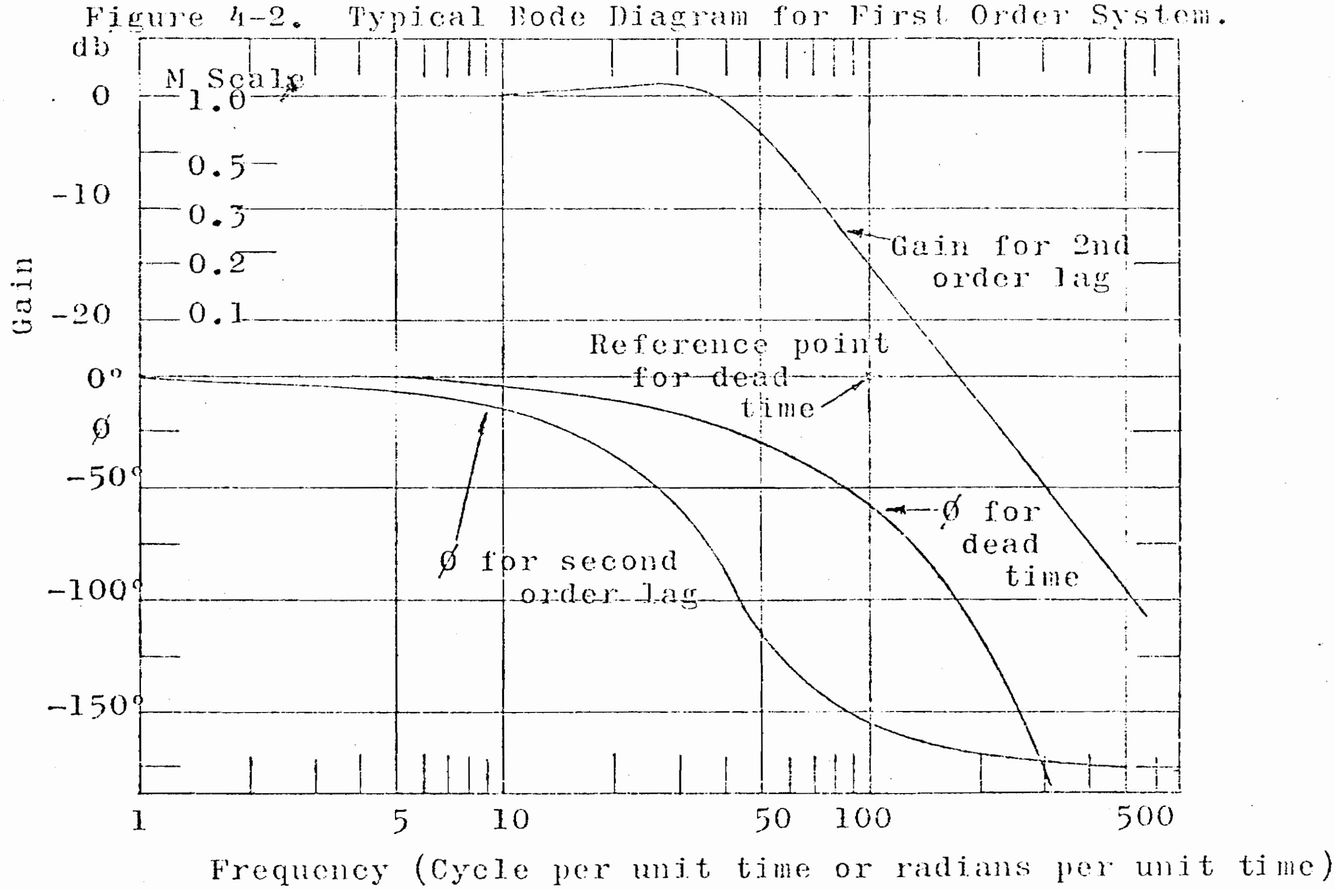

Figure 4-3. Typical Bode Diagram for Second Order System.

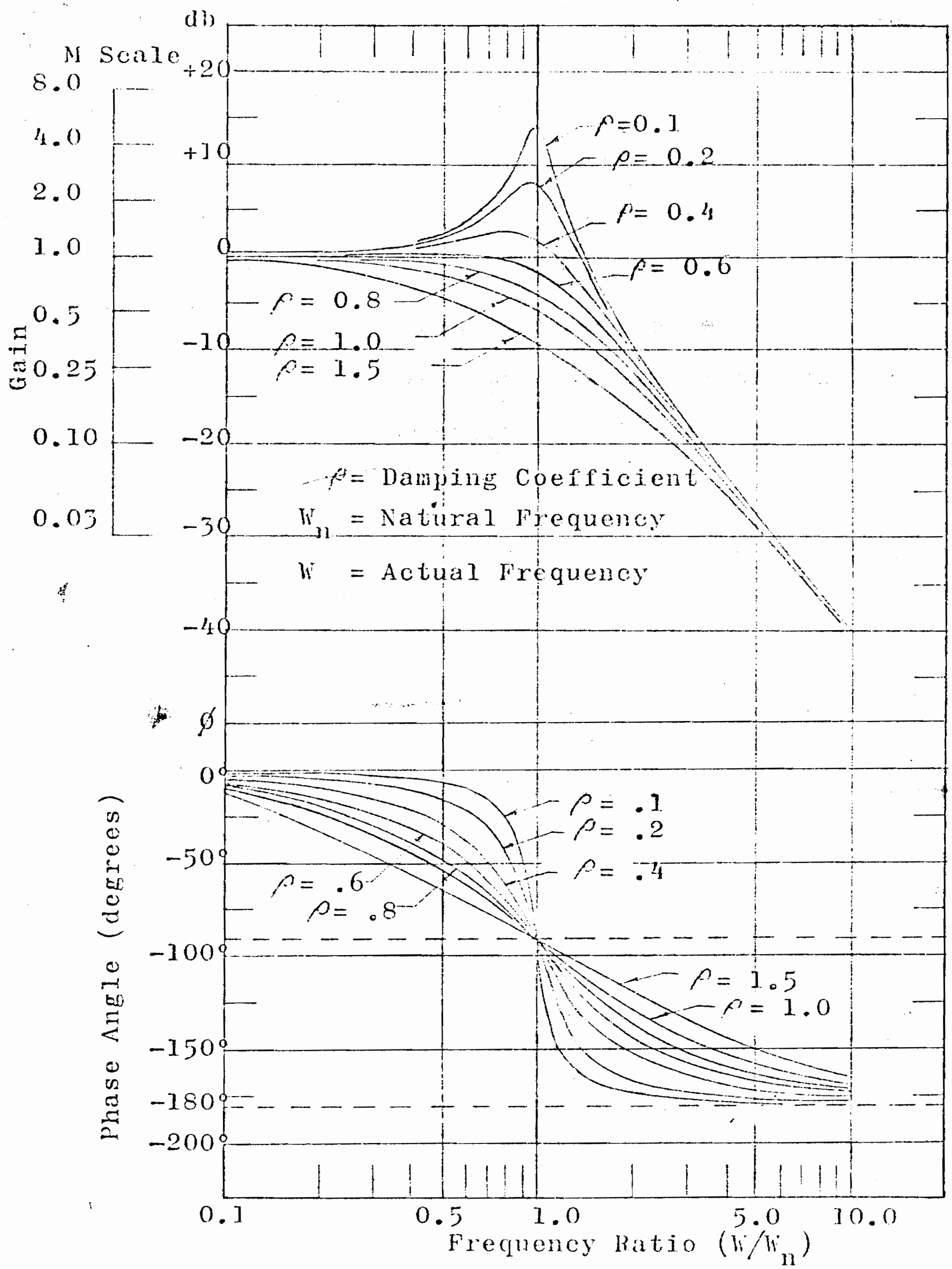

Figure 4-4. Frequency Response of Second-Order Systems Showing Damping Coefficients for Various Gain Curves and Phase Angle Curves.

beginning of output change. Dead time, T_d, affects the shape of the phase shift curve. An example phase shift curve for dead time is shown in Figure 4-3.

The frequency response approach is an easily used technique. If it can be used in hydrologic systems, then prediction of runoff for a catchment may be easily calculated by digital computer when the transfer function of the catchment is known. The transfer function may be found by the inputs and the outputs of the past events.

Theoretical Analysis

The parameters which affect the response of a drainage basin, or a natural hydrologic system, include catchment shape, average slope, soil type, surface conditions, rainfall intensity and duration, and land use. If we neglect the dynamic effect of the system and treat a drainage basin as a reservoir with uncontrolled outflow, the outflow, or the output (runoff), O_R, is a function of the stage in the reservoir and the hydraulics of the outlet system. (36, 39). Therefore,

$$O_R = C_1 E^{m_1} \tag{4-12}$$

Similarly, the storage can be expressed as

$$S_t = C_2 E^{m_2} \tag{4-13}$$

where C_1, C_2, m_1, m_2, are constants, and E is a measure of the reservoir surface elevation. In this study E is the flow depth at the outlet.

Combining equations (4-12) and (4-13) gives

$$S_t = C_3 O_R^{\ n} \qquad (4\text{-}14)$$

where C_3 is constant, and n is defined as a nonlinear parameter in this study.

Considering the dynamic effects, the storage is also a function of the rate of change of runoff. Therefore, equation (4-14) may be written as:

$$S_t = C_3 O_R^{\ n} + C_4 \frac{dO_R}{dt} \qquad (4\text{-}15)$$

by the continuity equation,

$$\Delta S_t = \Delta I - \Delta O - \Delta Q_L \qquad (4\text{-}16)$$

where ΔI is the rate of inflow, ΔS_t is the rate of storage, ΔO is the rate of outflow and ΔQ_L is the rate of total basin losses (neglected in this study). Equation (4-16) may be rewritten, by substituting rainfall excess and runoff instead of the rate of inflow and the rate of outflow respectively, as

$$\Delta S_t = R\Delta t - O_R \Delta t \qquad (4\text{-}17)$$

Substituting equation (4-15) into equation (4-17) gives

$$\Delta (C_4 \frac{dO_R}{dt} + C_3 O_R^{\ n})/\Delta t = R - O_R \qquad (4\text{-}18)$$

Equation (4-18) may be written in differential form as

$$A \frac{d^2 O_R}{dt^2} + B n\, O_R^{\,n-1} \frac{d\, O_R}{dt} = R - O_R \qquad (4\text{-}19)$$

where $A = C_4$ and $B = C_3$, both constant.

Equation (4-19) is the general form of the differential equation for the hydrologic system, neglecting losses. It is a nonlinear second order equation. When the system is in steady state it means all variables are independent of time, and then the equation (4-19) becomes

$$R = O_R \qquad (4\text{-}20)$$

An nth-order system may be characterized by an nth-order differential equation

$$a_n \frac{d^n Y}{dt^2} + a_{n-1} \frac{d^{n-1} Y}{dt^{n-1}} + \ldots + a_1 \frac{dY}{dt} + a_o Y = X(t) \qquad (4\text{-}21)$$

where Y is the output variable and X(t) is the input function. When n equals 2 the above equation becomes

$$a_2 \frac{d^2 Y}{dt^2} + a_1 \frac{dY}{dt} + a_o Y = X(t) \qquad (4\text{-}22)$$

If the system is linear, then

$$a_2 = T_c^{\,2}, \; a_1 = 2\rho T_c, \; a_o \propto G_k$$

where T_c = time constant, ρ = damping coefficient and G_k = gain constant which depends on the ratio of the output and the input in steady state.

If the system is nonlinear, then

$$a_2 = T_c^{\,2} f_1(Y), \quad a_1 = 2\rho T_c f_2(Y), \quad a_o = G_k f_3(Y)$$

where $f_1(Y)$, $f_2(Y)$, and $f_3(Y)$ are nonlinear parts of the function.

Comparing equations (4-19) with (4-22) gives

$$A = T_c^{\,2}, \quad B = 2\rho T_c$$

and equation (4-19) becomes

$$T_c^{\,2} \frac{d^2 O_R}{dt^2} + 2\rho T_c n \, O_R^{\,n-1} \frac{dO_R}{dt} = R - O_R \qquad (4\text{-}23)$$

Equation (4-23) has three unknown parameters, T_c, ρ, and n. The time constant and the damping coefficient may be obtained from a Bode plot, but the nonlinear parameter n needs to be solved by trial and error. With this information, the transfer function may be found.

The lag or dead time, is a function of the physical parameters of a drainage basin which effect timing, such as basin area, length in the longitudinal direction, slope of the basin, surface condition, soil types and basin shape. It also is affected by the rainfall pattern and intensity. Since the basins used for this study were impervious and also since a uniform distribution of rainfall was assumed, surface condition, soil types and rainfall pattern effects may be neglected. Thus,

$$T_d = f(L, R, S, A_a, \eta) \qquad (4\text{-}24)$$

where T_d is dead time, L is the longitudinal length, S is the average slope in the longitudinal direction, A_a is basin projection area and η is basin shape factor.

Once the input and output data are obtained, the Bode diagram may be plotted. From the Bode diagram, the time constant and damping coefficient (if the system is second order system) may be determined; then by using analog computer simulation, the nonlinear parameter, n, may be found. After the transfer function is found and with known dead time of a catchment, the hydrograph may be easily calculated.

V. RESULTS

In this chapter the scope of this thesis will be outlined. Experimental results and methods of analysis will be shown and briefly discussed.

Delay or Dead Time, T_d

As mentioned before, delay time is a function of basin area, basin longitudinal length, basin shape, longitudinal average slope and rain intensity.

Since the purpose of this thesis is to study the similarity relationships and to try to apply systems analysis to hydrologic system, the relationship between delay and rain intensity is an interesting phenomenon.

Experimental values of delay are listed in Table I. Plotting delay vs rainfall intensity on log-log paper, a straight line relationship is found. Figures 5-1 and 5-2 show this relationship. Plotting delay vs longitudinal average slope, S, also shows a straight line relationship on log-log paper. Figures 5-3 and 5-4 present this relationship.

Formulas which represent those relations were derived by fitting a straight line through the data.* The formulas so derived are:

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*These straight lines were drawn through the data by eye.

TABLE I. DEAD TIME

Basin Type	Slope % / I_R in/hr / Delay sec.	8 T_d	8 $\overline{T}_d$	6 T_d	6 $\overline{T}_d$	4 T_d	4 $\overline{T}_d$	2 T_d	2 $\overline{T}_d$
I	.83	44 43	43.5	53 50	51.5	60 63	61.5	87 85	86
	1.26	34 34 35 35	34.5	40.5 41 40	40.5	46.5 47 47	46.8	63 65	64
	6.26	14 14 13 13	13.5	15.5 16 15 15.5	15.5	18 17 17.5 17.0	17.4	25 26.5 26 25	25.6
II	1.27	31 30 30 29	30	36 37 36 38	36.8	42 42 44 43	42.8	62 60 62 64	62
	6.26	11.5 12.5 11.5 13	12.1	14 14 15 14	14.3	17 16 16 16	16.3	25 24 24 24	24.3
III	.83	36 37.5	36.7	42 42.5	42.3	49 48	48.5	64 64	64
	1.26	27 28 28 27	27.5	30.5 31 32 31.5	31.5	36 38 35 36	36.5	47.5 47 47.5 48	47.5
	6.26	11 10 10.5 11	10.6	12 11.5 11.5 12.5	11.9	13.5 13.5 13 14	13.5	18 19 19 19.5	18.9

T_d= mean value

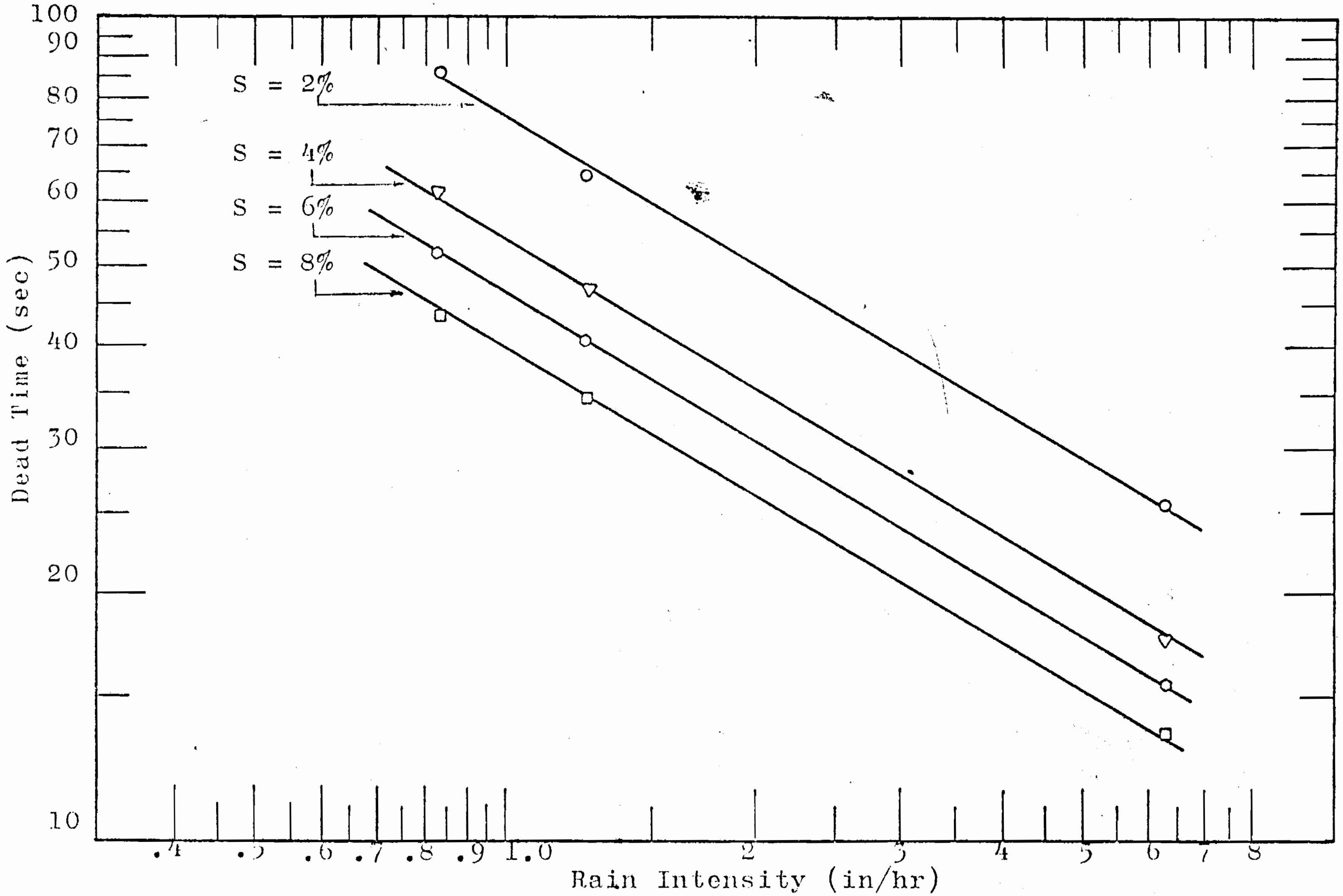


Figure 5-1. Relationship Between Dead Time and Rain Intensity for Basin Type I.

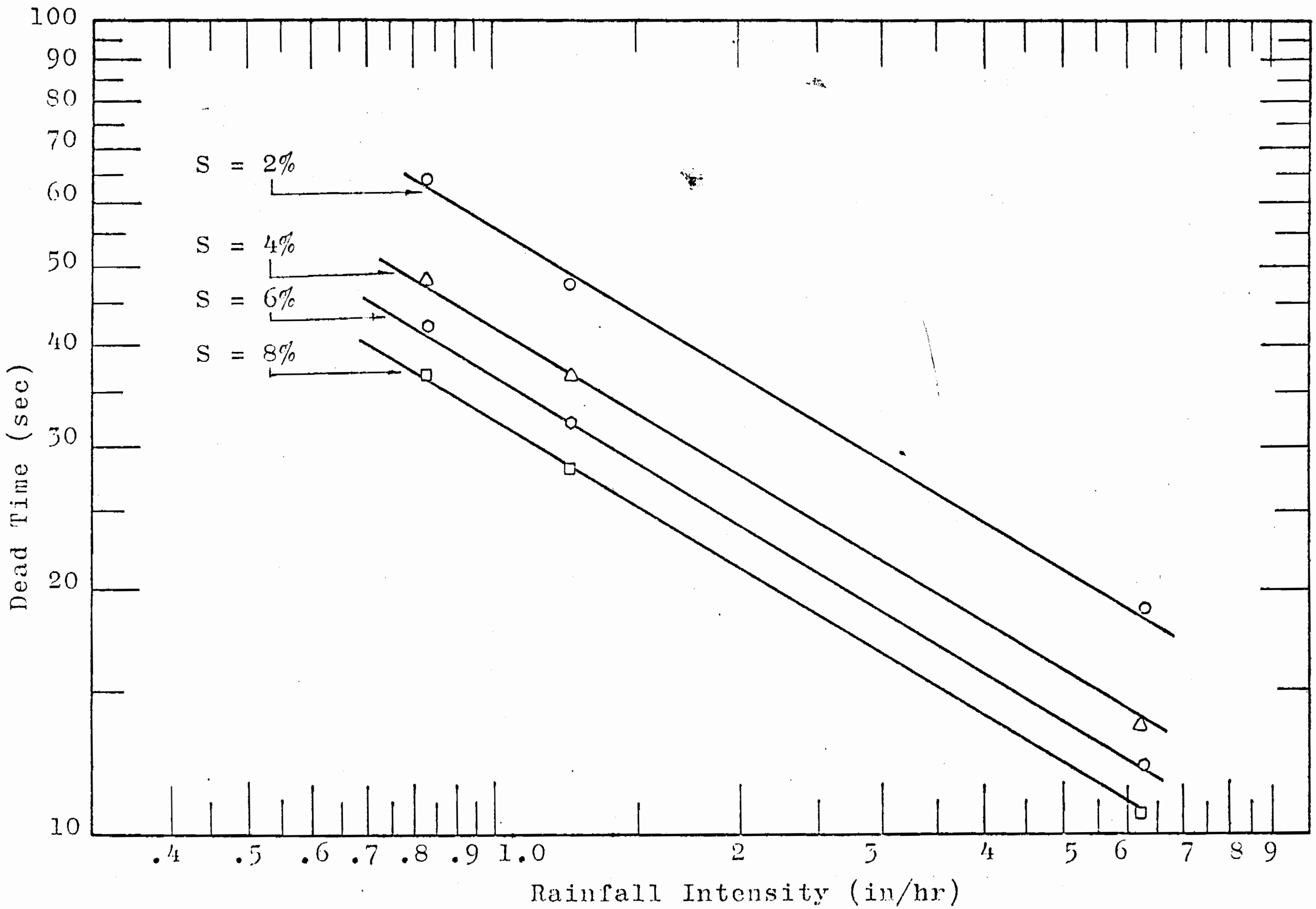


Figure 5-2. Relationship Between Dead Time and Rain Intensity for Basin Type III.

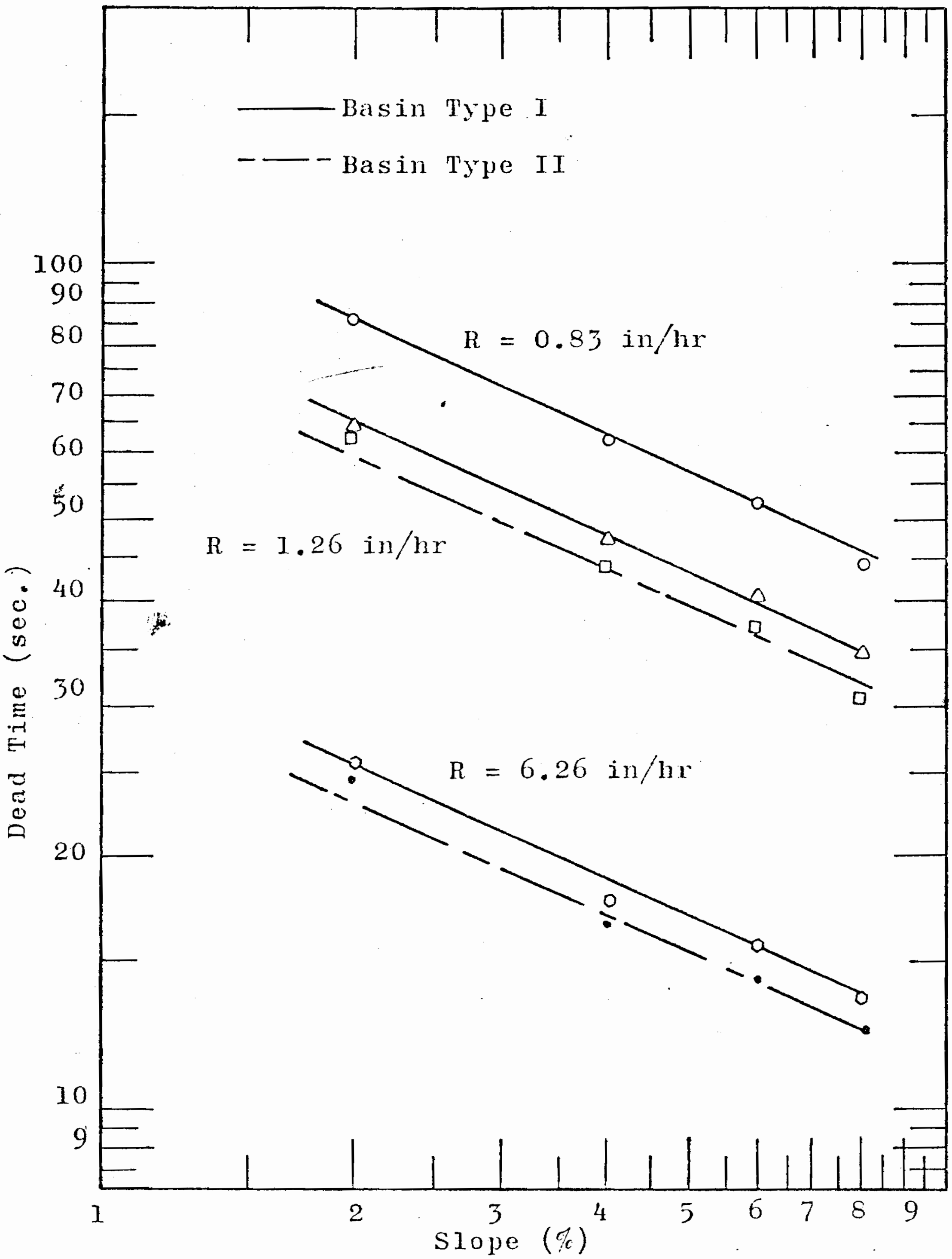


Figure 5-3. Relationship Between Dead Time and Basin Slope for Basin Types I and II.

