UNIVERSITY OF CENTRAL FLORIDA

Office of Graduate Studies

THESIS ACCEPTANCE

DATE: April 27, 1982

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION

BY Mr. David E. Anderson

ENTITLED "Evaluation of Swale Design"

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF Master of Science in Engineering

FROM THE COLLEGE OF Engineering.

Martin P Wanielista
Dr. Martin P. Wanielista, P.E.
Director of Thesis

BE Mathews
Dr. Bruce E. Mathews, P.E.
Assistant Dean

Recommendation Concurred In:

Shiou-San Kuo
Edson Jackson
Carla V Palmer
Committee on Final Examination

EVALUATION OF SWALE DESIGN

BY

DAVID EDWARD ANDERSON
B.S.E., University of Central Florida, 1980

THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science in Engineering
in the Graduate Studies Program of the College of Engineering
University of Central Florida
Orlando, Florida

Spring Term
1982

ABSTRACT

Swales are designed to infiltrate runoff from intermittent storm events. Present design methodologies have resulted in swales which operate under several conditions; these conditions are soil, vegetation, climatic and geographical location dependent. To attain a swale design which considers and accounts for the important factors under Florida conditions, adequate assessment of rainfall, overland flow, infiltration and soil moisture must be given priority treatment. Several roadside and residential swales were studied and relationships were drawn for soil moisture, porosity and infiltration rates. A design methodology is included and computer modeling of infiltration aids in the design.

ACKNOWLEDGEMENTS

Primarily, I wish to thank God for giving me the natural ability to perform the enclosed work. I also wish to thank Dr. M.P. Wanielista for his untiring efforts in guiding the research and for editing in the proper places. An unparallel expression of gratitude must be given to Mrs. Sharon Darling for her invaluable assistance in typing, grammatical, functional and bibliographical editing which produced the final draft you are now reading. In addition, I must thank Mohammed Ali Iranmanesh for his assistance in surveying and Jay Davoll for performing the art work on the figures enclosed. I wish to thank the other members of the review committee (Dr. Shiou-San Kuo and Dr. Clarence Head) whose technical input provided the guiding impetus for a speedy completion of the enclosed efforts. Lastly, I wish to thank Mom and Dad who provided the author of the enclosed works.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

CHAPTER I

SCOPE AND OBJECTIVES

Swale systems used to control stormwater quantities can be effective for pollution control if proper considerations for volume routing and infiltration conditions are evaluated in the design phase. Favorable soil conditions which enhance substantial infiltration are controlling criteria for swale system placement. Varying soil moisture affects runoff curve numbers, soil moisture storage depletion capacity and infiltration capacity. The combination of the above site-specific parameters determine the applicability and effectiveness of swale systems for stormwater quantity and quality control.

An external input to swale design methodology is an appropriate quantity of precipitation which must be diverted. The frequency of volumes considered applicable to specific areas provides a measure of usefulness of the designated system. Hydrograph generation is important in determining many of the physical characteristics of a swale and ultimately influences swale length. Among other external factors which control swale design and placement are geographical location of proposed swale systems, cost of the designed/constructed facility and socio-economic and aesthetic factors (human input).

Any of the above factors considered separately makes for inefficient design of stormwater management facilities; however, all factors applied in conjunction provide for management systems which are technically sound and aesthetically acceptable.

Infiltration tests were performed on several existing swale systems in Orange and Seminole Counties. Tests were done using a double-ring infiltrometer under saturated conditions. Soil properties were evaluated - grain size distribution, water content and porosity. It was assumed that specific gravity was relatively constant for the sandy soils encountered.

A method is presented in which superposition of precipitation volume curves upon measured infiltration volume curves produce the desired runoff hydrograph for estimation of swale area. For preliminary design purposes, rainfall instead of rainfall excess is used to determine swale geometry; consequently, deeper and longer swales will be designed. Swale length can be predicted from overland flow velocities. Safety factors are incorporated to account for uncertainties in the design.

CHAPTER II

BASIC CONSIDERATIONS

A swale, as defined by the Florida State Department of Environmental Regulation (1981), is a shallow trench used to convey stormwater and permit infiltration/percolation. Swale systems comprise a network of channels which convey rainfall excesses to desired locations for retention, detention, storage or discharge as a means of final disposal. Network evaluation of the system by nodal analysis is perhaps the most appropriate method for effectiveness evaluation (Beard, Weiss and Austin 1972; Flatt 1978). Volume routing depends upon the geometry of the individual channel as well as hydrologic characteristics of the site.

Site conditions such as runoff curve numbers, antecedent moisture conditions, existing foliage, soil types and distributions, type of undesirable debris, and land slope affect the efficiency of a swale. Collective consideration of site factors influence the overall effectiveness of management efforts. In a watershed in which land use and moisture conditions predict high runoff curve numbers or where percolation capacity is limited, virtually little or no foliage exists to induce plant uptake of available rainfall excesses, a hard and relatively impervious soil exists (as a general condition), and mulch or lawn clippings clog soil pores, the effectiveness of swales placed in such a watershed should not be expected to perform as well as swales placed in areas in which exactly opposite conditions exist.

Rainfall

Rainfall data must be available to aid design and the evaluation of rainfall data is largely statistical. Two basic methods are employed for finding the average basin precipitation. They are the Thiessen and Arithmetic Average Methods. Other less popular methods may also be used (Wanielista 1978). The concept of return period is usually evaluated through manipulation of statistical probability distributions and equations which aid in the computation of rainfall intensities.

Hydrographs

Hydrograph generation is usually the result of the application of a mathematical model. It is the modeling of storm excess which appears as runoff reaching receiving streams. Models such as Santa Barbara Urban Hydrograph, Unit Hydrograph and the Rational Method are most widely used in calculating hydrograph shapes (Wanielista 1978). Other models exist which may be used to generate hydrographs, but are not as popular as those mentioned above (Delleur and Dendrou 1980). Each model contains parameters which must be evaluated for accurate calibration. Digital and analog computers have proven to be most efficient in generation of hydrographs and model calibrations.

Infiltration

Infiltration volume is defined as the volume of water which is stored in the soil as a result of a storm event. Movement of water through the soil is considered as infiltration. Darcy's Law and the Principle of Continuity of Flow through porous media dictate the form of equations which describe the rate of infiltration for a particular soil.

Surface effects are of overriding concern in the prediction of infiltration rates. Sedimentation may clog soil pores and halt the infiltration process altogether. Surface sealing effects also affect the rate of infiltration. Foliage may slow the velocity of raindrops reaching the ground and, thus, reduce surface sealing of soil upon impact of raindrops.

Modeling of infiltration depends upon soil makeup, hydraulic conductivities, runoff flow, moisture deficits, hydraulic head and capillary action of the wetting front. Investigators have included other factors to describe the rate of infiltration. The most popular equation used to describe infiltration is the Green-Ampt Model. Several other models and numerical techniques exist to approximate infiltration (Morel-Seytoux 1982). Each must be evaluated on its own merits, for each contains parameters which must be calculated and consequent calibration of the model results.

Soil Parameters

Soil parameters of interest to stormwater management are:

1. Soil Permeability
2. Grain Size
3. Porosity
4. Grain Distribution
5. Moisture Content
6. Specific Gravity
7. Hydraulic Conductivity
8. Soil Stratification/Depth of Layers
9. Silting/Sedimentation Potential
10. Stability of Soil Layers (Erosivity Index)

Soil surveys to determine the above soil parameters usually require arduous hours of laboratory study. In situ tests are perhaps more representative of conditions which exist in the field. However, accuracy obtained in field measurements is usually quite lower than accuracy obtained from laboratory tests. The trade-off between the two is a matter of preference for a particular investigator. Standard procedures exist for measuring some of the parameters listed (Bowles 1979).

General Design Procedures

Basically, the objectives of hydrologic design are to reduce the volume of runoff from a particular drainage basin, attenuate the peak of runoff hydrographs and provide a measure of control (retention or detention) of rainfall excess in a watershed. Through enhanced infiltration, vertical flow routing is effected.

1. Soil Permeability
2. Grain Size
3. Porosity
4. Grain Distribution
5. Moisture Content
6. Specific Gravity
7. Hydraulic Conductivity
8. Soil Stratification/Depth of Layers
9. Silting/Sedimentation Potential
10. Stability of Soil Layers (Erosivity Index)

Soil surveys to determine the above soil parameters usually require arduous hours of laboratory study. In situ tests are perhaps more representative of conditions which exist in the field. However, accuracy obtained in field measurements is usually quite lower than accuracy obtained from laboratory tests. The trade-off between the two is a matter of preference for a particular investigator. Standard procedures exist for measuring some of the parameters listed (Bowles 1979).

General Design Procedures

Basically, the objectives of hydrologic design are to reduce the volume of runoff from a particular drainage basin, attenuate the peak of runoff hydrographs and provide a measure of control (retention or detention) of rainfall excess in a watershed. Through enhanced infiltration, vertical flow routing is effected.

Through design of hydraulic structures, horizontal flow routing is brought under control. Rainfall excess control may commence with the design of swales or holding basins. Outflow discharge requirements and downstream flooding conditions along with expected rainfall volumes and basin characteristics will determine which type of facility is more suited to the task. Another very important factor to be considered (especially in designing under urban conditions) is the compatibility of the designed system to the capabilities of existing flow control systems. To meet the objectives of hydrologic design, the designer must call upon his technical competency and temper it with sound engineering judgement.

CHAPTER III

LITERATURE REVIEW

Infiltration

Infiltration is the vertical inflow and movement of water in soil strata. Many factors combine to define this water transport rate. Such soil surface phenomena as the closing of soil pores by rainfall impact, silting caused by turbulent flow and surface sealing by man-made pollutants seek to control the rate of influx. Musgrave and Holtan (1964) have determined factors which affect infiltration; they are listed as:

1. Surface Entry
2. Transmission Through Soil
3. Depletion of Soil Storage Capacity
4. Soil Characteristics
5. Infiltrating Fluid Characteristics

Another factor which merits additional consideration is the surface water depth during infiltration. It indirectly determines the time for completion of ponding and provides a driving force for the infiltration process.

Currently, two types of infiltrometers exist. They are the flooding type (single and double-ring infiltrometers) and simulation type (rainulators). Neutron probe methods have been used to assess percolation rates (Vinson and Mahr 1981). Laboratory assessment of the coefficient of permeability, hydraulic conductivity, moisture content and capillary action of a perceived wetting front provides bases for several infiltration models. Conditions which are not representative of field conditions exist in the laboratory determinations and as such, provide another degree of uncertainty in the description of infiltration. Infiltration rate curves presented by Beaver (1977), curves by Musgrave and Holtan (1964), Vinson and Mahr (1981) and Schulze (1972) graphically depict infiltration rate. All curves encountered show an exponential decrease in infiltration with time, though some show an initial positive infiltration rate. This increase may be due (in part) to unsaturated conditions for the first few minutes of the test. A mathematical correlation of infiltration rate, time of test and saturated conditions must exist.

Infiltration Models

Numerous investigators have made attempts to mathematically describe the infiltration function. Under conditions such as homogeneous and non-homogeneous soils, ponded vs. unsaturated conditions, variable vs. non-variable heads, constant vs. variable rainfall rate and surface delay effects, wide variations in model forms can be expected. There exists a need for a convergence of testing procedures and uniqueness of model forms. At present, no such model exists. However, all investigators agree on the non-linearity of the infiltration process.

Mein-Larsen Model

The Mein-Larsen Model (1973) postulates a two-step process to include surface delay effects during infiltration. In this model, infiltration rate is related to hydraulic conductivity, initial moisture content, wetting front position, rainfall intensity and capillary action at the wetting front. Uniform initial moisture content in the zone of infiltration, constant rainfall intensities and homogeneous soil types are assumptions upon which the model is based. The Mein-Larsen Model has merit and predicts infiltration within its assumptions but the quantity of parameters which must be measured to define the process may be unattractive to some potential users of the model.

Green-Ampt Model

Green and Ampt (1911) developed an infiltration model which has historically proven to be one of the more popular models for researchers and investigators seeking to produce better infiltration prediction equations. Several modifications and redefinitions of parameters have been made to the model to exact some degree of practical applicability from it. Among some of the modifications are:

1. Permitting the value of the wetting front capillary suction to equal the water input value (Bouwer 1966).
2. Permitting the wetting front capillary suction value to equal the height of capillary rise in the soil (Phillip 1957).

3. Morel-Seytoux and Khanji (1972) added the effect of air flow behind the wetting front. This attempt led to the incorporation of more hydraulic soil parameters into the model.

4. Van Duin (1955), Bouwer (1969) and Childs and Bybordi (1969) modified the original model to account for the use of layered soils in their infiltration tests.

5. Hillel and Gardner (1970) and Mein and Larsen (1981) altered the model to account for surface delay effects.

6. Finally, Neuman (1976) showed that the modifications imposed by Bouwer (1969)(i.e., negative pressure head at the wetting front equals the cumulative relative permeability of the soil) was applicable if strict adherence to the original Green-Ampt assumptions were followed (e.g., water content equals saturated water content and the model is applicable only to uniform soil profiles).

The Green-Ampt Model makes the infiltration rate proportional to the saturated hydraulic conductivity. Hydraulic conductivity can be measured in either field or laboratory environments (Wang and Overman 1974; Klute 1972). The trade-off for either measurement is representativeness and accuracy. There are, however, models which include fewer ambiguities concerning its parameters and models which require simple tests to describe infiltration.

Power Law Functions

Holtan and Kirkpatrick (1950) expressed the infiltration rate function as a power law equation. The equation recognizes a constant saturated infiltration rate and says that the rate is proportional to the available storage in the surface layer of soil. Since the soil is the intended storage medium, depletion of available storage depicted by Holtan seems quite reasonable. However, it becomes a matter of test conditions (soil type, cover conditions, moisture content, temperature and porosity) to assist the investigator in the determination of the exponent in Holtan's equation.

The Kostiakov equation (as presented by Childs 1967) expresses the infiltration process as the product of soil dependent constants and is inversely proportional to time. Phillip (1975) modeled the process as a time dependent polynomial. These equations predict undefined rates at the outset of testing and large values for small initial increments of time. This is often the case, but as previously stated, some investigators show an increase in infiltration rate for small increments of time at the beginning of testing. Power law equations are very good indicators of non-linear infiltration rates.

Horton's Equation

R.E. Horton (1940) postulated that the rate of infiltration follows an exponential decay form. His observations of a saturated flow condition depicts a model of piston flow. A substantial head must exist at the soil surface and the initial surface moisture condition must be such that infiltration is favorable (wilting point exceeded). In effect, Horton's approach uses intrinsic soil parameters and adopts the exterior (macroscopic) approach to infiltration prediction. The equation is:

$$f(t) = f_c + (f_o - f_c)e^{-kt} \qquad (1)$$

where: $f(t)$ is the time varying infiltration rate (L/T)

f_o is the initial infiltration rate (L/T)

f_c is the saturated constant infiltration rate (L/T)

k is the recession constant (1/T)

f_o is usually much larger than f_c for natural conditions. In field tests, a curve of the form described by Horton is fitted to measured rata data.

Horton's method of describing infiltration makes it one of the easier methods to gather rate data for, but there are shortcomings to the use of the equation. Horton's equation is descriptive of ponded conditions and has no direct discernable dependence on rainfall intensity. The equation must be calibrated for different soil types and cover conditions (Musgrave and Holtan 1964). The relationship of f_o to initial moisture content could use verification. The question of whether the f_c value is the true predictor of saturated hydraulic conductivity needs investigation. The variation of the k factor with soil, type moisture and cover conditions is also a subject for future determination. Engineers and hydrologists who wish to explain the infiltration process without utilizing elaborate field and laboratory equipment would be wise to resort to Horton's equation.

Other Models

Other models such as the SCS and coefficient models exist. These models relate the parameters of the hydrologic cycle to infiltration. Rainfall and runoff are measured, a percentage of ultimate storage is accounted for by abstraction and infiltration is computed from the hydrologic relationships. Store models such as Stanford Watershed, Sacramento Watershed and USDAHL (United States Department of Hydrology Laboratory) models are hybrid models which are also based on soil moisture storage and hydrologic characteristics of the watershed.

Prediction of infiltration is a difficult process to model. Inclusion of soil parameters and moisture content data along with statistical procedures for curve fitting produces equations which can (at best) estimate infiltration rate. The procedure that seems to suffice is to measure the infiltration rate and express soil characteristics, moisture content and surface depth data for the site and soil specific test performed.

Soil Moisture

The importance of soils in stormwater hydrology cannot be oversimplified; it is a complex and critical factor in design and must be given due consideration prior to the design process. Of utmost importance in soil study for the control of rainfall excess is the stochastic variation of soil moisture. Variation of soil moisture with depth over time merits due consideration also.

Primarily, the question must be asked - How can soil moisture be determined; what is soil moisture?

For the purpose of stormwater control technology, soil moisture may be defined as that volume of water contained in the soil including the ground water table. Hough (1957) has differentiated between adsorbed water and capillary water in defining moisture in soil strata. Adsorbed water is commonly referred to as bound water. Capillary water, then, may be thought of as that water which occupies the pore spaces of the soil. As Hough (1957) has stated, it is common to think that capillary water has been drawn up from the ground water table, it is also possible for water percolating downward from the ground surface to be arrested and held between adjacent particles as water may be held between adjacent glass plates. All water that percolates does not become immobilized in the soil; some adds to the level of ground water, plant uptake accounts for a portion, evaporation and interflow account for whatever portion remains. If the soil is to be used as a storage medium, a need exists to quantify the volume of water held in the soil.

To determine soil moisture, investigators have invented various techniques which employ a broad range of engineering and physics concepts. The techniques may be divided into two broad classes, they are: (1) in-situ methods and (2) remote sensing methods. Currently, five general methods of in-situ soil moisture exist. They are: (1) electromagnetic measurements, (2) gravimetric analysis, (3) hygrometric determinations, (4) nuclear implantation, and (5) tensiometric measurements. These five and the remote sensing techniques are discussed in a survey paper by T.J. Schmugge, T.J. Jackson and H.L. McKim (1980). Thermal and microwave methods constitute the remote sensing technique.

Finally, an examination of the movement of water in the soil and stochastic as well as environmental accounting must be given to the subject of soil moisture. Hough (1957) describes three types of ground water flow. They are: (1) gravitational flow, which is usually the flow defined by Darcy's Equation, (2) capillary flow, the multi-dimensional interflow of capillary water in soils, and (3) osmotic flow - flow which occurs due to the imbalance of concentration of moisture in different soil strata. As a discussion of stochastic and environmental effects of soil moisture, we need to examine the processes of evaporation, plant uptake and the hysteretic effect of soil moisture content with time.

In considering the hysteretic effect of soil moisture content, several methods have been developed to study the effect. Fitted equations and tabular numerical values have been employed by Rubin (1967), Staple (1966), Gardner (1970) and Whisler and Klute (1965). Hysteresis models developed by Poulovassilis (1971), Topp and Maulem (1969) describe the hysteresis effect through application of an independent domain theory. A non-independent domain theory was postulated by Childs and Poulovassilis (1971) and has been used to simulate the rainfall-runoff process. The overriding conclusion of this matter is that an hysteresis effect exists in the hydrologic process and its effect upon the stormwater control picture when the soil is considered as a contaminant medium cannot be neglected.

Rainfall

From a natural systems management and design perspective, rainfall can be thought of as the input phase of the hydrologic cycle. Its variability of occurrence and duration make it a very difficult parameter to predict. Egbuniwe (1975) has analyzed rainfall data and developed rainfall simulation models to generate synthetic hourly precipitation patterns using statistical concepts. Randkivi and Lawgun (1970) have performed similar studies for urban areas. The basis of studies of this type is that generalizations are drawn from observed data. While this procedure seems the natural order of scientific investigation, there is the express need for greater accuracy in defining intensity variation within a storm and for defining the storm frequency and drought periods.

In a study of one-minute rainfall rates, Huff (1970) investigated the time rate of change in storm rainfall rate of connective storms using sequential variability analysis. Johnson and Bras (1980) performed rainfall prediction studies for events of one hour or less and concluded that the degree of prediction difficulty varies from one event to another and when prediction leads are very short (less than 10 minutes), it is impossible to capture the fine structure of rainfall variability (rate).

Efforts by other investigators (Packman and Kidd 1980; Eagleson 1981; Hardison 1974; and Barry 1972) have produced evaluations of the use of statistical techniques to predict rainfall events of various durations, depths, intensities, frequencies and areal relations.

Notwithstanding, rainfall intensity and frequency are important in the design of stormwater control systems, but the prediction of depth and duration are the determining criteria for quality in the design. Again, following the natural order of scientific investigation, Alexander (1981) considers two methods by which the occurrences of rainy and dry episodes are estimated from climatological data. Statistical methods of mean and variance and the method of maximum likelihood were used. An exponential distribution of both variables was discovered. Farmer and Homeyer (1974) used Markov Models to achieve the same ends. Observation of recorded data, statistical evaluation and sound engineering judgement reflect the trend of predictive rainfall analysis.

Overland Flow

Overland flow best describes the state of conditions in which rainfall input exceed the instantaneous capacity of the soil to infiltrate rainfall excess. Related attempts by Overton (1970) and Singh (1979) to model the overland flow process have led to the production of an equation which has its basis in the kinematic wave function and the equation of continuity. Singh and Sherman (1976) have applied overland flow equations to natural watersheds, included the effects of infiltration and related overland flow to areas of geometrically converging surfaces. The necessity of an overland flow model mandates the use of hydrographs to describe time varying flow processes which ultimately will define the size of stormwater control system to be implemented.

The other popular concept for the description of flood routing is use of the inventory equation which was first postulated by Goodrich (1931). A verbal description of the routing process is: inflow minus outflow equals the time rate of change in basin storage. The inventory equation provides a generation basis for other routing methods such as the Santa Barbara Urban Hydrograph Routing Model. Computer models also exist which use routing techniques to model the runoff process.

The kinematic flow routing model of Wooding (1965) was used to predict surface runoff from a V-shaped watershed. Overton and Brakensiek (1970) formulated a similar model based on the same principles.

Hydraulic equations used to calculate the unit discharge and average flow velocity are presented by Chow (1959). The equations differentiate overland flow in the laminar and turbulent flow regimes. Kinematic viscosity is a determining criterion at low surface water depths and surface roughness predominates at turbulent flow. The equations presented by Chow are products of the works of Horton (1933) and other investigators.

CHAPTER IV

PROCEDURES

The current study proceeded with the evaluation of rainfall data. The purpose of this kind of a study is to determine (with some assurance) the probability of occurrence, the volume and duration of a design storm for the areas of concern. Data was provided by the U.S. Department of Commerce (1975-79) for Florida gaging stations. To obtain locations for which the resulting distributions may be representative of Florida, the 15 locations shown in Figure 1 were chosen. Also, the locations were chosen because data was available at these stations. A simple statistical procedure was employed to evaluate the data.

Generation of a probability distribution for rainfall events are based on statistical procedures. A probability distribution may be defined as the relationship between a random variable (X) and its associated probability p(X). For discrete (countable) distributions, the graphical representation utilized is a histogram (bar chart). Histograms of rainfall event volumes were generated for key locations in Florida. These are presented in Appendix A.

The procedure for generating the probability distribution found in Appendix A and results seen in Figure 2 constitute Table 1.

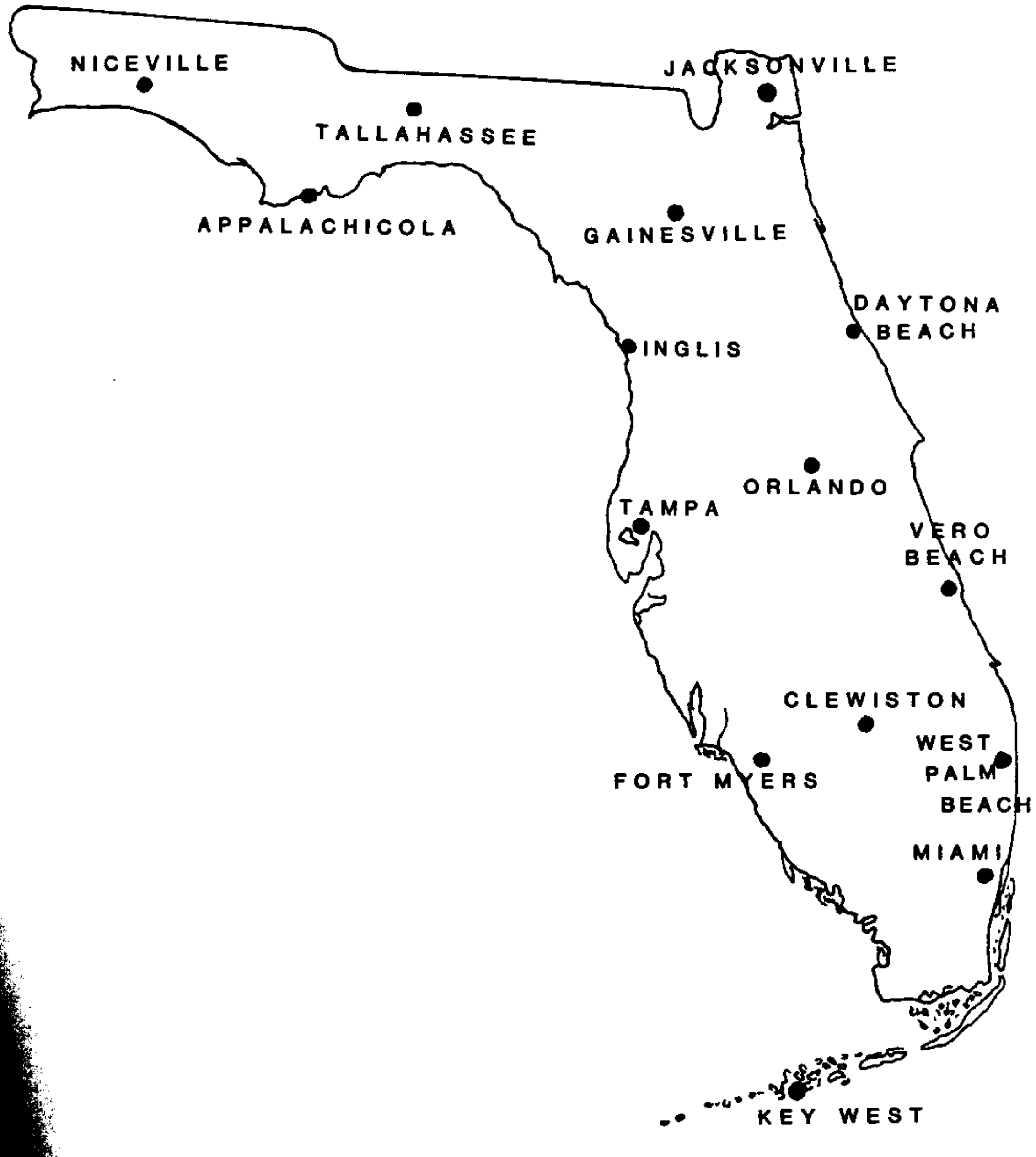


Fig. 1. Map of Florida showing the location of U.S. Weather Bureau rain gaging stations.