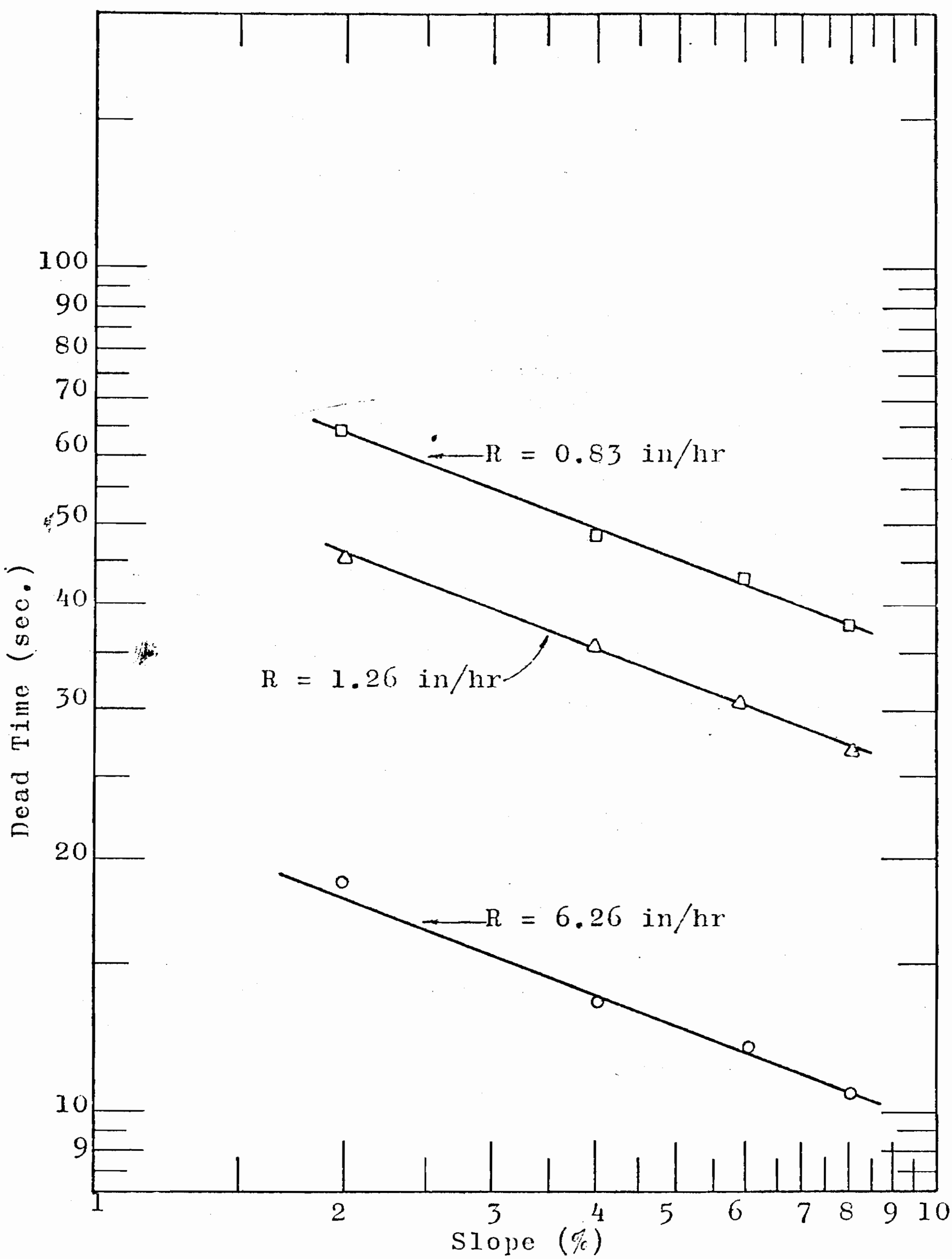


Figure 5-4. Relationship Between Dead Time and Basin Slope for Basin Type III.

For basin type I.

$$T_d = K_1 S^{-.46} R^{-.598} \qquad (5\text{-}1)$$

For basin type II

$$T_d = K_2 S^{-.46} R^{-.598} \qquad (5\text{-}2)$$

For basin type III

$$T_d = K_3 S^{-.38} R^{-.597} \qquad (5\text{-}3)$$

where T_d is the dead time in seconds, S is the longitudinal average slope, R is the rainfall intensity in in/hr, and K_1, K_2, K_3 are constants depending upon basin shape, surface condition, area and length. The values of K_1, K_2, and K_3 are 102.5, 93.5, and 76.3 respectively.

From these formulas, it is clear that the dead time is inversely proportional to the rain intensity raised to 0.598 power. This relation is independent of basin characteristics. The relation between delay and slope does depend on the basin shape. The exponent of the slope does change with basin shape. The larger the slope and the rain intensity, the shorter the dead time.

Response

Experimental data included three different input intensities, R = 0.83, 1.26, 6.26 in/hr, and four different input durations, 5 min, 10 min, 15 min, and 20 min. Four different longitudinal slopes for the basin were also studied, 2%, 4%, 6% and 8%. Input and output data are in Appendix C except for the data for a duration of 20 min.

Some of the response data are plotted in Figures 5-5, 5-6, 5-7 and 5-8. Figure 5-5 shows the response for several different slopes. Figure 5-6 shows the response with duration varying. Figure 5-7 shows the response for input intensity varying. Figure 5-8 illustrates the effects of changing basin types.

It can be noted that the response can be separated into steady-state response and transient response. The transient response can be divided into a head part and a tail part, as shown in Figure 5-6. When $t = 0$, $O_R = 0$ and $O_R' = 0$, then

$$T_c^2 \, (s^2 O_R(s)) + 2\rho T_c \, n \, s \, (O_R(s))^n + O_R(s) = R(s)e^{-sT_d}$$

Therefore

$$G(s) = \frac{O_R(s)}{R(s)} = \frac{e^{-sT_d}}{T_c^2 s^2 + 2\rho T_c n s (O_R(s))^{n-1} + 1} \qquad (5\text{-}4)$$

Equation (5-4) is the general form of the transfer function for a hydrologic system.

A standard transfer function for a second order linear system is

$$G(s) = \frac{G_k e^{-sT_d}}{T_c^2 s^2 + 2\rho T_c s + 1} \qquad (5\text{-}5)$$

where G_k is the gain constant.

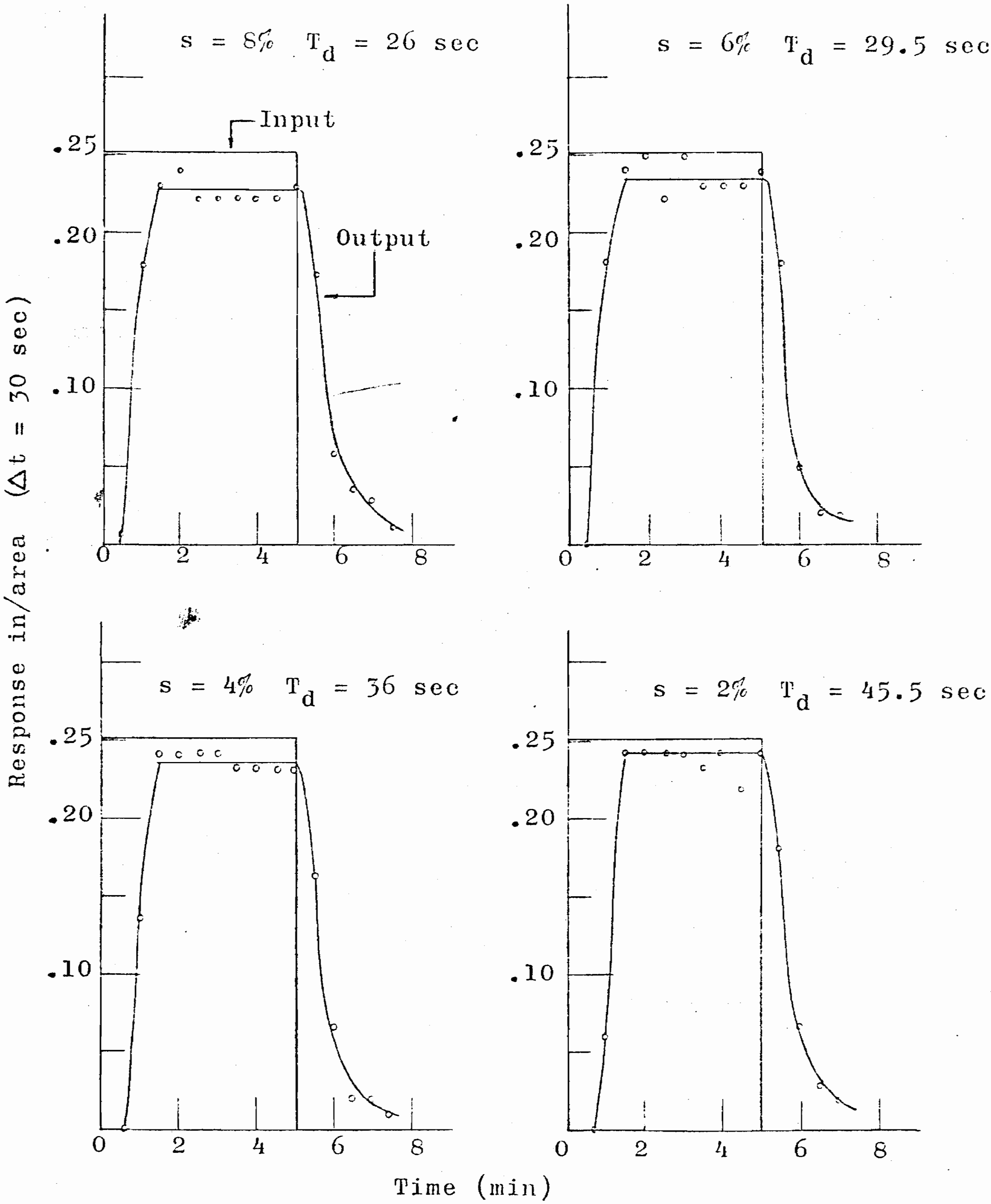


Figure 5-5. Response for Basin Type III for R = 1.26 in/hr for Various Slopes.

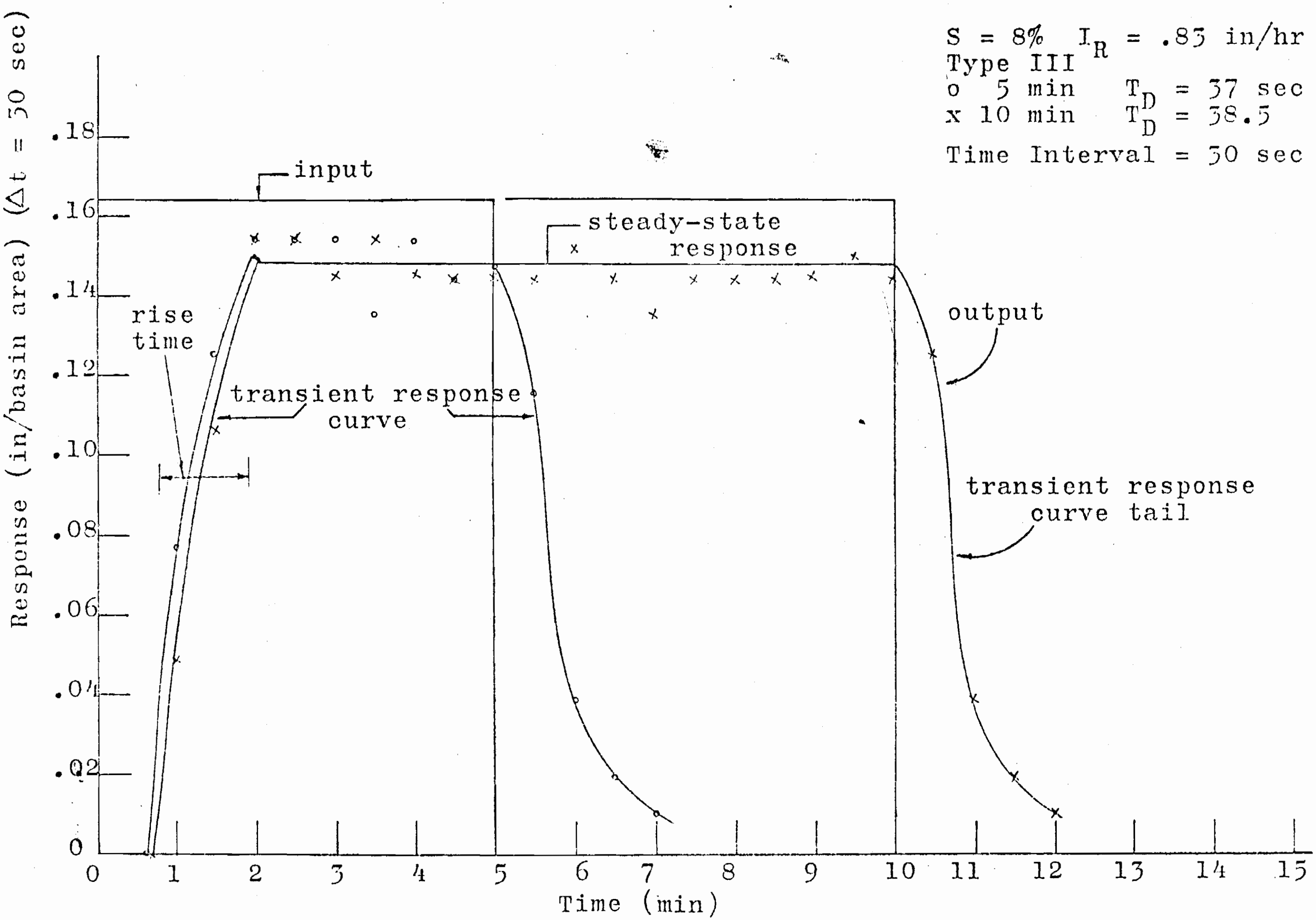


Figure 5-6. Response for Different Durations (Basin Type III, S = 8%, R = .83)

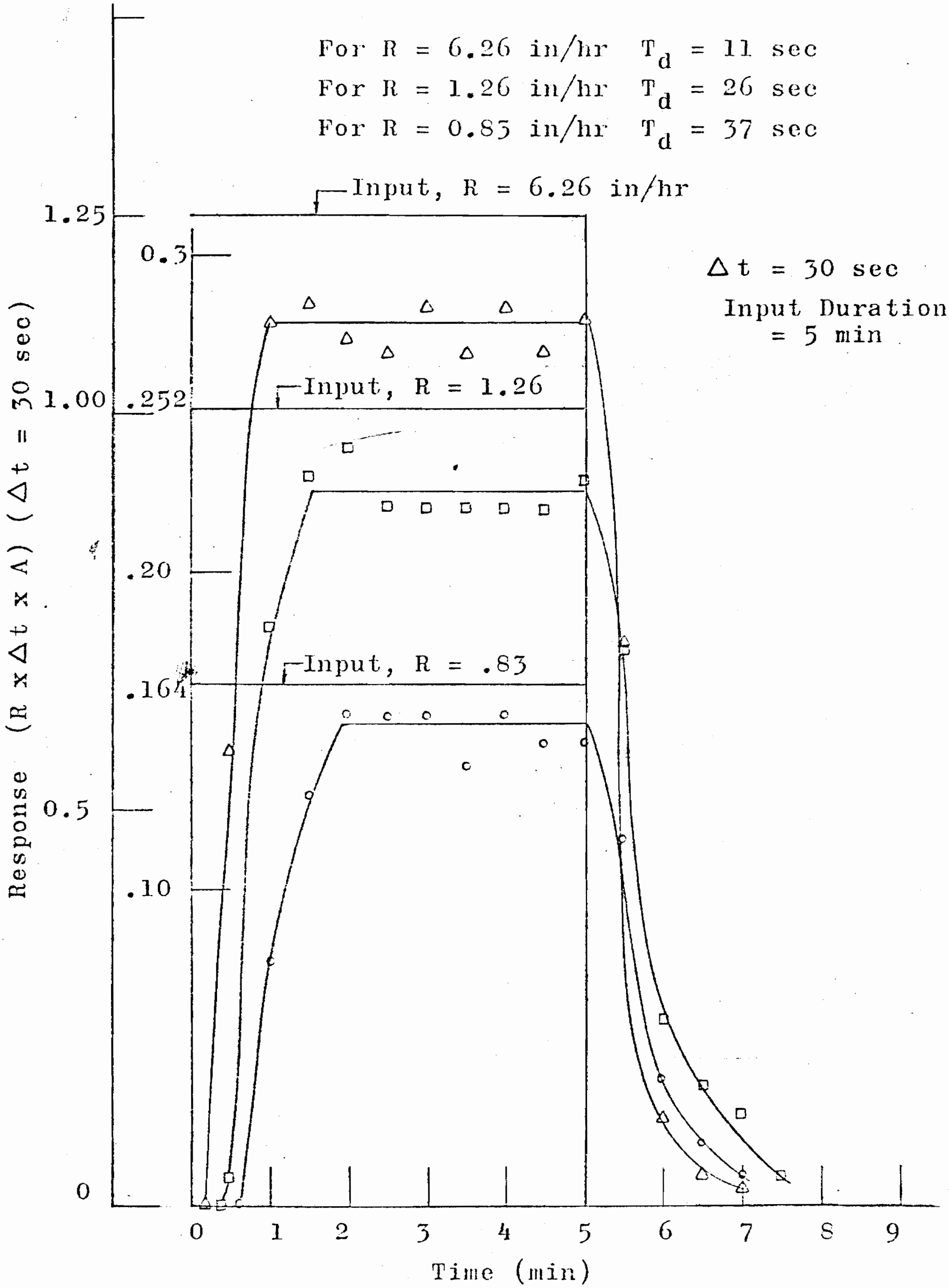


Figure 5-7. Response for Basin Type III for Various Rainfall Intensities at S = 8%.

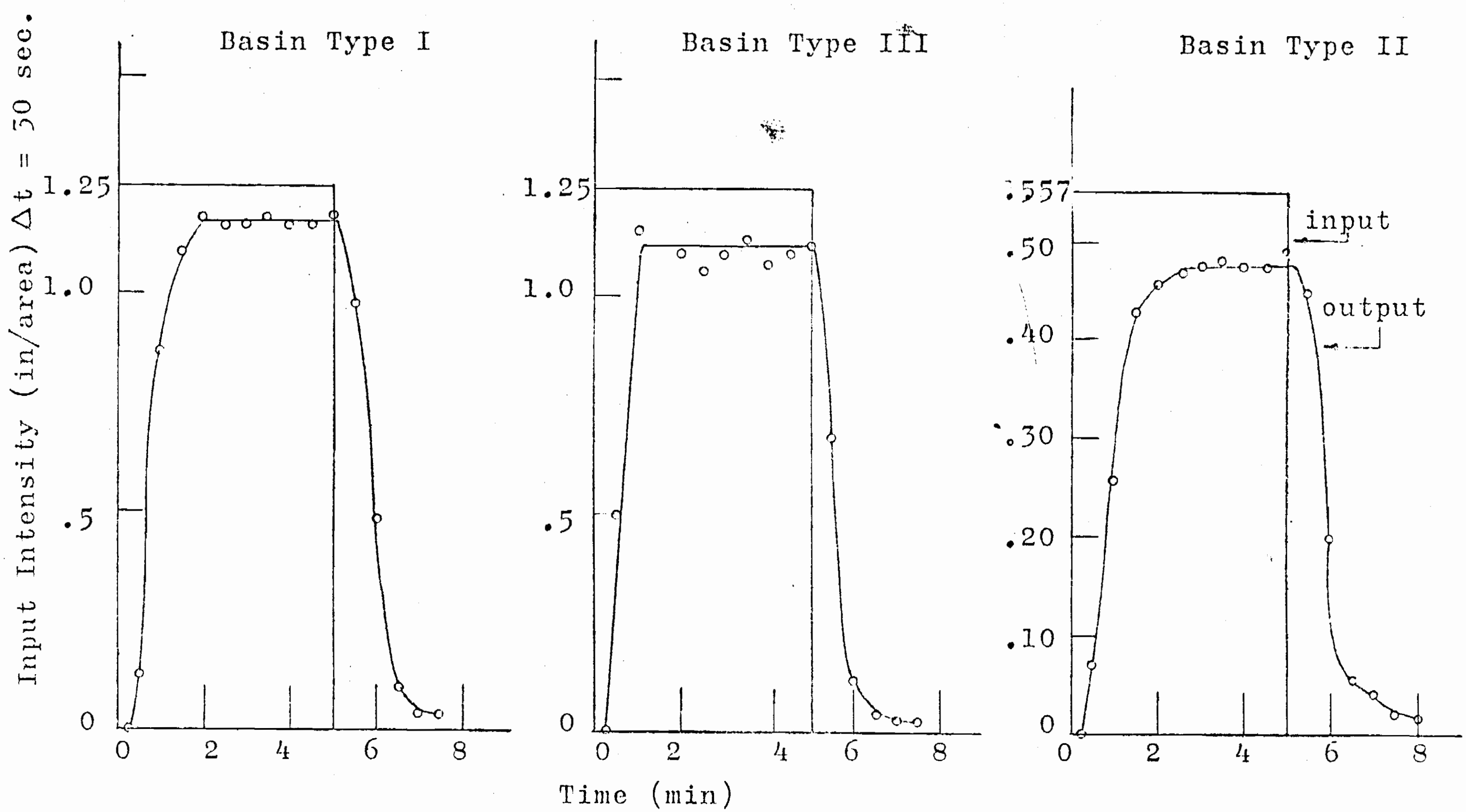


Figure 5-8. Response for Basin Type Varying, R = 6.26 in/hr, S = 4%.

When n = 1, equations (5-4) and (5-5) should be equal, therefore the gain constant K_G for the hydrologic system is unity.

In equation (4-23) when the dynamic effects of the system are negligible, as in basin types I and II at slope less than 2%, then the equation can be reduced to

$$2\rho T_c \, n \, O_R^{n-1} \frac{dO_R}{dt} = R\,(t - T_d) \qquad (5\text{-}6)$$

and the transfer function becomes

$$G(s) = \frac{e^{-sT_d}}{T_c' s \, n[O_R(s)]^{n-1} + 1} \qquad (5\text{-}7)$$

Equation 5-7 represents a nonlinear, first order system transfer function. T_c' is the time constant, about twice the value of T_c.

In equations (5-4) and (5-7), if the system is linear, i.e. n = 1, then the transfer function for the first and second order linear hydrologic systems are:

$$G(s) = \frac{e^{-sT_d}}{T_c^2 s^2 + 2\rho T_c + 1} \qquad (5\text{-}8)$$

The steady state response is constant and should theoretically be equal to the input for catchments without losses. The difference in the results were caused by minor losses and experimental errors in measurement, recorder reading and calibration. Transient response curves were varied by changing the slope of the basin, the shape of the basin and the input intensity. Transient response is, however, independent of the duration of rainfall.

The results showed that changing the longitudinal slope of the basin affected the tail part of the transient response more than the head part. The larger the slope the faster the response returned to the original level line. This effect was not significant for basin type III and for basin types I and II at slope greater than 2%. For basin types I and II at slope less than or equal to 2% this effect is significant.

Roll wave phenomena were seen in the basin types I and II at slopes greater than 4% at higher input intensities. Roll waves are an interesting phenomenon in open channels. They appear as slight irregularities in the water surface, ripples proceeding downstream, accelerating and increasing in size until a breaking front is acquired. According to Rouse (42) this phenomenon is due to the weight action affecting the flow and is named "slug flow" or "roll waves". This really consists of a series of wave fronts of shock type, and is formed at a constant frequency. In basin type III, roll waves were not seen. The period of roll waves seen in basin types I and II was short, and the amplitude was small. The effects of the roll waves can be neglected.

Since the responses reached steady-state, it is obvious that the durations of the input were relatively long for the pulse testing method. For the pulse testing method, the input signal to the system is varied in a pulse-like manner. The principal requirements in conducting a pulse test is that the system dynamics are excited. But if the width of the input is long the dynamics of the system are only moderately excited. In this case, the gain curve was obscured or non-existent at high frequency, especially for the square pulse input. If a very short input duration was used, there was no output, because a certain amount of water was needed to wet the basin and also to provide for some detention, which could not be avoided and would never become runoff.

In the experimental procedure, before every run, the basin was dried. If the basin had not been dried, the output and the dead time for the following run was not correct because there was some detention water in the basin, and that reduced the dead time and increased the output.

Bode Diagrams

Bode diagrams are plotted in Figures 5-9, 5-11, 5-12, 5-13, 5-14, 5-15 and 5-16. Magnitude ratios and phase angles for selected frequencies were calculated by digital computer. The computer program is based on the equations derived by Hougen and Walsh (28) and Clements and Schnelle (14).

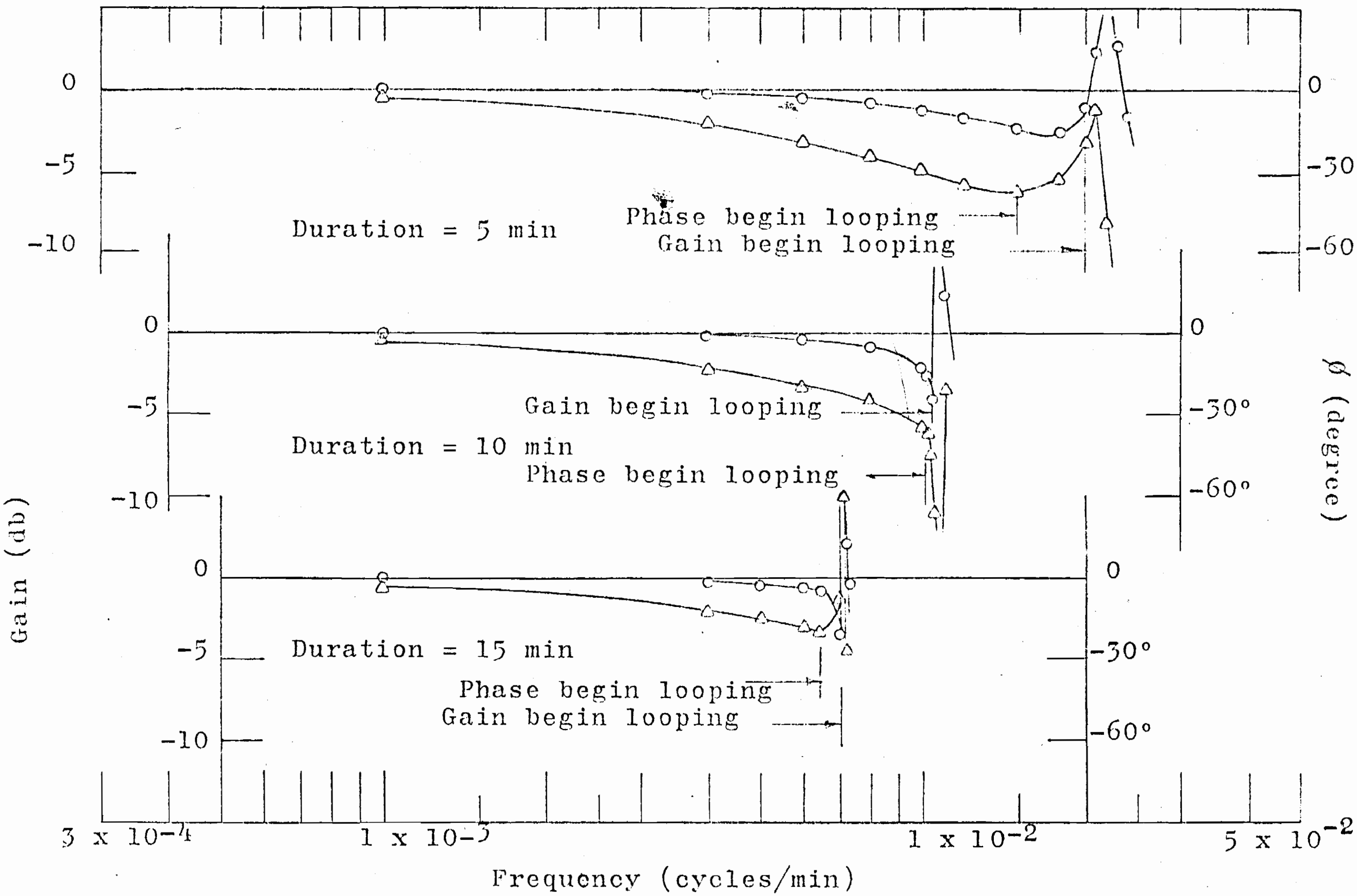


Figure 5-9. Bode Diagram for Varying Durations, Basin Type I, R = 1.26 in/hr
S = 4%

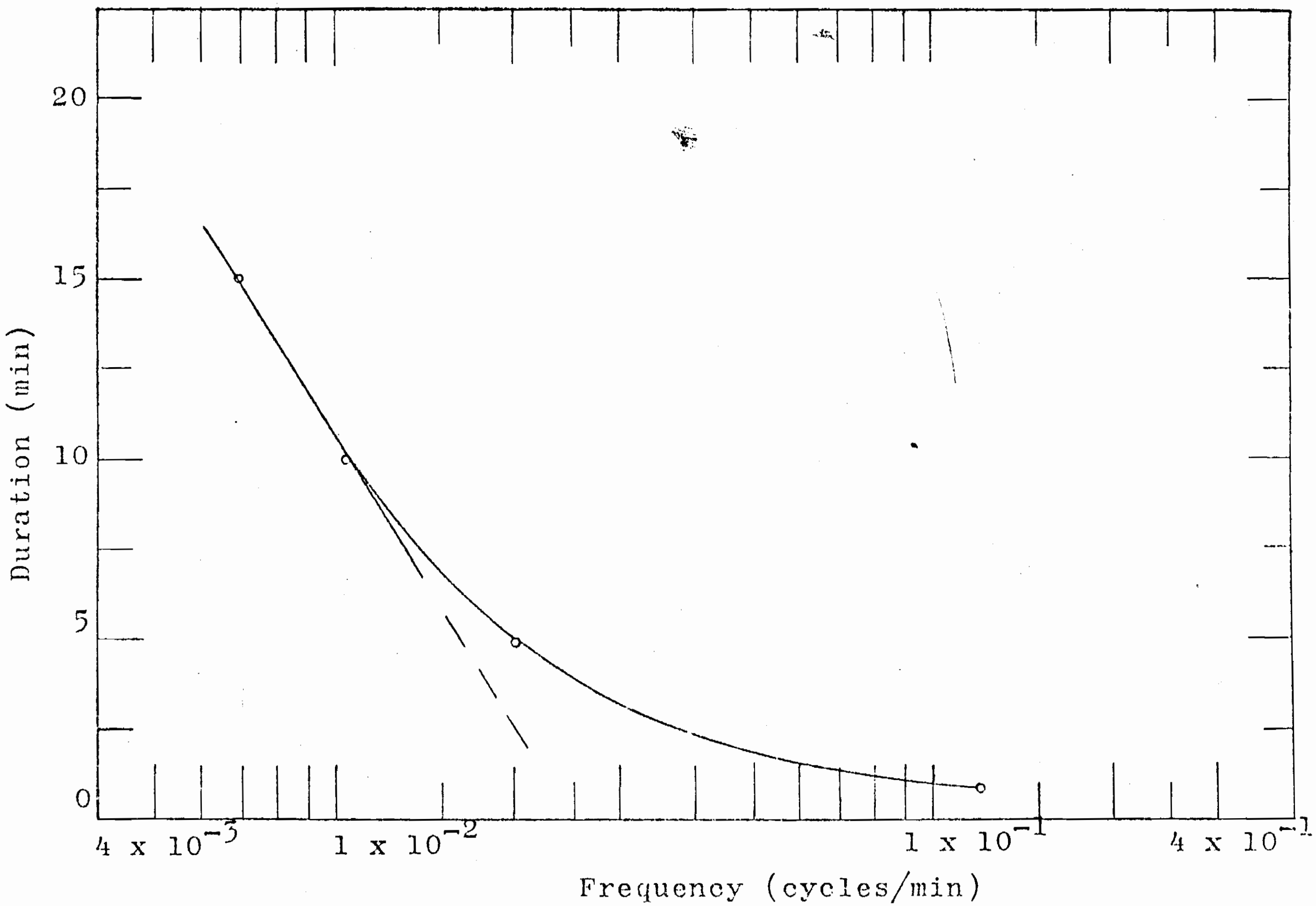


Figure 5-10. Relationship Between Maximum Frequency of Gain Curve and Input Duration.

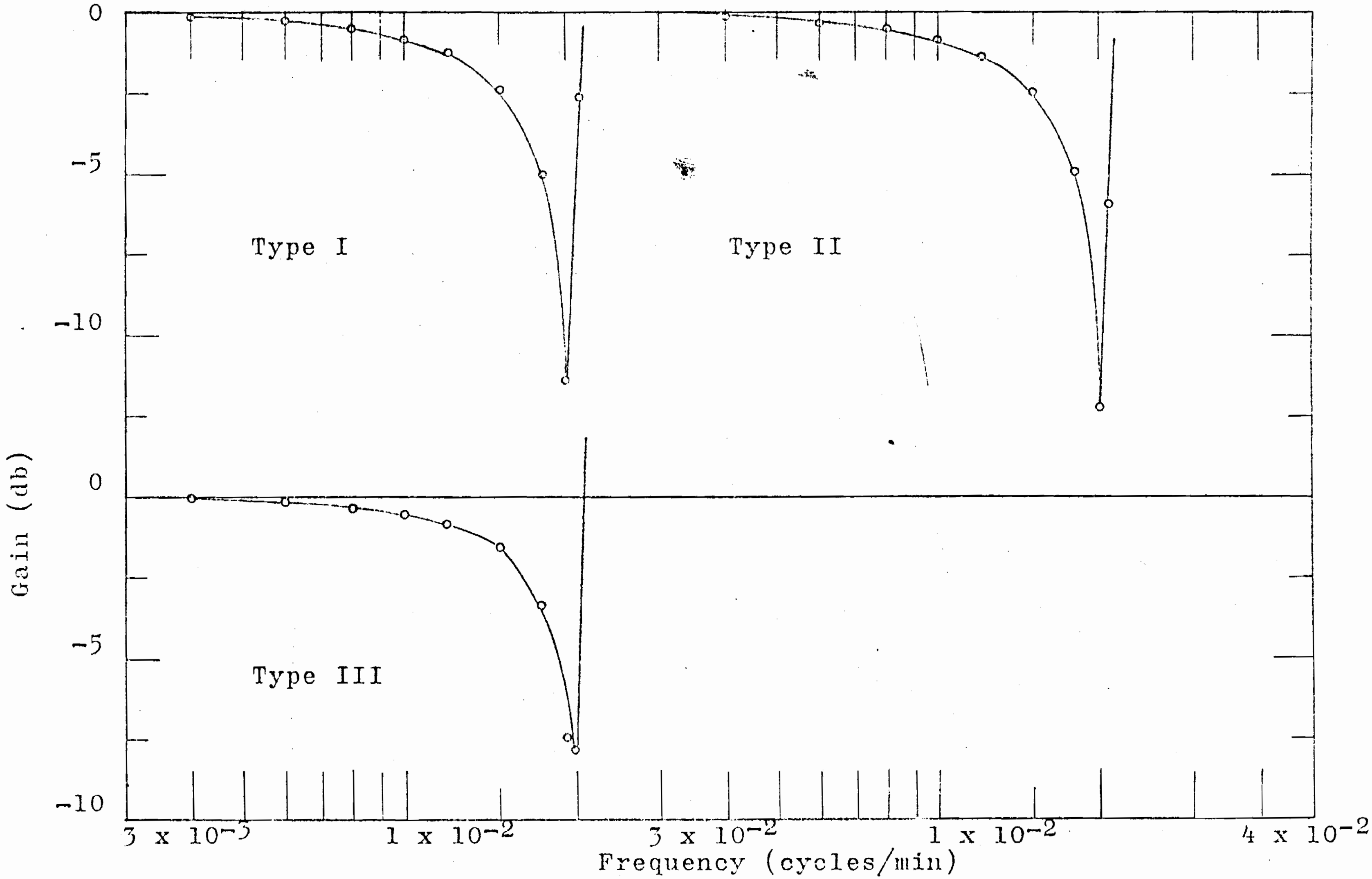


Figure 5-11. Gain Curves for Different Basin Types at S = 8%, R = 6.26 in/hr.

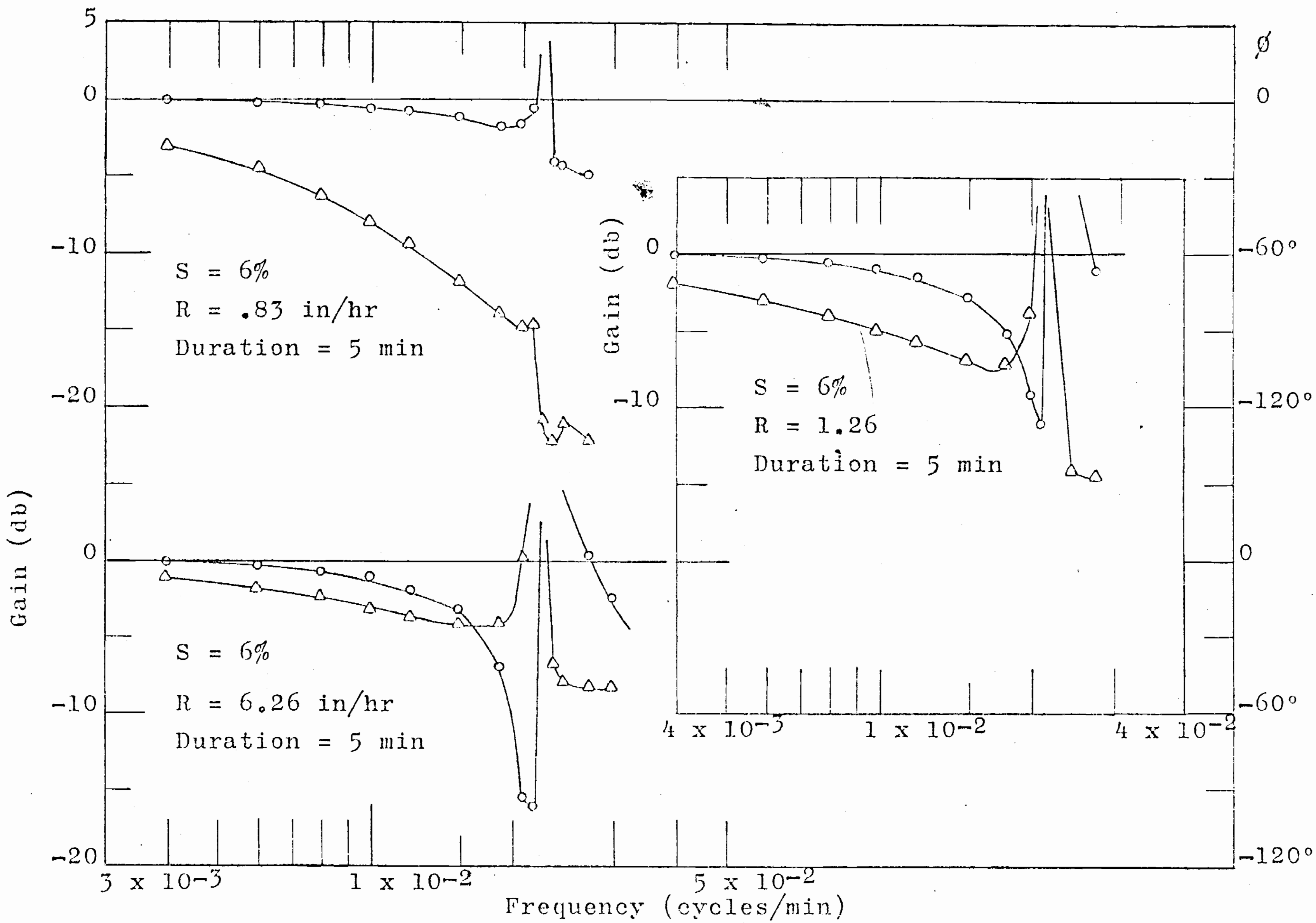


Figure 5-12. Bode-Diagram for Input Intensity Varying at S = 6%, Basin Type III.

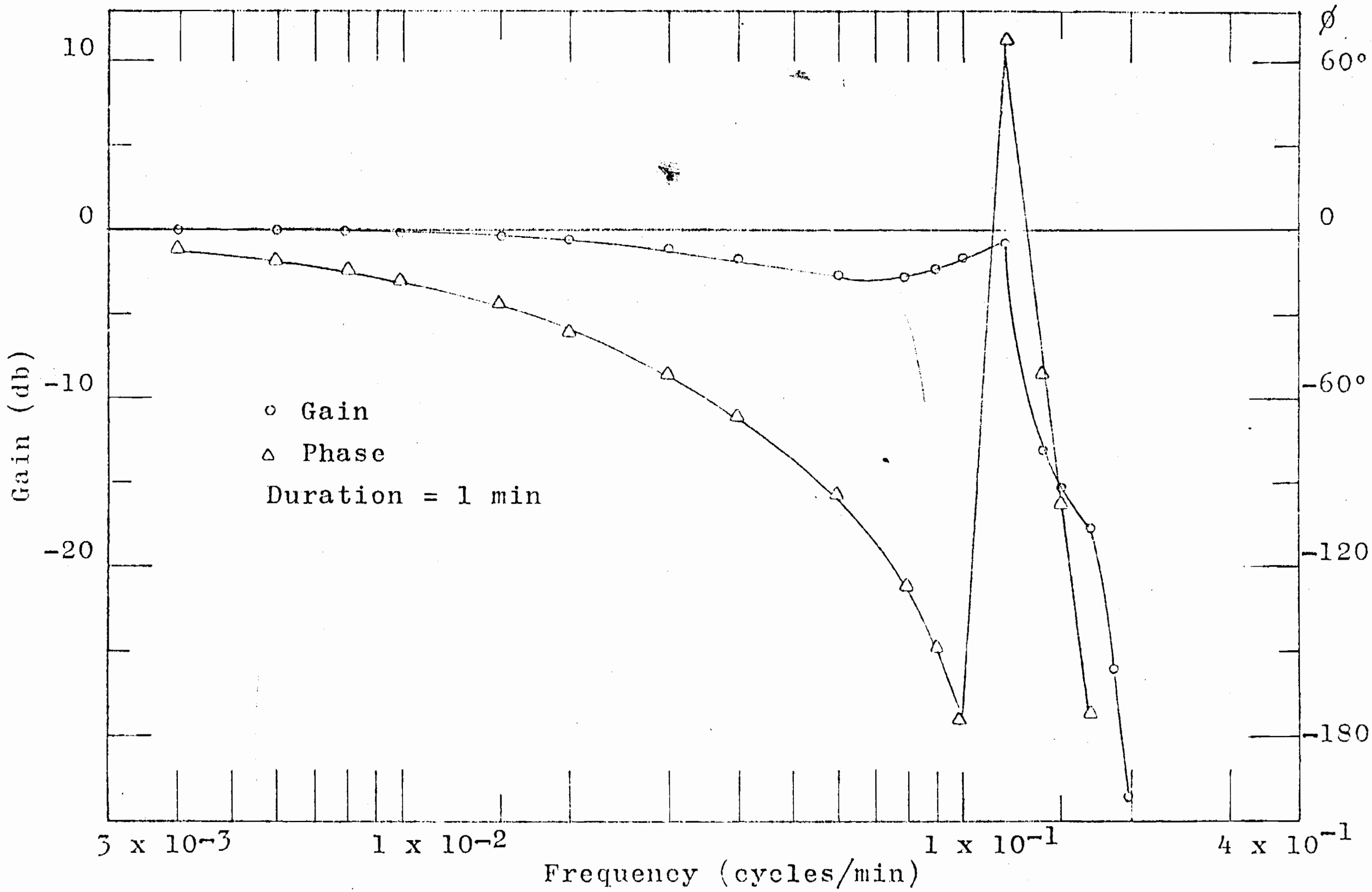


Figure 5-13. Bode-Diagram for S = 8%, R = 1.26 in/hr, Basin Type III.

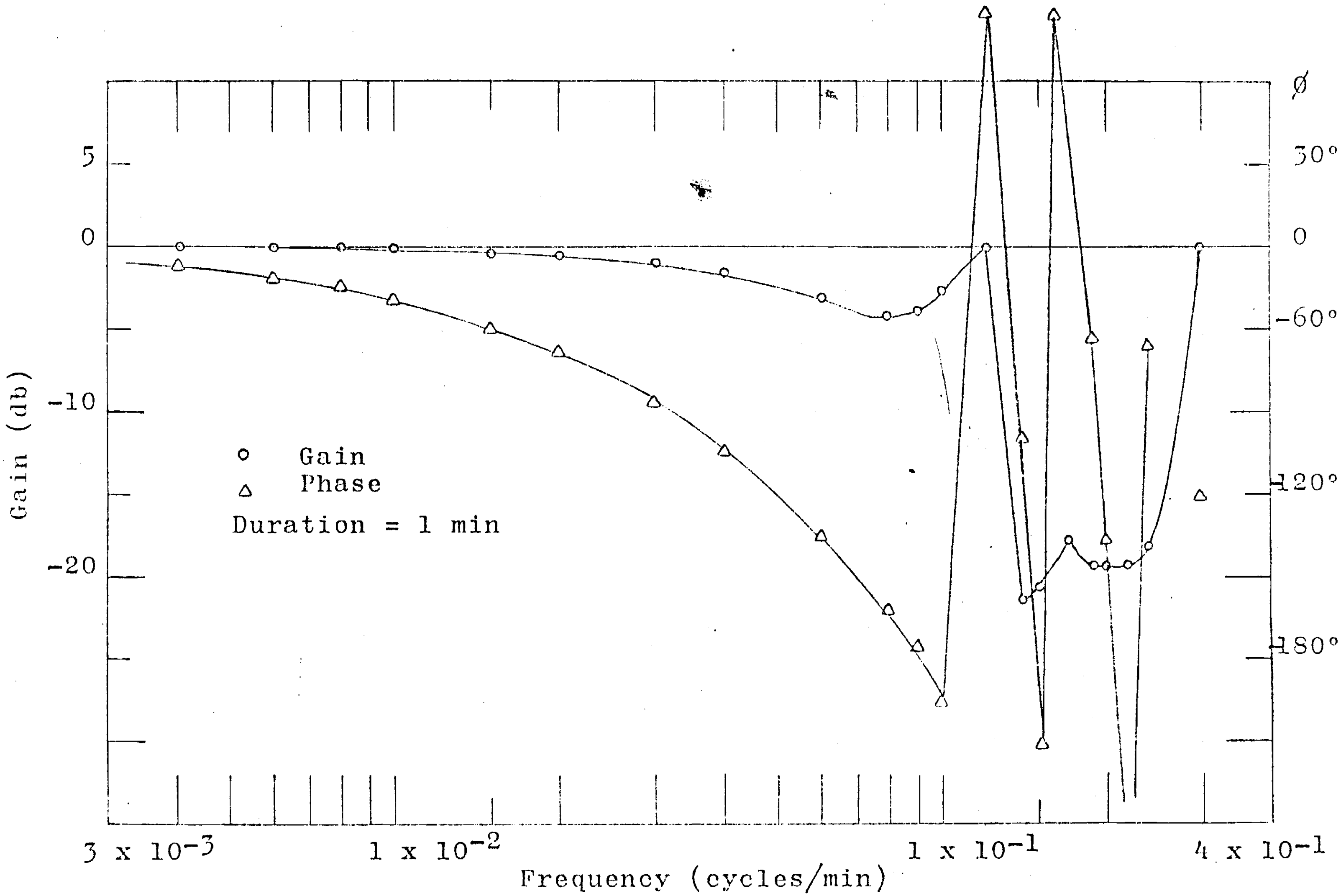


Figure 5-14. Bode-Diagram for S = 6%, R = 1.26, Basin Type III.

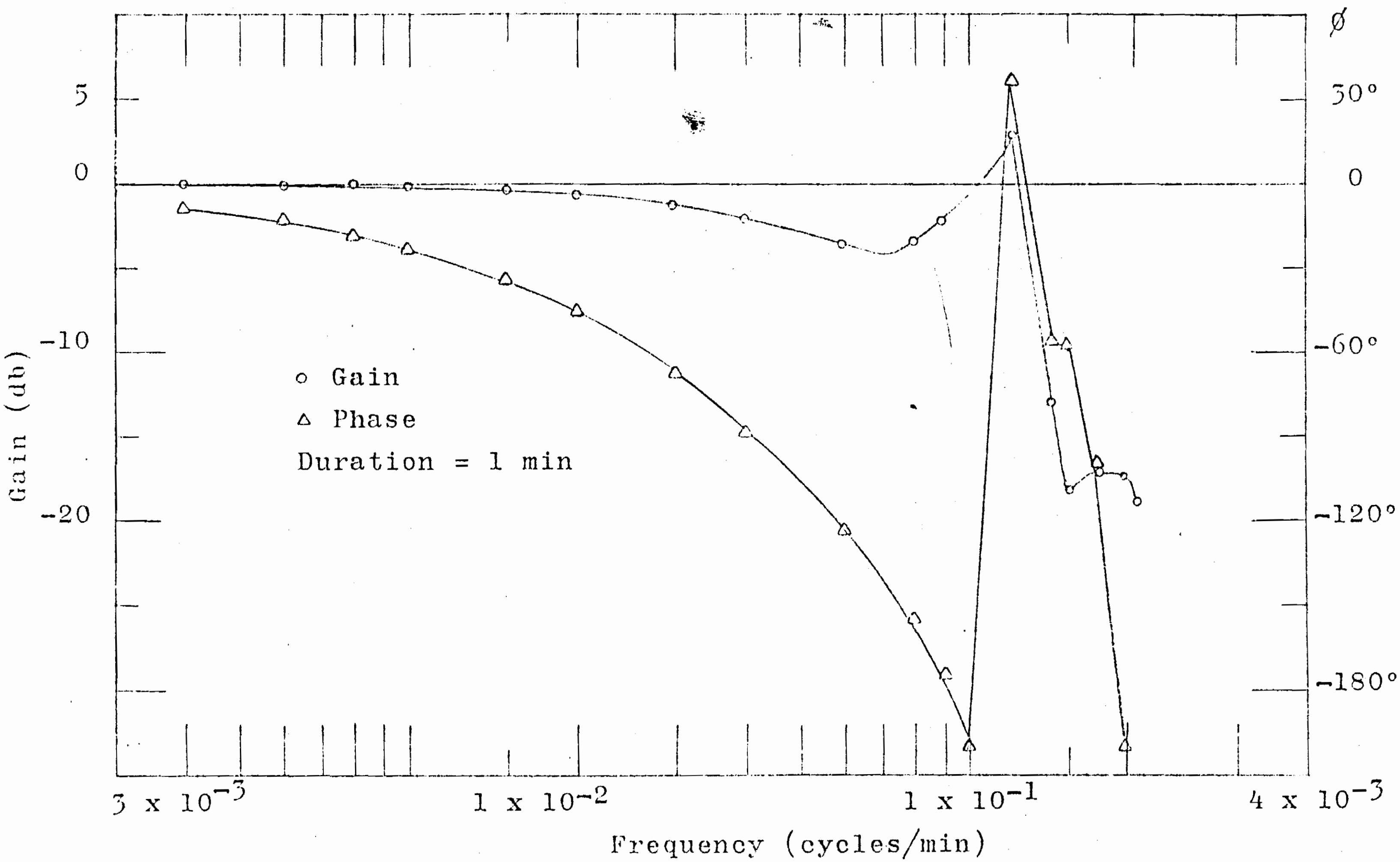


Figure 5-15. Bode-Diagram for S = 4%, R = 1.26 in/hr, Basin Type III.

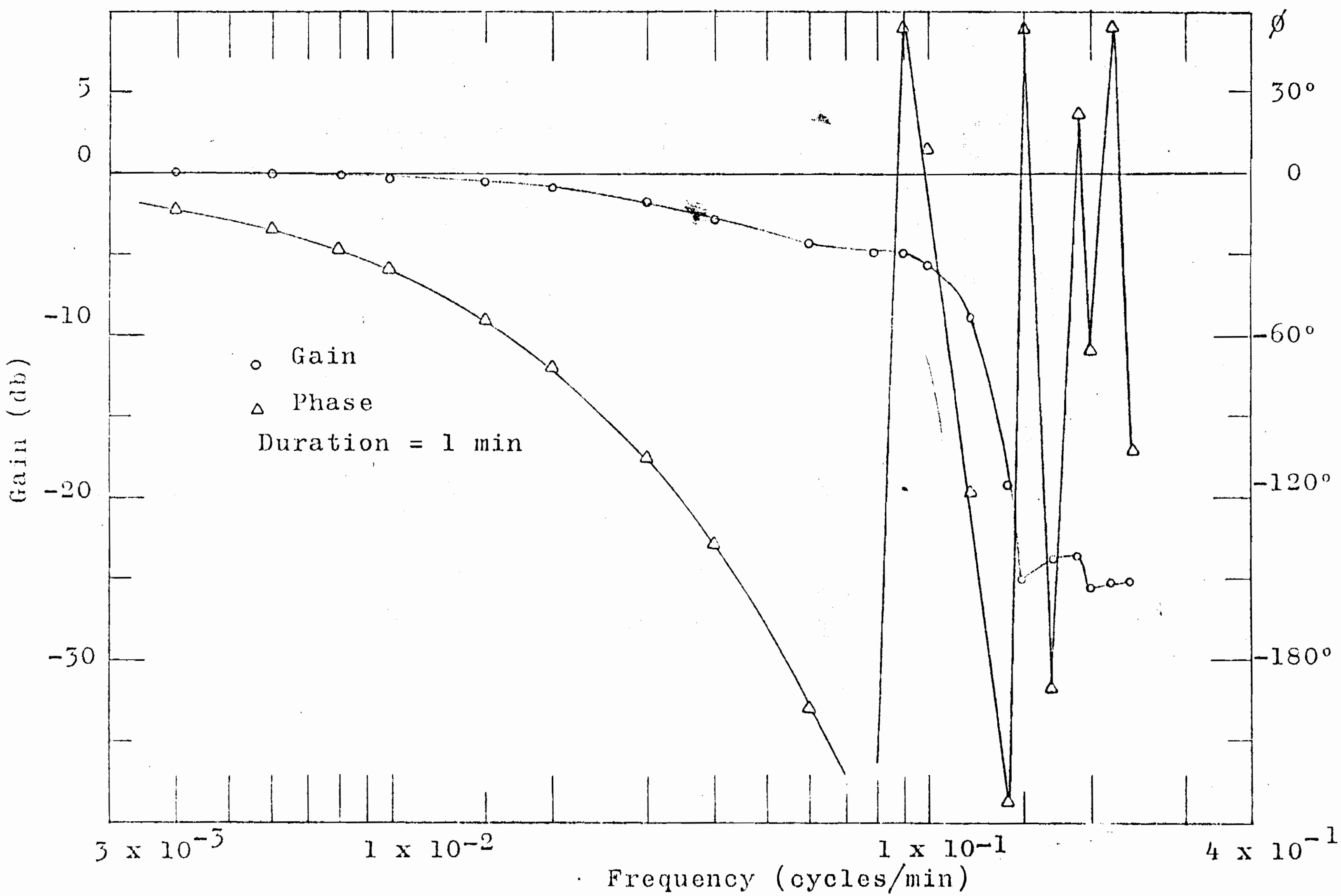


Figure 5-16. Bode-Diagram for S = 2%, R = 1.26 in/hr, Basin Type III.