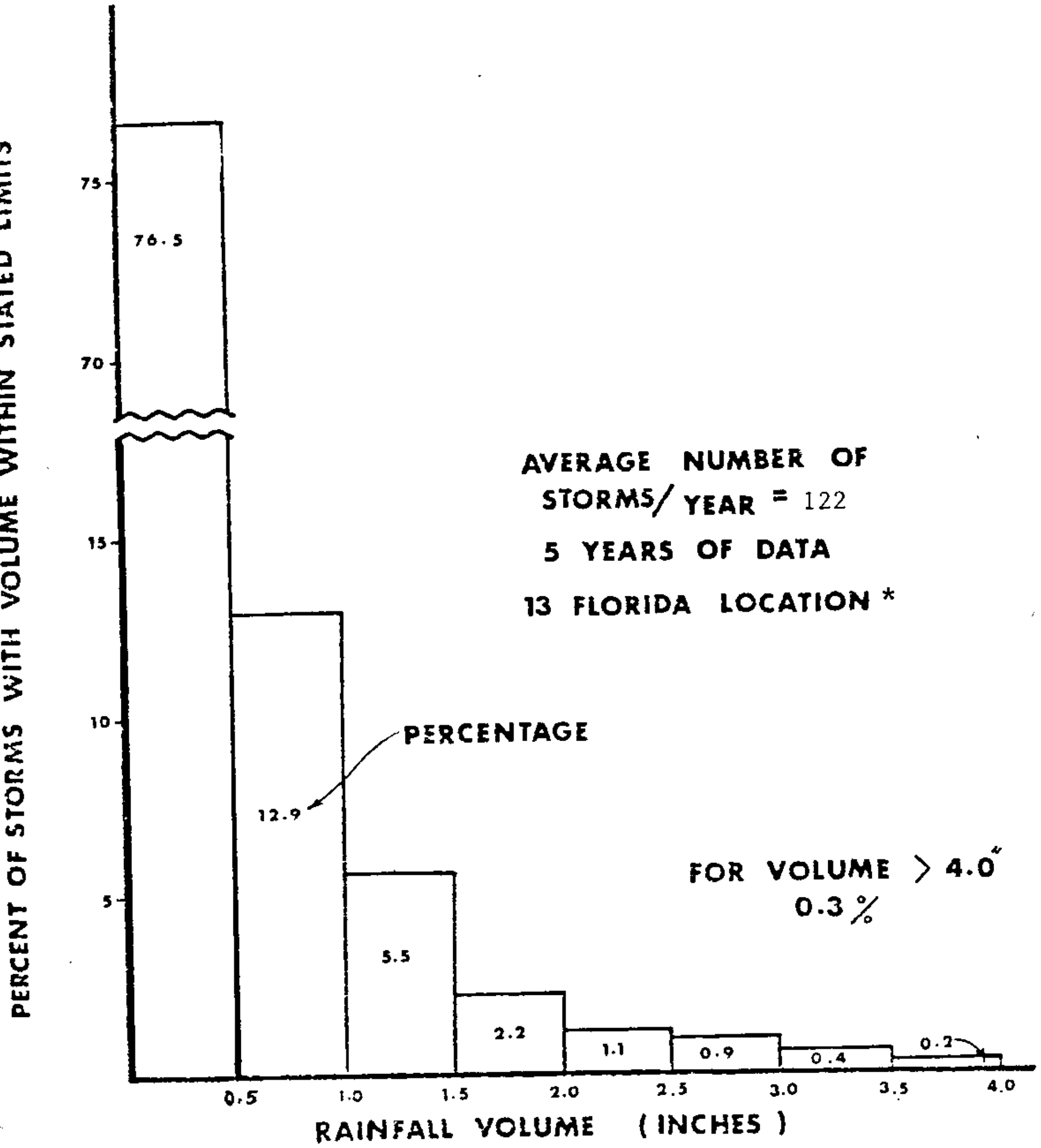


Fig. 2. Distribution of rainfall volume for 13 locations in Florida over a 5-year period.

* Data for West Palm Beach and Ingus not included.

TABLE 1

HISTOGRAM

Generation Procedure

1. Obtain records of local climatological data. Data must be of such time intervals as to produce the desired accuracy upon generation of histograms. The length of record must be of such a length so that a consistent pattern may be identified.

2. For each location, record the volume intervals of rainfall desired. An example would be to record volumes within each half-inch:

0-.50"	.51-1.00"	1.01-1.50"	1.50-2.00"	...etc
F_1	F_2	F_3	F_4	...etc

where: F_i = the number of storms with volumes between stated limits

3. A rainfall event was defined as a storm of such duration for which the time between storms was four hours or greater. The rainfall event must be of such volume so as to be detectable by weather station recording instrument. Therefore, traces of rain for which a stated volume was not listed were not considered as rainfall events.

4. Tally the number of storms with volumes within each interval. Record total number of storms.

5. Perform the following calculations:

$$P(X) = 100\, n_i/N \qquad N = \Sigma n_i \tag{2}$$

$$F(X) = P(x \leq X) = \sum_{X} p(x) \tag{3}$$

where: n_i is the number of storms in interval i

N = total number of storms

x = interval volume

TABLE 1 (Continued)

X = random variable describing probability

6. Plot histograms as shown in Figure 2 and Figures A1-A15 in Appendix A. This figure is a plot of Equation 2.
7. Plot the cumulative probability distributions shown in Figure 3 and depicted in Table 2.
8. Figure 3 is a plot of Equation 3 and Table 2 shows the variability of cumulative rainfall probability for the locations chosen.

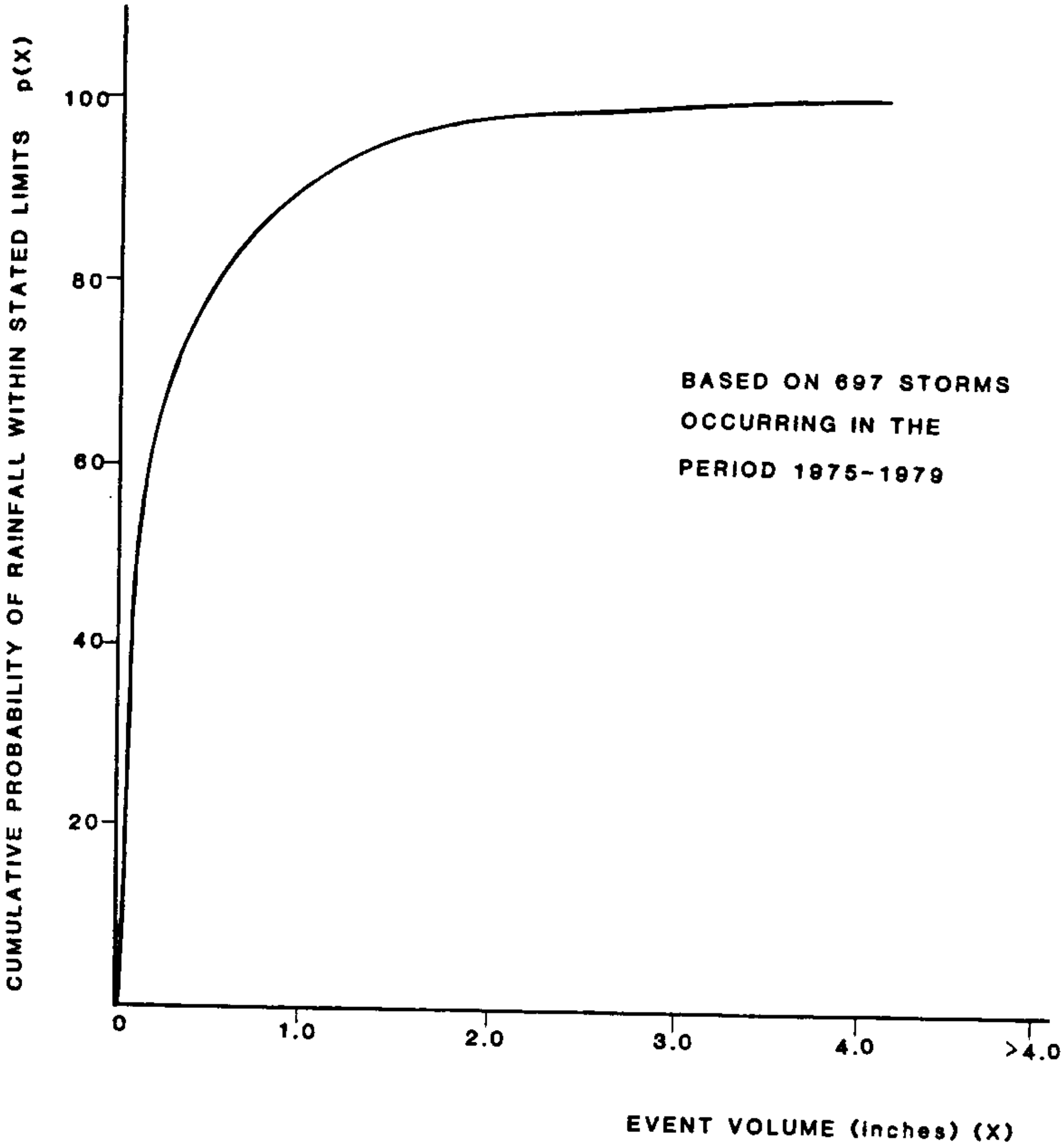


Fig. 3. Cumulative probability distribution curve for Orlando McCoy Airport over a 5-year period.

TABLE 2

CUMULATIVE PROBABILITY VALUES (%) FOR 15 FLORIDA LOCATIONS

Location	Volume (in)/Probability (%)				
	0-1/2	1/2-1	1-2	2-3	3-4
Niceville	68.2	84.5	93.8	97.7	98.4
Tallahassee	70.3	83.7	94.2	98.0	99.6
Jacksonville	77.1	91.7	97.7	99.1	99.6
Appalachicola	75.3	87.9	97.4	99.3	99.7
Gainesville	76.9	90.0	97.0	98.9	99.8
Daytona	75.9	89.3	96.2	98.7	99.8
Inglis	71.1	85.1	96.6	99.2	99.8
Orlando	80.1	90.0	98.0	99.6	99.9
Tampa	76.4	89.7	97.9	99.5	99.9
Vero Beach	77.5	89.9	98.7	99.3	99.5
Clewiston	74.3	87.3	97.0	98.9	99.6
West Palm Beach	80.6	90.8	97.0	98.7	99.1
Fort Myers	70.5	86.4	95.6	98.4	99.6
Miami	82.7	93.3	98.5	99.4	99.6
Key West	84.9	94.0	98.4	99.3	99.6
Florida	76.4	89.0	97.0	99.0	99.6

Figure 4 is a plot of annual treatment volume for storm events of a specified duration (x). The no-diversion curve presents the percentage of yearly volume for storms of an event volume. The diversion curve implies treatment of the first x inches of all storm events which will allow the designer to specify a corresponding percentage of yearly volume.

Frequency analyses require long periods of observations to form a valid conclusion about the return period of a storm event of volume (x) and duration T. The U.S. Weather Bureau (1972) has produced frequency-duration curves for the southeastern United States. The values at the end of each curve are the expected volumes for the given frequency and duration. The curves (like the one shown in Figure 5) reflect the long term trend of rainfall patterns.

To further define the duration of a rainfall event, local climatological data for the Orlando area was again analyzed to obtain a probability distribution. The method of evaluation is the same as that presented in Table 1 of this chapter for the distribution of rainfall volume. A record of 5 years of observations was studied. The resulting histogram is shown in Figure 6.

Additional criteria was added to validate the study methodology. These criteria were:

1. A storm volume recorded in an hour (t_i) was believed to have been built-up over the previous hour ($t_i - 1$).

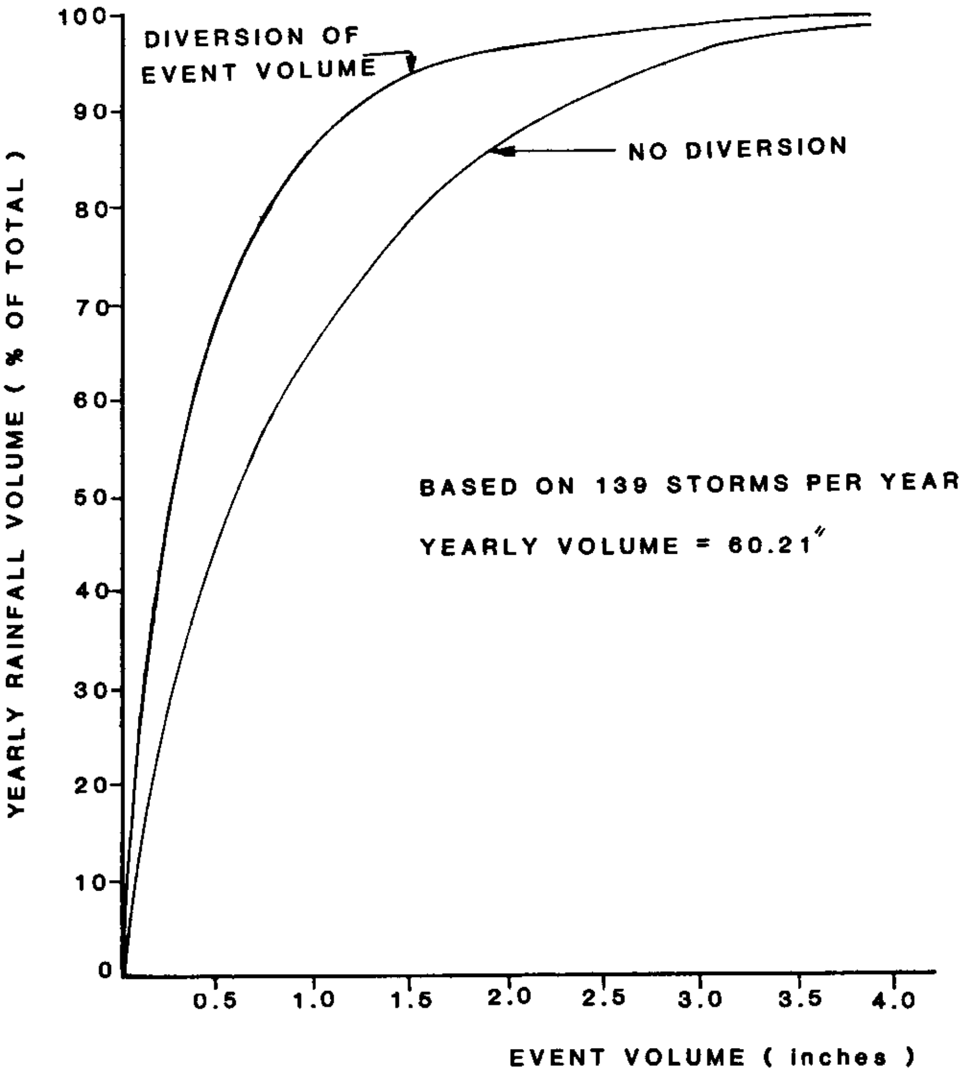


Fig. 4. Yearly treatment volume for a stated rainfall event using Orlando area meteorological data.

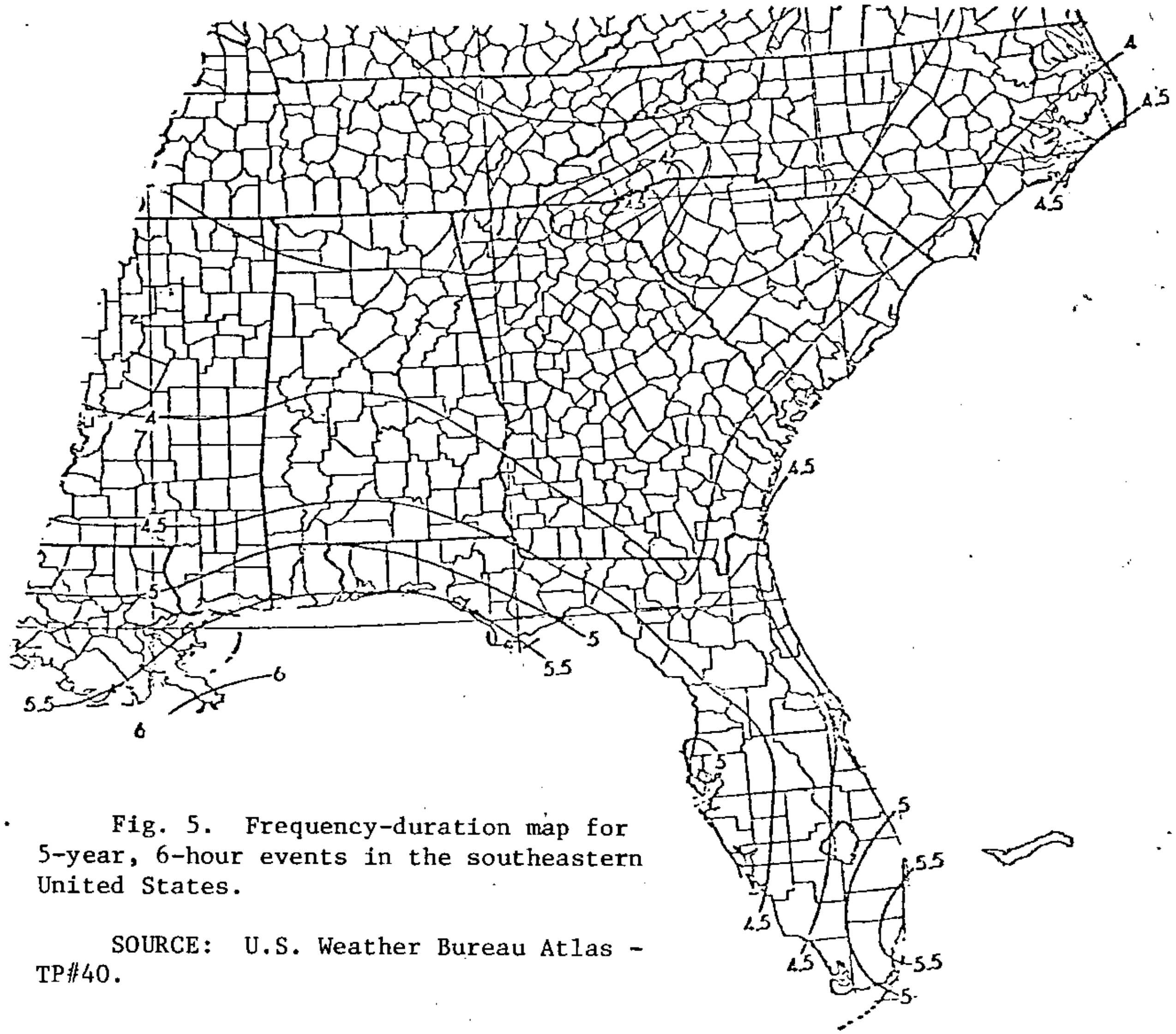


Fig. 5. Frequency-duration map for 5-year, 6-hour events in the southeastern United States.

SOURCE: U.S. Weather Bureau Atlas - TP#40.

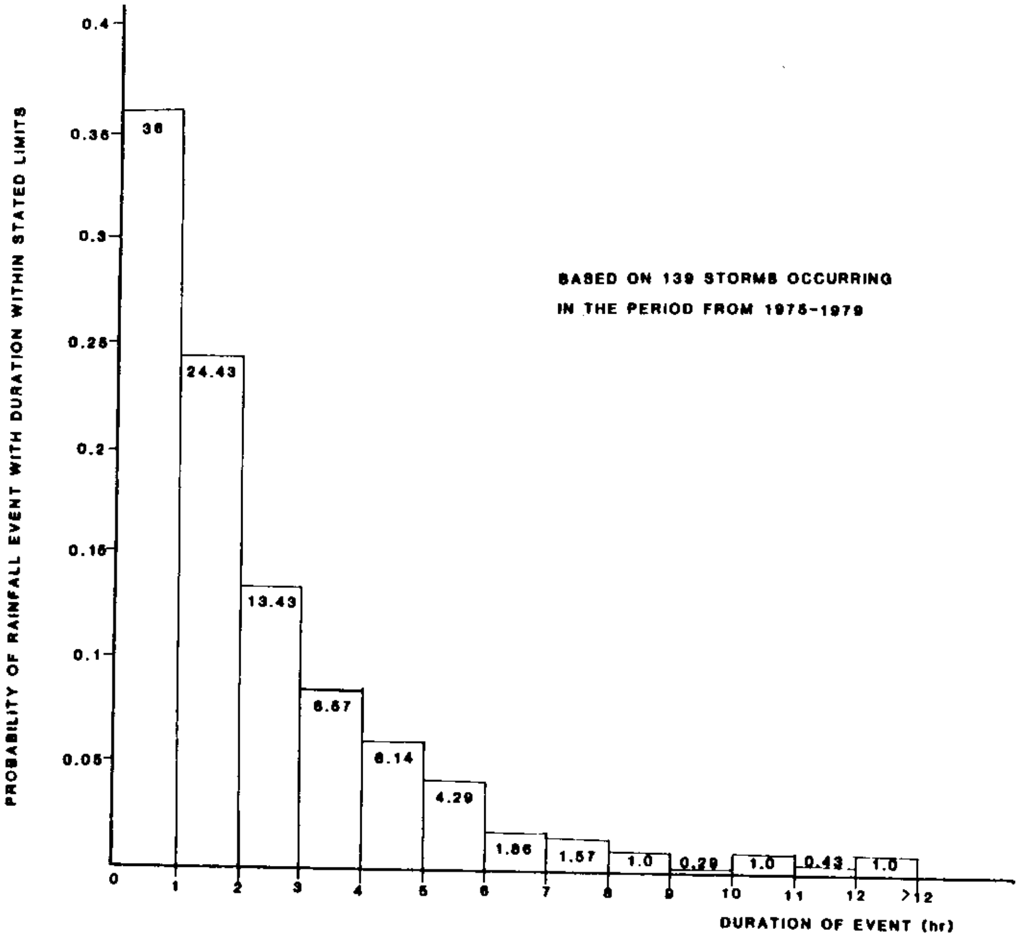


Fig. 6. Distribution of event duration using Orlando meteorological data.

2. Storm events end at the record of report.
3. These conditions represent the maximum duration conditions for any storm.

As a result of the study, it can be concluded that the probability of storm duration less than or equal to three hours is 74%. The design distribution for a particular duration now becomes a matter of major importance.

Table 3 presents a summary of average storm depths for the 15 locations studied. The mean values were computed using the total annual number of storms and the volume of precipitation for each station. Note the high volume storms of north Florida. These are indicative of infrequent, relatively low intensity, moderate duration storms while the storms in central and south Florida are generally low volume, high intensity, short duration storms. Coastal areas also exhibit the low volume pattern experienced in south and central Florida.

Numerous models of the rainfall process constitute the necessary requirements to describe that part of the hydrologic cycle. Perhaps most important to the design of stormwater management is the distribution of rainfall during a particular storm. To obtain accurate representations of rainfall distributions, precise continuous data must be compiled. Tipping bucket rain gauges produce the necessary data. Reliability of such recording equipment is determined by the ability to maintain operation of the unit. However, for rainstorms of long duration, rainfall records can

TABLE 3

ARITHMETIC AVERAGE RAINFALL VOLUME FOR A STORM EVENT*

Location	Volume/Storm (cm)
Niceville	.61
Appalachicola	.45
Inglis	.42
Tallahassee	.58
Gainesville	.46
Jacksonville	.39
Daytona	.43
Orlando	.34
Tampa	.39
Vero Beach	.46
Clewiston	.48
West Palm Beach	.37
Fort Myers	.54
Miami	.32
Key West	.28

* Geometric values would perhaps better define the central tendency.

produce the necessary information with an adequate degree of accuracy. Figure 7 used in conjunction with the volume histogram for Orlando (Appendix A) eliminates two phases of uncertainty in predicting storm events and provides the designer with two important facts in deciding a design storm.