The equations were derived by converting pulse to frequency response form utilizing the theory of Fourier transformation. The magnitude ratio or gain is the ratio of the output frequency content to that of the input. Thus

$$\text{M.R.} = \left| \frac{\int_0^{T_y} y(t)e^{-j\ t}\,dt}{\int_0^{T_y} x(t)e^{-j\ t}\,dt} \right|$$

where M.R. = magnitude ratio

T_y, T_x = width of system output pulse and input pulse respectively

$y(t)$ = arbitrary function of time of system output

$x(t)$ = arbitrary function of time of system input

$j = \sqrt{-1}$

ω = selected frequency

t = time

The integrals involved in the above equation can be evaluated approximately by changing the equation to summation form. When the time intervals for both input (independent) and output (dependent) variables are equal, the gain and the phase angle can be evaluated by the following equations.

$$\text{M.R.}(\omega) = \sqrt{\text{Re}^2(\omega) + \text{Im}^2(\omega)}$$

$$\phi = \tan^{-1}(\text{Im}(\omega)/\text{Re}(\omega))$$

and $$\text{Re}(\omega) = \frac{AC + BD}{C^2 + D^2}, \quad \text{Im}(\omega) = \frac{AD - BC}{C^2 + D^2}$$

Where ϕ = phase angle

$$A = \Delta t_y \sum_{K=1}^{n} y\ (k\Delta t)\ \mathrm{Cos}(\omega k \Delta t)$$

$$B = \Delta t_y \sum_{K=1}^{n} y\ (k\Delta t)\ \mathrm{Sin}(\omega k \Delta t)$$

$$C = \Delta t_x \sum_{K=1}^{n} x\ (i\Delta t)\ \mathrm{Cos}(\omega i \Delta t)$$

$$D = \Delta t_x \sum_{K=1}^{n} x\ (i\Delta t)\ \mathrm{Sin}(\omega i \Delta t)$$

Re = real part of system performance function

Im = imaginary part of system performance function

$x(i\Delta t)$ = the value of the independent variable

$y(k\Delta t)$ = the value of the dependent variable at time $k\Delta t$

k = the interval number

The performance function is defined as "the ratio of the Fourier transform of the output pulse to that of the input." (28)

Figure 5-9 shows the Bode diagrams for different input durations. It illustrates that varying the duration shifts the gain curve. Since the Bode diagram shows the dynamic effect and the time effect of the system, the longer the duration the more suppressed the dynamic effect, and the less significant the Bode diagram.

The gain curves and the phase shift curves are folded and looped at higher frequencies. For example, in Figure 5-9, the gain curves begin to loop after ω is equal to 0.02 and the phase shift curves begin to loop after ω is equal to 0.015 cycles/min for the duration equal to 5 min. This is because at the higher frequencies the input pulse does not contain enough harmonic content to produce accurate results. The harmonic content of a pulse is related to the shape and width of the input, and the frequency at which the the magnitude ratio is computed, and also related to the time interval used for output measurement. For a given shape of input pulse, the frequency at which the gain curve begins to fold depends mostly on input duration. The shorter the input duration the higher the frequency. This is shown in Figure 5-10. The phase shift curve is looped earlier than the gain curve.

Figure 5-11 shows the gain curves for different basin types. It indicates that the gain curves for basin types I and II are almost the same, which means the effect of changing the size of the basin proportionately can be neglected.

Figure 5-12 shows the Bode diagrams with intensity varying. It is noticed that for large input intensity, the dynamics effects of the system are shown more clearly by the gain curve, but the phase shift curve is folded earlier. This is because the higher the input intensity the more the system dynamics are excited.

Figures 5-13, 5-14, 5-15 and 5-16 show the effect on the Bode diagram of slope variation. The change of gain curves and the phase shift curve due to the changing of the basin longitudinal slope is not large for slopes 4%, 6% and

8%. For slope equal to 2% the shape of the gain curve is changed a little and the phase shift curve is folded earlier.

Damping Coefficient and Time Constant

Even by careful study, an accurate time constant could not be found, since when comparing the Bode diagram with the standard second order Bode plot it is found that the damping coefficient falls in the range of 0.9 to 1.0. When the damping coefficient is greater than 0.7, the natural frequency is hard to determine by comparison to standard curves. This can be seen from Figure 4-4.

The time constant for a system should be a constant which is not changed by varying the input duration. The gain curve of the Bode diagram calculated by the pulse testing method was shifted when the input duration was varied. This is due to the nonlinearity of the system and to the fact that the input duration is relatively long. Therefore, the time constant found from the Bode diagram is not the true time constant.

An approximate method of finding the time constants for a second order linear system has been used to find the time constant for the system. This method, according to Tucker and Wills (45), may be summed up as follows:

1. Drawing the response curves on larger scale paper for clear reading. For example, as in Figure 5-17.

2. Finding the inflection point of the head part of

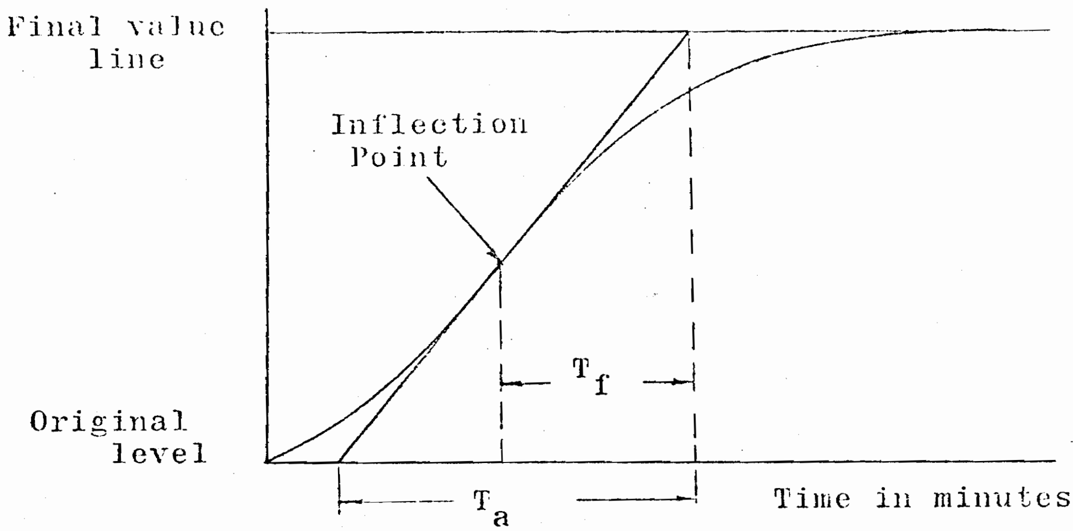


Figure 5-17. Typical Process Reaction Curve (Dead Time Neglected).

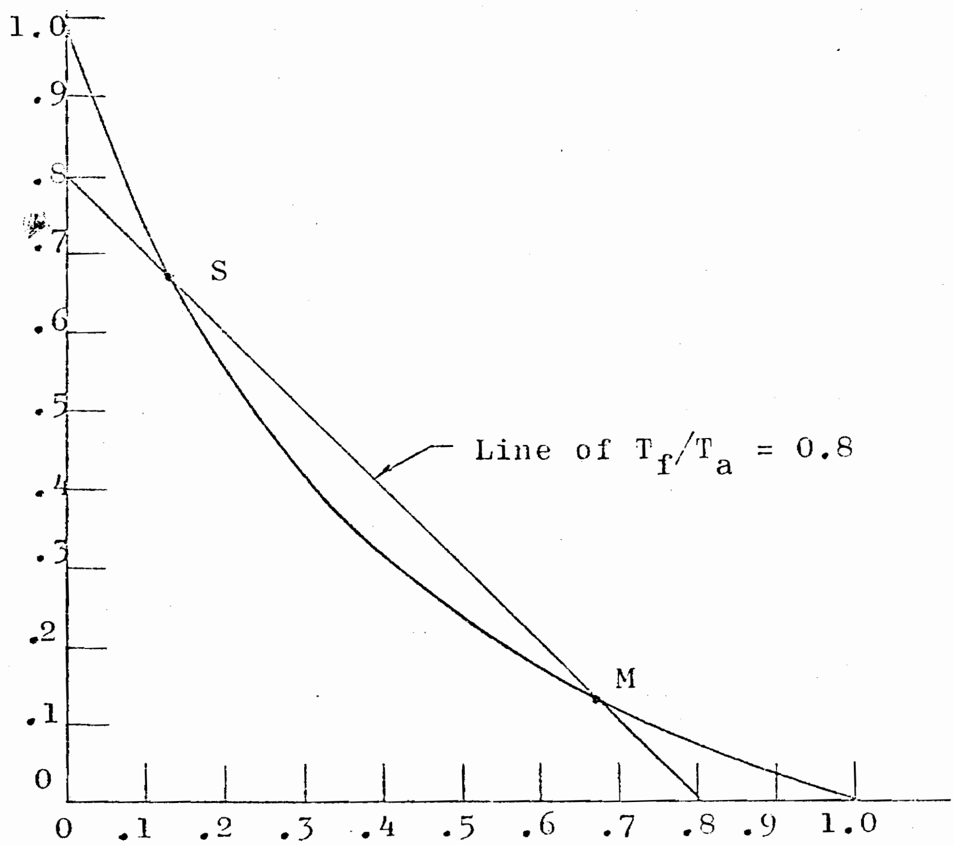


Figure 5-18. Graph for Finding Equivalent Time Constant from Process Reaction Curve. (After Tucker and Wills(45)).

the transient response curve. The inflection point is defined as the point where the slope first starts to decrease. Drawing a tangent line through the inflection point.

3. Measure T_a and T_f and find the ratio T_f/T_a.

4. On the curve reproduced in Figure 5-18 mark this ratio on both coordinates as shown at points 1 and 2. Connect the two points. If the ratio is larger than 0.73, there will be two intersection points. Either one of the two intersection points (like point M or S) will give a reading on the two scales. The two time constants are given by multiplying these two values by T_a.

5. If the ratio T_f/T_a is equal to or less than 0.73, there will be only one intersection point or no intersection point. If the ratio is equal to 0.73, then a time constant equal to 0.365 times T_a is the only time constant. But when the ratio of T_f/T_a is less than 0.73 the time constant found by this method is less accurate, the smaller the ratio the less accurate the time constant. To use this method, it is better to use a small time interval for the output, since it gives a better and more accurate response curve.

The time constants found by this method were not satisfactory either, since they were too small. This is because the system is not a linear system. Also, because the response reaches to its steady state value very fast, the ratio of T_f/T_a is much smaller than 0.73.

The time constants were found finally by trial and error, since with the information given by the Bode diagram and by the approximate method, the neighborhood of the time constant is not hard to find. Figure 5-19 shows the effect on outflow of varying the time constant in a second order system. The time constants were between 0.45 min and 0.60 min for basin Type III. For basin types I and II, at slopes greater than 2%, the time constants were between 0.48 min and 0.65 min. For slopes equal to or less than 2%, the system may be approximately simulated by a first order linear system with a time constant of about 0.8 min.

The time constant is a function of input intensity, basin shape and basin slope, the larger the slope the smaller the time constant and the larger the input intensity the shorter the time constant. For a natural basin, it should be a function of the basin characteristics and input intensity.

Nonlinear Parameter, n

There is no simple way to find the nonlinear parameter, n. A trial and error method is suggested. The value of n obviously depends on basin shape, slope, and the outlet size and shape. According to Prasad, "For a basin with vertical wall around and with a proportional-weir type outlet, the nonlinear parameter n is equal to one." (39). Figure 5-20 shows the effect of varying n on the outflow for a second

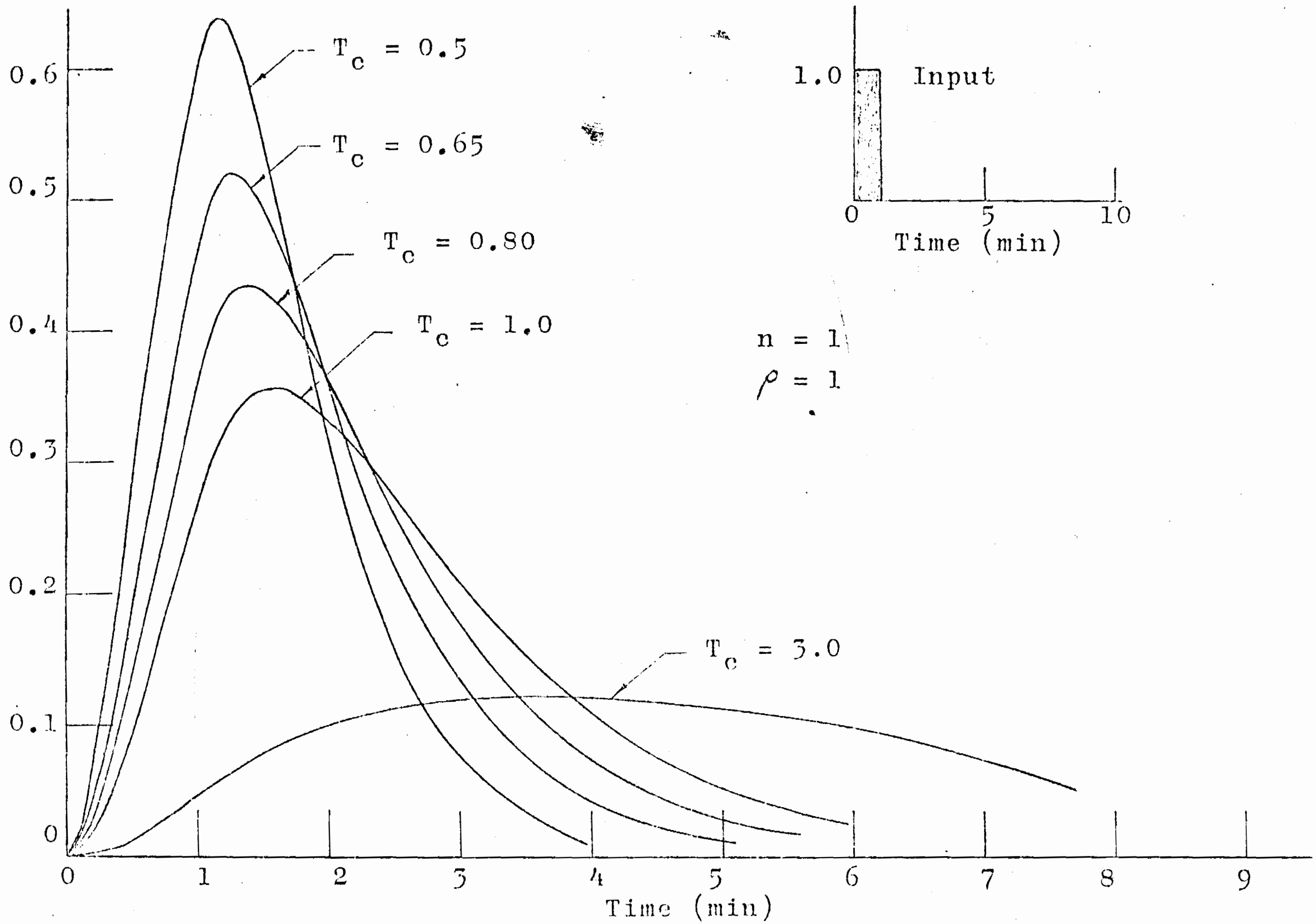


Figure 5-19. Effect of Varying Time Constant T_c on Outflow for A Second Order System ($n = 1$, $\rho = 1$).

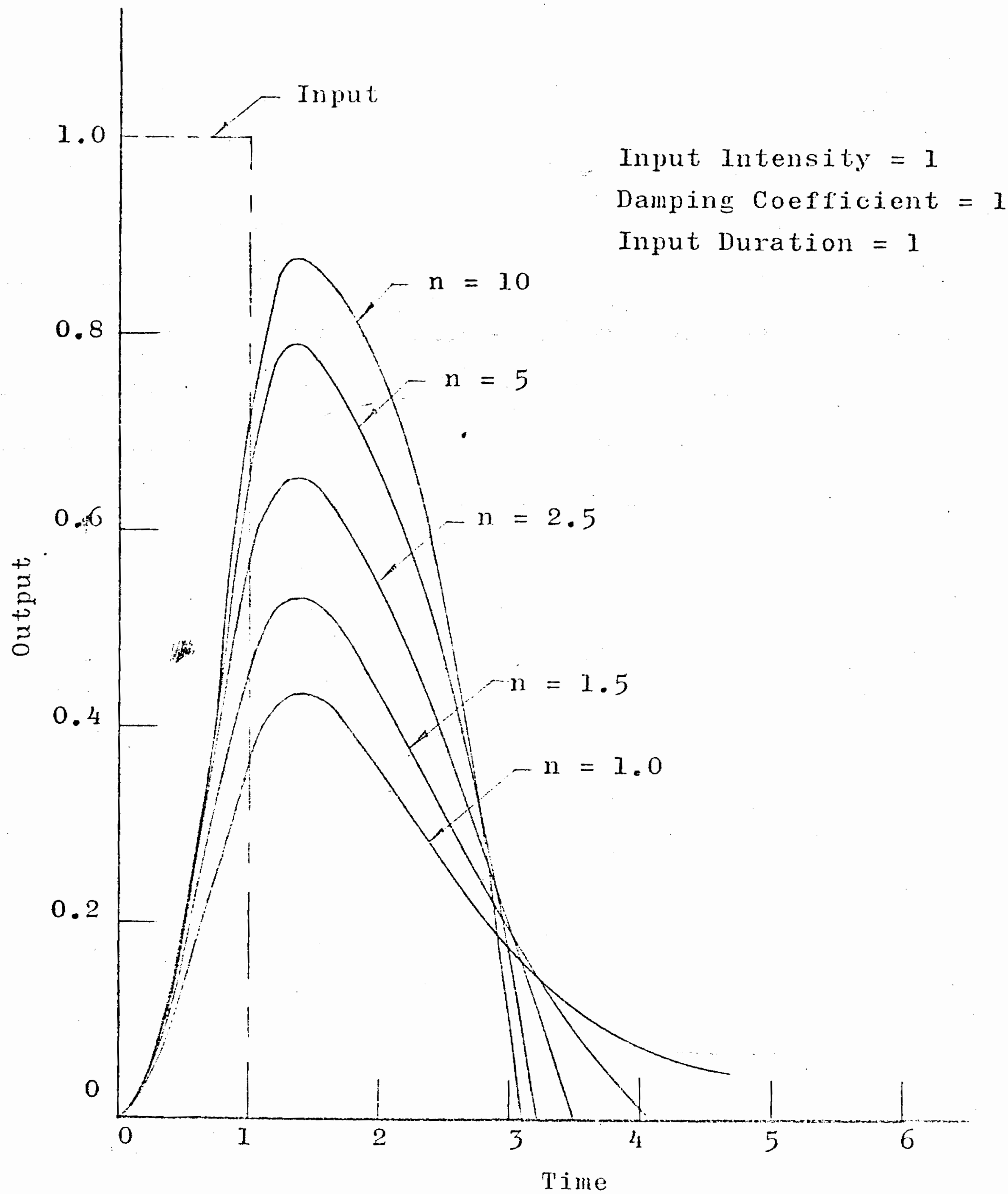


Figure 5-20. Effect of Varying n on Outflow for A Second Order Nonlinear System.

order system. For slopes greater than 2%, the nonlinear parameter for basin types I and II was found to be about 1.15. For basin type III, it was about 1.25. When the slope was equal to 2%, for the plane basins (basin types I and II), the system becomes approximately a first order linear system. This is because when the slope was small there was some water gathered at the end of the basin which could turn the outlet of the basin to a proportional-weir type decreasing the nonlinear parameter n to unity. This phenomenon also could happen at higher input intensity. The detention water in the basin would also reduce the dynamic effect of system and make it negligible, especially for small input intensity. The dynamic effect for a system depends upon the input intensity and the depth of the detention water in the basin, the larger the input intensity the more significant the dynamic effect, but the larger the depth of the detention water, the smaller the dynamic effect.

Transfer Function

The general differential equation describing the system is

$$T_c^2 \frac{d^2 0_R}{dt^2} + 2\rho T_c \, n \, 0_R^{n-1} \frac{d\,0_R}{dt} = R(t - T_d) - 0_R \qquad (4\text{-}23)$$

The Laplace transform of the above equation is

$$T_c^2 \left[s^2 \, 0_R(s) - s0_R(0) - 0_R'(0)\right]$$

$$+ 2\rho T_c\, n \left[O_R(s)\right]^{n-1} \left[sO_R(s) - O_R(0) + O_R(s)\right]$$

$$= R(s)e^{-sT_d}$$

when $t = 0$, $O_R = 0$ and $O_R' = 0$, then

$$T_c^{\,2} \left[s^2 O_R(s)\right] + 2\rho T_c\, n\, s \left[O_R(s)\right]^n + O_R(s)$$

$$= R(s)e^{-sT_d}$$

Therefore

$$G(s) = \frac{O_R(s)}{R(s)} = \frac{e^{-sT_d}}{T_c^{\,2}\, s^2 + 2\rho T_c ns \left[O_R(s)\right]^{n-1} + 1} \qquad (5\text{-}4)$$

Equation (5-4) is the general form of the transfer function for a hydrologic system.

A standard transfer function for a second order linear system is

$$G(s) = \frac{G_k\, e^{-sT_d}}{T_c^{\,2}\, s^2 + 2\rho T_c\, s + 1} \qquad (5\text{-}5)$$

where G_k is the gain constant.

When $n = 1$, equations (5-4) and (5-5) should be equal, therefore the gain constant G_k for the hydrologic system is unity.

When the dynamic effects of the system are negligible, as in basin types I and II at slope less than 2%, then the equation (4-23) can be reduced to

$$2\rho T_c\, n O_R^{\,n-1} \frac{dO_R}{dt} = R(t - T_d) \qquad (5\text{-}6)$$

and the transfer function becomes

$$G(s) = \frac{e^{-sT_d}}{T_c{'}\ s\ n\left[0_R(s)\right]^{n-1} + 1} \tag{5-7}$$

which is a nonlinear, first order transfer function, where $T_c{'}$ is the time constant, about twice the value of T_c.

In equations (5-4) and (5-7), if the system is linear, i.e. n = 1, then the transfer function for the first and second order linear hydrologic systems are:

$$G(s) = \frac{e^{-sT_d}}{T_c^2\ s^2 + 2\rho T_c + 1} \tag{5-8}$$

and

$$G(s) = \frac{e^{-sT_d}}{T_c{'}\ s + 1} \tag{5-9}$$

respectively.

Equations (5-4), (5-7), (5-8) and (5-9) all are the transfer functions for hydrologic systems. But, equations (5-7), (5-8) and (5-9) are three special cases of equation (5-4). Therefore, equation (5-4) is the general transfer function.

Hydrologic systems are different, one from the other, but most of them are one of these four types--first order linear or nonlinear, second order linear or nonlinear. Since the general nonlinear expression is all inclusive, the transfer function of hydrologic systems can be written in the form of equation (5-4).

It was found that for basin type III and for basin types I and II at slope greater than 2%, the transfer function of the system was in the form of equation (5-4). For basin types I and II at slopes equal to or less than 2% the transfer function was in the form of equation (5-9), i.e. the system could be described by a first order, linear equation.

Digital-Analog Simulation

Often the equations required to adequately describe a complex system cannot be solved by any rigorous process. This situation has led to the extensive development and use of machine aids to computation, such as analog and digital computers which now play an important role in engineering analysis.

A Digital-Analog simulator program, called PACTOLUS (7), uses operational blocks to synthesize a problem as an analog-oriented program on a digital computer. The technique of drawing a PACTOLUS block diagram for a differential equation is that of drawing a block diagram for an analog computer. One first has to solve the equation for the highest derivative term. Then, according to the new equation, one draws the block diagram. Each block must have a number and a symbol to represent the operation of the block.

A primary difference between a PACTOLUS block diagram and an analog computer block diagram is that in a PACTOLUS block diagram the integration block only integrates the input function; it does not change the sign as in an analog computer block diagram. The sign in PACTOLUS is assigned in a summation block.

Equation (4-23) may be solved for the highest derivative term as

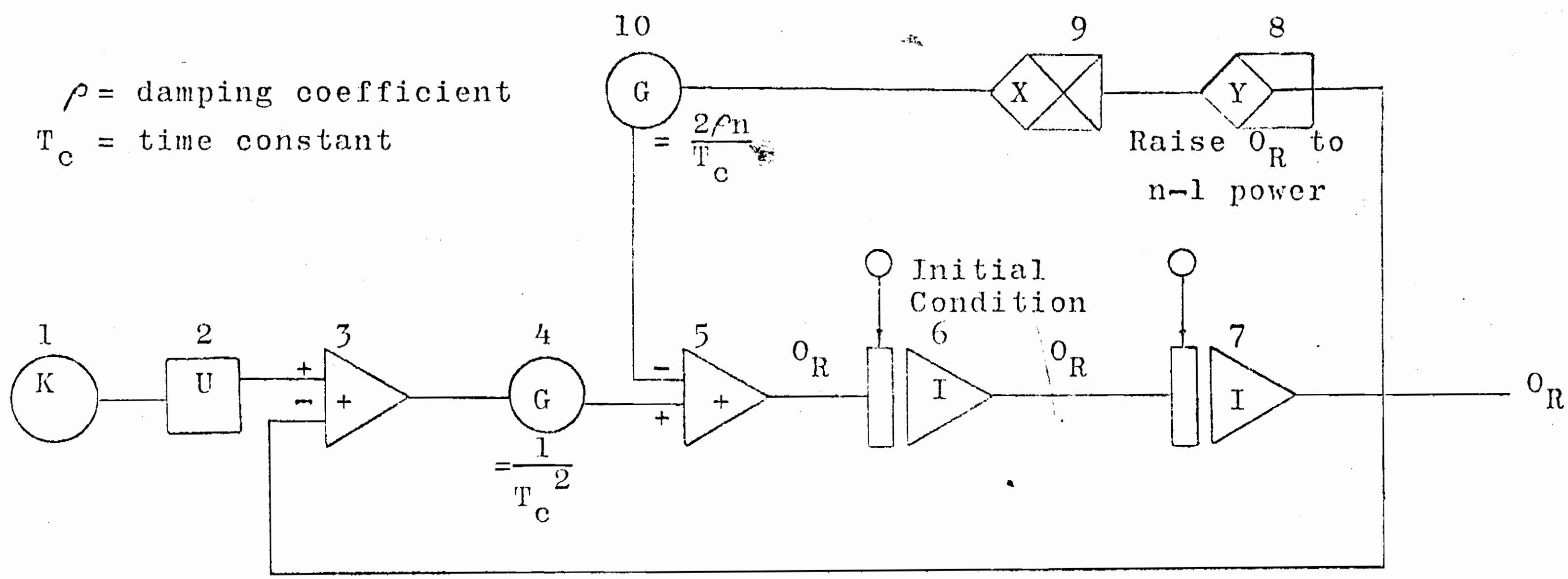
$$\frac{d^2 O_R}{dt^2} = \frac{R - O_R}{T_c^{\,2}} - \frac{2\rho n\, O_R^{\,n-1}}{T_c} \cdot \frac{d\, O_R}{dt} \qquad (5\text{-}10)$$

The PACTOLUS block diagram for equation (5-10) is shown in Figure 5-21.

Figures 5-22, 5-23 and 5-24 compare the output calculated by analog-digital simulator and the experimental results. From these figures, it is clear that for a definite system (definite basin shape, outlet, and slope) and a given input intensity the time constant is a constant, i.e. the time constant is independent of input duration.

Application to Natural Basins

A number of sets of data for natural basins in Detroit metropolitan area, Michigan, have been tested by the technique of systems analysis. Part of the data were used to find the basins' parameters (such as time constant, nonlinear parameter), and part of the data were used for



Second Order Equation = $T_c^2 \; O_R + 2\rho T_c n O_R^{n-1} \; O_R = R - O_R$

If $n = 1$ linear

$n \neq 1$ nonlinear

If $n = 1$ and $1/T_c^2$ and $2\rho/T_c$ are rational numbers the equation may be factorable to two first order.

Figure 5-21. PACTOLUS Block Diagram for Hydrologic Systems.

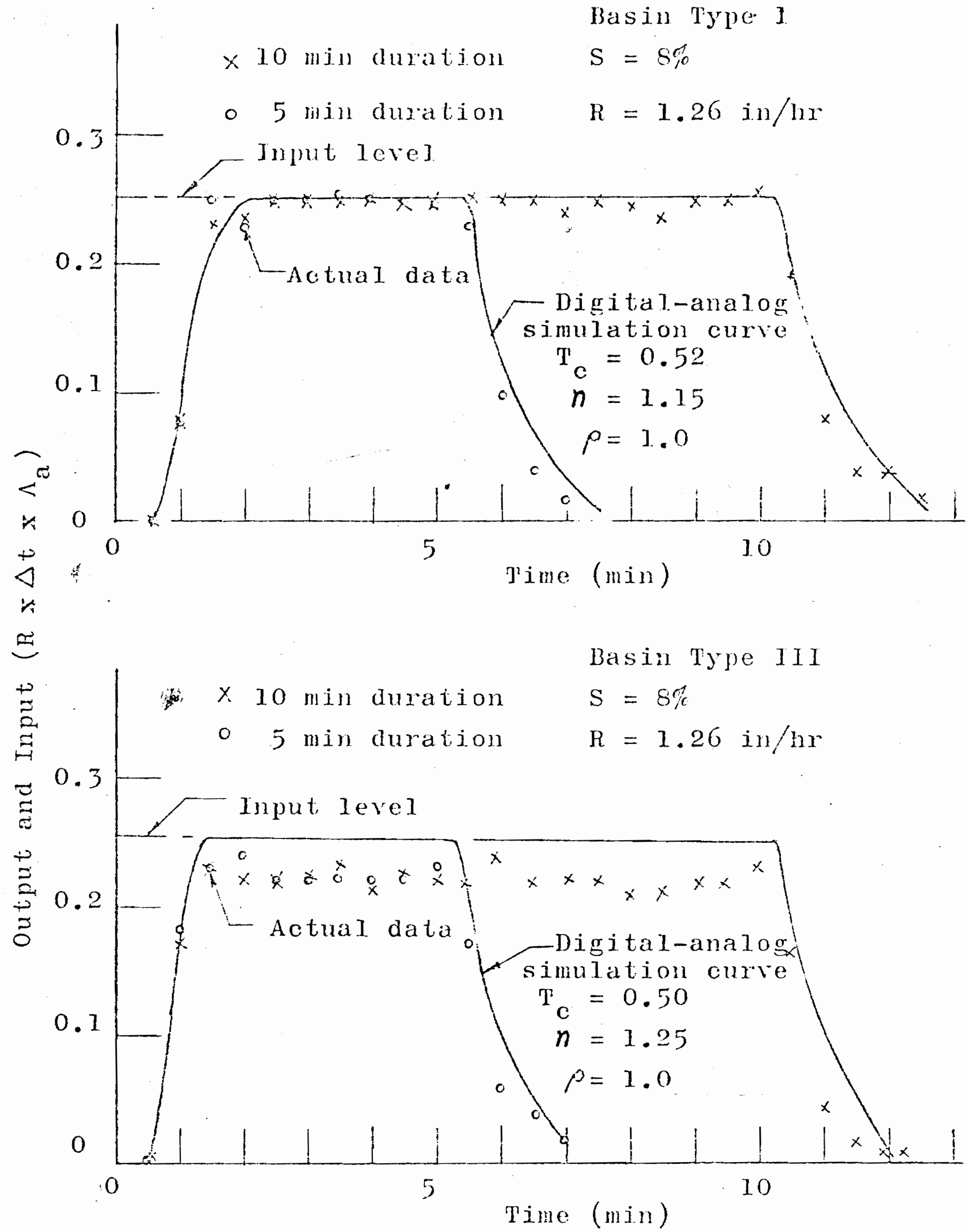


Figure 5-22. Comparison of Digital-Analog Simulation Curve and Actual Data for Duration Varying.

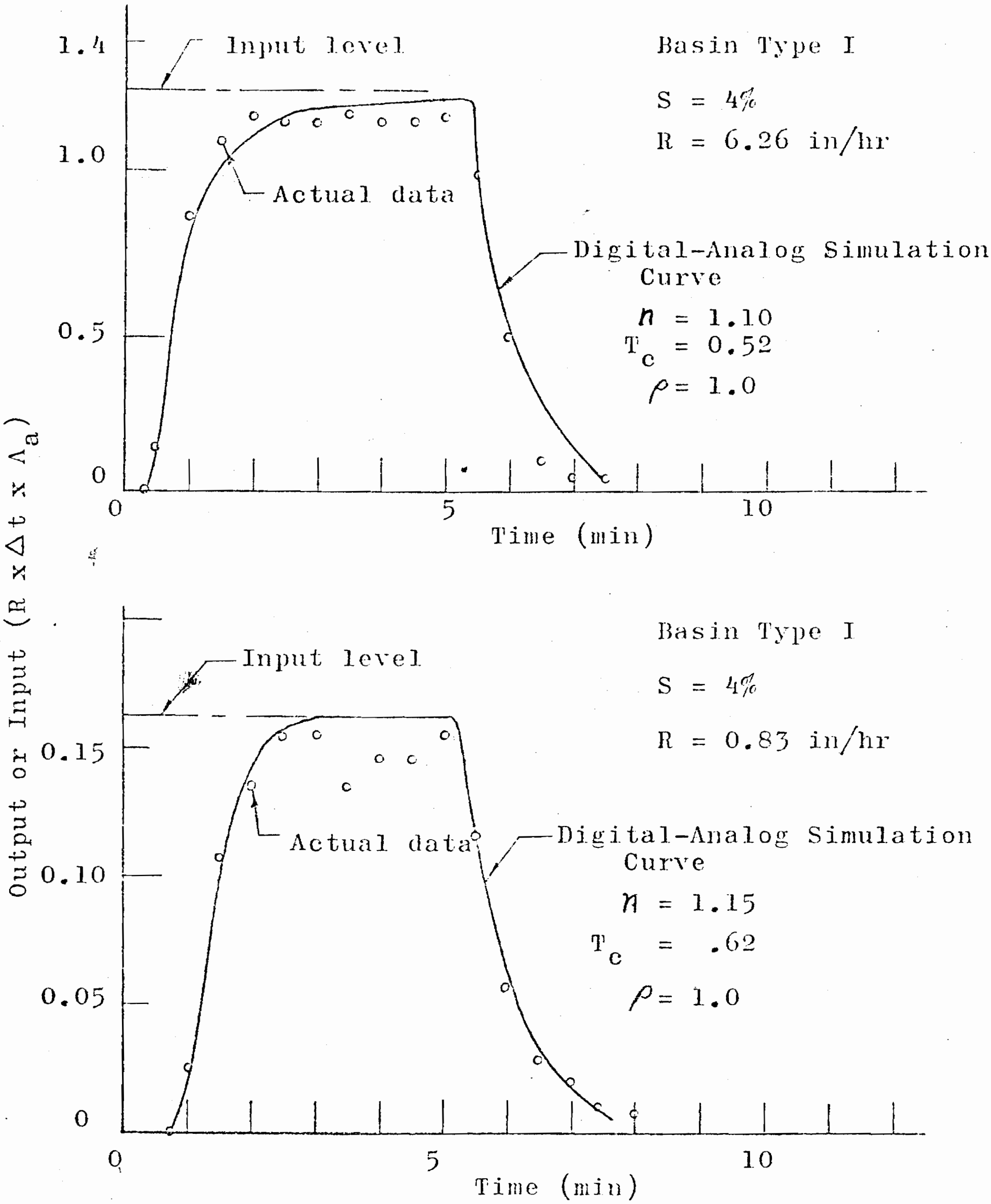


Figure 5-23. Comparison of Digital-Analog Simulation Curve and Actual Data for Input Intensity Varying.

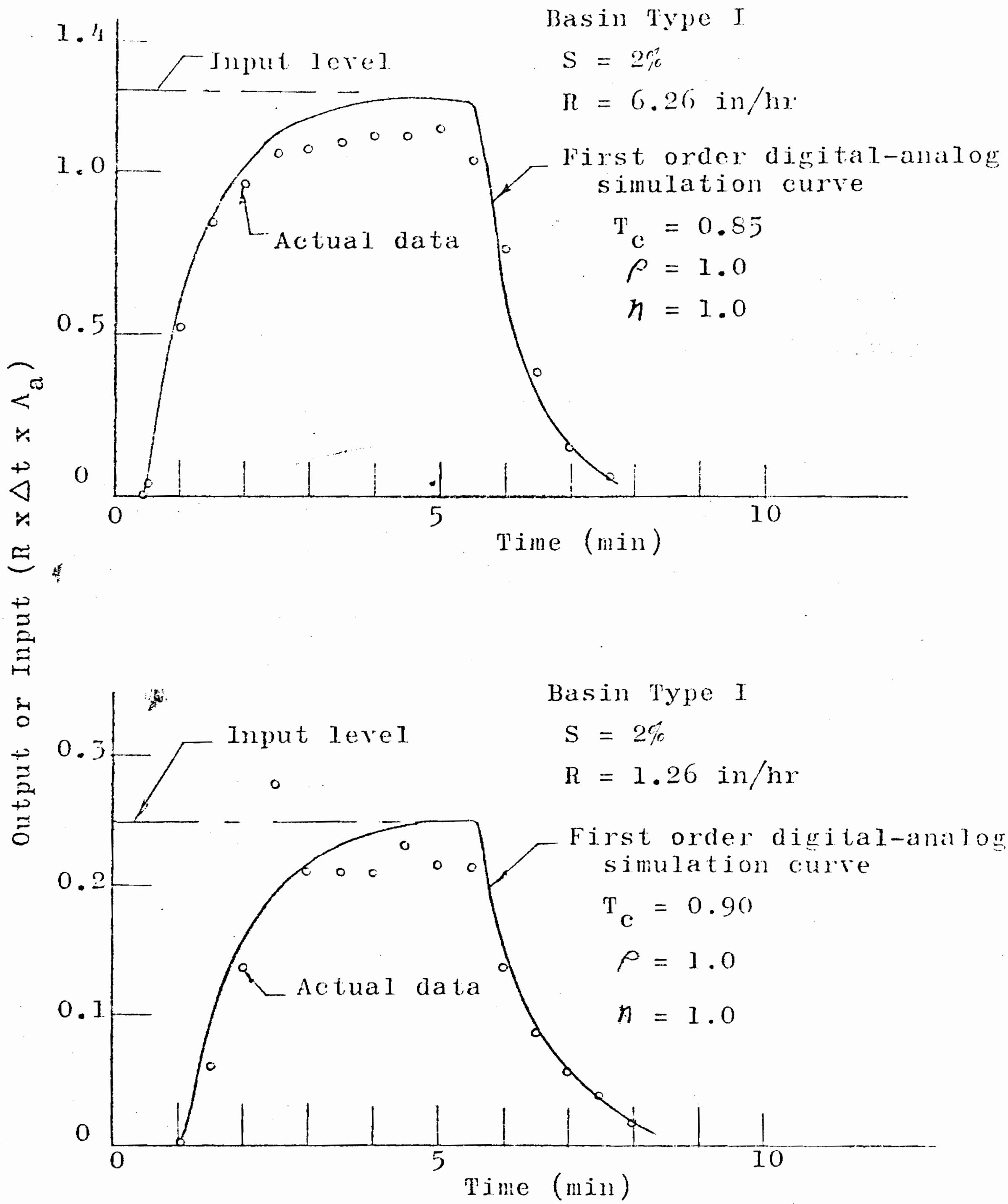


Figure 5-24. Comparison of Digital-Analog Simulation and Actual Data by First Order, Linear System for Basin Type I, S = 2%.

checking. The values of the parameters were found from Bode diagrams which were calculated by applying the pulse testing technique to the data. The method of selecting the base line for separating surface runoff and infiltration from precipitation was to take a horizontal line to cut the precipitation rate graph at a level such that the total volume of precipitation above this line equaled the total volume of surface runoff. The computer program for these routine calculations are in Appendix A. After the parameters of the basins were found, the outflows were compared with the actual data.

Figure 5-25 shows the Bode diagram calculated from the data taken at station 3 at Macomb County, April 7, 1959. Curve A is the actual gain curve which was separated into curves B and C, both standard, first order, linear system gain curves. Therefore the system can be represented by a second order linear system which is a combination of two first order linear systems. The two time constants found from curves B and C were 5.067 and 2.22 respectively. By using these time constants in the PACTOLUS program, the outflows for the rainfall excess at April 7, 1959, April 5, 1957 and May 11, 1956 were calculated, and are plotted with the actual surface runoff data on Figures 5-26, 5-27 and 5-28, respectively. Results for April 7, 1959 and April 5, 1957 show satisfactory agreement, but for May 11, 1956 the simulation is poor. A little correction of the time

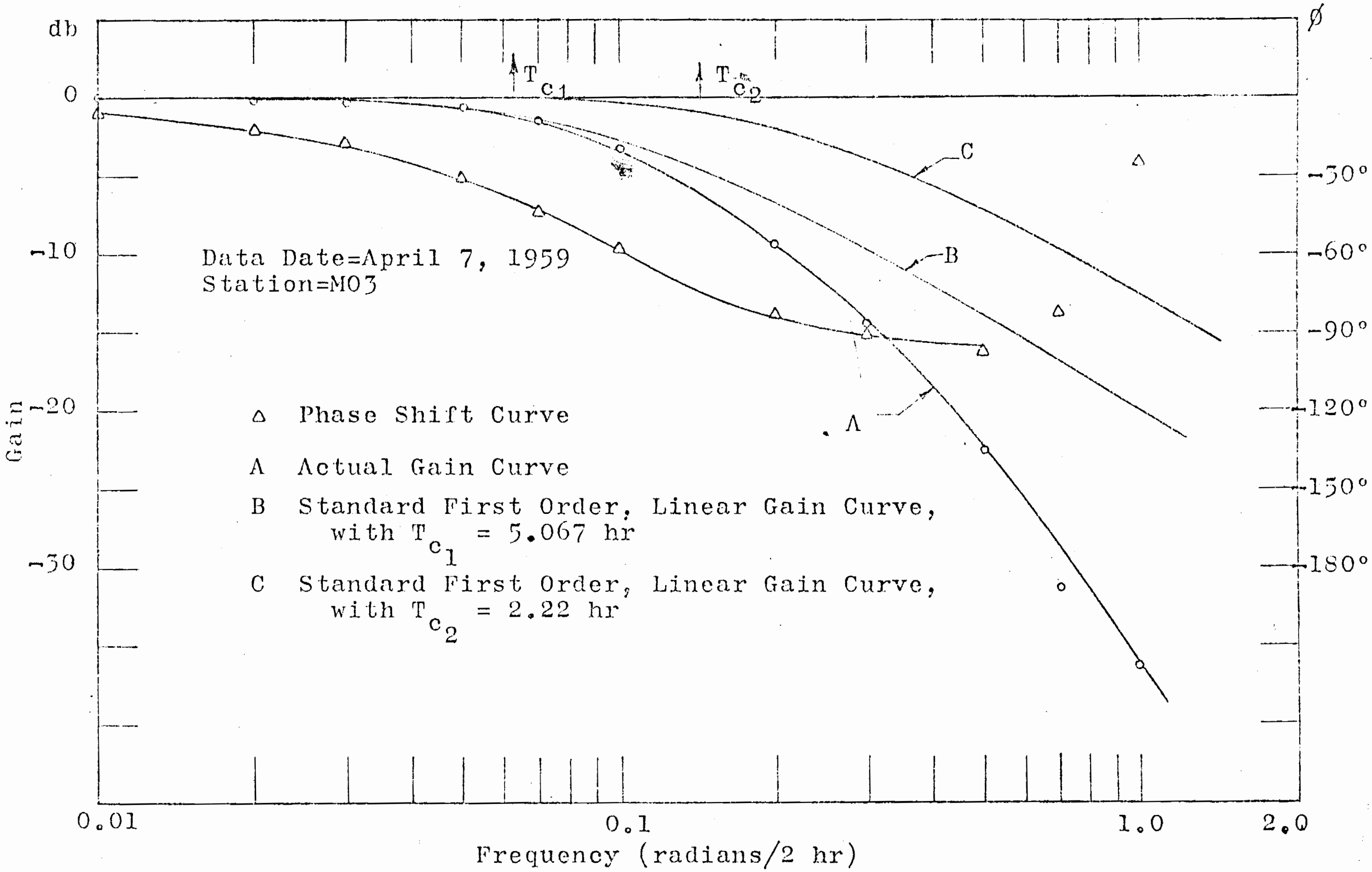


Figure 5-25. Bode Diagram for Natural Basin, Macomb County, Michigan.

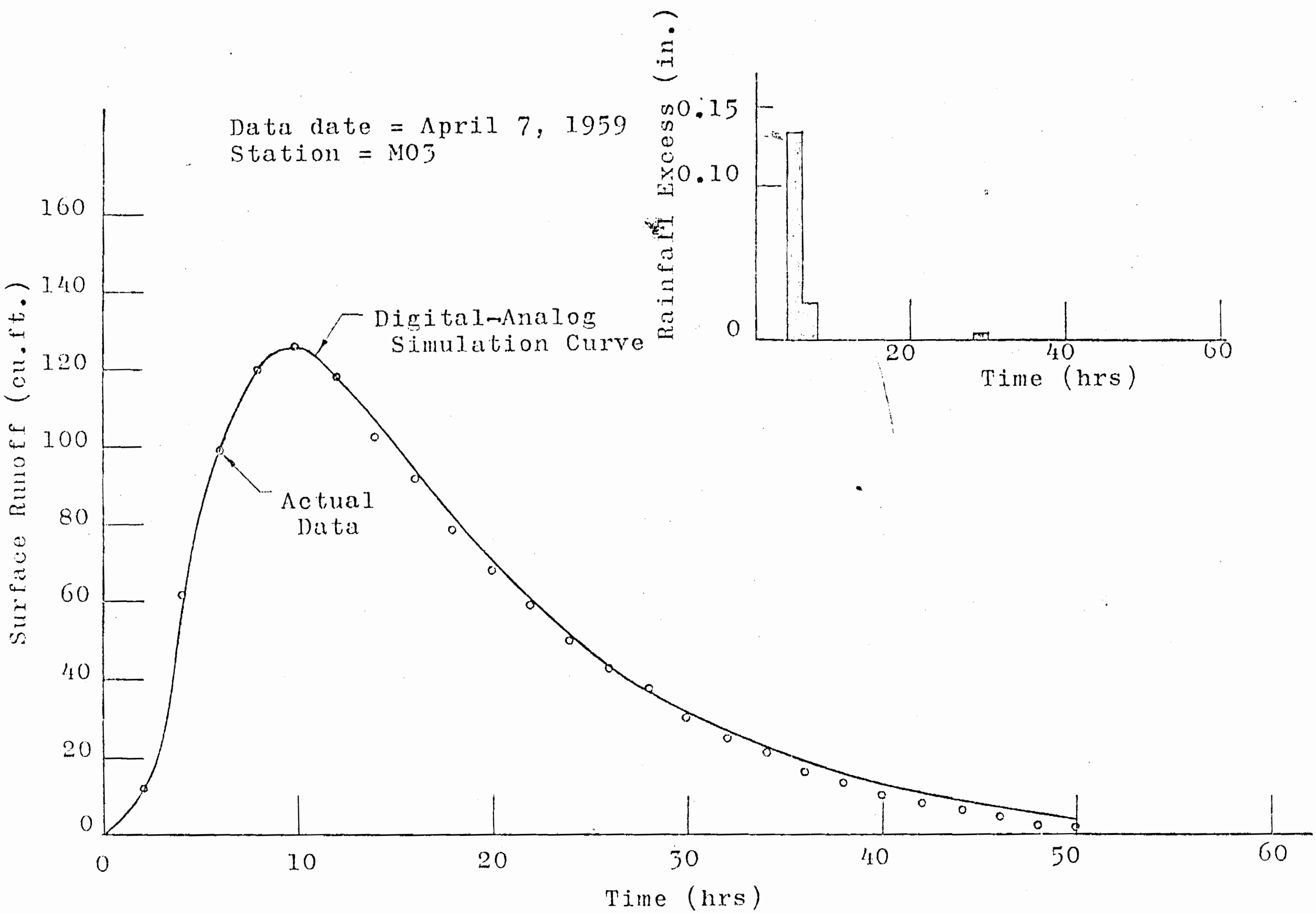


Figure 5-26. Comparison of the Actual Data with Digital-Analog Simulation Curve.

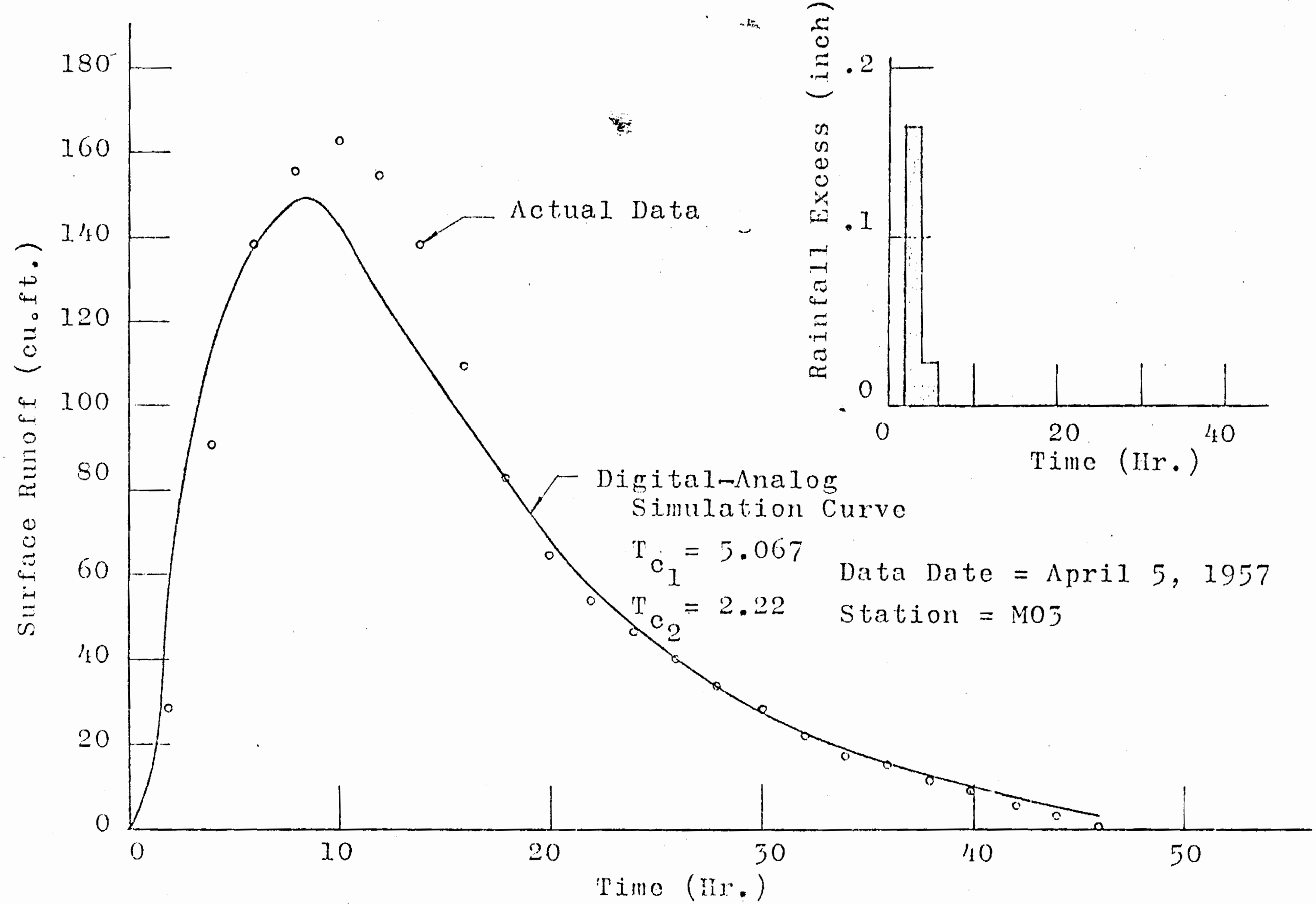


Figure 5-27. Comparison of Actual Data with Digital-Analog Simulation Curve.