Infiltration

Infiltration is a complex phenomenon which merits due consideration in the design of stormwater management systems. Its place is most important where land costs are not a determining factor in the ultimate use of the land and where infiltration of rainfall can easily be achieved. Infiltration is complex in that the rate of infiltration in soil varies with soil type, water content, depth to water table, degree of compaction, local foliage, and depth of surface water imposed upon the area under test. Most urban areas are not suitable for swales as management practices, but suburban and rural areas are readily adaptable to the use of swale systems.

Tests to determine the infiltration rate were carried out with the use of a double-ring infiltrometer. The purpose of using two rings instead of the conventional single ring was to confine the measured flow to an area such that vertical flow was predominant. An infiltrometer (either single or double-ring) in which water is applied to the soil en masse is called a flooding type infiltrometer (Chow 1964). Surface water level was maintained at a constant depth of two inches. A schematic showing the set-up

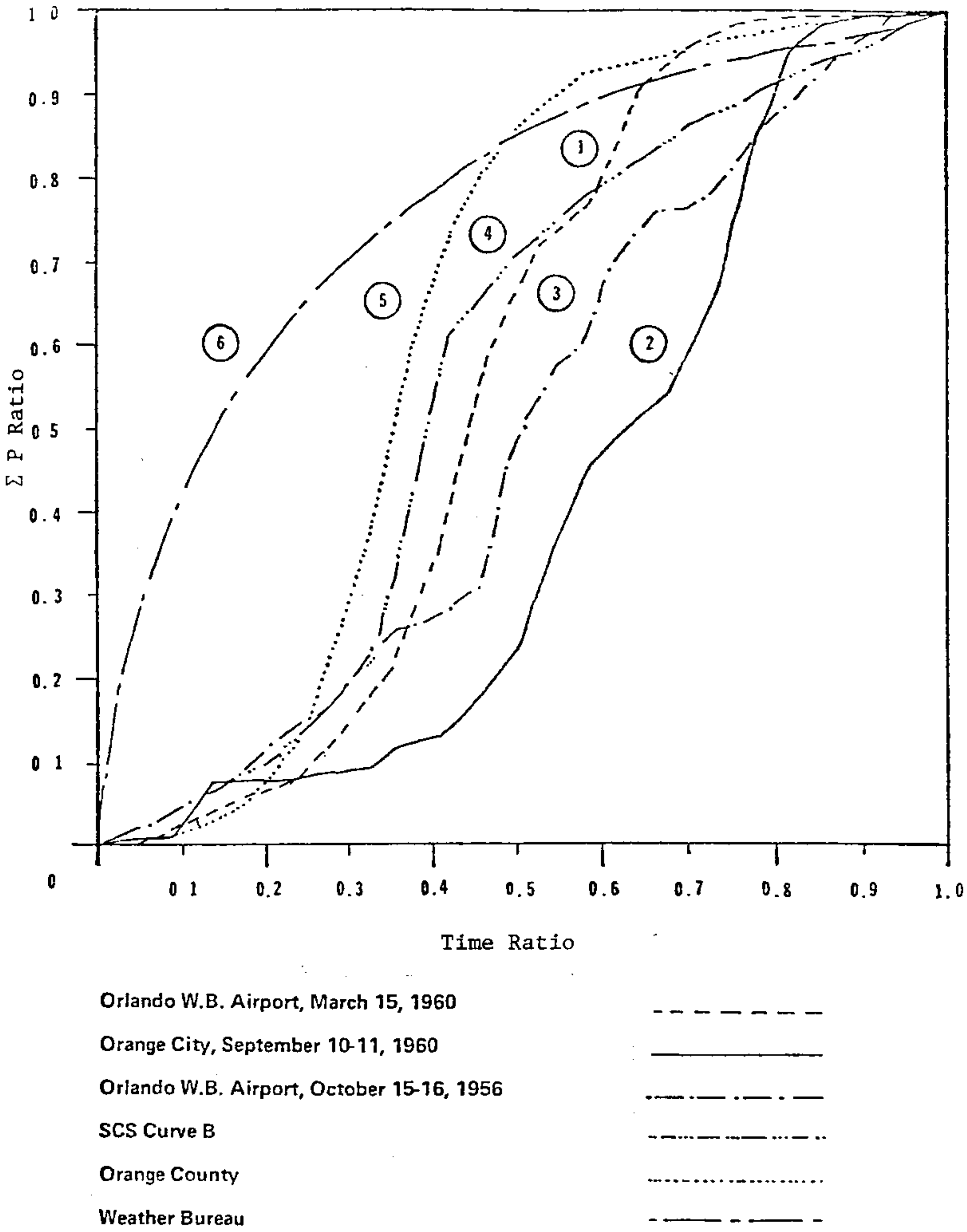


Fig. 7. Dimensionless mass rainfall curves.

SOURCE: Wanielista, 1978.

of the infiltrometer is shown in Figures 8 and 25. The rings were pushed into the ground at depths shown in the figure. To maintain concentricity of the rings, a set of centering pegs was used. The pegs were first calibrated in the laboratory and maintained throughout the testing period. The results from the use of the double-ring infiltrometer are believed to be more representative of true vertical flow than results obtained had another type flooding infiltrometer been used.

To measure the vertical flow rate of water into the soil, a buret was used to input water to maintain a constant surface water depth of two inches. Laboratory calibration of the buret was performed by weighing the dried assembled buret, adding a volume of distilled water from a graduated cylinder, recording the water temperature and measuring the specific gravity of the suspension. Additional water was added to bring the level to a decimate volume and tape was placed at the mark. Exclusion of the meniscus effect was accounted for upon placement of transparent tape. Later the buret was scored with a conventional metal engraver at the edge of the tape marks and volume levels were added. This procedure produced a buret which was accurate and large enough to handle the expected volumes of water encountered in infiltration tests.

Operation of the buret in the field was as follows:

1. A set of hoses (garden hoses and tygon tubing) and a 55-gallon drum of water was used to convey the water from its storage point to the rings.

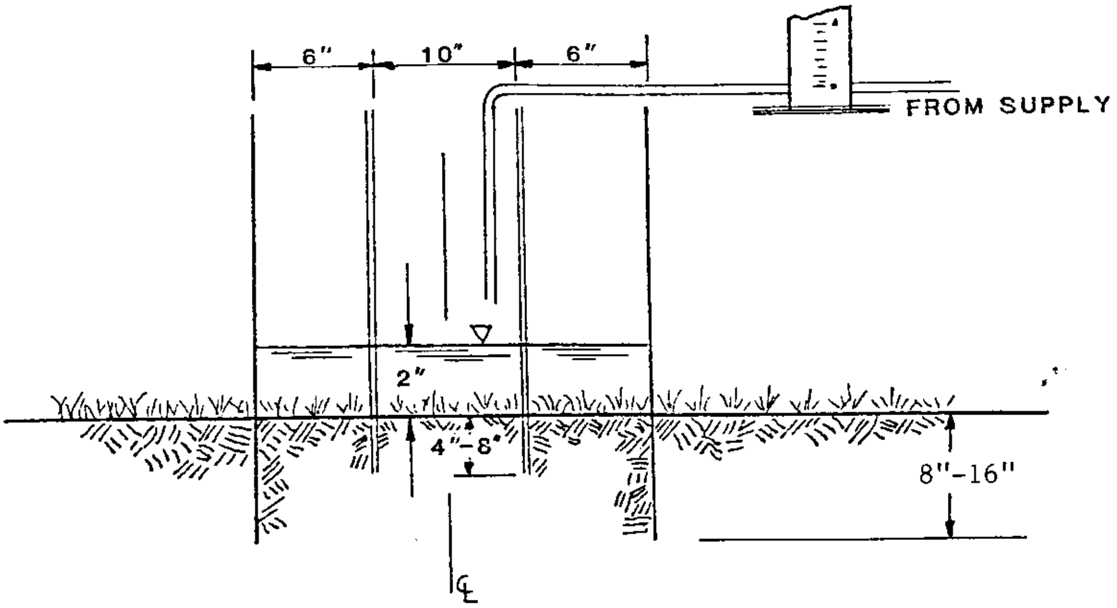


Fig. 8. Schematic of double-ring infiltrometer configuration.

NOTE: The depth of water was kept at 2". Even though it is recognized that the swale flow depth can be much deeper, the 2" depth was believed to produce lower infiltration rates for design purposes.

2. After the outer ring was set in place in the field, a 2" x 4" plank was placed across the top of the ring. A spirit level was then placed on the plank. If the ring was not level, as measured by the spirit level, the ring was hammered deeper into the ground until a level ring was obtained.

3. The buret was then placed on the plank and filled with water by regulation of a valve on the intake side of the buret. The intake valve was then closed and the water level brought to mark by venting the outlet valve and permitting the water to flow into the outer ring. The depth of water in the inner ring was brought to two inches above the surface of the test area and the time was recorded at which a slight increase in the water level was detectable. Regulation of the outlet valve and subsequent recording of the changes in water levels and time intervals directly produce the desired rate of infiltration pattern.

The operational pattern employed saved time by eliminating constant manual refilling of the buret and permitted careful observance of the water level fluctuations.

Vegetation enhances infiltration, provides a resistance to overland flow and acts as a soil binder to help prevent erosion. It also helps to dissipate soil-erosive energy imparted by raindrops. Grasses and other vegetation enhances infiltration primarily by providing a moist base at the surface of the earth. The antecedent moisture conditions are maintained in a range which makes infiltration favorable. Plant uptake of applied waters provides a degree of abstraction. Table 4 shows the physical characteristics of swales studied. Note that most of the swales studied were grassed swales. Unless the texture and porosity of soils is favorable for infiltration, grassed swales are usually utilized.

TABLE 4

PHYSICAL CHARACTERISTICS OF SWALES STUDIED

Location	Slopes (%)		Crop Cover	Antecedent Moisture Condition
	Longitudinal	Lateral*		
UCF Roadside	0.06	0.12	Uncovered	Wet
UCF Physical Plant	1.11	0.16	Low grass (unsodded)	Normal
SR 520L	1.63	0.08	Grassy cover < 3"	Normal
SR 520R	1.36	0.12	Sparse grass < 3"	Normal
East Highway 50	1.02	0.17	Grassy Cover > 3"	Wet
Seminole 419	0.50	0.19	Dried grass and mud	Dry
Geneva SR46	0.98	0.16	Low grass (unsodded)	Wet
Tuskawilla	0.64	0.08	Low grass (unsodded)	Normal
Mandarin	1.54	0.11	Grassy cover (sodded)	Normal
Seminole 426	0.85	0.16	Grassy cover > 3"	Wet
East-West Expressway	3.14	0.29	Grassy cover < 3"	Wet

*This is an average of each lateral slope in triangular and trapezoidal channels.

TABLE 4

PHYSICAL CHARACTERISTICS OF SWALES STUDIED

Location	Slopes (%)		Crop Cover	Antecedent Moisture Condition
	Longitudinal	Lateral*		
UCF Roadside	0.06	0.12	Uncovered	Wet
UCF Physical Plant	1.11	0.16	Low grass (unsodded)	Normal
SR 520L	1.63	0.08	Grassy cover < 3"	Normal
SR 520R	1.36	0.12	Sparse grass < 3"	Normal
East Highway 50	1.02	0.17	Grassy Cover > 3"	Wet
Seminole 419	0.50	0.19	Dried grass and mud	Dry
Geneva SR46	0.98	0.16	Low grass (unsodded)	Wet
Tuskawilla	0.64	0.08	Low grass (unsodded)	Normal
Mandarin	1.54	0.11	Grassy cover (sodded)	Normal
Seminole 426	0.85	0.16	Grassy cover > 3"	Wet
East-West Expressway	3.14	0.29	Grassy cover < 3"	Wet

*This is an average of each lateral slope in triangular and trapezoidal channels.

Percent saturation, s, is a function of local porosity, n, (non-capillary) water content and specific gravity of the suspension. Equations relating those parameters may be found in Bowles (1977). The equation which relates specific gravity to degree of saturation is:

$$s = \frac{g_s (1 - n)(W.C.)}{n} \tag{4}$$

where: W.C. = water content

For a direct increase in water content, a corresponding increase in degree of saturation can be evidenced. Also, porosity is in-inversely proportional to degree of saturation, thus for highly porous sandy soils, the degree of saturation can be expected to be relatively low. Values of water content and depths to water table are shown in Table 5. For most sandy soils, water content varies over a narrow range.

Soil texture, described by grain size distribution, is the most important factor in the vertical infiltration of water. Coarse textured soils usually permit easy influx of water imposed and percolation rates are high. To assess the texture of the soils, grain sizes were evaluated. Table 6 gives the results of those evaluations. ASTM (1980) methods were used on grain size analysis and all other soil tests in the study. As clay fines and silt contents increase, the rate of infiltration will decrease. A clay soil shows a high initial infiltration rate,

TABLE 5

POROSITY, WATER CONTENT AND APPARENT WATER TABLE DEPTHS FOR SWALES STUDIED

Location	Porosity* (n)	Water Content (W.C.)	Depth to Water Table
UCF Physical Plant	0.14	12.15	42"
Mandarin	0.15	9.58	> 42"
Tuskawilla	0.16	4.06	> 42"
SR 520L	0.15	4.00	> 42"
SR 46	0.17	6.76	> 42"
SR 520R	0.15	5.52	> 42"
UCF Roadside	0.13	10.48	36"
East Highway 50	0.34	18.20	24"

* Porosity values are V_w/V_t (volume of water/total volume of sample).

TABLE 6a

GRAIN SIZE DISTRIBUTIONS FOR SOILS STUDIED

Location	Grain Sizes*			Uniformity Coefficient
	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	D_{60}/D_{10}
UCF Roadside	0.11	0.16	0.20	1.8
UCF Physical Plant	0.07	0.15	0.22	3.1
SR 520L	0.08	0.12	0.16	2.0
SR 520R	0.09	0.13	0.19	2.1
Mandarin	0 .12	0.18	0.29	2.4
Tuskawilla	0.10	0.15	0.23	2.3
SR 46	0.10	0.16	0.21	2.1
CR 426	0.04	0.10	0.16	4.0
CR 419	0.05	0.11	0.18	3.6
East Highway 50	0.08	0.14	0.19	2.4
East-West Expressway	0.17	0.26	0.32	1.9

* Diameter in inches = mm/25.4

TABLE 6b

COMPUTER PERMEABILITIES AND RECESSION CONSTANTS FOR SOILS STUDIED

Location	Permeability (k_p)*	Recession Constant (kH)
	(in/hr)	(1/hr)
UCF Physical Plant	7	3.6
SR 520L	9	3.0
Highway 50E	9	3.0
SR 520R	13	6.0
Tuskawilla	14	1.2
SR 46	14	1.2
UCF Roadside	17	1.8
Mandarin	20	1.5

* Computed by Hazen formula, $k = CD_{10}^2$. C = 100 for sands. D_{10} may be found from Table 5.

NOTE: A plot of the data in Table 6b shows a curvilinear relationship between the recession constant and permeabilities. Comparison of the permeabilities with those of Table 8 shows that values computed and those of Table 8 are comparable.

swells and chokes off the void spaces and infiltration stops. An over-abundance of fine sands may seem impervious due to low porosity. The inter-related combined effects of porosity and soil texture defines the capacity for vertical infiltration at a point.

Soil sampling was carried out with the use of an auger. Two-fold uses of the auger were to find the apparent water table and to extract a sample for laboratory testing and visual inspection. If the depth to water table was greater than 42 inches, the apparent water table could not be found. The sample was immediately wrapped in a plastic bag and transported to the laboratory for testing within one hour of extraction. The layers were usually left intact and as such, a representative portion of each layer could be divided out to obtain average values for the entire depth of soil. Grass was removed upon laboratory testing of the sample. A Speedy Moisture Content Analyzer (Model MC 320) was used to detect moisture contents for the latter portion of the study. Again, a representative portion of each soil layer (by visual inspection) was loaded into the Speedy to obtain an average water content value.

Slopes were determined through standard methods outlined in Breed and Hosmer (1977). Two-hundred to five-hundred foot lengths were taped and the differences in elevations were recorded using a Geotec Model AL-23 self adjusting level. Slopes were then calculated by standard computations (see Breed and Hosmer 1977).

CHAPTER V

METHODOLOGIES AND RESULTS

Introduction

Results from field studies of swales which resulted in Horton parameters, soil characteristics and rainfall distributions combine to create a mix of events suitable to evaluate the design of swales. Methodologies that followed were based on standard tests determined by long-term studies of testing agencies. The time of year in which the swales were studied was considered as a period in which recovery from intermittent rainfall was most favorable; the time between successive rainfall events is longest during late fall and winter months. Seminole and Orange County areas were used as testing sites due to their close proximity to the university. Extreme care was taken in evaluating soil parameters to ensure representative values for each swale. There seems to be a lack of a detailed consistent methodology for design of swales. The following discussion provides one approach which is simple enough to be understood by informed laymen, yet technical enough to be appreciated by proven professionals.

Rainfall

Rainfall is a result of meteorological processes of heating and cooling of air masses over a considerable area. Solar heating of the surface of the earth and of water bodies causes evaporation to occur; a consequent warm air mass rises, heat loss and condensation results and vapor particle agglomeration produces rainfall. Rainfall records show that volumes and duration of rainfall for adjacent meteorological areas vary considerably (U.S. Department of Commerce, 1975-79). Urban development, temperatures, wind movements and geographic location are some reasons for rainfall event variances. A study of rainfall patterns in Florida shows these factors to be predominant.

The variability in rainfall volumes, durations and distributions can be partially explained by wind effects upon precipitation. Another partial explanation is found when the siting and recording accuracy of rain-gaging stations is evaluated. Thirdly, and perhaps more important to man is the concept that land use and the extent of urbanization and industrialization within an area greatly influences the distribution, duration and volume of rainfall. An ordering and summary of factors which induce variations in rainfall patterns would consist of these items:

1. Local climate
2. Degree of urbanization and industrialization
3. Temporal meteorological conditions
4. Siting of gaging stations and reliability in recording data

With the inconsistencies that are inherent in rainfall patterns, it seems hardly likely that one general model can be applied which completely describes all rainfall occurrences.

Upon the occurrence of a precipitation event, recorded volumes over a length of time describes the distribution of a storm event. Determining a mathematical model to describe the distribution of rainfall in a storm event is difficult due to the interrelation of parameters (volume, intensity, duration and frequency). U.S. Weather Bureau (1973) and Golding (1973) have developed graphical models which describe rainfall distributions. These are the set of dimensionless curves presented in Figure 7. Evaluation of local climatological data show that the distributions are consistent for areas around the state of Florida.

The usefulness of the cumulative probability distribution shown in Figure 3 is to define the relative level of occurrence of a stated volume of rainfall. It defines the probability of a rainfall event being less than or equal to a stated volume. For example, for all of Florida, the probability of an event being less than or equal to one-half inch is 76.5%. For treatment by diversion of a desired volume, a distribution can be used to determine the overall yearly volume to divert and the percentage of storms per year which must be treated to achieve "first flush" effects. Figure 4 shows the results of calculations for rainfall data at Orlando, Florida. Table 7 presents calculated values of percentages of yearly storm volume to treat if first flush effects are treated. Note the remarkable differences in values for diverted and undiverted volumes. Note, also, for locations Miami and Key West, the percentage of yearly volume for undiverted

TABLE 7

PERCENTAGES OF YEARLY RAINFALL PRODUCED BY STORMS EQUAL TO OR LESS THAN STATED EVENT VOLUME

Location	Level of Treatment					
	1/2"		1"		2"	
	DIV	UNDIV	DIV	UNDIV	DIV	UNDIV
Niceville	53.7	27.8	73.0	47.7	89.2	69.0
Tallahassee	55	29.8	74.6	46.8	91.3	71.3
Jacksonville	61.6	38.5	77.4	60.4	94.4	84.4
Appalachicola	63.5	38.3	82.0	57.8	95.4	84.4
Gainesville	65.4	41	83.0	61.7	93.7	81.5
Inglis	59.8	33.0	78.1	52.4	95.4	82.8
Daytona	62.9	38.4	80.5	58.8	93.6	78.1
Orlando*						
Tampa	66.5	41.0	85.0	62.4	96.0	86.1
Vero Beach	66.4	42	84.2	62.1	95.4	89.4
Clewiston	61.7	36.5	82.4	55.8	97.0	83.3
Fort Myers	58.5	31.8	78.0	53.3	93.2	77.3
West Palm Beach	65.1	44.0	80.8	60.6	92.0	79.1
Miami	71.7	50.5	86.5	69.9	95.3	87.5
Key West	74.7	55.2	88.3	73	95.8	88.0
AVERAGE						

* See Figure 4.

treatment is +50 percent. Another interesting point to observe is the increase in percentage of storms as one progresses from location to location down the state.

Design methods for storm excess control usually require the use of a design storm to simulate conditions under which the system will operate. The graphical models of Figure 7 are needed to define the pattern of rainfall during the storm. Caution must be used in applying the curves to all situations; for to say that all storms are distributed in such a manner can lead to gross misestimation of more applicable rainfall patterns. However, the plots do provide a sense of direction where none exists when a stormwater control system is in the design phase. Similar curves for other areas may be developed by following the procedures used by Golding (1973). An illustrative example showing the use of dimensionless curves will be presented in a later section of the text.

While the distribution of rainfall during a storm is an essential part of the design process, an even more significant distribution is one which defines the long term pattern of rainfall events. This type of distribution gives the designer some idea of what volume to expect from a storm event and the probability occurrence of that volume. It defines the level of hydraulics/hydrologic and (if coupled with chemical investigations) to some extent, the level of quality treatment required. If the designer knows what storm volume is exceeded what percent of the time, the initial step in defining the size and type of volume control facility has been completed.

Overland Flow/Runoff

For natural systems, overland flow will occur from point to point if the rate of infiltration and surface conditions are conducive to runoff. One example of an area which is blatantly prone to increased rainfall excess is an urbanized area in which highly impervious pavements exist. Abstraction will be limited to rooftop storage and that part of precipitation which is held in small surface depressions and eventually evaporates or infiltrates. For natural (earth/grass-covered land) systems, if the ability of the first few inches of soil to become saturated is severely hampered, overland flow results.

On soils which are dried below the wilting point, a surface phenomenon exists in which waters applied to the soil fails to saturate the top soil layers sufficiently to permit infiltration. Runoff occurs much the same as for an impervious pavement until the upper surface of the soil becomes saturated and infiltration can result. During the period of acclimation, substantial amounts of loose sediment are transported downstream. The determining factor for detachment and consequent transport of soil is storm erosivity and scour velocity (degree of compaction) of the flows in the channels. Consequently, clays and soils high in clay content tend to be less erosive upon drying of the surface layers.

sandy fine and silty fine soils which are not well-compacted will tend to lose sediment. The wilting point phenomenon depends upon the soil layer structure, moisture content, foliage type, soil texture and the relative frequency of rainfall within the region.

Evapotranspiration is the mechanism by which soils may be dried to or below the wilting point. Plant uptake accounts for a portion of water taken from the soil. The ability of a soil to hold water is its water or moisture retention capacity. The water retention capacity for each layer of several soils for Orange and Seminole Counties are listed in the Orange County Soil Survey Supplement (1975) and the Seminole County Soil Survey Supplement (1966). A brief table of soil properties and moisture retention capacities is listed in Table 8.

TABLE 8

SOIL PROPERTIES AND MOISTURE
RETENTION CAPACITIES OF SEVERAL SOILS

Soil Type	Soil Type	Permeability in/hr	Available Water Capacity in/in
Blanton Fine Sand			
0-60"	Fine sand	10->20	0.03-0.05
60-72"	Sandy clay loam	2.5-5.0	0.10-0.15
Lakeland Fine Sand			
0-60"	Fine sand	10->20	0.05-0.08
60-72"	Sandy clay loam	2.5-5.0	0.10-0.15
Lakewood Sand			
0-70"	Sand	>20	0.02-0.05
Leon Fine Sand			
0-24"	Fine sand	10->20	0.03-0.05
24-30"	Fine sand	0.8-2.5	0.10-0.15
30-60"	Fine sand	10->20	0.03-0.05
St. Lucie Fine Sand			
0-52"	Sand	>20	0.02-0.05

The depth of soil layer saturated determines the overland flow potential for a watershed. Evaporation is usually substantial in the first few layers of the soil surface but excessive periods between rainfall events may dry the soil to several feet below the surface.

Compaction along with build up of a surface layer of impervious material increases the potential for overland flow. In roadside swales, a "shmutzdecke" effect may be prevalent. Oils and grease deposited on the road by passing cars are washed into the swale and a thin film builds up on the soil surface (Wanielista 1982). If velocities of flow entering the swale are such that the surface layer cannot be washed away or floated, the volume of water entering will travel along the swale until an area large enough and favorable enough to permit infiltration is found. If no such area is found, the volumes of water entering will ultimately become runoff at the end of the swale. Compaction of swale soils inhibits infiltration and enhances runoff. Excessive vehicular traffic on swaled areas would be the major cause of overland flow due to compaction after swales have been constructed. Prior to swale construction, compaction of the earth by heavy equipment causes low infiltration rates upon testing of the area for percolative abilities. The top layers of soil along with deeper layers become excessively compacted and an otherwise favorable area for infiltration is assessed as a low potential area for the installation of swales as a management practice. Of course, the physical consistency of the soil will determine the degree to which soil may be compacted. Realize, that the silts and clays which aid in effective compaction will also tend to reduce the rate of infiltration on uncompacted soils. Therefore, an interrelation of infiltration inhibiting factors exists.

Construction of a swale may require that some compaction of the soil occur. Musgrave and Holtan (1964) report that one pass of a tractor has been shown to reduce non-capillary pore space by fifty percent and infiltration by eighty percent. In a study by Gifford and Hawkins (1979), it was discovered that infiltration capacity was reduced by the intensity of grazing. The investigators developed specific equations based on the land types, range conditions, intensity of land use and climate prevalent for their study area. A general form of their equation can be expressed as:

$$f_u = a + b\ f_n \tag{5}$$

where:

a is a constant depending on factors mentioned above

b is a constant based on intensity of land use

f_n = normal infiltration rate for grazing conditions

f_u = ungrazed, uncompacted infiltration rate

The researchers also determined linear relationships for recovery of rangelands from heavy grazing. An important point to note here is that soils eventually recover from compressive action. The time frame involved for recovery may be excessively long and full recovery may never occur. Some compaction of swale soils is unavoidable, but to maximize infiltrative capacities, appropriate efforts should be made to minimize compaction in areas where swales are to be constructed.

One factor which has received moderate treatment in infiltration studies is infiltration into sloping soils. With a substantial slope, it becomes almost impossible to investigate the vertical infiltration rate; interflow will impart its effects and values obtained in conventional tests (rainulators and flooding type infiltrometers) will be misleading. In conditions described, the potential for overland flow greatly exceeds the potential for infiltration. In all swales studied, large slopes were not encountered and as such, were not considered a problem.

Infiltration

While many models exist to describe the rate of infiltration (see Literature Review), few exist which model this phenomenon with a high degree of completeness. Horton's equation describes infiltration best by allowing the measured data to be fit to a non-linear equation. The equation can immediately be recognized as a form of the exponential decay function. At low values of t, the equation can be expected to be linear and at higher values of t, the equation predicts a constant or steady rate of infiltration. Figures 9-16 reinforce the previous statements.

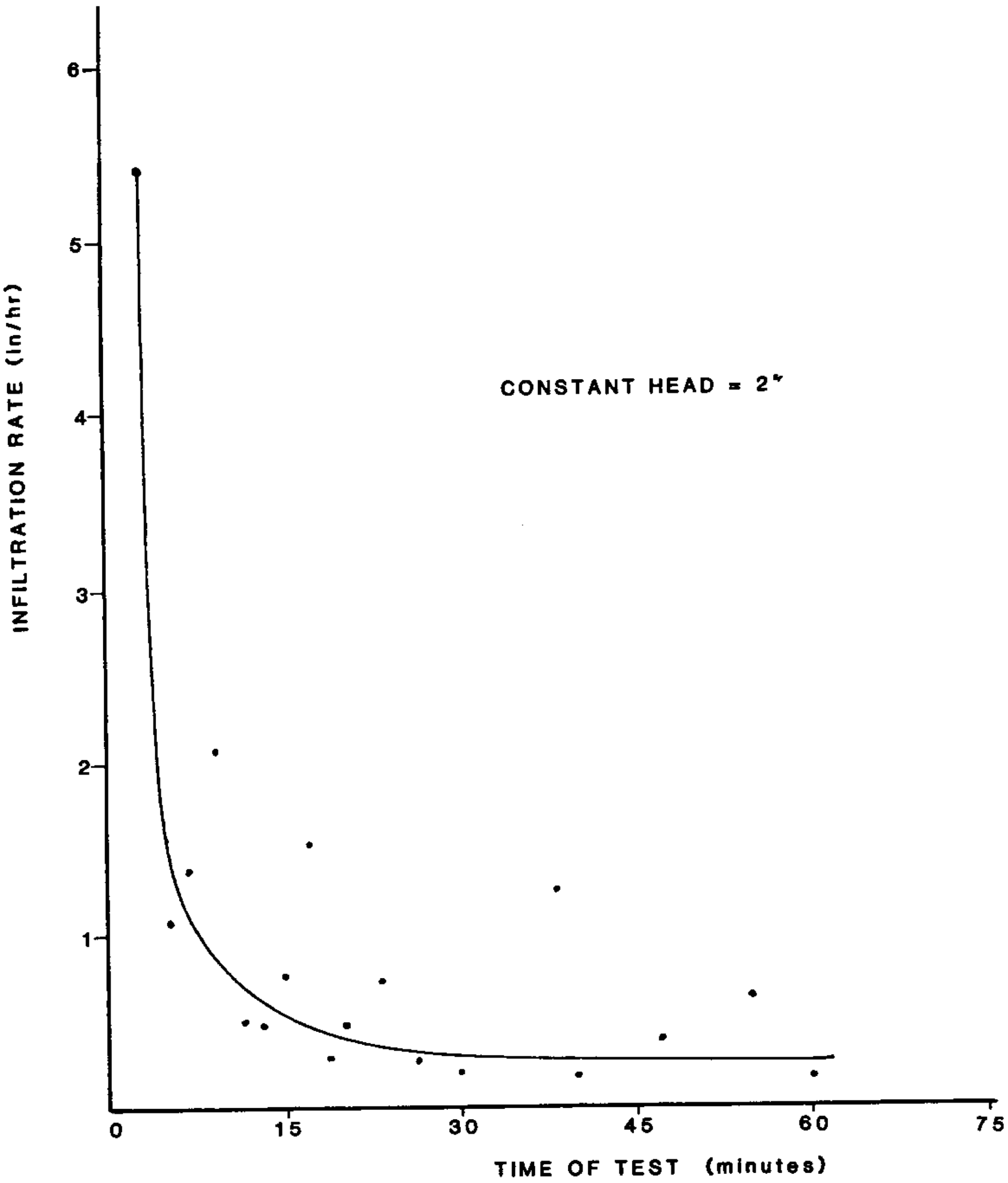


Fig. 9. Infiltration rate curve for roadside swale at SR 520, north of Orange County line.

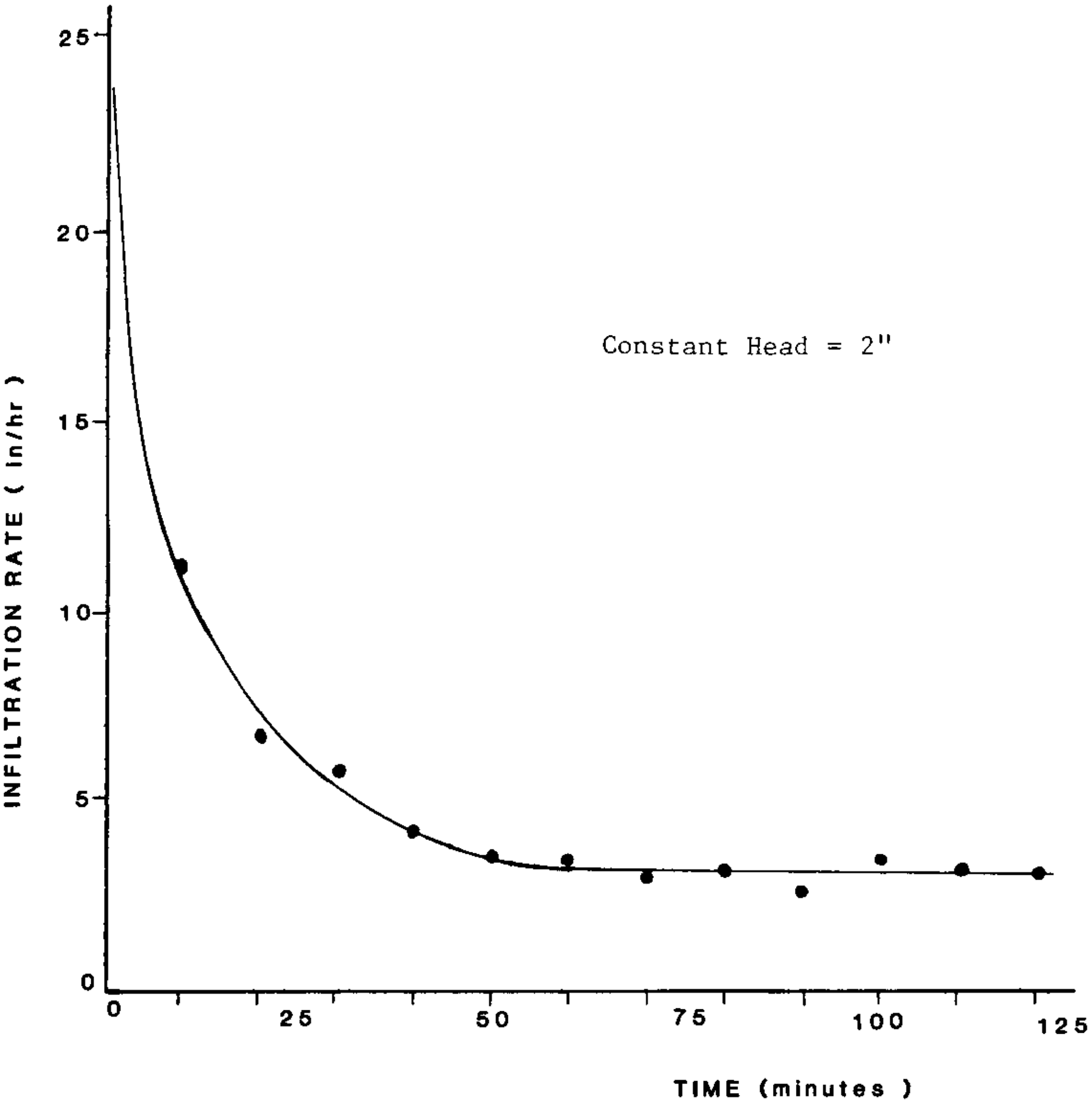


Fig. 10. Infiltration curve for residential swale at Mandarin Homes subdivision - Seminole County line.

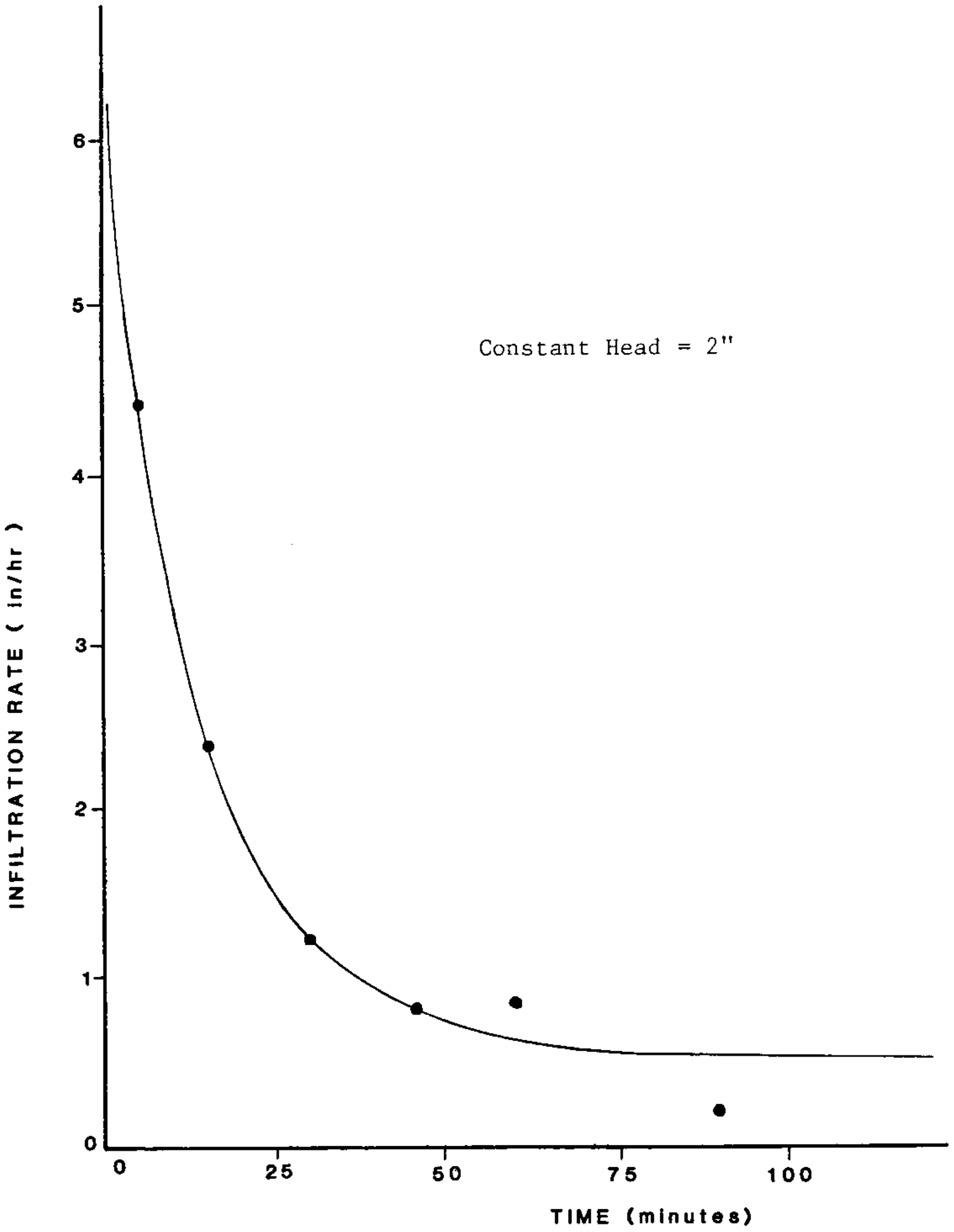


Fig. 11. Infiltration curve for UCF roadside swale - Orange County.

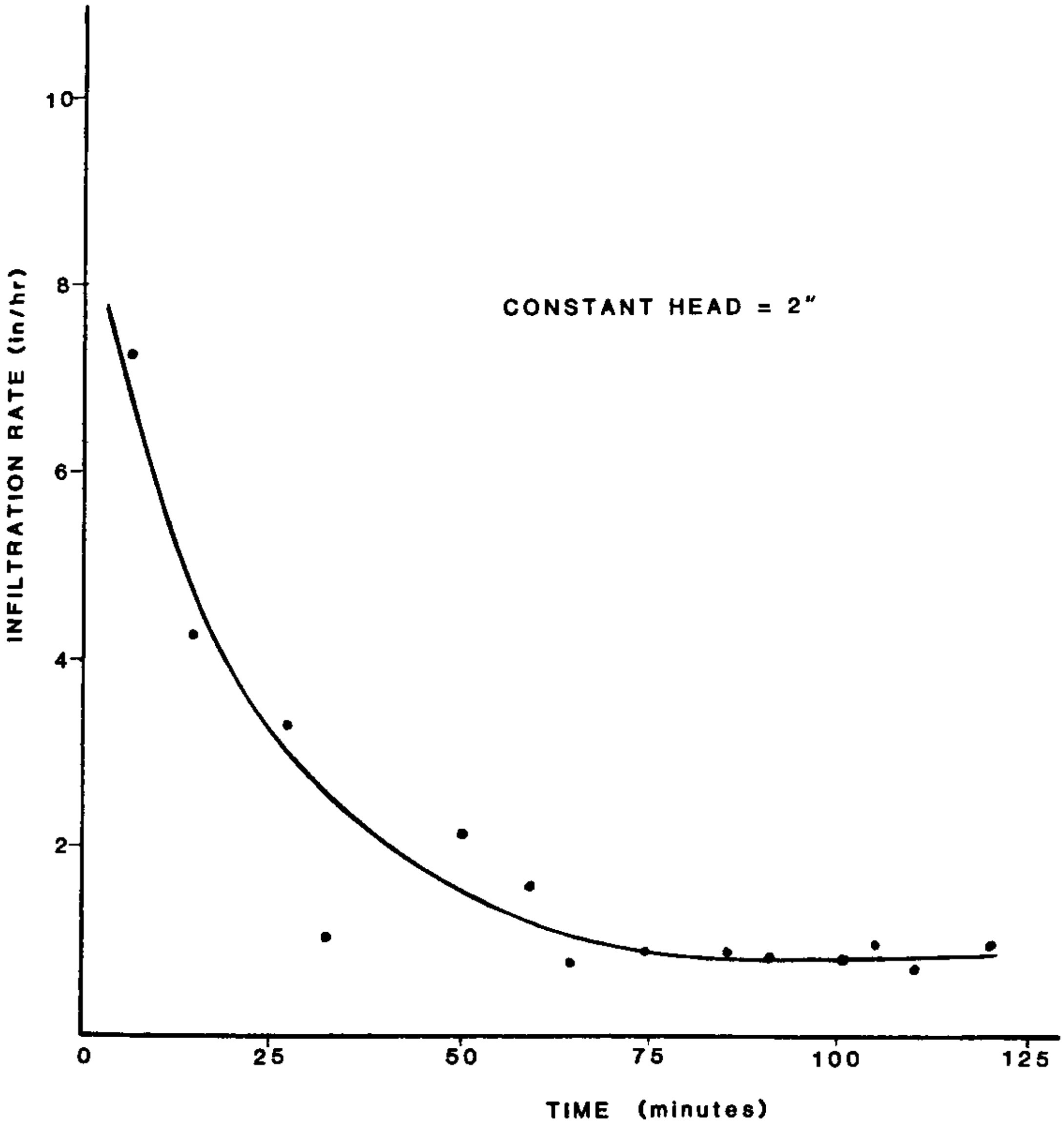


Fig. 12. Infiltration rate curve for Tuskawilla residential swale - Seminole County.

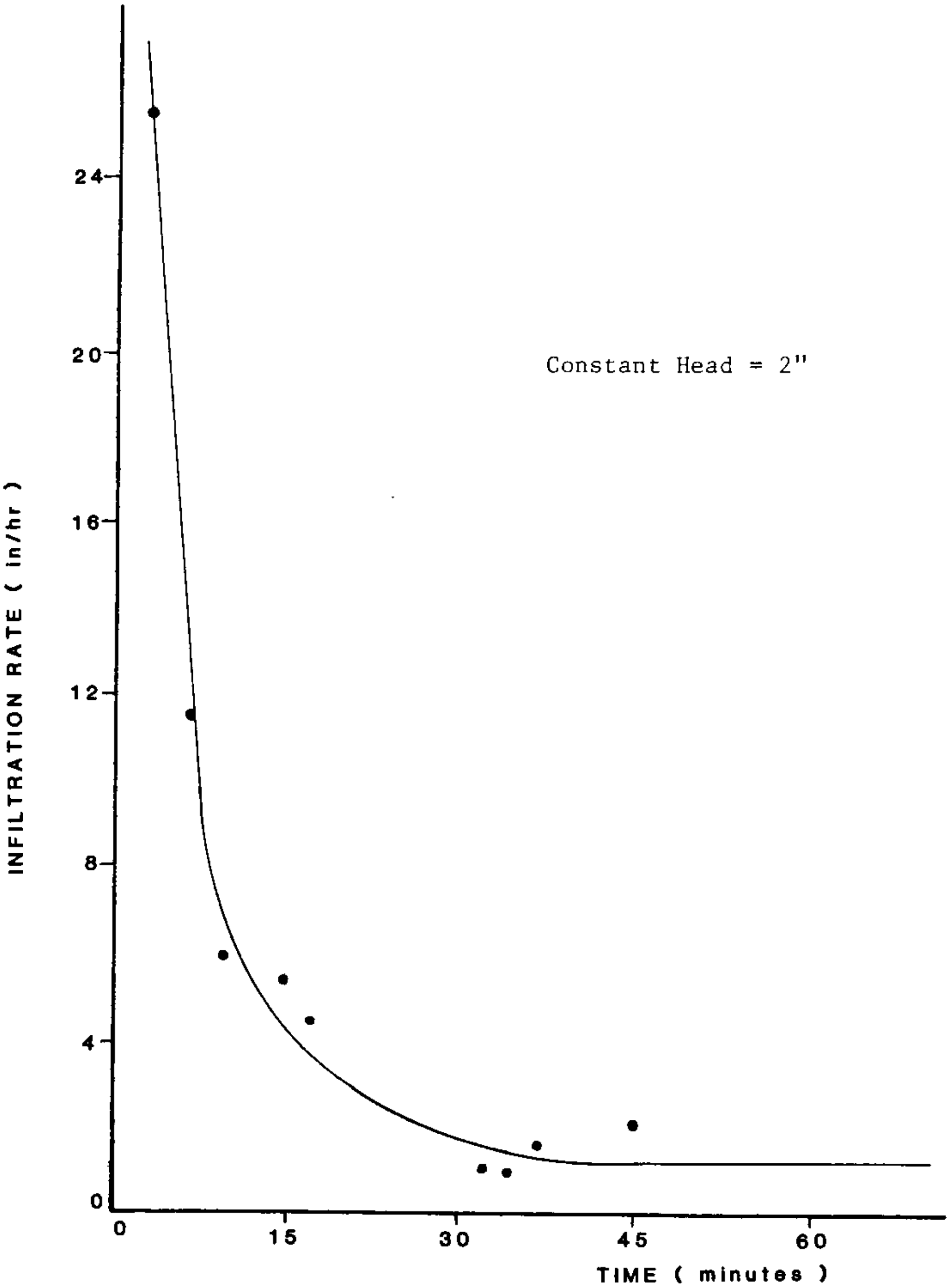


Fig. 13. Infiltration rate curve for UCF swale near physical plant.

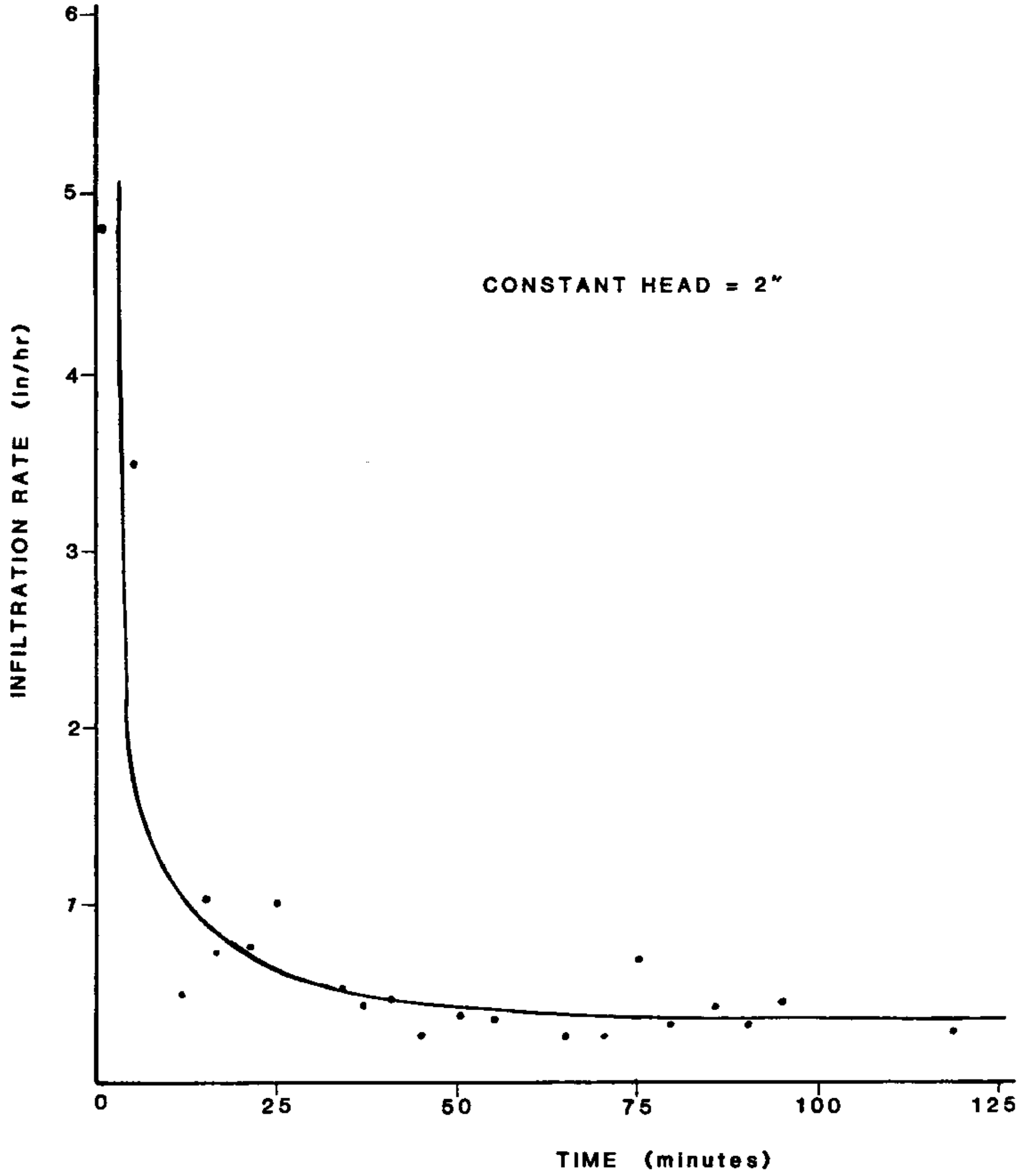


Fig. 14. Infiltration rate curve for roadside swale at SR 46, west of Geneva, Florida.