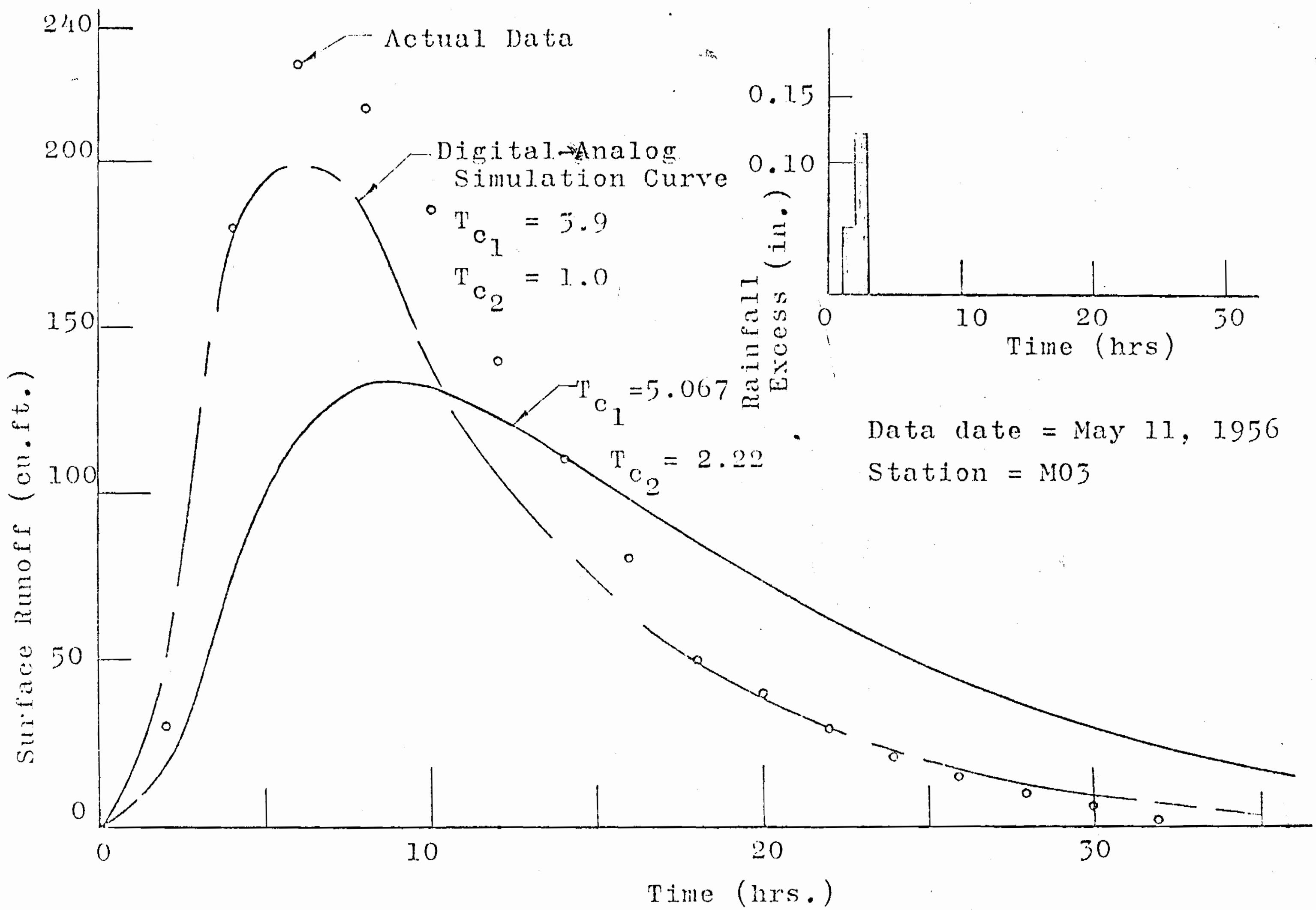


Figure 5-28. Comparison of Actual Data with Digital-Analog Simulation Curve.

constant shows better fitting. For finding the reasons, the original data have been carefully studied. Figure 5-29 shows these data. It can be concluded that the surface runoff data for May 11, 1956 was not caused by the rainfall data of May 11, 1956 alone, since the dead time for the data was too short compared with the other two sets of data. The following table shows these comparisons.

Data Date	Total Rainfall Volume/ Basin Area (in.)	Dead Time (Hrs.)
May 11, 1956	0.27	2
April 5, 1957	0.51	13
April 7, 1959	0.67	12

The dead time for natural basins was usually long, especially for small rainfall intensity. The rainfall volume for May 11, 1956 was smaller than the rainfall volume either of April 7, 1959 or April 5, 1957, but the dead time was much shorter which is contradictory to the notion that the larger the input intensity the shorter the dead time.

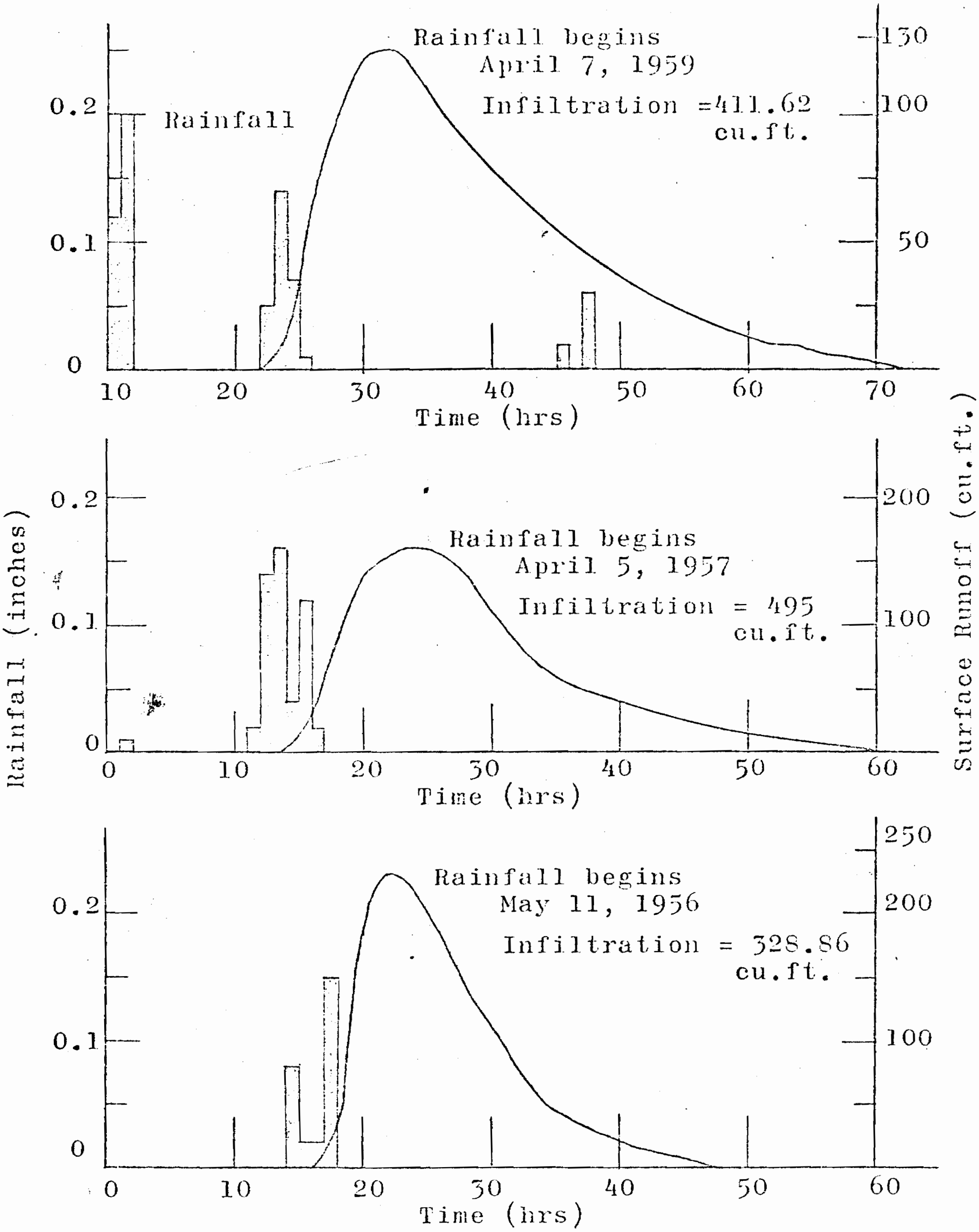


Figure 5-29. Rainfall and Surface Runoff Data.

VI. DISCUSSION

Hydrologic systems are very complex. Every catchment is different from others; therefore there is no accurate method or equation which is applicable to all kinds of catchments for prediction of storm runoff. Systems analysis techniques are useful methods for finding the transfer functions of a system, which then provides a mathematical model of the system. Application of systems analysis techniques to hydrology has been tested and the results show that it is useful, not only for artificial basins, but also natural catchments. Any catchment with some previous data is susceptible to the use of systems analysis techniques to find the transfer function for rainfall excess and runoff, and that function can then be used for future prediction of runoff.

The general differential equation (Eq. 4-23) for hydrologic systems, derived by treating the drainage basin as a reservoir with uncontrolled outflow and by adding a dynamic effect term, is a useful form which not only represents second order linear or nonlinear hydrologic systems but also represents first order linear or nonlinear systems. The order and the linearity of hydrologic systems can be determined from the Bode diagram which is computed by applying systems analysis techniques to the previous data of that catchment.

The dead time, which is the important part of the time to peak, is a function of basin physical characteristics (such as area, length, shape, slope, surface condition, etc.) and rainfall intensity. The writer believes that the functional form of the time to peak should be the same as dead time, not only a function of basin characteristics as Wu (47) derived, but also a function of rainfall intensity. Wu's equation

$$t_p = 31.42\ A^{1.085}\ L^{-1.233}\ S^{-0.668}$$

is dimensionally incorrect. If the rainfall intensity is included, the dimensions may become correct. The suggested functional form for time to peak is

$$t_p = K\ A_a^x\ L^y\ S^z\ R^w$$

where t_p is time to peak, K is a dimensionless constant, A_a is the basin area, L is the length of the basin, S is basin slope, R is rainfall intensity and x, y, z, w are exponential constants. Further study is necessary for determining the exponents and the constant K.

The time interval of observation used in this study is somewhat large, and the duration of the input pulse is relatively long. A shorter duration and a smaller time interval are recommended for further study. A larger input intensity will also give better results for the same duration. The sine wave or smooth curve pulse input instead of square pulse input is suggested, requiring an automatic control for generating the input. A sine wave input would permit frequency response testing, adding to the validity of results deduced from the Bode plots found by pulse testing.

The time constant for natural basins depends on the basin's physical characteristics which also should include the soil moisture deficiency of the basin.

The similarity criteria for time derived by Grace and Eagleson (22) does not quite hold for the timing terms used in system analysis. This is shown in Figure 6-1. The lines A and A' were calculated according to the dead time data for basin type I by Grace and Eagleson's equation,

$$t_r = \left[L_r \frac{\tan \theta_p}{\tan \theta_m} \right]^{\frac{1}{2}}$$

when $\theta_p = \theta_m$, $t_r = (L_r)^{\frac{1}{2}}$. Lines B and B' were plotted according to the data measured for basin type II. The difference is 10% and 12% for rainfall intensity 1.26 in/hr and 6.26 in/hr respectively.

The dynamic reactions of basin types I and II (the plane basins), with the slope equal or less than 2%, are different from the other slopes which can be simulated approximately by a first order linear system. This is coincident with what Grace and Eagleson (22) stated. The reason is that when the slope was small, the detention water gathered at the end of the basin, which turned the basin

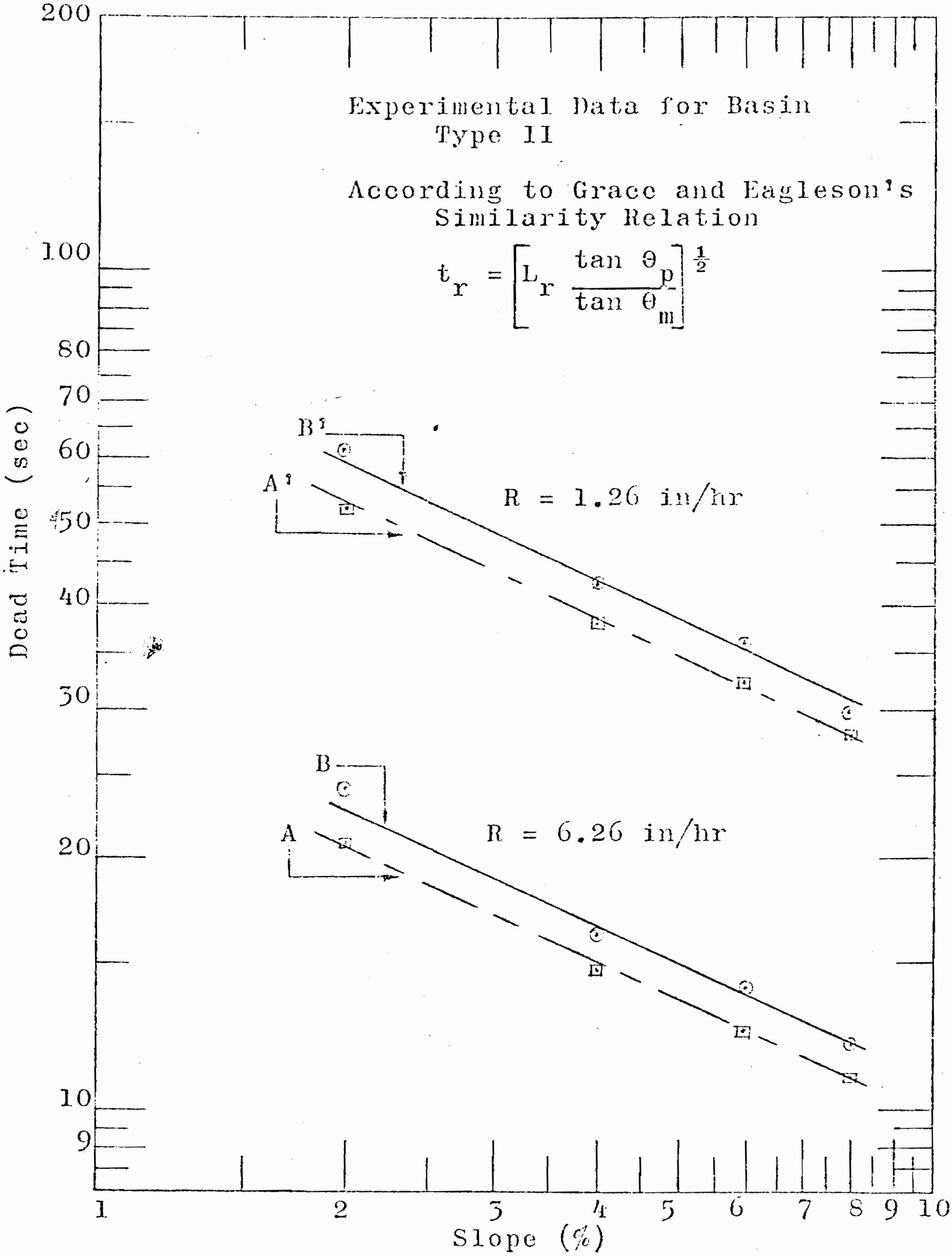


Figure 6-1. Comparison of Actual Data and the Calculation by Grace and Eagleson's Similarity Relation for Dead Time.

into a reservoir with proportional weir type outlet; therefore the nonlinear parameter was reduced to unity. This also reduced the dynamic effect of the system and made it negligible.

The problem in applying systems analysis techniques is that when the system linearity and order is not known there is no standard method for determining the form of the transfer function or the parameters.

VII. CONCLUSIONS

After a careful study and analysis of the experimental data of the hydrologic systems, using different input intensities, different basin areas, shapes and slopes, the following conclusions may be drawn.

1. Systems analysis methods are applicable to hydrologic systems, not only to artificial ones but also to natural hydrologic systems. Some analyzing technique is needed to find the time constant for a nonlinear system from basin parameters and rainfall intensity.

2. The relation between the dead time and the input intensities for artificial hydrologic systems can be represented by the equation

$$T_d = f\ (R^{-0.598})$$

where T_d is dead time (lag) and R is input intensity; f represents a function dependent upon basin characteristics. Further study is necessary to find the relation between dead time and basin characteristics.

3. The damping coefficient for hydrologic systems is close to unity, especially for natural basins. This means that the basin is critically damped if the second order representation is nearly correct.

4. The time constant for hydrologic systems is not only related to the basin characteristics but also depends

on rainfall intensity. For natural basins, the time constant also depends on the infiltration capacity at that time. Further study is necessary to find these relationships. Also needed is the relation between infiltration and rainfall rates.

5. The general transfer function for hydrologic systems is of the form

$$G(s) = \frac{1}{T_c^2 \, s^2 + 2 \, T_c \rho n \, O_R^{\,n-1} \, s + 1}$$

6. For design of an artificial basin, a transverse slope is necessary for fast drainage purposes, and also reduces the detention time.

VIII. GLOSSARY

The letter symbols in this thesis are defined where they first appear and are assembled for convenience of reference in the following

A, B, A_i, C_i, K_i, $i = 1, 2, \ldots n$ = Arbitrary constant

A_a = Area, sq.ft.

C_{fr} = Ratio of friction coefficients, model to prototype

e = Base of the natural logarithm

E = The stage or the elevation of water surface in a reservoir.

F_p = Prototype infiltration intensity

G = Gain

G_k = Gain constant

I = Inflow

L = Length, ft.

L_r = Ratio of a horizontal reference length in the model to prototype

m_1, m_2 = Arbitrary exponent

n = Nonlinear parameter

O_R = Surface runoff

R = Rainfall intensity, in/hr

S = Slope, %

S_t = Storage

s = Laplace transform symbol

t = Time

T_c, T_{c_1}, T_{c_2}, T_c' = Time constant

T_d = Dead time

T_p = Time to peak

T_r = Time ratio, model to prototype

U_r = Velocity ratio, model to prototype

U(t) = Unit function

Y_r = Depth ratio, model to prototype

β = Momentum correction factor

ρ = Damping coefficient

η = Basin shape factor

ξ = $(1 - F_p/R_p)$

ϕ = Phase angle, degree

θ_m = Average basin slopes in model

θ_p = Average basin slopes in prototype

ω = Frequency, radians per time or cycles per time.

IX. ACKNOWLEDGMENTS

The author would like to take this opportunity to express his appreciation to his thesis advisor, Dr. James M. Wiggert, not only for his kind encouragement and generous guidance in the preparation of this thesis, but also for his constructive criticism and personal contact.

The author also wishes to express his gratitude to his major professor, Dr. Henry M. Morris, Head, Department of Civil Engineering, for his advice and encouragement; to Dr. Richard M. Barker, for his invaluable aid during this research; to Dr. Henry R. Bungay III, who through his careful lectures gave the author the necessary knowledge of analog computer; to Professor Paul F. Clemens, for his encouragement during the graduate study; and to his wife, Alice, for her wonderful support and understanding.

He is deeply appreciative to the Water Resource Research Center for the financial support for this research; to Dr. E. F. Brater, Professor, Department of Civil Engineering, University of Michigan, for providing the natural basin data.

Many thanks to Mrs. R. D. Walker who typed this thesis in a limited time.

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XI. VITA

Tsung-Ting Chiang was born in Peng-Pu, Anhwei, China, on November 15, 1936. In 1948, he moved to Taiwan along with his family. After graduating from Taiwan Province Tainan Vocational Industrial High School he worked with the Chinese Military Construction Committee as an assistant engineer for six months and then entered college.

He received the B.S. degree in July, 1960 from Chun Yuan College of Science and Engineering in Taiwan. After this he served as a second lieutenant in the Chinese Army for two years.

In September, 1962, the author came to the United States for graduate study. He completed the requirements for the Master of Science degree in December, 1963, and continued work toward a Doctor of Philosophy degree in Civil Engineering Department at Virginia Polytechnic Institute. He held a research assistantship for four years.

He is a member of the American Society of Civil Engineers and Sigma Xi.

The author is married to the former Alice Mei-Fang Shih and has one son, Vincent.

T. T. Chiang

XII. APPENDICES

Appendix A. Computer Program for Separation of the Base Flow From Overland Flow and Pulse Testing.

```
$IBFTC PULSE
C      DIGITAL COMPUTER PROGRAM PDTFR
C
C      CONVERSION OF PULSE DATA TO FREQUENCY RESPONSE DATA
C
       DIMENSION W(100), PIN(600), POUT(600), TRFFR(100),PREC(100),
      1PHASE(100), GAINM(100), GAIND(100), TRFFI(100),RO(100),PREC1(100),
      2A(100)
C
C      INPUT DATA
C
C      NO OF SETS OF DATA, NO OF OMEGA VALUES, I2, 8X, I3
C      OMEGA VALUES, F10.0
C      DATA DESCRIPTION, 72H
C      NUMBER OF SUBDIVISIONS PER TIME INTERVAL, F10.0
C      NUMBER OF DATA POINTS, I3
C      TIME INTERVAL BETWEEN DATA POINTS, F10.0
C      INPUT DATA, OUT PULSE DATA, 2F9.0
C      DATA TYPE ,2L5, .TRUE. IF DATA IS RATE INFO, .FALSE. OTHERWISE.
C
       INTEGER SRCST,SROEND,TSRO
       LOGICAL TEST1,TEST2
       READ(5,100) JOB, M
   100 FORMAT( I2, 8X, I3 )
       READ(5,101)( W(J), J = 1, M )
   101 FORMAT( F10.0 )
       DO 99 JN = 1, JOB
     1 READ(5,105)
   105 FORMAT( 72H
      1                   ,  )
       DO 63 I=1,100
       PREC(I)=0.
       PREC1(I)=0.
    63 RO(I)=0.
```

```
      READ(5,101) SUBINT
      READ(5,101) XINT
      READ (5,118)TEST1,TEST2
  118 FORMAT (2L5)
      READ (5,200)A1,A2,A3,A4,NPD
  200 FORMAT (A6,3A2,2X,I1,65X)
      NPP=NPD*24
      READ (5,201)(PREC(I),I=1,NPP)
  201 FORMAT (20X,12F5.2)
      READ (5,203)B1,B2,B3,B4,B5,SROST,INA,PKTIM,PKFLO,SROEND
  203 FORMAT (A6,F6.0,3A2,2I3,F5.1,F5.0,I3)
      NROP=(SROEND-SROST)/INA+1
      READ (5,204)(RO(I),I=1,NROP)
  204 FORMAT (20X,12F5.0)
      WRITE (6,202)A1,A2,A3,A4,NPD,NPP
  202 FORMAT (9H1GAGE NO.,A6,6H, DATE,3(1X,A2)/20H PRECIPITATION DAYS,,I
     12,8H, HOURS,,I3/25H            PRECIPITATION)
      WRITE (6,207) (PREC(I), I=1,NPP)
  207 FORMAT (1X,12F5.2)
      WRITE (6,205)SROST,INA,SROEND
  205 FORMAT (7HOSROST=,I3/5H INA=,I3/8H SROEND=,I3)
      WRITE (6,208)(RO(I),I=1,NROP)
  208 FORMAT (4HOSRO/(1X,10F7.0))
          COMPUTING THE NUMBER OF OUTPUT DATA POINTS
      TSRO=SROEND-SROST
      ISRO=TSRO/INA+1
      DO 40 I=2,ISRO
      PREC1(I)=0.
      DO 41 J=1,INA
      JJ=SROST+(I-2)*INA+J-INA
      IF(JJ.LE.0) GO TO 47
   41 PREC1(I)=PREC1(I)+PREC(JJ)
      GO TO 40
   47 PREC1(I)=0.
```

```
 40 CONTINUE
    JJ=ISRO+1
    DO 43 I=JJ,100
 43 PREC1(I)=0.
    PREC1(1)=0.
    IF(SROST.LE.2*INA) GO TO 44
    J=SROST-INA
    J1=J-INA
    DO 42 I=J1,J
 42 PREC1(1)=PREC1(1)+PREC(I)
    GO TO 46
 44 DO 45 I=1,INA
 45 PREC1(1)=PREC1(1)+PREC(I)
 46 WRITE(6,116)
116 FORMAT( 1H1 )
    DO 50 I=1,ISRO
    PIN(I)=PREC1(I)
    POUT(I)=RO(I)
 50 WRITE (6,115) I, PIN(I), POUT(I)
115 FORMAT( 10X, I3, 2F15.6 )
    ADD=0.
    DO 60 I=1,ISRO
 60 ADD=ADD+POUT(I)
    FACT=.0015495857
    XINT=INA
    VOLSRO=FACT*XINT*ADD/82
    WRITE (6,301)ADD,XINT,VOLSRO
301 FORMAT (5HOSUM=,F6.0,8H    INT=,F3.0,11H    VOLSRO=,F6.4)
    DO 700 I=1,ISRO
700 A(I)=PIN(I)
    ISROM=ISRO-1
    DO 70 I=1,ISROM
    J=I+1
    DO 70 K=J,ISRO
```

```
      IF(A(I).GE.A(K)) GO TO 70
      B=A(K)
      A(K)=A(I)
      A(I)=B
   70 CONTINUE
      WRITE (6,304)(I,A(I),I=1,ISRO)
  304 FORMAT (10X,I3,F15.6)
      DO 151 I=2,ISRO
      II=I-1
      VALUE=0.
      DO 150 J=1,II
  150 VALUE=VALUE+A(J)-A(I)
      IF(VALUE.GT.VOLSRO)GO TO 152
  151 CONTINUE
      WRITE (6,302)A1,A2,A3,A4
  302 FORMAT (22H1 INFILTRATION FAILURE,1X,A6,1X,A2,1X,A2,1X,A2)
      GO TO 1
  152 ADD=0.
      DO 153 I=1,II
  153 ADD=ADD+A(I)
      FINF=(ADD-VOLSRO)/FLOAT(II)
      DO 154 I=1,ISRO
      PIN(I)=PIN(I)-FINF
      IF(PIN(I))155,155,154
  155 PIN(I)=0.
  154 CONTINUE
      WRITE (6,303) FINF,(PIN(I),I=1,ISRO)
  303 FORMAT(14H1INFILTRATION=,F8.4,/(5X,F8.4))
      N=ISRO
      XINT=INA
      WRITE (6,119) N, XINT
  119 FORMAT (I10,F10.3)
C
C     SERIES SUMMATION
```

```
      IF(TEST1)GO TO 1000
      N=N-1
      DO 30 I=1,N
   30 PIN(I)=PIN(I+1)-PIN(I)
 1000 IF(TEST2) GO TO 1001
      IF(.NOT.TEST1) GO TO 32
      N=N-1
   32 DO 31 I=1,N
   31 POUT(I)=POUT(I+1)-POUT(I)
 1001 XINT=XINT/SUBINT
C
C     INDEX J CHANGES OMEGA
C
C     INDEX I CONTROLS THE DATA POINT LOCATION
C
      DO 98 J = 1, M
      SSIR = 0.0
      SSII = 0.0
      SSOR = 0.0
      SSOI = 0.0
      AA=0.0
      NN =  N - 1
      DO 10 I = 1, NN
C
      DELI = ( PIN(I+1) - PIN(I) )/SUBINT
      DELO = ( POUT(I+1) - POUT(I) )/SUBINT
      DELI1 = PIN(I)
      DELO1 = POUT(I)
      IT = SUBINT
      DO 9 K = 1, IT
      DELI2 = DELI1 + DELI
      DELO2 = DELO1 + DELO
      FUNTI = (DELI1 + DELI2)/2.0
      FUNTO = (DELO1 + DELO2)/2.0
```

```
      AA=AA+1.0
      X=((2.0*AA-1.0)/2.0)*XINT*W(J)
      SSIR = SSIR + FUNTI*COS( X )
      SSII = SSII + FUNTI*SIN( X )
      SSOR = SSOR + FUNTO*COS( X )
      SSOI = SSOI + FUNTO*SIN( X )
      DELI1 = DELI2
    9 DELO1 = DELO2
   10 CONTINUE
C
C     CALCULATION OF TRANSFER FUNCTION FOR GIVEN OMEGA
C     TRFFR IS TRANSFER FUNCTION REAL PART
C     TRFFI IS TRANSFER FUNCTION IMANGARY PART
C
      TRFFR(J) = (SSOR*SSIR + SSOI*SSII)/
     1 (SSIR*SSIR + SSII*SSII)
      TRFFI(J) = (SSII*SSOR - SSOI*SSIR)/
     1 (SSIR*SSIR + SSII*SSII)
      GAINM(J) = SQRT(TRFFR(J)*TRFFR(J)+TRFFI(J)*TRFFI(J))
      GAIND(J) = 20.0*ALOG10( GAINM(J) )
      PHASE(J) = 57.29578*(ATAN( TRFFI(J)/TRFFR(J) ) )
      IF( TRFFR(J) ) 11, 14, 17
   11 IF( TRFFI(J) ) 12, 13, 12
   12 TAN = PHASE(J) - 180.
      GO TO 20
   13 TAN = -180.
      GO TO 20
   14 IF( TRFFI(J) ) 15, 21, 16
   15 TAN = -90.
      GO TO 20
   16 TAN = -270.
      GO TO 20
   17 IF( TRFFI(J) ) 21, 21, 18
   18 TAN = PHASE(J)
```

```
 20 PHASE(J) = TAN
 21 CONTINUE
 22 IF( J - 1) 23, 23, 24
 23 SSPHAS = PHASE(1)
    SSGAM = GAINM(1)
    SSGAD = GAIND(1)
 24 PHASE(J) = PHASE(J) - SSPHAS
    GAINM(J) = GAINM(J)/SSGAM
    GAIND(J) = GAIND(J) - SSGAD
    IF( J-1 ) 98, 25, 26
 25 WRITE(6,106)
106 FORMAT( 1H1, 15X, 27HFREQUENCY RESPONSE RESULTS ,
   1 14HFOR PULSE TEST//  )
    WRITE(7,106)
    WRITE(6,105)
    WRITE(7,105)
    WRITE(6,107)
107 FORMAT(//17X, 12HSTEADY-STATE, 3X, 11HPHASE ANGLE,
   14X,12HSTEADY-STATE,/22X,4HGAIN,10X,7HDEGREES,7X,
   2 8HDECIBELS    )
    WRITE(7,107)
    WRITE(6,108) SSGAM, SSPHAS, SSGAD
108 FORMAT(13X,E13.4, 7X, F8.4, 7X, F8.4   )
    WRITE(7,108) SSGAM, SSPHAS, SSGAD
    WRITE(6,109)
109 FORMAT( //9X, 9HMAGNITUDE, 5X, 11HPHASE ANGLE, 7X,
   14HGAIN, 9X, 9HFREQUENCY, /11X, 5HRATIO, 9X,
   27HDEGREES, 7X, 8HDECIBELS, 6X, 11HRADIANS/MIN  )
    WRITE(7,109)
 26 B = J
    B1 = B/5.0
    J1 = J/5
    B2 = J1
    IF(B1-B2) 27, 28, 27
```

```
   27 WRITE(6,110)(GAINM(J), PHASE(J), GAIND(J), W(J) )
  110 FORMAT( 7X, F9.4, F16.2, F14.4, F15.4,16X, I3 )
      WRITE(7,110)(GAINM(J), PHASE(J), GAIND(J), W(J), J )
      GO TO 98
   28 WRITE(6,117)( GAINM(J), PHASE(J), GAIND(J), W(J) )
  117 FORMAT( 7X, F9.4, F16.2, F14.4, F15.4// )
      WRITE(7,111)(GAINM(J), PHASE(J), GAIND(J), W(J), J )
  111 FORMAT( 7X, F9.4, F16.2, F14.4, F15.4,16X, I3// )
   98 CONTINUE
      WRITE(7,112) SSGAM, SSPHAS, SSGAD
  112 FORMAT(3F10.5 )
      WRITE(7,113)( TRFFR(J), TRFFI(J), W(J), J, J=1,M   )
  113 FORMAT( 3F10.5, 40X, I3 )
   99 CONTINUE
      STOP
      END
$ENTRY          PULSE


GND TOTAL
```