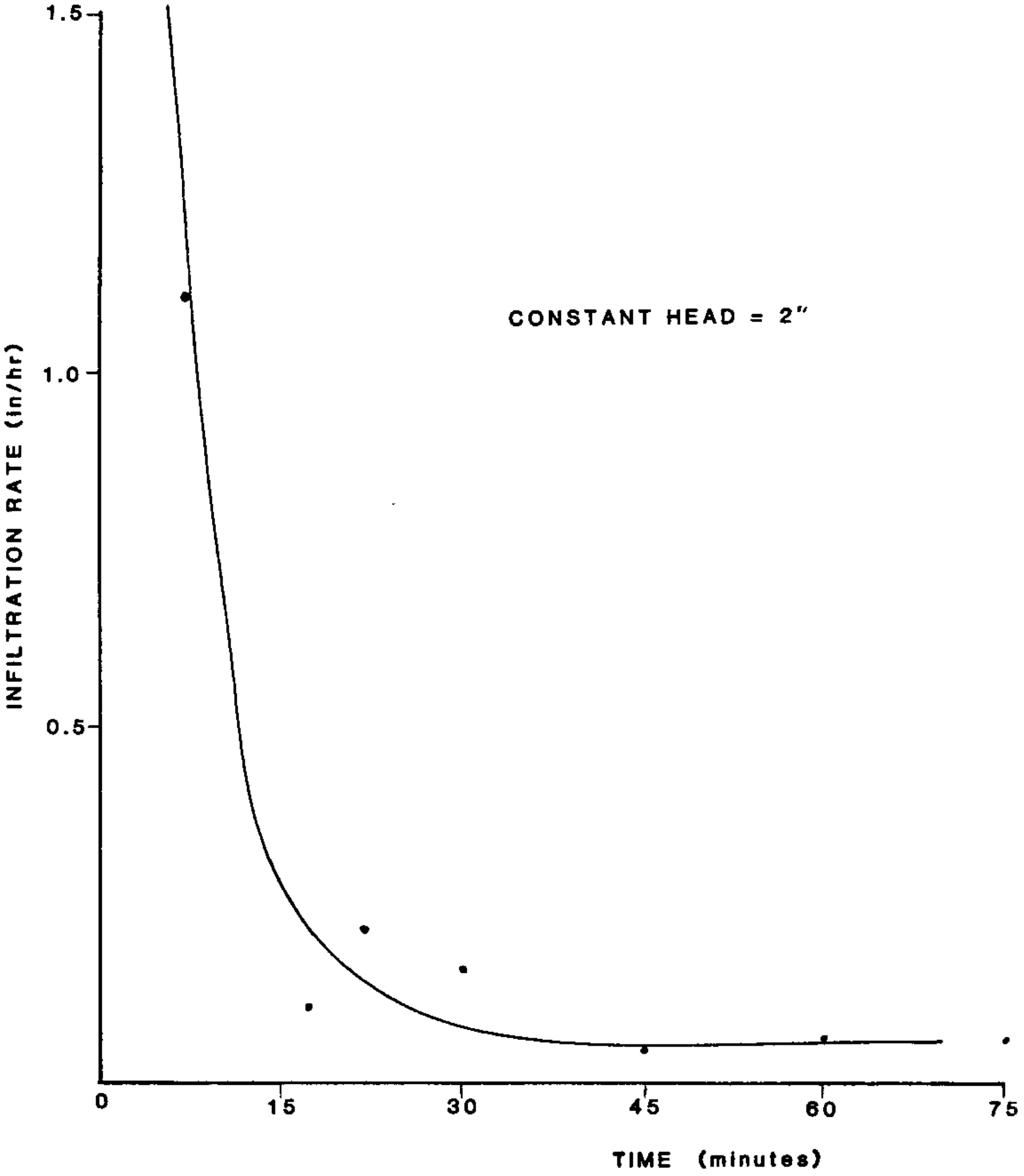


Fig. 15. Infiltration rate curve for east highway 50 roadside swale - Orange County.

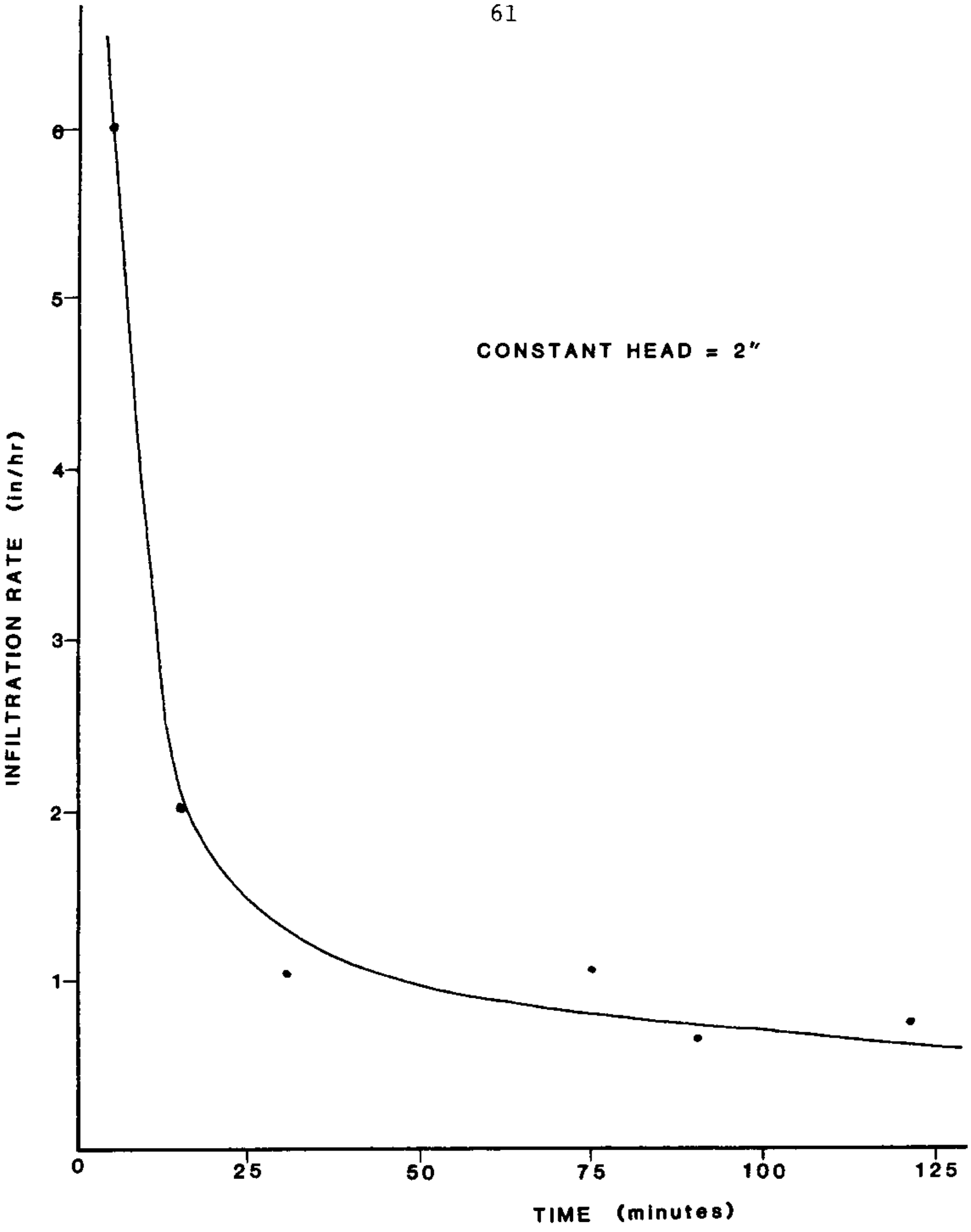


Fig. 16. Infiltration rate curve for SR 520 roadside swale north of Orange County line.

Calculation procedures used to develop the curves shown may be found in most hydrology textbooks. Horton's model, though an extrinsic method of assessing the infiltration rate, predicts the pattern of infiltration fairly accurately.

Horton's Parameters

The recession constant or shape factor (k) determines the rate of fall of the infiltration rate curve. The values shown in Table 9 are assumed to be reflective of actual conditions because the effect of flow spreading is eliminated by use of the outer ring. The flow spreading effect is explained by Figure 17. Since lateral outflow is accounted for by the outer ring, flow in the inner ring is assumed to be vertical. The vertical flow area is calculated as 78.54 square inches. Recession constants vary from 6.00/hour to 1.20/hour (see Table 9). The results obtained are within the range of k values obtained by Beaver (1977) using a ring infiltrometer. For the test encountered, soil type and grass cover are factors which differentiate swales with good infiltration from those with poor infiltration. Recognizing that the values of f_o and f_c obtained for the swale at Mandarin subdivision were for newly sodded lawns, a correlation is apparent for f_o and f_c. The relationship is approximately linear with a correlation coefficient of 0.83.

Isolation of groups of tests to evaluate the effect of crop cover on the values of f_c and f_o show that crop cover has a

TABLE 9

RECESSION CONSTANTS AND HORTON'S PARAMETERS DEPICTED IN FIGURES 9-11

Location	k	f_o	f_c	Soil Type
	/min	in/hr	in/hr	
Tuskawilla	-1.2	9.0	0.80	Blanton (low phase)
Mandarin	-2.0	24.0	3.10	Blanton (high phase)
UCF Roadside	-1.8	6.3	0.55	St. Lucie-Pomello
SR 520L	-3.0	8.5	0.55	Rutlege Fine Sand
SR 520R	-6.0	7.0	0.50	St. John's
East Highway 50	-3.0	2.51	0.06	Leon-Rutlege Fine Sand
SR 46	-1.2	8.0	0.35	Lakewood-Lakeland
East-West Expressway*				Muck
SR 426*				Leon-Rutlege
SR 419*				Rutlege Mucky Fine
UCF Physical Plant	-3.6	36.0	1.10	Leon Fine Sand

* Near zero infiltration.

profound effect on both f_o and f_c. For the roadside swale at UCF, the initial infiltration rate is slightly above the rate found for the roadside swale at East Highway 50. The difference here is that the swale at UCF has no crop cover while the one at East Highway 50 has excessive unkept crop cover. These two swales illustrate the pore clogging effect of unprotected soils and soils which contain excessive silt and clays. For areas which have a developed mat of crop covers (such as Mandarin swale, and the swale at UCF's physical plant), values of initial and final infiltration rates can be expected to be high when the soil permits sustained infiltration. The swales studied show that crop cover has an indeterminable effect on the recession rate constant.

Initial unsaturated water content has a profound effect on the initial infiltration rate. An ordering of the data shows that a graphical relation may be developed (see Figure 18). The data for swales at SR 46 was omitted because it was the only one encountered in which soils were not layered to the extent that discoloration, texture differences and increasing wetness could be visibly detected. The effect of porosity upon the initial infiltration rate cannot be deduced because of the slight variation in sandy soils. The noticeable difference is found for the initial surface silts and muds of East Highway 50 swale (0.34). Since surface water depth was constant, its effect on initial infiltration rate could not be assessed.

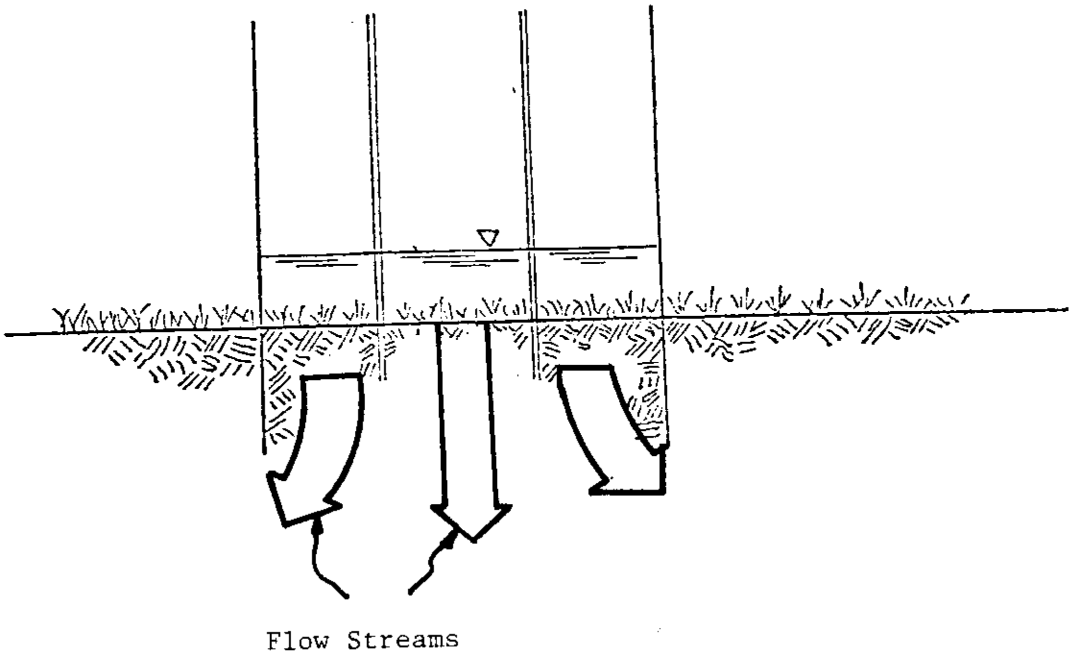


Fig. 17. Flow assumptions in double-ring infiltrometer.

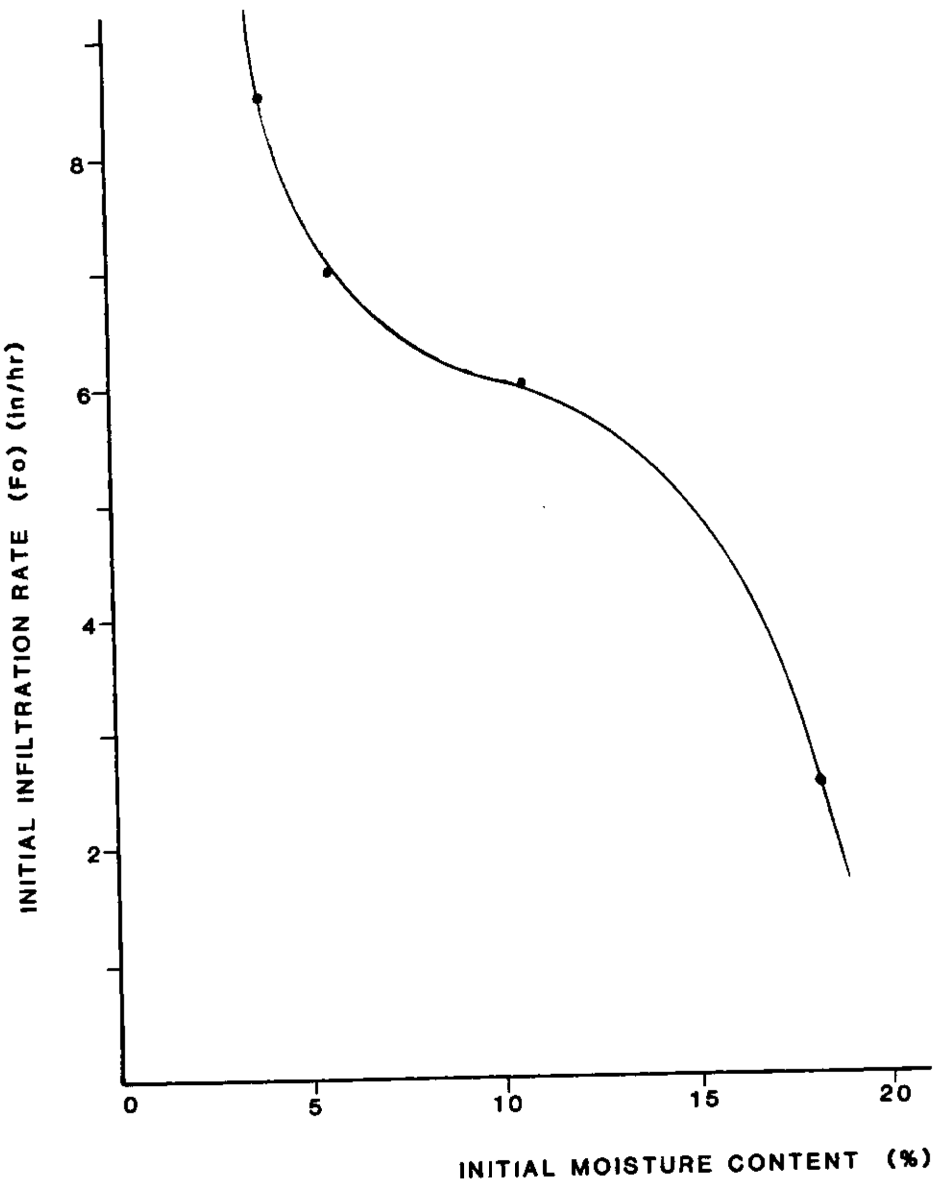


Fig. 18. Relationship of initial infiltration rate and unsaturated moisture content for swale studied.

Depth of surface water in the test has an impact upon the final infiltration rate. In a laboratory study by Reeder et. al. (1981), the authors show that for a uniform crushed Monterey dune sand, the effect of changing the surface water depth is to shift the infiltration rate curve to the right. The recession constant remained essentially the same, a slight increase in the initial infiltration rate and a significant increase in the final infiltration rate occurred. Generally, the effect can be modeled as in Figure 19. More detailed research needs to be initiated for the study of Horton's parameters under various test conditions.

Infiltration is an integral part of the hydrologic cycle. One method for assessing it is to measure the rainfall into the watershed and the runoff leaving the watershed. The resulting differences are combined interceptions, abstractions and infiltration. Another method is to measure the potential for infiltration directly. Test conditions will dictate the accuracy of the measurements and the abilities to accurately gage both rainfall and runoff will give some indication of the accuracy of the first method. Which ever method is used, it must be realized that in the design of stormwater management practices, infiltration cannot be neglected.

Soils and Soil Moisture

The soil may be thought of as a reservoir in which rainfall may be stored. The capability of soil to store water can be expressed as:

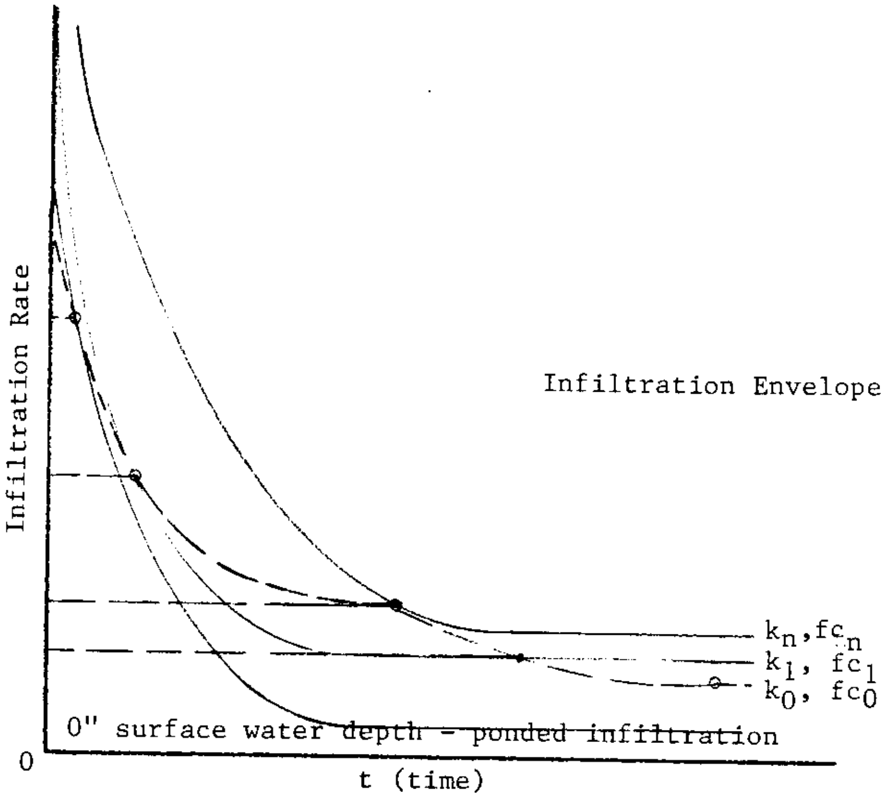


Fig. 19. Illustration of the concept of Reeder, et. al. and the infiltration envelope.

During a rainfall event, the intensity of rainfall changes; changes in surface water depths result and the curves of Reeder, et. al. (1980) partially describe depth fluctuations. For changing intensities, the resulting curve derived defines the upper bound of the infiltration envelope. This curve may be used as a design curve for infiltration rate at a point. The shape factor (k) represents the mean value of the family of curves between each point of intersection. f_c values consistent with the initially ponded condition are usually evidenced.

$$V_s = (1 - s)\ nd\ A \tag{8}$$

where:

V_s = volume of water to be stored in the soil (L^3)

s = percent saturation of soil (L^3/L^3)

n = porosity

d = depth to water table (L)

A = area over which n and s apply (L^2)

The above equation expresses the theoretical water storage capacity of the soil. To account for storage in any layer of soil, one only needs to determine parameters n, s, and d for the layer(s) of concern. Soil storage during an infiltration test will be much less than the theoretical soil storage capacity. Equation 8 is a direct function of water content and porosity.

Water Content

Water content is the volume of water present in a layer of soil. In a natural system, the water content increases as the water table is approached. High water contents can usually be expected to be found in soils which have high organic matters and clays. Of course, the water content is dependent upon the volume of water input to the soil and the ability of the soil to retain that water. In a study by Calhoun et. al. (1973) to assess the influence of particle size and organic matter on water retention of selected Florida soils, a 0.945 correlation found by multiple regression was obtained for the relation of organic matter and clay to water retention. The important fact to note here is that an hysteresis effect exists for soil water and should be considered when evaluating the soil in a proposed swale area.

Evaluation of Horton's parameters and porosity data shows that there is a correlation between porosity and final infiltration rate. The relationship (as shown in Figure 20) is exponential. A correlation coefficient of 0.94 was computed. Note that the values and relationship found may be applicable only for the range of porosity values of the study.

Porosity and water content data are shown in Table 5. For sandy soils, a narrow range of porosity values were measured. Porosity, compaction, water content and grain sizes are interrelated (Bowles 1977). Grain size distributions of interest to soil classification analyses are presented in Table 6. Low values of D_{10} were obtained for the clay soil of the swale at CR 419 and the silty soil at CR 426. Though the silt layers were present in the swale at East-West Expressway, larger grains were found beneath the surface mats of grass and mud. Uniformity coefficients range between 4.0 and 1.8. Large values of the uniformity coefficient are indicative of large grain size variations between the diameter of soil at 10 percent and 60 percent passing. Since the D_{30} and D_{10} sizes are not nearly equal, the soils can be classified as well graded by the criterion of Bowles (1977).

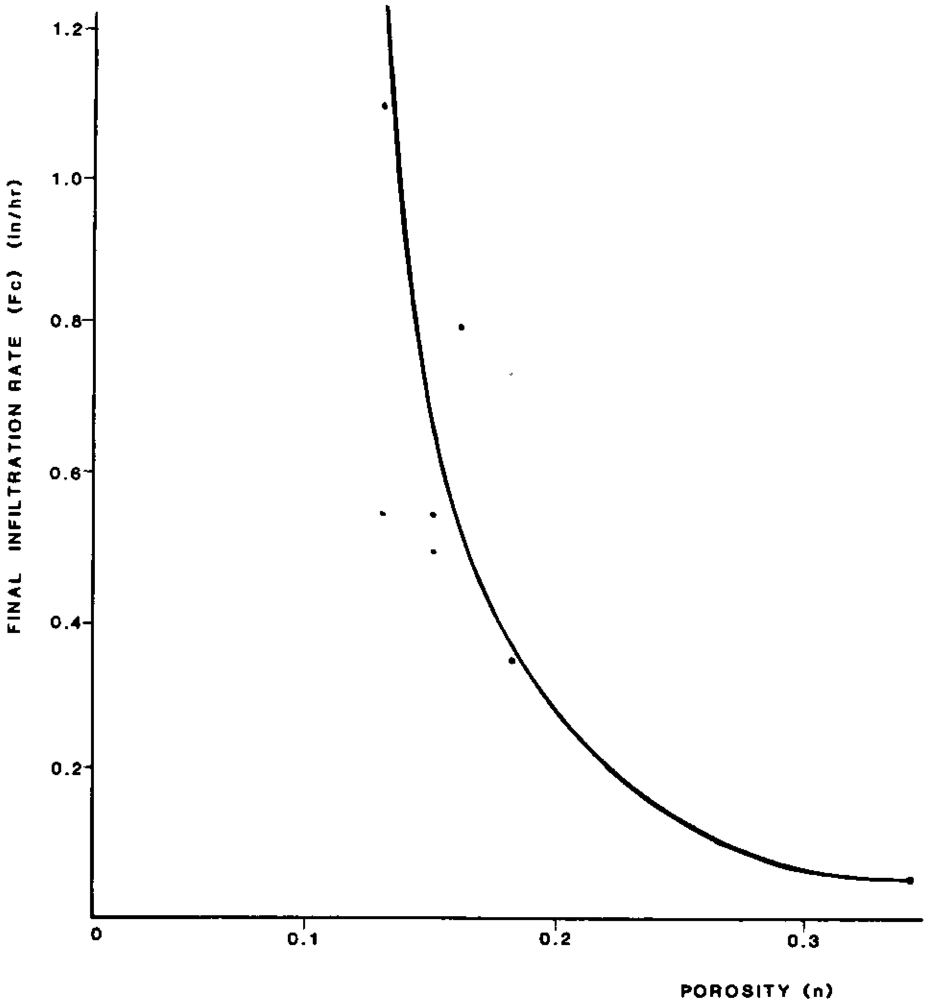


Fig. 20. Relationship of final infiltration rate to unsaturated porosity for swale studied.

Table 4 presents some physical characteristics of the swales studied. Slopes ranged from 0.06 to 3.14 down the swale and average bank slopes ranged from approximately 1:12 to 1:3 (vertical: horizontal). What is now needed is some physical representation of the swlaes studied. The next section presents pictorial representations of some of the swales researched.

Swales Studied

UCF Roadside Swale

The UCF Roadside Swale presented in Figure 21 is the only one encountered in which grass was not present in the swale. This photograph was taken after work done in cleaning debris from the swale was performed. Be aware that swales without a crop cover are subject to severe erosion (as was the case for this swale when infiltration tests were performed) and poor performance due to a build up of silt layers. Note also, the slow advance of grass toward the swale; the soil encountered here was low in organics. Culverts (seen at the end of this portion of the swale) are used to convey flowing waters under roads at intersections. Because of the lack of clay in this soil, compaction was not a problem.

Swale at UCF Physical Plant

The inland swale near UCF's physical plant (see Figure 22) is one in which crop cover is sparse. Note that this swale is well maintained. Except for infrequent travel by light-duty

Fig. 21. UCF roadside swale.

Fig. 22. Swale at UCF Physical Plant.

vehicles, traffic on the swale is minimal. High initial infiltration rates were calculated and a constant infiltration resulted. Observe how well the side slopes of the swale blend into the rest of the landscape. In addition, the trees on the right side of the swale aids in rainfall interception and slows the momentum of wind-driven rains from a westerly direction.

Swale at SR 520 North of Orange County Line (L)

This swale is in the left right-of-way of SR 520 in Seminole County, Florida (see Figure 23). The swale is usually well maintained. It receives intermittent flow from the slash pine forest shown on the left (from heavy rainfalls). The grass cover is slightly less than 3 inches. The swale receives runoff from the highway and dissipates the flow. Percolation removes a substantial percentage of pollutants in the runoff. The slope (longitudinal) is steeper than on most swales studied. The broad soil class found beneath the swale is St. John's fine sand with intermittent traces of clay. Due to the crop cover, the soil remains moist and favorable for percolation.

Swale at SR 520 North of Orange County Line (R)

The swale in the right right-of-way of SR 520 in south Seminole County shows the variability in sites within a short distance of each other (see Figure 24). Note the sparse grass and visible white sand. Traces of clay were also inter-mingled with the Rutlege fine sand. Traffic on the swale is limited to

Fig. 23. Swale at SR 520 north of Orange County line (L).

Fig. 24. Swale at SR 520 north of Orange County line (R).

emergencies experienced by motorists and utilities service vehicles. The recession constant value is highest for this combination of soil and crop cover.

Swale at SR 46, Seminole County

The swale along SR 46 west of Geneva, Florida shows a healthy crop cover (see Figure 25). The swale receives overland flow from the pasture enclosed by the fence on the left. Flow from the highway enters the swale from the right. The soils beneath this swale are deep, yellow sands of coarse grains in the Lakewood-Lakeland Association. The extreme depth to apparent water table encountered here makes this swale one of the potentially more promising ones studied. At the time of study, the first few inches of soil were wetted by a previous rainfall, evaporation of soil moisture had begun and infiltration was somewhat slowed.

Swale at CR 426, Seminole County

This swale located along county road 426 in Seminole County, Florida showed poor infiltration characteristics (see Figure 26). A combination of high grasses and the clay and clayey soils encountered here produced a swale which shows no favorable percolation. The clays are a determining factor, but swales were encountered in which clay was present, yet percolation occurred. The inclusion of this swale in the study is to stress the need for swale maintenance.

Fig. 25. Swale at SR 46, Seminole County.

Fig. 26. Swale at CR 426, Seminole County.

Swale at SR 50, Orange County

This swale located along SR 50 in east Orange County stresses the recovery concept of swale systems (see Figure 27). The swale, though showing visible surface moisture, high unkept grasses, visible silts and muds and a shallow depth to apparent water table showed low (but favorable) percolation rates. With an initial infiltration rate of 2.51 in/hr (0.11 cm/sec) and a final infiltration rate of 0.06 in/hr (0.0025 cm/sec), the swale was believed to be under a recovery period from the previous rainfall event. Again, soil type, cover crop and maintenance cannot be overemphasized as criteria for swale design and use.

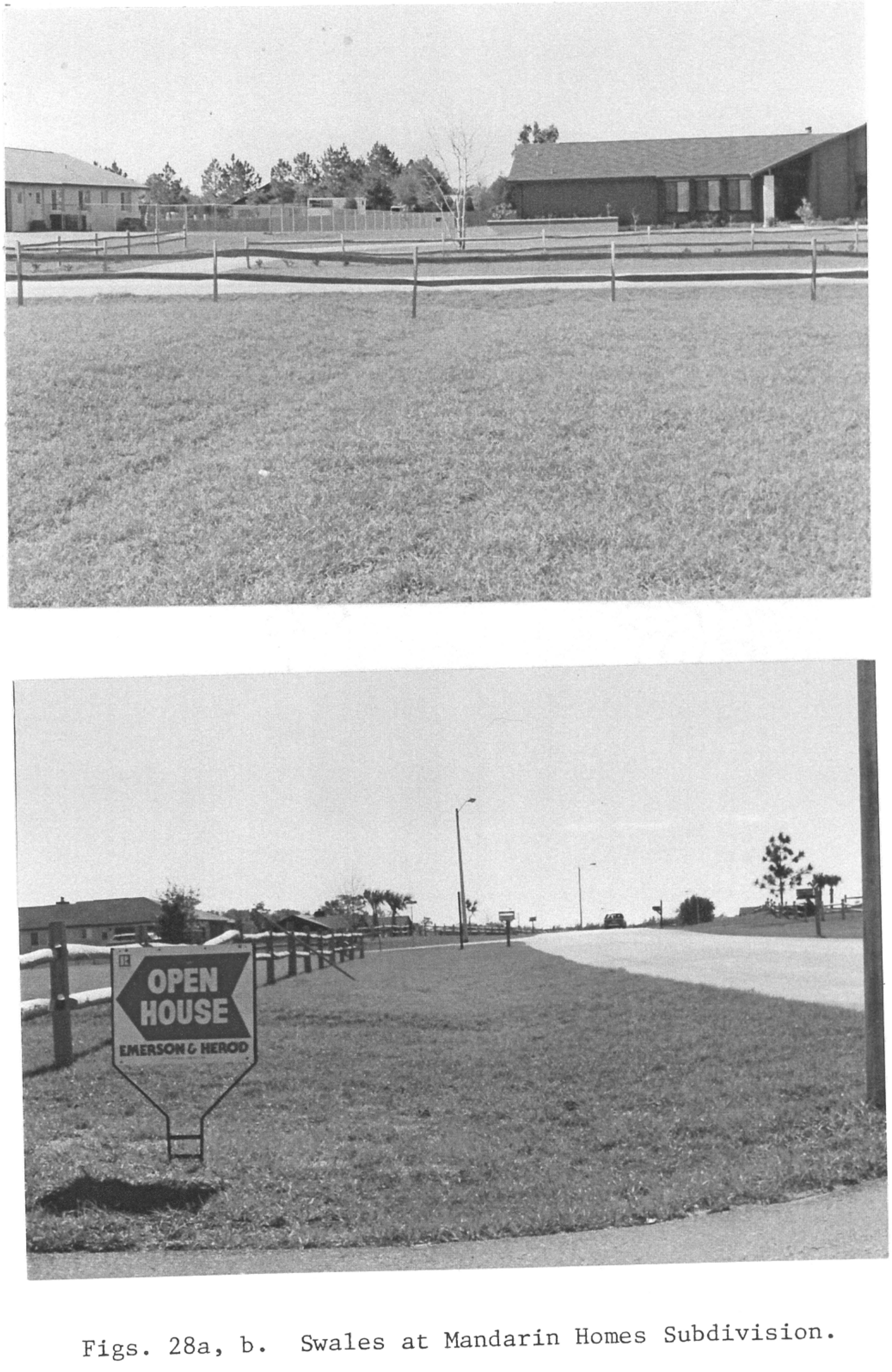
Swales at Mandarin Homes Subdivision

The residential swale shown in Figures 28a and 28b showed favorable infiltration patterns (see Table 9). It has been recently constructed and the sod placed is beginning to take root. Note the channel transition under the near rail fence; the adjoining channel takes runoff from the lot and diverts it to the larger swale at street side. Figure 28b gives a better look at the smaller diversion channel.

Swale at Tuskawilla Development, Seminole County

This swale at Tuskawilla in Seminole County, Florida showed initial favorable infiltration rates (see Figure 29). The important observation to make here is that the grass cover was initially placed sod. Through time, the grass has become acclimated to the

Fig. 27. Swale at SR 50, Orange County.



Figs. 28a, b. Swales at Mandarin Homes Subdivision.

Fig. 29. Swale at Tuskawilla Development, Seminole County.

area. Thick mats of roots have developed (brown spots in lawn). This swale is a very good example of one which is suitable to dissipate the erosive capacity of storm events, slow the entering raindrops and provide a stable moisture content necessary for good initial infiltration rates.

Other Swales Studied

Swales at the Spessard-Holland East-West Expressway and the roadside swale at Seminole County SR 419 are not shown. As can be seen from Table 9, they exhibited no infiltration under test conditions. The slopes of the swale at the expressway were well maintained but the grass clippings were placed in the swale and these acted as sediment traps. Long-term retention of sediment transported down the swale caused a substantial build-up of surface silts; vertical infiltration was essentially zero. The swale along SR 419 exhibited standing water in some reaches of the channel. This swale was located in an agricultural area and received runoff from the street. Visible surface debris and mud is the reason this swale did not infiltrate.

CHAPTER VI

DESIGN METHODOLOGY

The proposed methodology is based on hydrologic principles and the inventory equation. The inventory equation is:

$$P - Q = \Delta S \qquad (9)$$

where:

P = volume input to the system

Q = any volume output of the system

ΔS = system storage change

Spatially and stochastically, it can be shown that this relation holds for finite differences in inflow and outflows. A schematic representation of the appropriate phases of the hydrologic cycle may be modeled by the block diagram shown in Figure 30.

If we consider a system in which surface runoff from the watershed is negligible or zero and inputs to subsurface flows are beyond the boundaries of the system, it can be said that abstraction and infiltration equals precipitation. This is equivalent to saying that the first few inches of soil will be used to detain rainfall excess. For most natural systems, this assumption is valid. Water table fluctuations will determine the ultimate volume of storage allowable in the soil. High water tables make conditions favorable

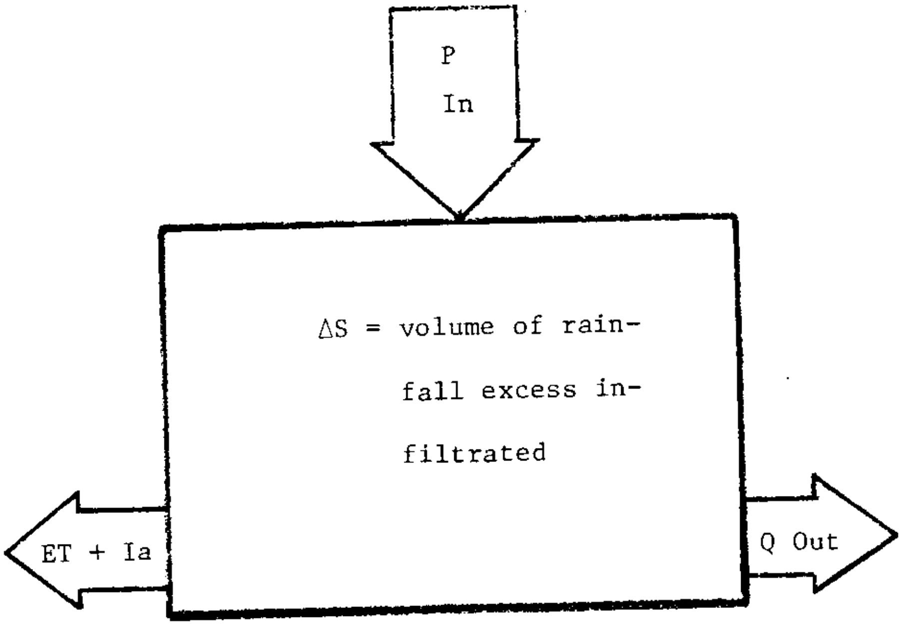


Fig. 30. Schematic of inventory equation for design method.

for low volume storms. Soil storage is directly dependent on watershed geometry, depth to water table, soil type, available foliage, and land use characteristics.

Based on the principles of superposition used in Figure 31, a graphical technique can be employed to determine the swale area required for a design storm. One method would be to sum the difference in cumulative infiltration and precipitation for infiltration volume less than rainfall volume. The equation by which this can be accomplished is:

$$V_{dep} = \sum_{tr_1}^{tr_2} \Delta(P - F)_t \text{ for } P > F \qquad (10)$$

where:

tr_1 = point of intersection of cumulative volume curves

tr_2 = point of intersection of cumulative volume curves

P = cumulative rainfall excess volume

F = cumulative infiltration volume

Runoff hydrographs may be produced from Figure 31.

The magnitude of rainfall and infiltration volumes are usually less than one foot. Use of Equation 10 and considering the area of the drainage basin, one can determine the volume of swales required to handle the rainfall excess. The flow velocity in the swale will be determined by channel geometry and depth of flow. Overland flow velocities can be calculated using hydraulic equations presented in Chow (1959), page 149, or by use of the SCS nomograph

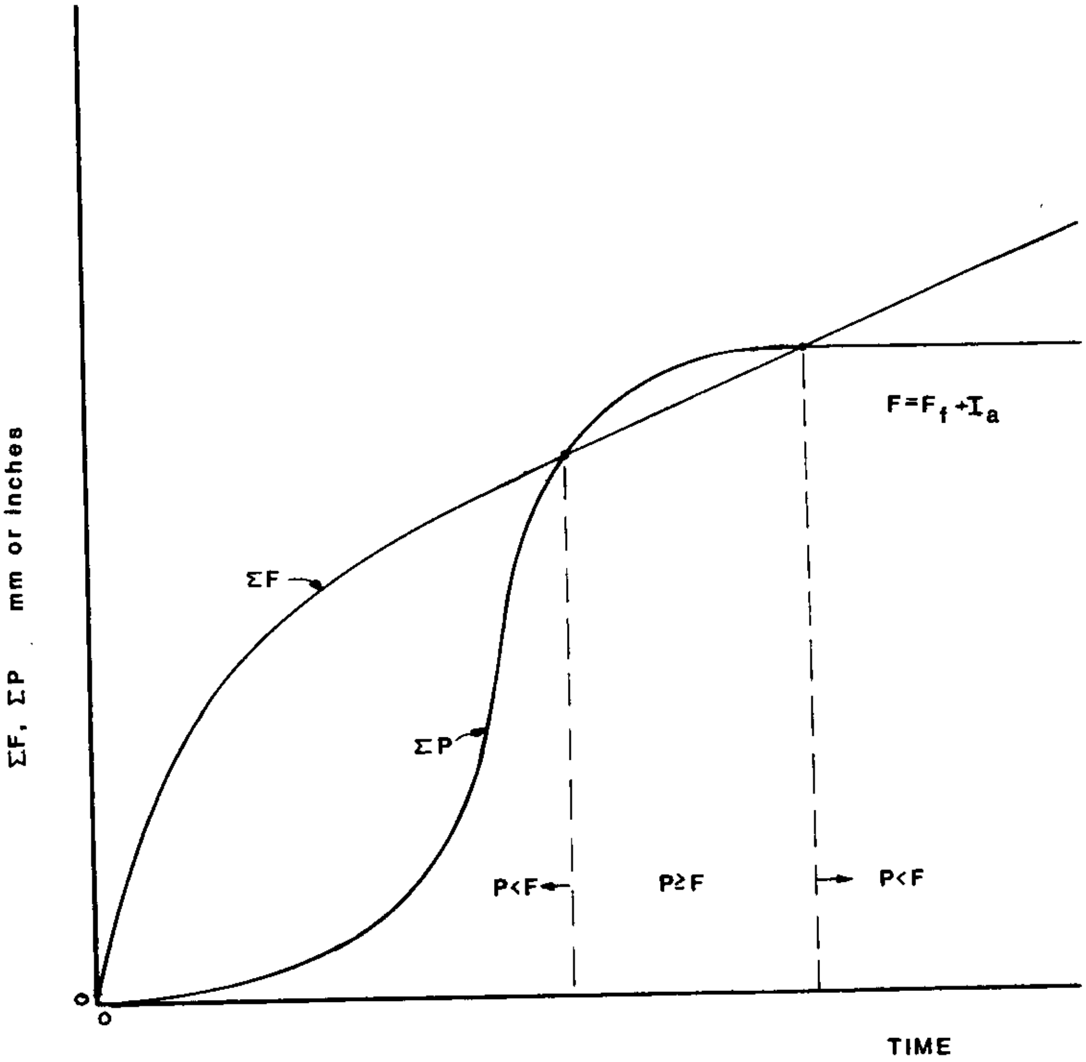


Fig. 31. Graphical model for determination of runoff hydrograph and flow depth.

The volume of storage under the precipitation curve is less than the volume under the infiltration curve. This results because of the choice of precipitation curves. For different intensities, the relationship will vary. These curves are used to simulate a region of worst conditions for design, i.e., when P exceeds F.

presented in Wanielista (1978), page 109. For the swales studied, note that overland flow will be less than 1.5 feet per second; overland slopes vary from 0 to 5 percent. The SCS nomograph gives average flow velocities and equations by Chow (1959) are developed on the depth of flow which may be obtained using the procedure of Figure 32.

The magnitude of rainfall for design should be such that 80% of all storms percolate. For Florida, this volume is one inch (see Figure 6). Distribution of the rainfall is more critical to design. Two sets of curves exist by which rainfall distribution may be determined. The first is presented in Chapter IV of this text. The second can be found in Wanielista (1978), page 141. The mass curves found in Wanielista are for 25 year 24-hour return periods. From the figure, a storm of cumulative volume of one inch has a duration of 5 hours. From Figure 6, Chapter IV of this text, that duration of rainfall has a probability of 0.06 and a less than probability of .89. Use of the rainfall mass distribution curves will be presented in a design example.

Slope Modification

Slopes found in natural drainage basins in Florida vary from 0 to 8 percent (Orange and Seminole County Soil Survey Supplement Data 1975). Use of the sheet flow equation in Chow (1959) requires knowledge of kinematic viscosity of the fluid if the flow

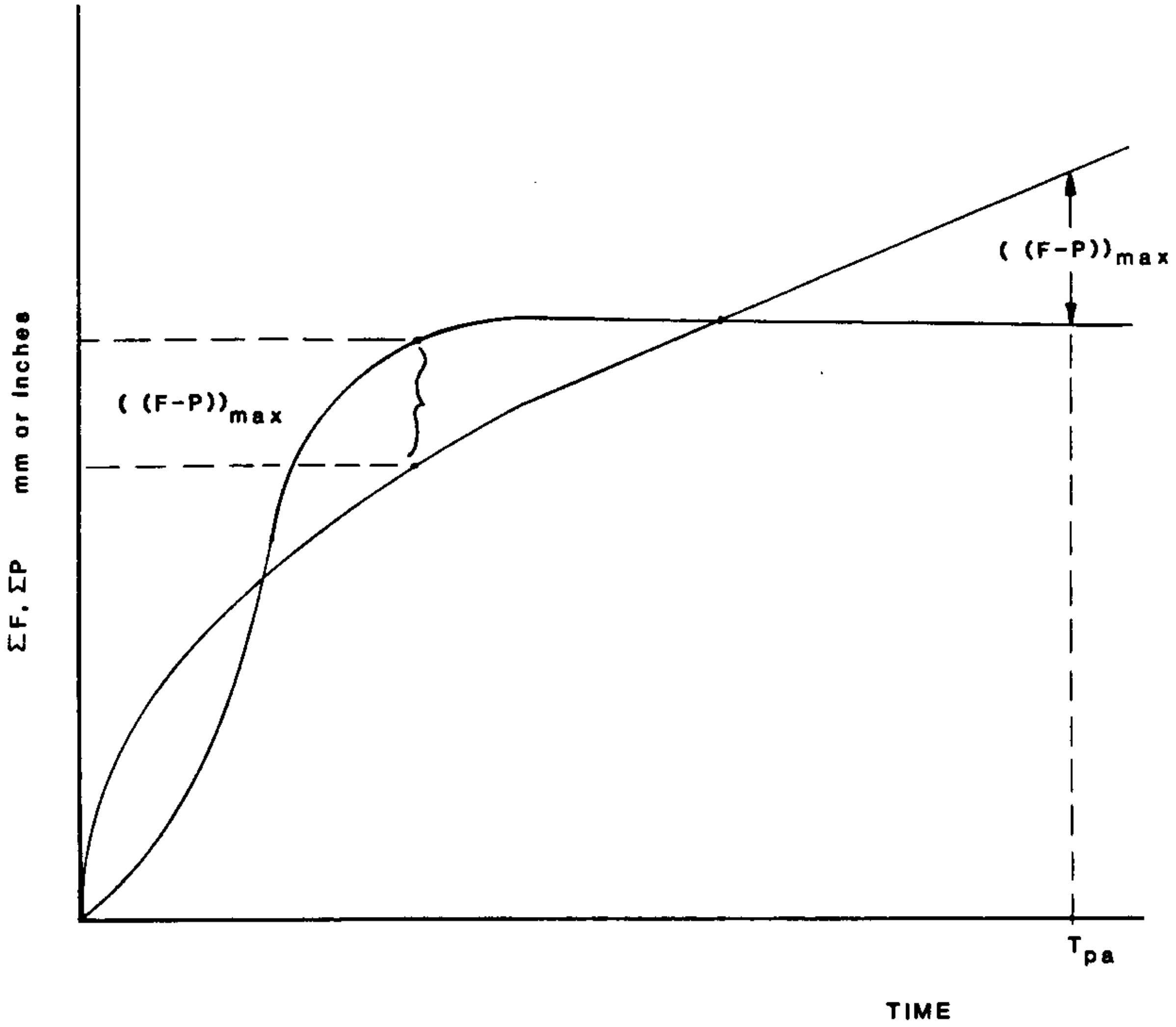


Fig. 32. Illustration of hydrograph peak attenuation using superposition model.

is laminar. For turbulent flow, Mannings equation is appropriate and the depth of flow and surface roughness are determining factors. In both methods, flow is proportional to slope. Computation of slopes is of utmost importance in deciding overland flow. Slight modifications may be required to control discharge within the basin. Caution must be exercised in slope modifications because compaction of the infiltrating surface will decrease infiltration. South Florida Water Management District (1980) has presented design curves to account for the effect of compaction on Florida soils within the district. Slope modification reduces soil moisture storage.

Grasses

One of the more indicative results to come from the research efforts put forth is that grassed swales percolate at higher rates than swales in which grass is absent. This is due in part to the pore clogging action created by soil disturbance upon application of water to the earth's surface. During a storm event, grasses (and especially sodded areas) tend to break the momentum of raindrops. Grasses also maintain a surface moisture content and abates the wilting point effect when soils dry out. Well maintained swale areas experienced higher percolation rates than areas which were unkept. The choice of grasses is a matter of preference for the individual designer, but realize that the designer's choice will be limited to grasses that grow well in the region. For Florida, warm season grasses such as:

1. Bahia grass (pospolum notatum fluggae)
2. Bermuda grass (Cynodon)
3. Centipede grass (Eremochla ophiuroides)
4. Japanese lawn grass (Zoysia japonica)
5. Manila grass (Zoysia matrella)
6. St. Augustine grass (Stenophatrum secundatum)

are good sod-forming grasses and are limited to soil pH and the amount of maintenance required to keep them healthy.

Quality

Quality considerations in swale design are functions of the volume of water infiltrated. First-flush effects will occur if swale lengths are such that contact and infiltration of the first volumes of rainfall excess are possible. If total volume of rainfall is precipitated, treatment efficiencies approach 100 percent. Contamination of groundwater is a matter to be considered in swale design and total rainfall containment in the basin. For surface flow reaching receiving streams, Wanielista (1978) has determined that treatment efficiency of residential swales is on the order of 80 percent. For grassed swales, nutrients will be utilized to maintain swale grasses. Additional inputs will be necessary if nutrients in excess of those contained in runoff are required.

Compatability to Existing Systems

Compatability with existing landuse characteristics of a drainage basin makes the use of swale systems all the more attractive. In the urban environment, we experience greatly increased peak flow rates upon the construction and use of impervious surfaces. Increased pollution is also a problem of urban stormwater management. Installation of porous pavements would decrease the quantity of water and pollution carried by storm sewers and reaching receiving streams. Set aside natural areas of high infiltration capacity would also be feasible if the relative value of the land used is not such that alternative use would serve a better purpose. Swales used in conjunction with pervious pavement surfaces (which can be designed to permit infiltration rates greater than 25 in/hour, Crane 1973) are potentially feasible stormwater pollution and flow control practices.

Costs

Swale costs will be decided by land costs required, cost of construction and regular maintenance costs. Land costs are determined by the location of the proposed swales. Construction costs are costs of excavating and grading the designed facility. Costs of sod and its placement are also included in construction costs. If grasses are to be planted by seeding, the area must be protected until a hearty growth is evident. To minimize compaction, hand grading and excavation of the area may be required.