Appendix B. An Example of Frequency Response Results for Pulse Test

RUN 2, S=0.02, R =1.26 IN/HR, TIME=1 MIN, LAG=45 SEC, TYPE 3

STEADY-STATE GAIN	PHASE ANGLE DEGREES	STEADY-STATE DECIBELS
0.8016	-0.3671	-1.9210

MAGNITUDE RATIO	PHASE ANGLE DEGREES	GAIN DECIBELS	FREQUENCY RADIANS/MIN
1.0000	0.00	0.0000	0.0001
1.0000	-1.10	-0.0003	0.0004
0.9999	-2.20	-0.0010	0.0007
0.9998	-2.94	-0.0017	0.0009
0.9998	-3.30	-0.0021	0.0010
0.9990	-6.97	-0.0085	0.0020
0.9985	-8.81	-0.0133	0.0025
0.9978	-10.64	-0.0191	0.0030
0.9961	-14.31	-0.0340	0.0040
0.9939	-17.97	-0.0531	0.0050
0.9912	-21.63	-0.0764	0.0060
0.9881	-25.28	-0.1039	0.0070
0.9845	-28.93	-0.1355	0.0080
0.9805	-32.57	-0.1712	0.0090
0.9760	-36.20	-0.2111	0.0100
0.9474	-54.23	-0.4696	0.0150
0.9098	-71.93	-0.8208	0.0200
0.8182	-105.95	-1.7431	0.0300

0.7250	-137.67	-2.7936	0.0400
0.6139	-197.22	-4.2375	0.0600
0.5819	-265.94	-4.7032	0.0800
0.5563	53.40	-5.0940	0.0900
0.5206	8.11	-5.6692	0.1000
0.0546	54.28	-25.2621	0.1500
0.0931	-65.60	-20.6199	0.2000
0.9189	68.73	-0.7345	0.4000
0.5797	89.71	-4.7361	0.5000
0.1219	-139.97	-18.2804	0.7000

GND TOTAL

Appendix C. Experimental Data

Basin Type	I	Rain Intensity	6.26 In/Hr	Duration 5 Min.	Time Interval	30 Sec.
No.	Runoff / Rainfall		S = 8 % T_D = 14 Sec	S = 6 % T_D = 15.5 Sec	S = 4 % T_D = 18 Sec	S = 2 % T_D = 25 Sec
1	1.25		0.2885	0.2692	0.1346	0.0385
2	1.25		1.1154	1.0577	0.8654	0.5192
3	1.25		1.1731	1.1538	1.0962	0.8462
4	1.25		1.1538	1.1538	1.1731	0.9615
5	1.25		1.1923	1.1923	1.1538	1.0577
6	1.25		1.1923	1.1923	1.1538	1.0769
7	1.25		1.1538	1.1731	1.1731	1.0962
8	1.25		1.1538	1.1923	1.1538	1.1154
9	1.25		1.1731	1.1538	1.1538	1.1154
10	1.25		1.1731	1.1923	1.1731	1.1538
11	0.0		0.9808	0.9615	0.9808	1.0385
12	0.0		0.3654	0.3077	0.4808	0.7692
13	0.0		0.0962	0.0769	0.0962	0.3846
14	0.0		0.0385	0.0385	0.0385	0.1538
15	0.0		0.0192	0.0192	0.0385	0.0769

Basin Type	I	Rain Intensity	1.26 In/Hr	Duration 5 Min.	Time Interval	30 Sec.
No.	Runoff / Rainfall		S = 8 % T_D = 34 Sec	S = 6 % T_D = 40.5 Sec	S = 4 % T_D = 46.5 Sec	S = 2 % T_D = 63 Sec
1	0.252		0.0	0.0	0.0	0.0
2	0.252		0.0769	0.0514	0.0327	0.0
3	0.252		0.2500	0.2250	0.1692	0.0600
4	0.252		0.2308	0.2212	0.2212	0.1353
5	0.252		0.2500	0.2308	0.2308	0.2771
6	0.252		0.2510	0.2212	0.2212	0.2019
7	0.252		0.2551	0.2212	0.2115	0.2019
8	0.252		0.2500	0.2212	0.2212	0.2019
9	0.252		0.2500	0.2308	0.2212	0.2308
10	0.252		0.2500	0.2212	0.2115	0.2115
11	0.0		0.2308	0.1923	0.2115	0.2115
12	0.0		0.0962	0.0962	0.0962	0.1346
13	0.0		0.0385	0.0385	0.0577	0.0865
14	0.0		0.0192	0.0288	0.0384	0.0577
15	0.0		-	0.0192	0.0355	0.0385
16	0.0		-	-	0.0154	0.0193

Note: T_D = Dead Time S = Longitude Slope

Rain-fall = Total rainfall per basin area per time interval.

Run-off = Total runoff per basin area per time interval.

Basin Type	II	Rain Intensity	6.26 In/Hr	Duration	5 Min.	Time Interval	30 Sec.
No.	Runoff / Rainfall		S = 8 % T_D= 11.5 Sec	S = 6 % T_D= 14 Sec		S = 4 % T_D= 17 Sec	S = 2 % T_D= 25 Sec
1	0.557		0.1404	0.1154		0.0769	0.0192
2	0.557		0.4365	0.4038		0.2693	0.1923
3	0.557		0.4769	0.4423		0.4231	0.3077
4	0.557		0.4692	0.4808		0.4519	0.3846
5	0.557		0.4615	0.4615		0.4615	0.4038
6	0.557		0.4923	0.4615		0.4711	0.4231
7	0.557		0.4942	0.4808		0.4808	0.4423
8	0.557		0.4808	0.4615		0.4712	0.4615
9	0.557		0.4808	0.4712		0.4712	0.4615
10	0.557		0.5000	0.4808		0.4904	0.4615
11	0.0		0.3865	0.4423		0.4534	0.4615
12	0.0		0.1385	0.1538		0.2000	0.2885
13	0.0		0.0500	0.0577		0.0577	0.1538
14	0.0		0.0212	0.0254		0.0480	0.1154
15	0.0		0.0192	0.0192		0.0231	0.0577
16	0.0		0.0096	0.0192		0.0154	0.0481
17	0.0		-	-		-	0.0288

Basin Type	II	Rain Intensity	1.27 In/Hr	Duration	5 Min.	Time Interval	30 Sec.
No.	Runoff / Rainfall		S = 8 % T_D= 31 Sec	S = 6 % T_D= 36 Sec		S = 4 % T_D= 42 Sec	S = 2 % T_D= 62 Sec
1	0.113		0.0	0.0		0.0	0.0
2	0.113		0.0673	0.0673		0.0518	0.0
3	0.113		0.1154	0.1019		0.1058	0.0615
4	0.113		0.1154	0.1154		0.1058	0.0962
5	0.113		0.1115	0.1096		0.1058	0.1115
6	0.113		0.1096	0.1154		0.1058	0.1115
7	0.113		0.1115	0.1058		0.1115	0.1096
8	0.113		0.1115	0.1058		0.1058	0.1058
9	0.113		0.1115	0.1058		0.1058	0.1154
10	0.113		0.1058	0.1096		0.1058	0.1058
11	0.0		0.0712	0.0962		0.0865	0.0962
12	0.0		0.0500	0.0556		0.0576	0.0576
13	0.0		0.0288	0.0384		0.0384	0.0384
14	0.0		0.0192	0.0288		0.0288	0.0384
15	0.0		0.0192	0.0192		0.0192	0.0288
16	0.0		0.0096	0.0192		0.0192	0.0288
17	0.0		-	-		-	0.0196

Note: T_D= Dead Time S = Longitude Slope

Rainfall= Total rainfall per basin area per time interval.

Runoff = Total runoff per basin area per time interval.

Basin Type	III	Rain Intensity	6.26 In/Hr	Duration	5 Min.	Time Interval	30 Sec.
No.	Rainfall \ Runoff		S = 8 % T_D = 11 Sec	S = 6 % T_D = 12 Sec	S = 4 % T_D = 13.5 Sec		S = 2 % T_D = 18 Sec
1	1.250		0.5769	0.5769	0.5000		0.3846
2	1.250		1.1154	1.0962	1.1154		1.1538
3	1.250		1.1346	1.0769	1.0962		1.0962
4	1.250		1.0962	1.0769	1.0577		1.0577
5	1.250		1.0769	1.1154	1.0962		1.0962
6	1.250		1.1346	1.1154	1.1346		1.0962
7	1.250		1.0769	1.0962	1.0769		1.0769
8	1.250		1.1346	1.0769	1.1154		1.0769
9	1.250		1.0769	1.0962	1.0962		1.0577
10	1.250		1.1154	1.0962	1.1154		1.1346
11	0.0		0.7115	0.7500	0.6731		0.7885
12	0.0		0.1154	0.1346	0.1154		0.2115
13	0.0		0.0385	0.0385	0.0385		0.0577
14	0.0		0.0192	0.0192	0.0192		0.0288
15	0.0		0.0154	0.0154	0.0154		0.0192

Basin Type	III	Rain Intensity	1.26 In/Hr	Duration	5 Min.	Time Interval	30 Sec.
No.	Rainfall \ Runoff		S = 8 % T_D = 27 Sec	S = 6 % T_D = 30.5 Sec	S = 4 % T_D = 36 Sec		S = 2 % T_D = 47.5 Sec
1	0.252		0.0096	0.0	0.0		0.0
2	0.252		0.1827	0.1427	0.1346		0.0577
3	0.252		0.2308	0.2404	0.2404		0.2404
4	0.252		0.2404	0.2500	0.2500		0.2404
5	0.252		0.2212	0.2212	0.2491		0.2404
6	0.252		0.2212	0.2500	0.2404		0.2404
7	0.252		0.2212	0.2308	0.2308		0.2308
8	0.252		0.2212	0.2308	0.2308		0.2404
9	0.252		0.2212	0.2308	0.2308		0.2115
10	0.252		0.2308	0.2404	0.2308		0.2404
11	0.0		0.1731	0.1827	0.1635		0.1827
12	0.0		0.0577	0.0481	0.0673		0.0673
13	0.0		0.0385	0.0288	0.0385		0.0345
14	0.0		0.0192	0.0192	0.0192		0.0192

Note: T_D = Dead Time S = Longitude Slope

Rainfall = Total rainfall per basin area per time interval.
Runoff = Total runoff per basin area per time interval.

Basin Type	I	Rain Intensity	0.83 In/Hr	Duration	5 Min.	Time Interval	30 Sec.

No.	Runoff / Rainfall	$S = 8\%$ $T_D = 44$ Sec	$S = 6\%$ $T_D = 53$ Sec	$S = 4\%$ $T_D = 60$ Sec	$S = 2\%$ $T_D = 87$ Sec
1	0.164	0.0	0.0	0.0	0.0
2	0.164	0.0327	0.0135	0.0	0.0
3	0.164	0.1404	0.0827	0.0673	0.0019
4	0.164	0.1442	0.1346	0.1058	0.0469
5	0.164	0.1442	0.1346	0.1255	0.0962
6	0.164	0.1442	0.1538	0.1255	0.1250
7	0.164	0.1442	0.1269	0.1269	0.1346
8	0.164	0.1538	0.1423	0.1346	0.1346
9	0.164	0.1346	0.1423	0.1442	0.1423
10	0.164	0.1538	0.1446	0.1442	0.1442
11	0.0	0.1154	0.1250	0.1269	0.1346
12	0.0	0.0481	0.0577	0.0769	0.1005
13	0.0	0.0385	0.0385	0.0480	0.0679
14	0.0	0.0288	0.0288	0.0364	0.0481
15	0.0	0.0192	0.0192	0.0201	0.0357
16	0.0	0.0100	0.0100	0.0120	0.0288
17	0.0	-	-	-	0.0192

Basin Type	III	Rain Intensity	0.83 In/Hr	Duration	5 Min.	Time Interval	30 Sec.

No.	Runoff / Rainfall	$S = 8\%$ $T_D = 36$ Sec	$S = 6\%$ $T_D = 42$ Sec	$S = 4\%$ $T_D = 49$ Sec	$S = 2\%$ $T_D = 64$ Sec
1	0.164	0.0	0.0	0.0	0.0
2	0.164	0.0769	0.0385	0.0269	0.0
3	0.164	0.1250	0.1154	0.1077	0.0865
4	0.164	0.1538	0.1442	0.1347	0.1442
5	0.164	0.1538	0.1442	0.1538	0.1442
6	0.164	0.1538	0.1538	0.1538	0.1442
7	0.164	0.1346	0.1346	0.1346	0.1442
8	0.164	0.1538	0.1442	0.1442	0.1635
9	0.164	0.1442	0.1442	0.1442	0.1538
10	0.164	0.1442	0.1538	0.1538	0.1442
11	0.0	0.1154	0.1154	0.1154	0.1250
12	0.0	0.0385	0.0576	0.0576	0.0673
13	0.0	0.0211	0.0215	0.0288	0.0318
14	0.0	0.0192	0.0192	0.0195	0.0211
15	0.0	0.0100	0.0100	0.0100	0.0100
16	0.0	0.0851	0.0851	0.0851	0.0962

Note: T_D = Dead Time S = Longitude Slope

Rainfall = Total rainfall per basin area per time interval.
Runoff = Total runoff per basin area per time interval.

Basin Type III	Rain Intensity 1.26 In/Hr	Duration 1 Min.		Time Interval 15 Sec.	
No.	Runoff / Rainfall	S = 8 %, T_D = 25 Sec	S = 6 %, T_D = 29 Sec	S = 4 %, T_D = 37 Sec	S = 2 %, T_D = 45 Sec
1	0.126	0.0	0.0	0.0	0.0
2	0.126	0.006	0.002	0.0	0.0
3	0.126	0.053	0.040	0.017	0.0
4	0.126	0.095	0.093	0.067	0.013
5	0.0	0.122	0.101	0.117	0.042
6	0.0	0.056	0.068	0.073	0.091
7	0.0	0.018	0.025	0.037	0.090
8	0.0	0.010	0.013	0.019	0.064
9	0.0	0.006	0.007	0.012	0.021
10	0.0	0.004	0.005	0.010	0.014
11	0.0	0.003	0.003	0.006	0.008
12	0.0	0.003	0.003	0.003	0.006

Basin Type	Rain Intensity In/Hr	Duration Min.		Time Interval Sec.	
No.	Runoff / Rainfall	S = 8 %, T_D= Sec	S = 6 %, T_D= Sec	S = 4 %, T_D= Sec	S = 2 %, T_D= Sec

Note: T_D= Dead Time S = Longitude Slope

Rainfall= Total rainfall per basin area per time interval.

Runoff = Total runoff per basin area per time interval.

Basin Type	I	Rain Intensity	6.26 In/Hr	Duration	10 Min.	Time Interval	30 Sec.
No.	Runoff / Rainfall		S = 8 % T_D = 14 Sec	S = 6 % T_D = 16 Sec		S = 4 % T_D = 17 Sec	S = 2 % T_D = 26.5 Sec
1	1.25		0.2885	0.2308		0.1923	0.0192
2	1.25		1.1154	0.9808		0.9231	0.5000
3	1.25		1.1538	1.1346		1.0769	0.8654
4	1.25		1.1731	1.1538		1.1731	0.9808
5	1.25		1.1660	1.1538		1.1731	1.0577
6	1.25		1.1635	1.1731		1.1923	1.1154
7	1.25		1.1538	1.1346		1.1731	1.1346
8	1.25		1.1731	1.1538		1.2115	1.1538
9	1.25		1.1731	1.1731		1.1731	1.1538
10	1.25		1.1731	1.1731		1.1923	1.1731
11	1.25		1.1538	1.1538		1.1923	1.1731
12	1.25		1.1538	1.1731		1.1923	1.1923
13	1.25		1.1923	1.1538		1.1923	1.1538
14	1.25		1.1538	1.1538		1.1923	1.1731
15	1.25		1.1538	1.1731		1.2115	1.1538
16	1.25		1.1538	1.1731		1.1731	1.1731
17	1.25		1.1538	1.1538		1.1731	1.1538
18	1.25		1.1538	1.1538		1.1538	1.1731
19	1.25		1.1731	1.1731		1.1731	1.1538
20	1.25		1.1346	1.1731		1.2115	1.1731
21	0.0		0.9038	0.0423		0.9423	1.0577
22	0.0		0.2308	0.3077		0.4423	0.7692
23	0.0		0.0577	0.0577		0.0962	0.4038
24	0.0		0.0384	0.0385		0.0577	0.1538
25	0.0		0.0254	0.0254		0.0385	0.0769
26	0.0		0.0192	0.0192		0.0192	0.0384
27	0.0		-	-		-	0.0385

Note: T_D = Dead Time S = Longitude Slope

Rainfall = Total rainfall per basin area per time interval.

Runoff = Total runoff per basin area per time interval.

Basin Type	I	Rain Intensity	1.26 In/Hr	Duration	10 Min.	Time Interval	30 Sec.
No.	Runoff / Rainfall		S = 8 % T_D= 34 Sec	S = 6 % T_D= 41 Sec	S = 4 % T_D= 47 Sec		S = 2 % T_D= Sec
1	0.252		0.0	0.0	0.0		
2	0.252		0.0769	0.0502	0.0288		
3	0.252		0.2308	0.2212	0.1635		
4	0.252		0.2500	0.2212	0.2115		
5	0.252		0.2500	0.2308	0.2404		
6	0.252		0.2500	0.2308	0.2115		
7	0.252		0.2500	0.2212	0.2115		
8	0.252		0.2500	0.2404	0.2115		
9	0.252		0.2500	0.2212	0.2115		
10	0.252		0.2500	0.2212	0.2125		
11	0.252		0.2500	0.2212	0.2212		
12	0.252		0.2500	0.2308	0.2212		
13	0.252		0.2500	0.2212	0.2115		
14	0.252		0.2415	0.2212	0.2308		
15	0.252		0.2500	0.2212	0.2500		
16	0.252		0.2510	0.2212	0.2410		
17	0.252		0.2417	0.2115	0.2212		
18	0.252		0.2500	0.2115	0.2212		
19	0.252		0.2500	0.2115	0.2212		
20	0.252		0.2612	0.2212	0.2404		
21	0		0.1923	0.1923	0.2115		
22	0		0.0769	0.0673	0.0865		
23	0		0.0385	0.0385	0.0481		
24	0		0.0385	0.0288	0.0385		
25	0		0.0192	0.0211	0.0288		

Note: T_D= Dead Time S = Longitude Slope

Rainfall= Total rainfall per basin area per time interval.
Runoff = Total runoff per basin area per time interval.

Basin Type	I	Rain Intensity	0.83 In/Hr	Duration	10 Min.	Time Interval	30 Sec.
No.	Runoff / Rainfall		S = 8 %, T_D = 43 Sec	S = 6 %, T_D = 50 Sec		S = 4 %, T_D = 63 Sec	S = 2 %, T_D = 85 Sec
1	0.164		0.0	0.0		0.0	0.0
2	0.164		0.0481	0.0195		0.0	0.0
3	0.164		0.1442	0.0901		0.0500	0.0071
4	0.164		0.1442	0.1346		0.1135	0.0987
5	0.164		0.1500	0.1538		0.1346	0.1250
6	0.164		0.1481	0.1442		0.1250	0.1442
7	0.164		0.1442	0.1250		0.1250	0.1250
8	0.164		0.1442	0.1442		0.1346	0.1346
9	0.164		0.1442	0.1442		0.1346	0.1442
10	0.164		0.1442	0.1346		0.1346	0.1442
11	0.164		0.1538	0.1442		0.1538	0.1442
12	0.164		0.1442	0.1442		0.1442	0.1346
13	0.164		0.1538	0.1442		0.1442	0.1538
14	0.164		0.1442	0.1442		0.1250	0.1250
15	0.164		0.1442	0.1346		0.1538	0.1346
16	0.164		0.1442	0.1442		0.1346	0.1442
17	0.164		0.1442	0.1346		0.1442	0.1346
18	0.164		0.1442	0.1538		0.1346	0.1442
19	0.164		0.1442	0.1346		0.1250	0.1346
20	0.164		0.1442	0.1538		0.1442	0.1442
21	0.0		0.1346	0.1250		0.1250	0.1346
22	0.0		0.0577	0.0587		0.0673	0.1024
23	0.0		0.0231	0.0288		0.0480	0.0587
24	0.0		0.0154	0.0192		0.0481	0.0481
25	0.0		0.0087	0.0096		0.0192	0.0288
26	0.0		-	-		0.0076	0.0288
27	0.0		-	-		-	0.0192

Note: T_D= Dead Time S = Longitude Slope

Rainfall= Total rainfall per basin area per time interval.

Runoff = Total runoff per basin area per time interval.

Basin Type	II	Rain Intensity	1.27 In/Hr	Duration	10 Min.	Time Interval	30 Sec.
No.	Runoff / Rainfall	S = 8 % T_D = 30 Sec		S = 6 % T_D = 37 Sec		S = 4 % T_D = 42 Sec	S = 2 % T_D = 60 Sec
1	0.113	0.0		0.0		0.0	0.0
2	0.113	0.0673		0.0577		0.0510	0.0
3	0.113	0.1154		0.1154		0.1154	0.0769
4	0.113	0.1058		0.1154		0.1096	0.1058
5	0.113	0.1054		0.0962		0.1154	0.1154
6	0.113	0.1154		0.1154		0.1096	0.1096
7	0.113	0.1154		0.0962		0.1115	0.1115
8	0.113	0.1154		0.1058		0.1154	0.1154
9	0.113	0.1115		0.1058		0.1115	0.1058
10	0.113	0.1096		0.1058		0.1096	0.1154
11	0.113	0.1115		0.1058		0.1058	0.1058
12	0.113	0.1058		0.1058		0.1058	0.1115
13	0.113	0.1058		0.1058		0.1154	0.1096
14	0.113	0.1058		0.1058		0.1058	0.1115
15	0.113	0.1058		0.1115		0.1058	0.1115
16	0.113	0.1058		0.1058		0.1058	0.1154
17	0.113	0.1058		0.1115		0.1058	0.1154
18	0.113	0.1058		0.1058		0.1058	0.1058
19	0.113	0.1058		0.1058		0.1115	0.1058
20	0.113	0.0962		0.0962		0.1115	0.1115
21	0.0	0.0673		0.0865		0.0962	0.0962
22	0.0	0.0481		0.0481		0.0577	0.0769
23	0.0	0.0288		0.0288		0.0288	0.0384
24	0.0	0.0192		0.0194		0.0194	0.0288
25	0.0	-		-		0.0154	0.0192

Note: T_D= Dead Time S = Longitude Slope

Rainfall= Total rainfall per basin area per time interval.

Runoff = Total runoff per basin area per time interval.

Basin Type	II	Rain Intensity	6.26 In/Hr	Duration	10 Min.	Time Interval	30 Sec.

No.	Runoff / Rainfall	S = 8 %, T_D = 12.5 Sec	S = 6 %, T_D = 14 Sec	S = 4 %, T_D = 16 Sec	S = 2 %, T_D = 24 Sec
1	0.557	0.1346	0.1154	0.0865	0.0231
2	0.557	0.4615	0.4038	0.2981	0.1885
3	0.557	0.4423	0.4423	0.4231	0.2981
4	0.557	0.4808	0.4615	0.4423	0.3942
5	0.557	0.4615	0.4615	0.4615	0.4231
6	0.557	0.4423	0.4615	0.4615	0.4231
7	0.557	0.5000	0.4615	0.4712	0.4423
8	0.557	0.4808	0.4808	0.4712	0.4712
9	0.557	0.4615	0.4615	0.4808	0.4519
10	0.557	0.4615	0.4615	0.4615	0.4712
11	0.557	0.4712	0.4615	0.4808	0.4712
12	0.557	0.5096	0.4615	0.4424	0.4808
13	0.557	0.4808	0.4808	0.4808	0.4808
14	0.557	0.5000	0.4615	0.5000	0.4904
15	0.557	0.4808	0.4808	0.4615	0.4615
16	0.557	0.4615	0.4615	0.4615	0.4712
17	0.557	0.4808	0.4615	0.4808	0.4712
18	0.557	0.4808	0.4615	0.4808	0.4808
19	0.557	0.4808	0.4615	0.5000	0.4808
20	0.557	0.4615	0.4615	0.4615	0.4519
21	0.0	0.3462	0.4423	0.4423	0.4615
22	0.0	0.1250	0.1154	0.2308	0.3269
23	0.0	0.0346	0.0384	0.0769	0.2308
24	0.0	0.0340	0.0340	0.0385	0.1538
25	0.0	0.0192	0.0192	0.0192	0.0962
26	0.0	-	0.0115	0.0192	0.0603
27	0.0	-	-	-	0.0451
28	0.0	-	-	-	0.0200

Note: T_D = Dead Time S = Longitude Slope

Rainfall = Total rainfall per basin area per time interval.

Runoff = Total runoff per basin area per time interval.

Basin Type	III	Rain Intensity	6.26 In/Hr	Duration	10 Min.	Time Interval	30 Sec.
No.	Runoff / Rainfall	S = 8 % T_D = 10 Sec	S = 6 % T_D = 11.5 Sec	S = 4 % T_D = 13.5Sec	S = 2 % T_D = 19 Sec		
1	1.250	0.6346	0.5962	0.5000	0.3462		
2	1.250	1.0962	1.0962	1.1154	1.1346		
3	1.250	1.0769	1.0673	1.0962	1.0769		
4	1.250	1.0577	1.0865	1.0962	1.0962		
5	1.250	1.0577	1.0769	1.0769	1.0577		
6	1.250	1.1154	1.1154	1.1154	1.1154		
7	1.250	1.0962	1.0769	1.0769	1.0576		
8	1.250	1.0769	1.0962	1.0962	1.0577		
9	1.250	1.0769	1.0769	1.1154	1.0769		
10	1.250	1.0673	1.0962	1.0962	1.0577		
11	1.250	1.0865	1.0769	1.0962	1.0769		
12	1.250	1.0769	1.0962	1.0769	1.0769		
13	1.250	1.0577	1.0962	1.0962	1.0577		
14	1.250	1.0769	1.0769	1.0962	1.0962		
15	1.250	1.0577	1.0962	1.0769	1.0962		
16	1.250	1.0769	1.1154	1.0769	1.0577		
17	1.250	1.0577	1.0769	1.0577	1.0577		
18	1.250	1.0577	1.0962	1.0769	1.0962		
19	1.250	1.0769	1.0769	1.0577	1.0769		
20	1.250	1.0769	1.0962	1.0769	1.0769		
21	0.0	0.6154	0.6923	0.7500	0.7500		
22	0.0	0.0962	0.1154	0.1250	0.1923		
23	0.0	0.0385	0.0385	0.0385	0.0577		
24	0.0	0.0192	0.0192	0.0192	0.0288		
25	0.0	0.0096	0.0096	0.0096	0.0145		

Note: T_D = Dead Time S = Longitude Slope

Rainfall = Total rainfall per basin area per time interval.

Runoff = Total runoff per basin area per time interval.

Basin Type	III	Rain Intensity	1.26 In/Hr	Duration	10 Min.	Time Interval	30 Sec.
No.	Runoff / Rainfall		S = 8 %, T_D = 28 Sec	S = 6 %, T_D = 31 Sec		S = 4 %, T_D = 38 Sec	S = 2 %, T_D = 47 Sec
1	0.252		0.0096	0.0		0.0	0.0
2	0.252		0.1731	0.1427		0.0865	0.0673
3	0.252		0.2308	0.2404		0.2212	0.2500
4	0.252		0.2212	0.2404		0.2500	0.2692
5	0.252		0.2212	0.2404		0.2404	0.2308
6	0.252		0.2212	0.2500		0.2115	0.2500
7	0.252		0.2308	0.2212		0.2308	0.2500
8	0.252		0.2115	0.2404		0.2308	0.2308
9	0.252		0.2212	0.2308		0.2308	0.2308
10	0.252		0.2212	0.2308		0.2308	0.2308
11	0.252		0.2404	0.2308		0.2212	0.2404
12	0.252		0.2212	0.2500		0.2308	0.2500
13	0.252		0.2212	0.2308		0.2212	0.2308
14	0.252		0.2212	0.2308		0.2212	0.2308
15	0.252		0.2212	0.2308		0.2212	0.2308
16	0.252		0.2115	0.2404		0.2308	0.2404
17	0.252		0.2115	0.2308		0.2212	0.2308
18	0.252		0.2212	0.2308		0.2308	0.2404
19	0.252		0.2212	0.2308		0.2212	0.2404
20	0.252		0.2308	0.2404		0.2212	0.2308
21	0.0		0.1634	0.1635		0.1827	0.1923
22	0.0		0.0385	0.0577		0.0865	0.0769
23	0.0		0.0193	0.0193		0.0193	0.0193
24	0.0		0.0096	0.0096		0.0096	0.0193
25	0.0		0.0096	0.0096		0.0096	0.0096

Note: T_D= Dead Time S = Longitude Slope

Rainfall= Total rainfall per basin area per time interval.
Runoff = Total runoff per basin area per time interval.

Basin Type	III	Rain Intensity	0.83 In/Hr	Duration	10 Min.	Time Interval	30 Sec.

No.	Runoff / Rainfall	S = 8 % T_D= 37.5 Sec	S = 6 % T_D= 42.5 Sec	S = 4 % T_D= 48 Sec	S = 2 % T_D= 64 Sec
1	0.164	0.0	0.0	0.0	0.0
2	0.164	0.0481	0.0346	0.0288	0.0
3	0.164	0.1058	0.1154	0.1058	0.0865
4	0.164	0.1538	0.1384	0.1442	0.1346
5	0.164	0.1538	0.1538	0.1538	0.1538
6	0.164	0.1442	0.1442	0.1538	0.1442
7	0.164	0.1538	0.1442	0.1442	0.1442
8	0.164	0.1442	0.1442	0.1442	0.1538
9	0.164	0.1442	0.1442	0.1442	0.1442
10	0.164	0.1442	0.1442	0.1442	0.1442
11	0.164	0.1442	0.1442	0.1442	0.1442
12	0.164	0.1538	0.1538	0.1442	0.1538
13	0.164	0.1443	0.1443	0.1443	0.1443
14	0.164	0.1351	0.1442	0.1351	0.1442
15	0.164	0.1442	0.1442	0.1442	0.1351
16	0.164	0.1442	0.1442	0.1442	0.1346
17	0.164	0.1442	0.1480	0.1442	0.1500
18	0.164	0.1442	0.1405	0.1380	0.1331
19	0.164	0.1530	0.1442	0.1500	0.1442
20	0.164	0.1442	0.1442	0.1442	0.1530
21	0.0	0.1250	0.1346	0.1346	0.1250
22	0.0	0.0385	0.0385	0.0481	0.0553
23	0.0	0.0192	0.0192	0.0288	0.0198
24	0.0	0.0096	0.0115	0.0192	0.0192
24	0.0	-	0.0077	0.0096	0.0096

Note: T_D= Dead Time S = Longitude Slope

Rainfall= Total rainfall per basin area per time interval.

Runoff = Total runoff per basin area per time interval.

Basin Type	I	Rain Intensity	6.26 In/Hr	Duration	15 Min.	Time Interval	30 Sec.

No.	Rainfall \ Runoff	S = 8 % T_D= 13 Sec	S = 6 % T_D= 15 Sec	S = 4 % T_D= 17.5 Sec	S = 2 % T_D= 26 Sec
1	1.250	0.3462	0.3269	0.1731	0.0192
2	1.250	1.0769	0.9808	0.9231	0.5000
3	1.250	1.1731	1.0577	1.0962	0.8846
4	1.250	1.1346	1.1346	1.1538	1.0000
5	1.250	1.1923	1.1538	1.1538	1.0577
6	1.250	1.1731	1.1538	1.1538	1.0769
7	1.250	1.1346	1.1538	1.1731	1.1538
8	1.250	1.1731	1.1538	1.1538	1.2115
9	1.250	1.1731	1.1538	1.1538	1.0385
10	1.250	1.1346	1.1538	1.1731	1.1538
11	1.250	1.1538	1.1346	1.1731	1.1538
12	1.250	1.1731	1.1923	1.1538	1.1538
13	1.250	1.0769	1.1731	1.2115	1.1538
14	1.250	1.1346	1.1731	1.1538	1.1538
15	1.250	1.1923	1.1731	1.1731	1.1538
16	1.250	1.1538	1.1911	1.1538	1.1538
17	1.250	1.2445	1.1538	1.1731	1.1923
18	1.250	1.2013	1.1731	1.1731	1.1731
19	1.250	1.1731	1.1923	1.1923	1.1538
20	1.250	1.1731	1.2115	1.1923	1.1923
21	1.250	1.1923	1.1346	1.1347	1.1923
22	1.250	1.1731	1.1538	1.1923	1.1539
23	1.250	1.1538	1.2301	1.1538	1.2115
24	1.250	1.1923	1.1923	1.1538	1.1538
25	1.250	1.1538	1.1731	1.2115	1.1731
26	1.250	1.1731	1.1923	1.1346	1.2307
27	1.250	1.1538	1.1538	1.1731	1.1538
28	1.250	1.1731	1.1923	1.1538	1.1731
29	1.250	1.1731	1.1923	1.1538	1.1538
30	1.250	1.0981	1.2307	1.1923	1.1538
31	0	0.9138	0.9808	0.9615	1.0385
32	0	0.3208	0.3315	0.4231	0.7301
33	0	0.0577	0.0769	0.0962	0.3846
34	0	0.0384	0.0384	0.0384	0.1538
35	0	0.0336	0.0336	0.0336	0.0769
36	0	0.0192	0.0192	0.0192	0.0384

Note: T_D= Dead Time S = Longitude Slope

Rainfall= Total rainfall per basin area per time interval.

Runoff = Total runoff per basin area per time interval.

Basin Type	I	Rain Intensity	1.26 In/Hr	Duration	15 Min.	Time Interval	30 Sec.
No.	Runoff / Rainfall		$S = 8\%$ $T_D = 35$ Sec	$S = 6\%$ $T_D = 40$ Sec		$S = 4\%$ $T_D = 47$ Sec	$S = 2\%$ $T_D = 64$ Sec
1	0.252		0.0	0.0		0.0	0.0
2	0.252		0.0769	0.0498		0.0288	0.0
3	0.252			0.2115		0.1635	0.0567
4	0.252		0.4423	0.2308		0.2115	0.1332
5	0.252			0.2115		0.2212	0.1705
6	0.252		0.4904	0.2115		0.2210	0.2019
7	0.252			0.2212		0.2212	0.2115
8	0.252		0.4807	0.2212		0.2212	0.2212
9	0.252			0.2212		0.2212	0.2212
10	0.252		0.4712	0.2212		0.2212	0.2115
11	0.252			0.2115		0.2212	0.2212
12	0.252		0.4808	0.2115		0.2308	0.2212
13	0.252			0.2115		0.2115	0.2212
14	0.252		0.4904	0.2212		0.2308	0.2308
15	0.252			0.2115		0.2212	0.2404
16	0.252		0.4712	0.2115		0.2212	0.2404
17	0.252			0.2019		0.2212	0.2115
18	0.252		0.4519	0.2212		0.2212	0.2308
19	0.252			0.2019		0.2212	0.2115
20	0.252		0.4808	0.2115		0.2115	0.2308
21	0.252			0.2115		0.2308	0.2308
22	0.252		0.4712	0.2115		0.2212	0.2308
23	0.252			0.2019		0.2212	0.2212
24	0.252		0.4808	0.2019		0.2308	0.2212
25	0.252			0.2115		0.2212	0.2404
26	0.252		0.5090	0.2115		0.2404	0.2308
27	0.252			0.2212		0.2212	0.2212
28	0.252		0.4808	0.2308		0.2212	0.2404
29	0.252			0.2025		0.2212	0.2212
30	0.252		0.5192	0.2312		0.2308	0.2308
31	0			0.1731		0.1826	0.2115
32	0		0.2404	0.0769		0.0962	0.1538
33	0			0.0481		0.0576	0.0962
34	0		0.0577	0.0288		0.0384	0.0576
35	0			0.0288		0.0288	0.0211
36	0		0.0274	0.0192		0.0192	0.0192

Note: T_D = Dead Time S = Longitude Slope

Rainfall = Total rainfall per basin area per time interval.

Runoff = Total runoff per basin area per time interval.

Basin Type	II	Rain Intensity	6.26 In/Hr	Duration	15 Min.	Time Interval	30 Sec.
No.	Runoff / Rainfall		S = 8 % T_D = 11.5 Sec	S = 6 % T_D = 15 Sec	S = 4 % T_D = 16 Sec	S = 2 % T_D = 24 Sec	

No.	Rainfall	S = 8 %, T_D = 11.5 Sec	S = 6 %, T_D = 15 Sec	S = 4 %, T_D = 16 Sec	S = 2 %, T_D = 24 Sec
1	0.557	0.1404	0.1058	0.0865	0.0231
2	0.557	0.4173	0.3942	0.2981	0.1885
3	0.557	0.4769	0.4615	0.4231	0.3077
4	0.557	0.4692	0.4615	0.4423	0.3750
5	0.557	0.4481	0.4615	0.4423	0.4038
6	0.557	0.4808	0.4615	0.4615	0.4231
7	0.557	0.4942	0.4808	0.4423	0.4519
8	0.557	0.4865	0.4808	0.4615	0.4519
9	0.557	0.4904	0.4615	0.4615	0.4712
10	0.557	0.4615	0.4615	0.4615	0.4808
11	0.557	0.4519	0.4615	0.4615	0.4615
12	0.557	0.5192	0.4808	0.4615	0.4519
13	0.557	0.4904	0.4615	0.4615	0.4904
14	0.557	0.4808	0.4808	0.4808	0.4810
15	0.557	0.4808	0.4615	0.4615	0.4615
16	0.557	0.4904	0.4808	0.4615	0.4808
17	0.557	0.4808	0.4615	0.4615	0.4808
18	0.557	0.4904	0.4808	0.4615	0.4808
19	0.557	0.4904	0.4808	0.4615	0.4808
20	0.557	0.5000	0.4808	0.4808	0.4808
21	0.557	0.4808	0.4711	0.4808	0.4711
22	0.557	0.4808	0.4808	0.4423	0.4808
23	0.557	0.4808	0.4615	0.4615	0.4615
24	0.557	0.5000	0.4615	0.4615	0.4808
25	0.557	0.5000	0.4808	0.4615	0.4808
26	0.557	0.4808	0.4615	0.4615	0.4808
27	0.557	0.5000	0.4808	0.4615	0.4712
28	0.557	0.4808	0.4808	0.4615	0.4712
29	0.557	0.5000	0.4615	0.4615	0.4712
30	0.557	0.4808	0.4808	0.4615	0.4712
31	0.0	0.3846	0.4038	0.4038	0.4423
32	0.0	0.1058	0.1538	0.1923	0.3173
33	0.0	0.0385	0.0385	0.0769	0.2308
34	0.0	0.0192	0.0192	0.0481	0.1538
35	0.0	0.0192	0.0192	0.0192	0.0962
36	0.0	0.0096	0.0096	0.0096	0.0385
37	0.0	-	-	-	0.0096

Note: T_D = Dead Time S = Longitude Slope

Rainfall = Total rainfall per basin area per time interval.
Runoff = Total runoff per basin area per time interval.

Basin Type	II	Rain Intensity	1.27 In/Hr	Duration	15 Min.	Time Interval	30 Sec.
No.	Runoff / Rainfall		S = 8 % T_D = 30 Sec	S = 6 % T_D = 36 Sec		S = 4 % T_D = 44 Sec	S = 2 % T_D = 62 Sec
1	0.113		0.0	0.0		0.0	0.0
2	0.113		0.0673	0.0577		0.0504	0.0
3	0.113		0.0962	0.1058		0.1058	0.0615
4	0.113		0.1058	0.1154		0.1154	0.0981
5	0.113		0.1154	0.1058		0.1058	0.1096
6	0.113		0.1058	0.1058		0.1058	0.1154
7	0.113		0.1058	0.1154		0.1058	0.1154
8	0.113		0.1154	0.1154		0.1058	0.1058
9	0.113		0.1058	0.1058		0.1058	0.1115
10	0.113		0.1019	0.1058		0.1048	0.1096
11	0.113		0.1057	0.1058		0.1058	0.1154
12	0.113		0.1010	0.1058		0.1058	0.1154
13	0.113		0.1058	0.1019		0.1153	0.1115
14	0.113		0.1058	0.1153		0.1058	0.1019
15	0.113		0.1019	0.1115		0.1058	0.1132
16	0.113		0.1115	0.1019		0.1058	0.1058
17	0.113		0.1058	0.1058		0.1058	0.1154
18	0.113		0.1019	0.1019		0.1058	0.1115
19	0.113		0.1058	0.1019		0.1115	0.1096
20	0.113		0.1058	0.1058		0.1096	0.1115
21	0.113		0.1058	0.1019		0.1058	0.1096
22	0.113		0.1057	0.1096		0.1058	0.1115
23	0.113		0.1019	0.1019		0.1019	0.1115
24	0.113		0.1058	0.1115		0.1115	0.1096
25	0.113		0.1096	0.1154		0.1096	0.1154
26	0.113		0.1154	0.1058		0.1058	0.1058
27	0.113		0.1058	0.1115		0.1058	0.1058
28	0.113		0.1019	0.1019		0.1115	0.1115
29	0.113		0.1058	0.1058		0.1058	0.1058
30	0.113		0.1019	0.1058		0.1058	0.1115
31	0.0		0.0962	0.0962		0.0962	0.0962
32	0.0		0.0673	0.0769		0.0673	0.0769
33	0.0		0.0327	0.0385		0.0412	0.0576
34	0.0		0.0192	0.0192		0.0201	0.0288
35	0.0		0.0192	0.0192		0.0192	0.0192
36	0.0					0.0192	0.0192

Note: T_D = Dead Time   S = Longitude Slope

Rainfall = Total rainfall per basin area per time interval.
Runoff = Total runoff per basin area per time interval.

Basin Type	III	Rain Intensity	6.26 In/Hr	Duration	15 Min.	Time Interval	30 Sec.
No.	Runoff / Rainfall		S = 8 % T_D = 10.5 Sec	S = 6 % T_D = 11.5 Sec		S = 4 % T_D = 13 Sec	S = 2 % T_D = 19 Sec
1	1.250		0.5962	0.5962		0.5000	0.3462
2	1.250		1.0769	1.0962		1.1346	1.1346
3	1.250		1.0769	1.0769		1.0962	1.0769
4	1.250		1.0962	1.1154		1.0769	1.1154
5	1.250		1.0577	1.0577		1.0865	1.0577
6	1.250		1.0962	1.1154		1.0865	1.1154
7	1.250		1.0962	1.0962		1.0962	1.0769
8	1.250		1.0769	1.0962		1.1154	1.0962
9	1.250		1.0769	1.0769		1.0769	1.0769
10	1.250		1.0577	1.0769		1.0962	1.0577
11	1.250		1.0769	1.0577		1.0962	1.1154
12	1.250		1.0577	1.1346		1.1154	1.0769
13	1.250		1.0769	1.0577		1.0769	1.0769
14	1.250		1.0769	1.0962		1.1154	1.0769
15	1.250		1.0962	1.0769		1.0962	1.0962
16	1.250		1.0962	1.1154		1.0962	1.0769
17	1.250		1.1058	1.0962		1.0962	1.0769
18	1.250		1.0962	1.0577		1.0962	1.0962
19	1.250		1.0673	1.0577		1.0962	1.0769
20	1.250		1.0769	1.0385		1.1154	1.0962
21	1.250		1.0577	1.0577		1.0962	1.0769
22	1.250		1.0769	1.0962		1.0962	1.0769
23	1.250		1.0769	1.0385		1.0769	1.1154
24	1.250		1.0962	1.0769		1.1154	1.0577
25	1.250		1.0769	1.0577		1.0769	1.0962
26	1.250		1.0962	1.0769		1.0865	1.0385
27	1.250		1.0769	1.0601		1.1058	1.0962
28	1.250		1.0577	1.0577		1.0962	1.0962
29	1.250		1.0962	1.0769		1.0962	1.0769
30	1.250		1.0577	1.0577		1.0769	1.0865
31	0.0		0.6538	0.6538		0.7115	0.8365
32	0.0		0.0962	0.1154		0.1154	0.1923
33	0.0		0.0385	0.0385		0.0385	0.0577
34	0.0		0.0192	0.0192		0.0192	0.0265
35	0.0		0.0096	0.0096		0.0096	0.0100

Note: T_D = Dead Time S = Longitude Slope

Rainfall = Total rainfall per basin area per time interval.
Runoff = Total runoff per basin area per time interval.

Basin Type	III	Rain Intensity	1.26 In/Hr	Duration	15 Min.	Time Interval	30 Sec.
No.	Rainfall \ Runoff	S = 8 % T_D = 28 Sec	S = 6 % T_D = 32 Sec	S = 4 % T_D = 35 Sec	S = 2 % T_D = 47.5 Sec		
1	0.252	0.0096	0.0	0.0	0.0		
2	0.252	0.1827	0.1362	0.1346	0.0577		
3	0.252	0.2212	0.2308	0.2500	0.2404		
4	0.252	0.2404	0.2500	0.2404	0.2500		
5	0.252	0.2212	0.2404	0.2500	0.2308		
6	0.252	0.2115	0.2308	0.2404	0.2308		
7	0.252	0.2404	0.2308	0.2404	0.2308		
8	0.252	0.2019	0.2308	0.2308	0.2404		
9	0.252	0.2115	0.2308	0.2308	0.2212		
10	0.252	0.2115	0.2308	0.2308	0.2308		
11	0.252	0.2212	0.2308	0.2308	0.2212		
12	0.252	0.2308	0.2404	0.2500	0.2308		
13	0.252	0.2212	0.2308	0.2404	0.2308		
14	0.252	0.2212	0.2404	0.2308	0.2308		
15	0.252	0.2212	0.2404	0.2404	0.2308		
16	0.252	0.2212	0.2404	0.2365	0.2212		
17	0.252	0.2212	0.2308	0.2347	0.2404		
18	0.252	0.2212	0.2308	0.2308	0.2308		
19	0.252	0.2212	0.2404	0.2500	0.2308		
20	0.252	0.2308	0.2308	0.2308	0.2404		
21	0.252	0.2019	0.2115	0.2308	0.2212		
22	0.252	0.2212	0.2308	0.2500	0.2308		
23	0.252	0.2212	0.2308	0.2404	0.2115		
24	0.252	0.2308	0.2308	0.2404	0.2308		
25	0.252	0.2212	0.2365	0.2500	0.2404		
26	0.252	0.2212	0.2346	0.2308	0.2308		
27	0.252	0.2212	0.2250	0.2404	0.2212		
28	0.252	0.2212	0.2308	0.2212	0.2404		
29	0.252	0.2308	0.2308	0.2404	0.2308		
30	0.252	0.2212	0.2462	0.2115	0.2212		
31	0.0	0.1731	0.1538	0.1923	0.1827		
32	0.0	0.0385	0.0385	0.0577	0.0673		
33	0.0	0.0288	0.0231	0.0231	0.0288		
34	0.0	0.0192	0.0154	0.0192	0.0192		
35	0.0	0.0096	0.0096	0.0096	0.0096		

Note: T_D= Dead Time S = Longitude Slope

Rainfall= Total rainfall per basin area per time interval.

Runoff = Total runoff per basin area per time interval.

ANALYSIS OF HYDROLOGIC SYSTEMS

by

Tsung Ting Chiang, B.S., M.S.

Abstract

It was found that the systems analysis technique is a useful tool for hydrologic systems and is not only applicable to artificial hydrologic systems but also to natural catchments.

The general equation describing the relationship between surface runoff and rainfall excess of a hydrologic system is a second order nonlinear equation. The damping coefficient for hydrologic systems is approximately unity and the other parameters in the transfer function (Eq. 5-4) such as the time constant and the nonlinear parameter depend on basin characteristics and input intensity.