Maintenance of the swale includes costs for mowing and removal of grass clippings. With changes in grass maintenance equipment, this can be done in one operation, thus reducing the maintenance costs. Wanielista (1978) has produced cost data for swale systems as is shown in Table 10.

TABLE 10

COST AND EFFICIENCY DATA FOR TREATMENT BY SWALES

Management Practice	Overall (%) Efficiency[a]	ORM $/ac-mon	Average Costs ($/ac/% removal) Capital	PV (7%, 20 yr)
Diversion/ Percolation[b]	99	16.00	25.00	45.5
Percolation Pond[c]	99+	35.00	36.30	80.8
Swales with Percolation[d]	92	30.00	28.40	62.9
Residential Swales[d]	80	20.00	26.08	60.3
Sedimentation[e]	50	29.00	19.20	59.0
Fabric bag[f]	25	26.00	1.00	81.8
Advanced Sweeping[g]	68	26.00	30.40	80.5

[a] Yearly average of BOD_5, N, P and SS not discharged to surface waters.

[b] Designed 1 in. runoff diversion

[c] Designed for 4 in. runoff diversion

[d] 80% of the rainwater percolates

[e] Designed for 0.65 in. of runoff water from a watershed with runoff coefficient = 0.30

[f] Fabric bag replacement every two years

[g] Assumed 60% nitrogen in particulate form

CHAPTER VII

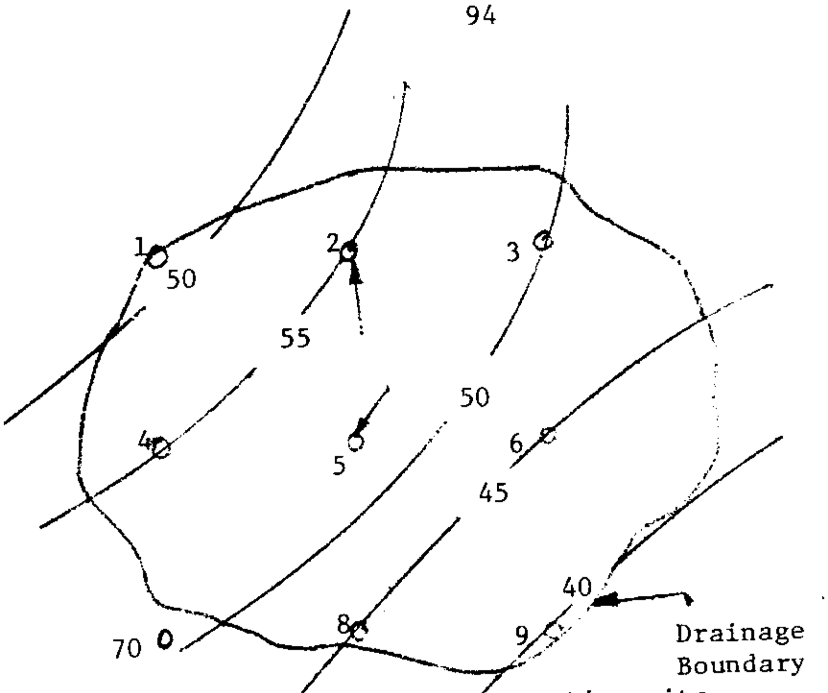
SUMMARY

1. Infiltration/percolation tests were done to determine the ability of a watershed to infiltrate the design volume of rainfall. To account for spatial variability, several tests may need to be run to obtain representative values of Horton's parameters. Schematically, this operation can be shown in Figures 33a and 33b. Selection of testing sites may be systematic if knowledge of soil types within the watershed is available. Otherwise, the use of a grid system and random numbers may be the best method to use in testing site selection (see Bowles, Chapter 7, 1979).

2. Soil types for the basin should be defined to determine their a priori capacities to infiltrate. If infiltration tests have been performed on the soils of the basin, evaluate the reasonableness of the data and proceed to use it with caution, if it is found to be reasonable. Such evaluation would consist of a knowledge of soil types, land uses and the following general statements:

a. Deep sands and sandy loams usually exhibit good infiltration capacities.

b. Shallow sands may exhibit good initial infiltration, but deeper layers may halt infiltration after a short period of time.



#0 numbers represent a testing site.

Fig. 33a. Illustration showing testing sites and contours for a drainage basin.

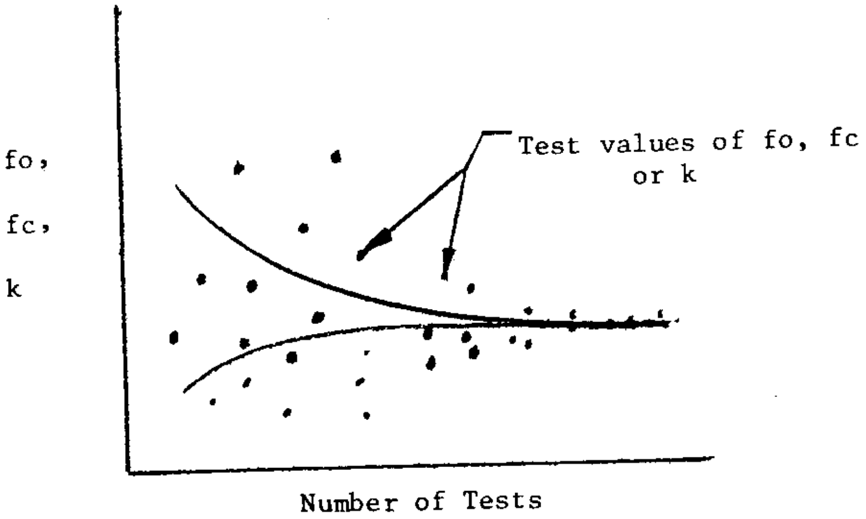


Fig. 33b. Convergence scheme for testing sites of Fig. 33a.

c. Clays exhibit (i) no infiltration capacity at all or (ii) high initial rates and after the clays become saturated, infiltration stops.

d. Mixtures of sands and clays exhibit swelling of the clays and infiltration is halted after a short duration.

e. Silts and sandy silts are low infiltration capacity soils; silts are high potential pore-clogging media.

f. Grassed areas on loamy sand are high potential infiltration areas.

If infiltration tests have not been performed, tests should be performed by the best available means. Keep in mind that only representative tests for each area should be acceptable. In addition, a map of iso-infiltration areas should be drawn. This helps define areas most suitable for swale placement.

3. An overlay technique described by Musgrave and Holtan (1964) and Anderson and Giovanelli (1980) in which an isohyetal map of the area is used as an overlay for the map of iso-infiltration areas. This will define areas which are not only good for swale placement, but areas from which contributing runoff will occur and areas for which aquifer recharge is substantial. For areas which contain existing lakes and streams, no runoff can be expected if flooding does not occur. Computations of a safe precipitation event to prevent flooding in such areas can be made. Otherwise, flood control practices should be enacted for open bodies of water.

4. Plot infiltration rate curves and superimpose precipitation rate curves upon these. At the intersection of infiltration and precipitation rate curves, surface detention of precipitation begins. On sloping and poorly infiltrating soils, surface detentions usually end up as runoff within the basin. Routing of this flow is necessary. An overland flow equation such as the one presented in Chow (1959) or velocity-detention curves such as those by Musgrave and Holtan (1964) or Wanielista (1978) are useful as flow routing methods.

5. The depth of surface detention required by use of Musgrave and Holtan's chart or the Y_m value in Chow's overland flow equation may be obtained by plotting cumulative infiltration volume vs. time and superimposing the cumulative precipitation volume vs. time. If the infiltration rate curve obtained is considered applicable for design and descriptive of the drainage basin, the resulting flow must be diverted to a swale which will infiltrate at a greater rate and have a longitudinal slope such that storage of a stated volume is possible. Site grading practices can be used to achieve a desired overland flow velocity.

6. For the case when precipitation is less than infiltration potential, all rainfall infiltrates and swales are not required. The alternative is when rainfall is much greater than infiltration potential and the cumulative volume of rainfall never intersects the cumulative infiltration volume curve. The differences in the volume is the depth of flow which must be routed and stored in a swale.

7. Swale length is computed assuming the flow at the end of the a length (L) is zero. With this in mind, the equation for swale length is:

$$L = V_{av} \Delta t \tag{11}$$

where:

V_{av} = average overland flow in the swale (L/T)

Δt = time between points of intersection for the swale infiltration potential curve and the cumulative precipitation volume curve

8. Decide site grading procedures to attain the desired overland flow.

9. Choose a grass or cover crop for erosivity abatement.

10. Perform costs analyses for construction operations and maintenance. Include cost using safety factors in the design to ensure that design conditions are (at least) met.

11. Utilize appropriate safety factors to account for design uncertainties. If the optimum infiltration envelope is chosen, an appropriate safety factor may be the volume found from using an infiltration curve which is less than optimum divided by the volume found using the optimum envelope .

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

The study described in former sections of the text utilized a mix of precipitation and soil-dependent infiltration observations which culminate into a design procedure for the design of swales. Existing residential and roadside swales were studied to obtain a consensus of information which could be used to specify a range of design conditions. Also, field studies to determine infiltration capacity and laboratory studies to determine soil parameters helped in reaching a conclusion on the optimal placement of swales. Following are conclusions which have been drawn from the study.

Rainfall

1. Rainfall patterns show that for locations in Florida, eighty percent of all storms generally have a volume of one inch or less. Distributions of storm frequency show that roughly 120 storms can be expected to occur in any location in Florida during the year. For northern locations, the number of storms may be slightly less than the average; southern locations exhibit patterns of frequent low volume storms. Studies show that for coastal areas of significant development, there is a slight rise in the

number of storms which exceed 4 inches in volume. For the five year period of study, the annual average number of storms for eastern coastal locations was consistently higher than for locations along Florida's west coast. Table 3 shows that for urbanized areas such as Tampa, Orlando, Miami and Jacksonville, the arithmetic average rainfall volume per event can be expected to be less than four-tenths of an inch. With the exception of Key West, Florida, the expected volume per event is always greater for the other locations. The rainfall mass distribution curves presented in Wanielista (1978) can be used in the following manner:

a. The curves presented by the U.S. Weather Bureau (curve number 6) can be applied to storms of short duration and high intensity; these are typical of Florida storms.

b. The other curves are for moderate and long duration storms with low intensities.

The previous conclusions are expected to extend the general knowledge of rainfall event patterns in Florida.

2. Specifically, for Orlando, a time of event distribution was developed. It shows that most storms (regardless of volume or intensity) can be expected to last less than 8 hours. This piece of information is useful in defining the time scale when choosing design storms. Other distributions may be calculated for other areas from hourly precipitation data.

Infiltration

Rate data for several swales were determined using a double ring infiltrometer to confine the flow area to approximately the area of the inner ring. Note that data obtained in this manner is point data. For a non-homogeneous watershed, infiltration rate can be expected to vary spatially and temporally. It was found that the rate of infiltration could be expressed by Horton's equation through curvi-linear regression of field data. Horton's parameters have shown that values as high as 36 inches per hour (0.03 cm/sec) and as low as 2.51 inches per hour (1.77×10^{-3} cm/sec) were obtained for swales within the study area. A more important parameter, the final infiltration rate, was usually found to be less than 1.0 inch per hour (2.31×10^{-5} ft/sec). This parameter is more important because it gives the designer some indication of minimum flow rates.

Soil parameters affect infiltration. It has been shown that water content adversely affects the rate of infiltration. As natural unsaturated water content increases, the initial infiltration rate decreases. It has also been shown that porosity has an effect upon the final infiltration rate. The curve developed shows that porosity and final infiltration rates are exponentially correlated. Grain sizes define the texture of a soil. The soils encountered were medium fine and fine sands, silts and clays. It has been discovered that as clay and silt contents increase, the capacity for infiltration decreases. Clays and silts are not defined by texture. Infiltration was found to be more favorable in soils with medium fine sands, little clay and silt content, low water content and high porosities.

Swales Studied

For the swales in the study area, the ones which had grass covers such that soil disturbance was minimized show better abilities to permit infiltration. Swales which were well maintained were shown to be more suited for use in storing larger volumes of rainfall. Side slopes were in the range of 1:12 and 1:3. Longitudinal slopes were found to be less than 3 percent. Swales which showed no capacity for infiltration did not exhibit at least one of the qualities previously mentioned.

Recommendations

All questions which enhance clarity on the subject of infiltration have not been answered and probably never will be. Horton's equation is a good predictor of infiltration rate, but its parameters need investigation to discover the single or combined soil-crop cover factors which influence each parameter most. Some suggestions for future studies of vertical infiltration and Horton's parameters are:

1. Logically, it seems that the initial infiltration rate is more a function of water content, crop cover and porosity in the upper layer of soil. Tests might be performed to identify the effect of crop cover mat thickness on the initial infiltration rate if porosity and water content are held constant. Then, the other parameters can be varied while the other two are held constant to assess the effect of each on the initial infiltration

rate. To be of any value, the soil type should be held constant. The effect of relative compaction on f_o, k, and f_c should be investigated.

2. It seems reasonable that a decrease in available pore spaces (i.e., an increase in water content) for various soil types defines the rate of decrease of infiltration. The recession constant is isolated. More soil types should be investigated to verify this.

The previous suggestions are intended to aid in reducing the amount of confusion about Horton's equation discovered by creators of other less appealing infiltration models.

Flooding type infiltrometers for assessing infiltration rate excludes the effect of soil disturbance. This is very unreasonable for rainfall events, because unless the rainfall intensity (raindrop velocity) is such that soil disturbance is negligible, some sediment transport occurs. Testing procedures are required to assess the changes in head versus changes in Horton's parameters and soil disturbance effects. Rainfall simulators attempt to recreate natural conditions, but the amount of equipment utilized in a rainulator experiment makes field testing laborious. Simplified testing procedures are needed for water depth changes and soil disturbance effects in flooding type infiltrometers.

Quality effects of swales which permit runoff to receiving streams should be assessed. Percent removals for a specified depth of saturation from a storm event would constitute valuable research to determine swale efficiency. For swales which contain the volume of precipitation, efficiency is believed to approach 100 percent. The effect on groundwater quality merits investigation.

Lastly, swale design by use of modeling techniques for retention/detention basin sizing can prove to be a valuable addition to the body of knowledge for stormwater management practices.

CHAPTER IX

DESIGN EXAMPLE

Design considerations for use of the methodologies postulated in previous portions of the text should include the following information:

1. watershed area
2. rainfall records for design storm
3. description of watershed topography
4. watershed land use coefficients, perviousness data of surface roughness data
5. data required to calculate soil water storage: porosity, water content, specific gravity and depth to water table
6. Horton's parameters: k, f_o, f_c
7. soil types

At first, this volume of data input may seem large, but a complete description of the problem improves the accuracy of the solution obtained. As an additional note, Horton's method of assessing the time rate of change of infiltration is used, however, other methods surveyed in the Literature Review Section of the text which are deemed more applicable by a designer may be used.

As an example, consider a watershed of 100 acres with various soil types and elevations, as seen in Figure 34. Assume that rain falls equally on all areas of the watershed; otherwise, a

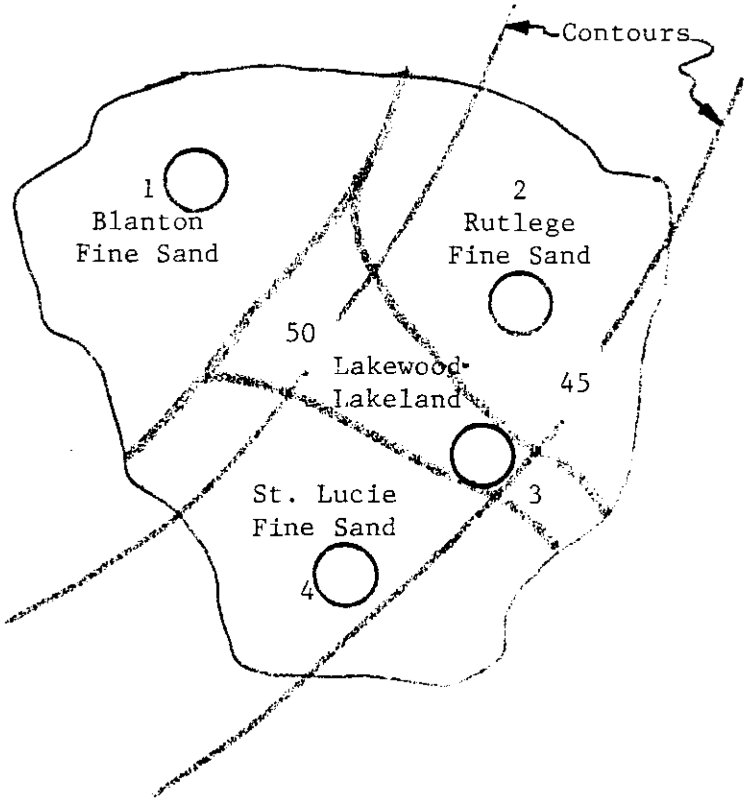


Fig. 34. Area illustration for design example.

precipitation averaging method must be used (see Basic Considerations Section of this text). Other data required for a simplified design method is presented in Tables 11 and 12. Plotting the rainfall record and superimposing the infiltration volumes upon these, we obtain Figure 35.

Flow depths established from Figure 35 are presented in Table 13. Notice that for area 4, infiltration controls and at no time during the rainfall event is surface water present. This area may serve as an outfall area for other areas in which flow occurs. From Table 14, a time varying swale volume results. This gives the designer room to design swales (individual channels) of variable breadth. Swale length may be computed by Equation 11, page 97.

Further design of individual channels should be carried out as recommended by Chow (1959), Chapter 7, for channel stability. The most important criteria for hydraulic design should be to maximize the wetted perimeter and maintain permissible velocities of 4-6 feet per second in the swales.

TABLE 11

INPUT DATA FOR DESIGN EXAMPLE

Location	fo (in/hr)	fc (in/hr)	k (1/hr)	Area (ac)
1	8.0	0.55	3.0	21.43
2	5.0	1.2	2.4	32.14
3	6.0	1.0	3.6	10.71
4	12.0	1.6	1.8	35.72

Total Acreage = 100 ac

TABLE 12

RAINFALL RECORD FOR DESIGN EXAMPLE*

Time (hrs)	Volume (in)	Cumulative Volume (in)
1	2.48	2.48
2	0.81	3.29
3	0.54	3.83
4	0.27	4.10
5	0.18	4.27
6	0.23	4.50

* Design rainfall record is for a 5-year, 6-hour (see Figure 5). The distribution is found using the U.S. Weather Bureau curve of Figure 7.

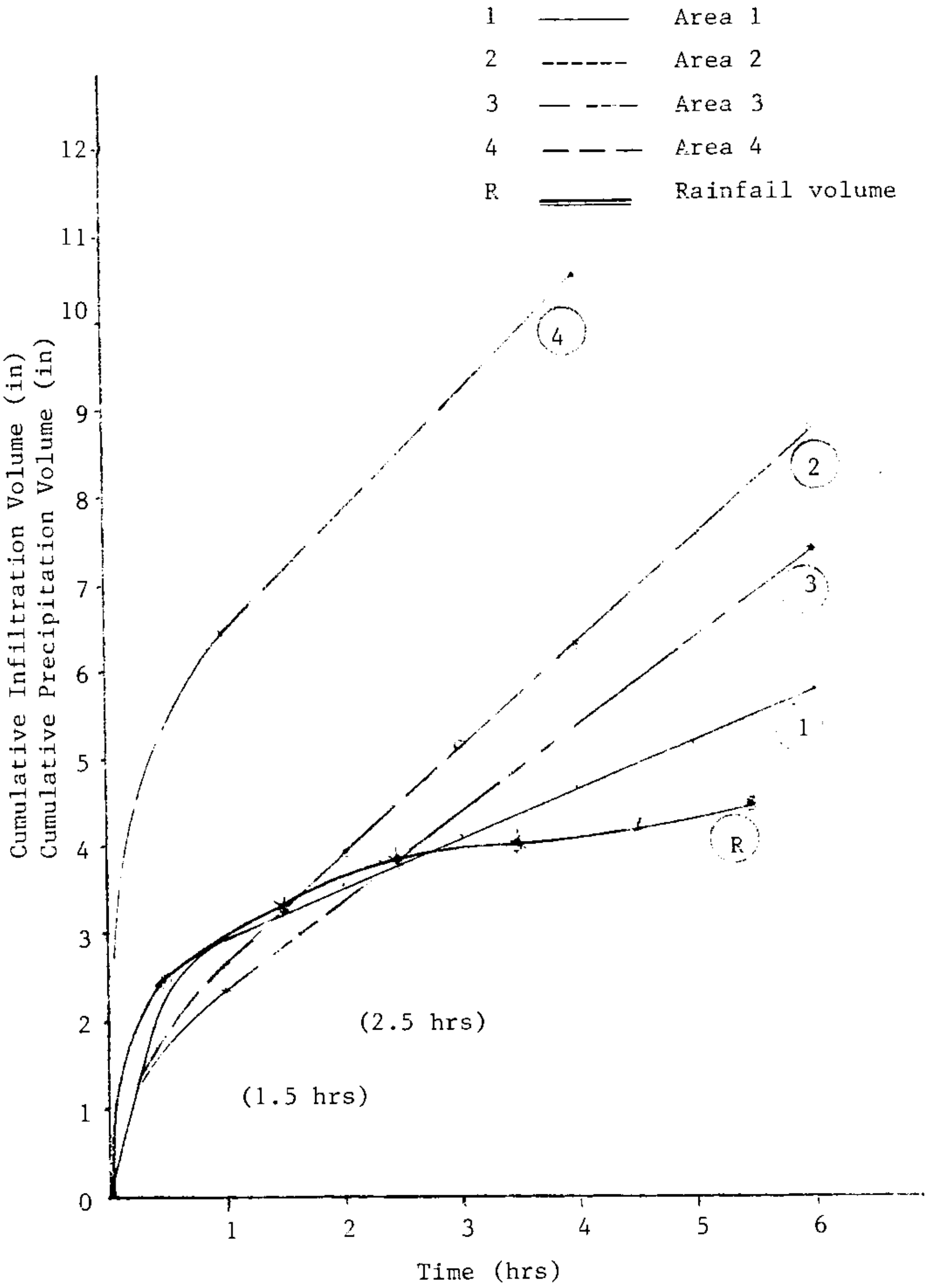


Fig. 35. Use of superposition model for design example.

TABLE 13

FLOW DEPTHS FOR DESIGN EXAMPLE

Time (hrs)	Rainfall (in)	Location/Depth (in)		
		1	2	3
½	2.48	+0.28	0.77	0.82
1½	3.29	0.01	-0.05	0.41
2½	3.83	-0.03	-0.75	-0.05

TABLE 14

VOLUME OF SWALE STORAGE REQUIRED

Time (hrs)	Location/Volume (ac-ft)			Total (ac-ft)
	1	2	3	
0.5	0.50	2.06	0.73	3.29
1.5	0.02	0.00	0.37	0.39
2.5	0.00	0.00	0.00	0.00

APPENDIX A

Technical Appendix A shows the results of applications of procedures outlined in Table 1 for the generation of frequency histograms. Rainfall data compiled by the U.S. Department of Commerce's National Weather Bureau for the period of study indicated on each distribution was evaluated and statistical procedures were utilized to obtain Figure 2 of the text. Individual storm volumes greater than 4 inches were not delineated because an aprion review of the data showed that few storms with volumes greater than 4 inches occurred with relatively large frequencies. Rainfall increments of one-half inch are a matter of preference and due to the large volumes of data required for smaller increments, increments of less than one-half inch were considered impractical. The histograms will serve as a valuable source of design information for engineers and hydrologists in the areas studied.

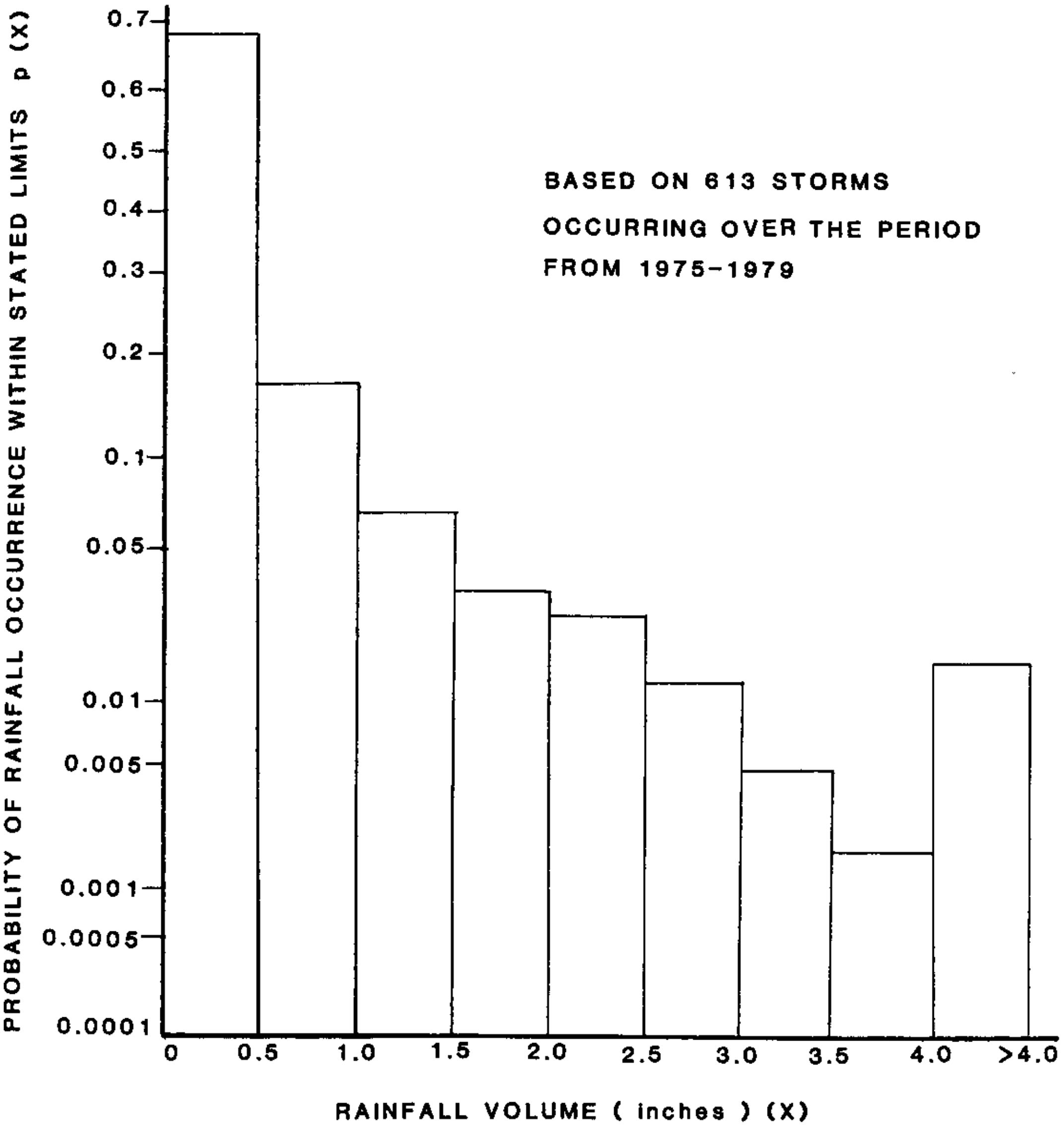


Fig. A-1. Frequency distribution of rainfall at Niceville over a 5-year period.

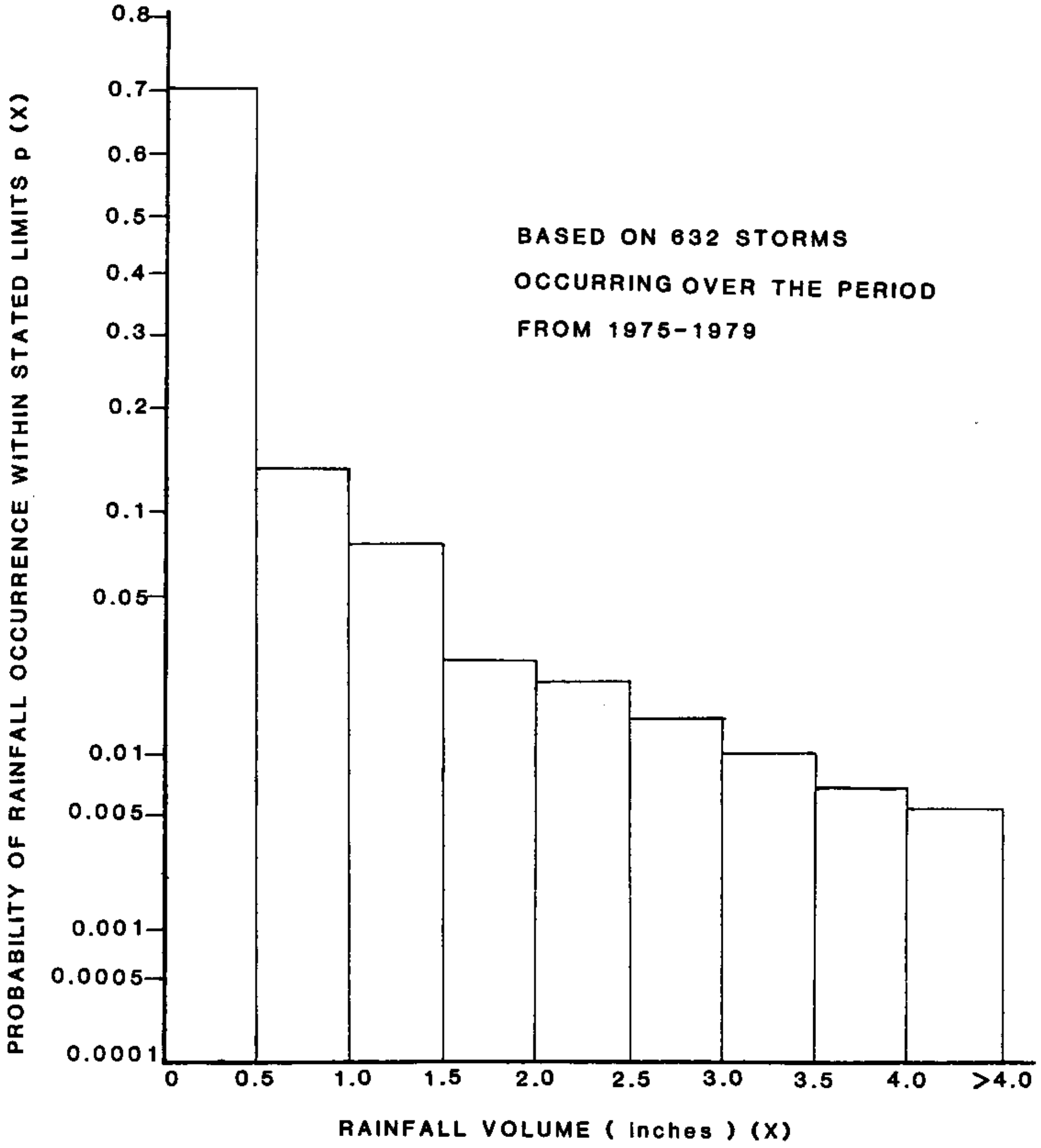


Fig. A-2. Frequency distribution of rainfall at Tallahassee WSO Airport over a 5-year period.

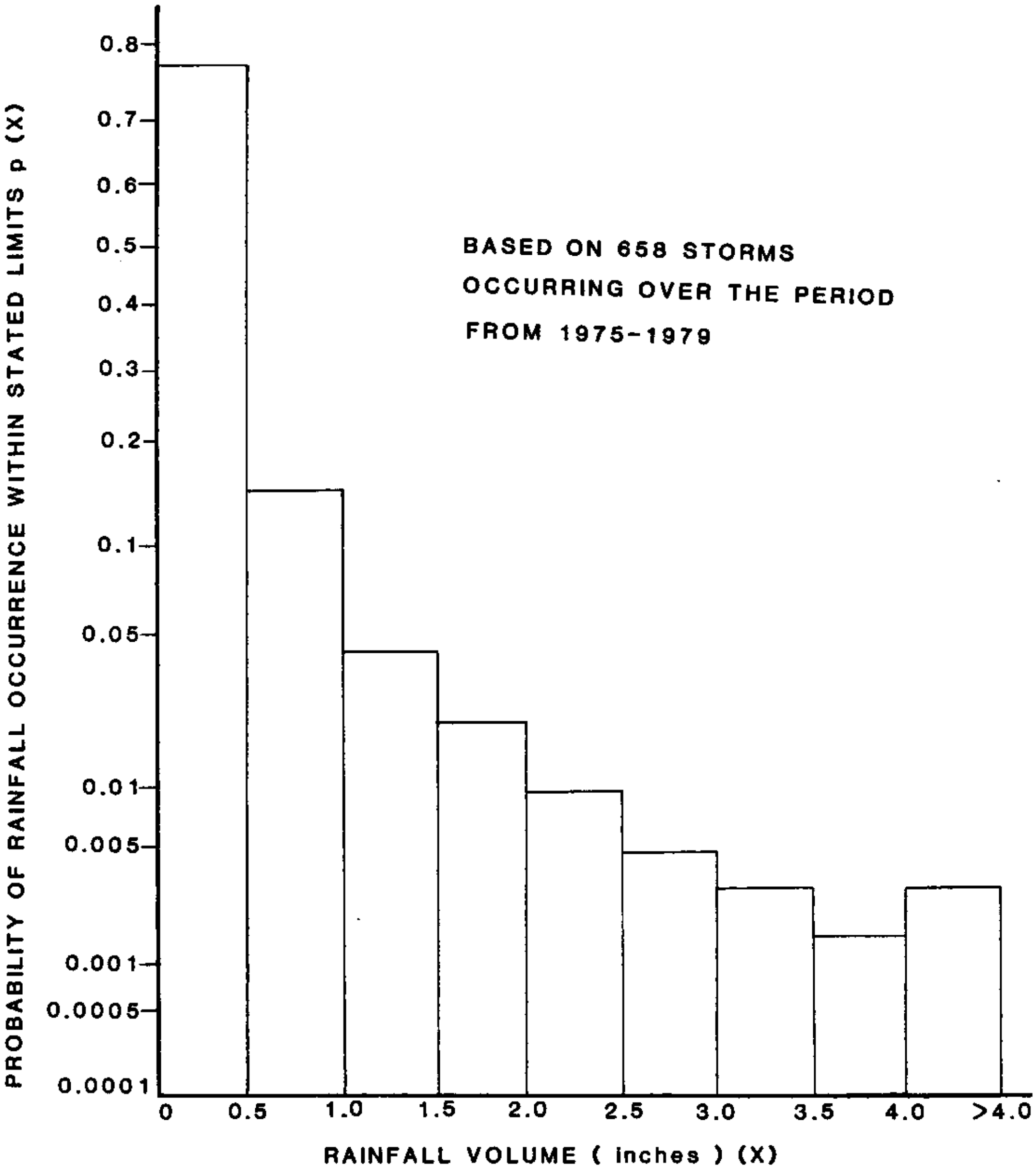


Fig. A-3. Frequency distribution of rainfall at Jacksonville over a 5-year period.

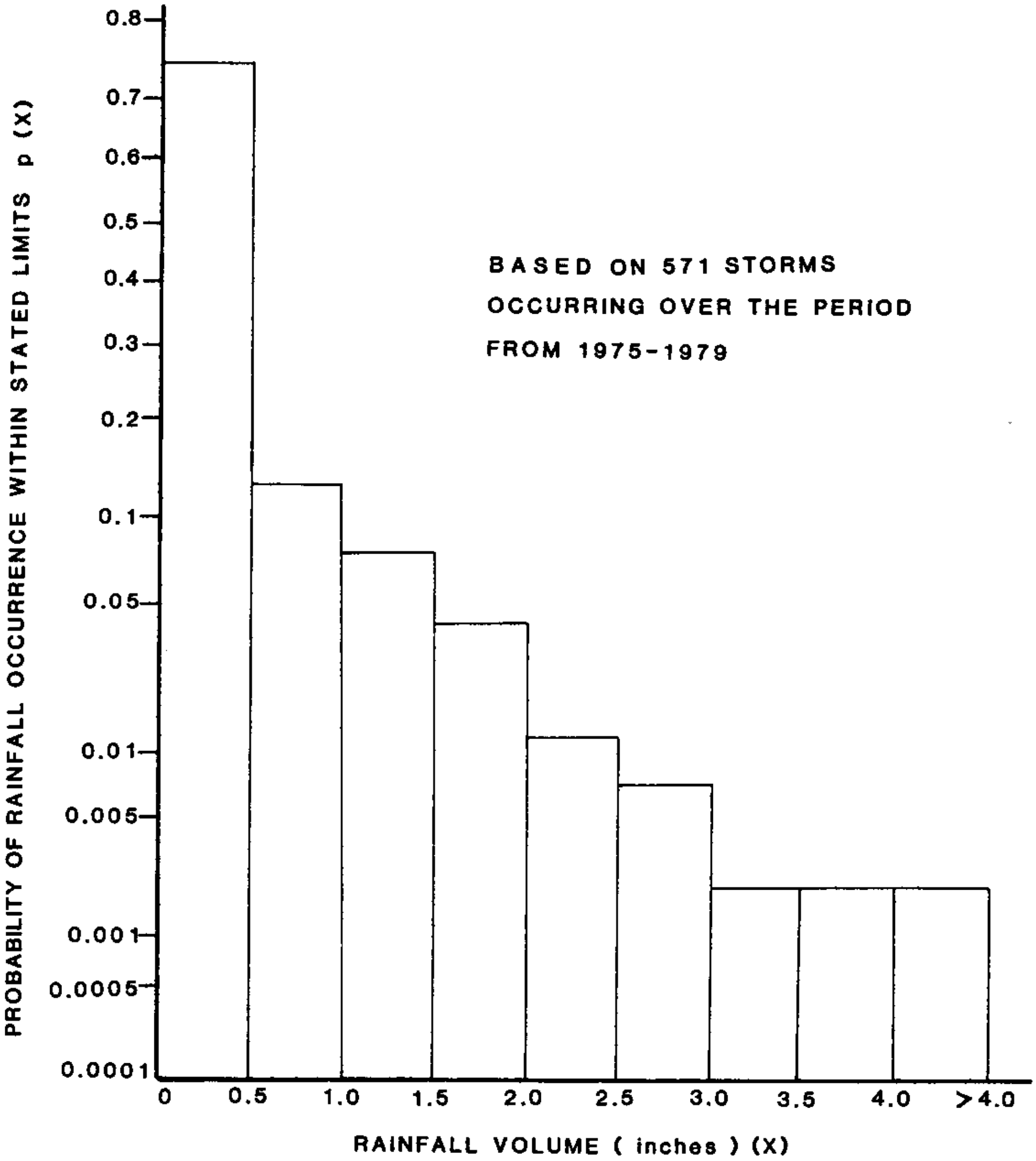


Fig. A-4. Frequency distribution of rainfall at Appalachicola WSO Airport over a 5-year period.

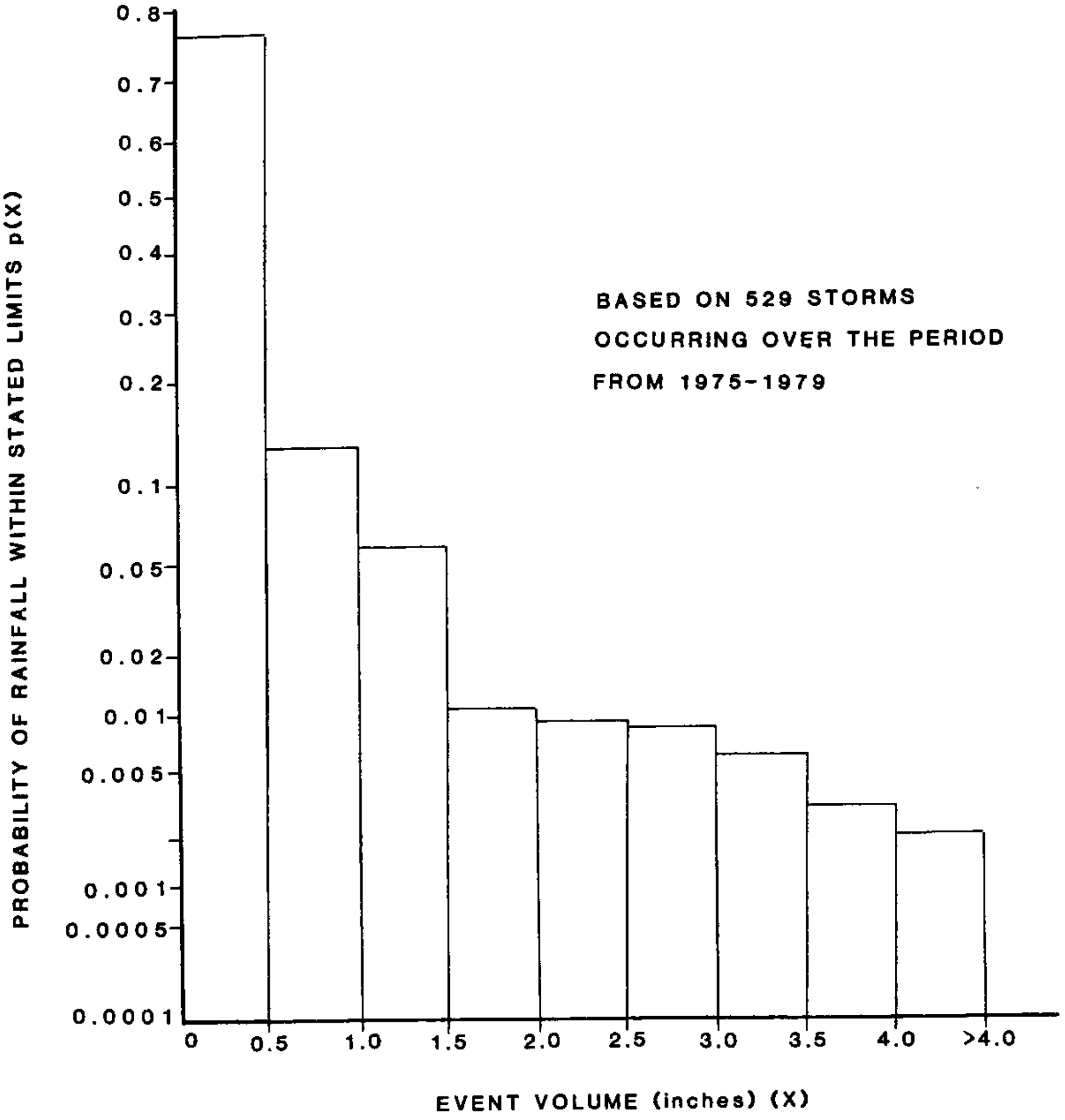


Fig. A-5. Frequency distribution of rainfall at Gainesville over a 5-year period.

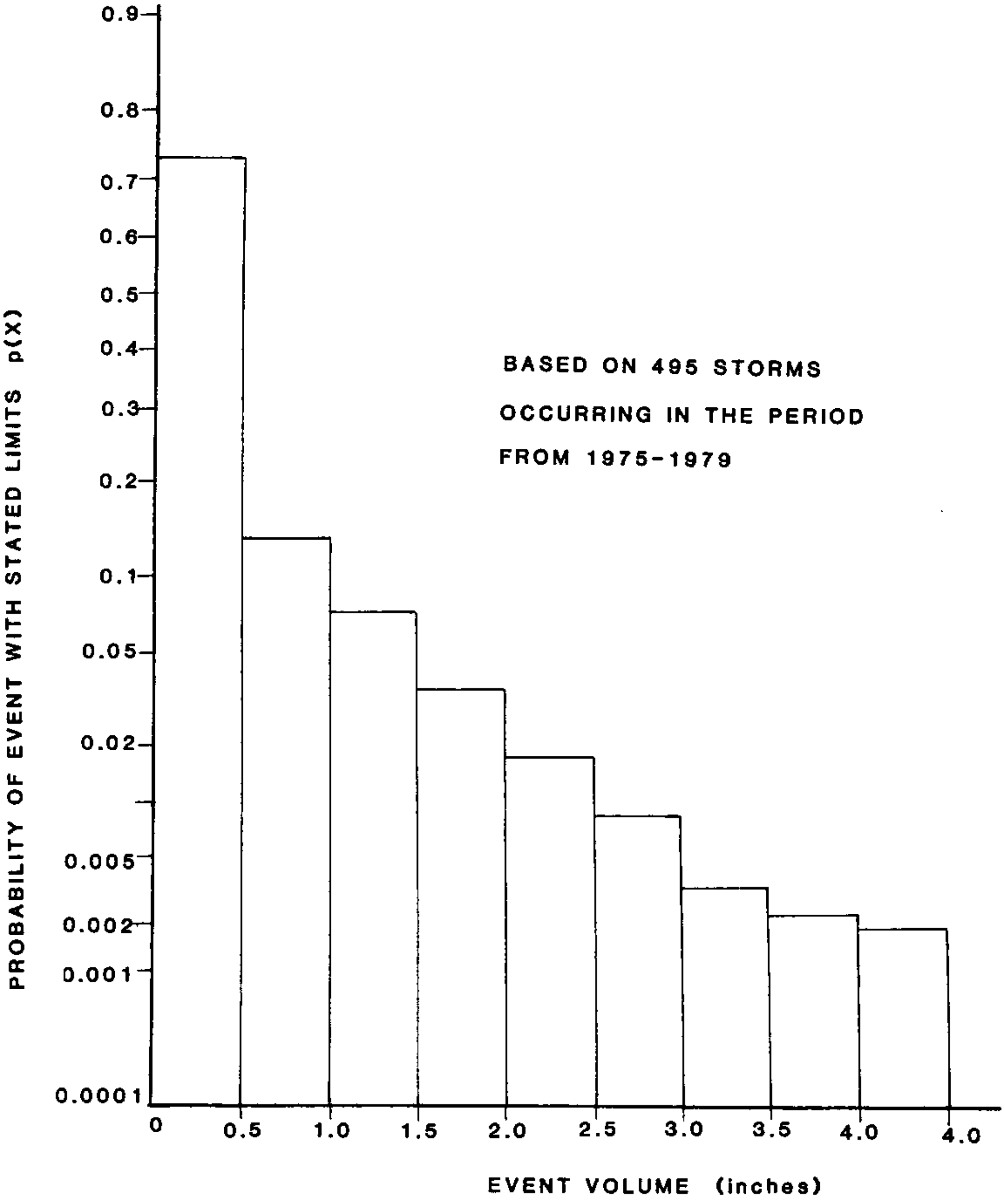


Fig. A-6. Frequency histogram for Inglis 5SSW weather station.

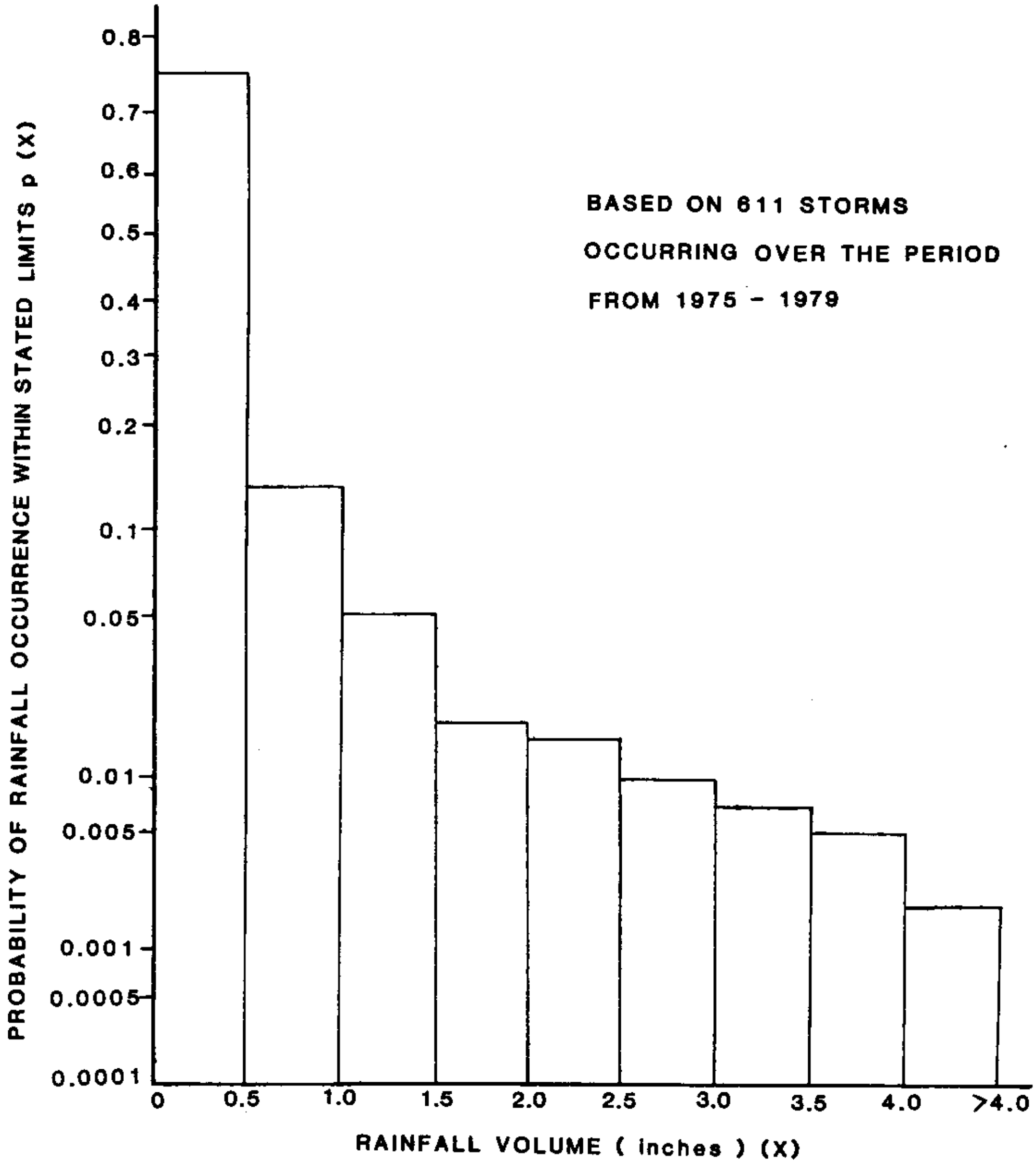


Fig. A-7. Frequency distribution of rainfall at Daytona Beach WSO Airport over a 5-year period.

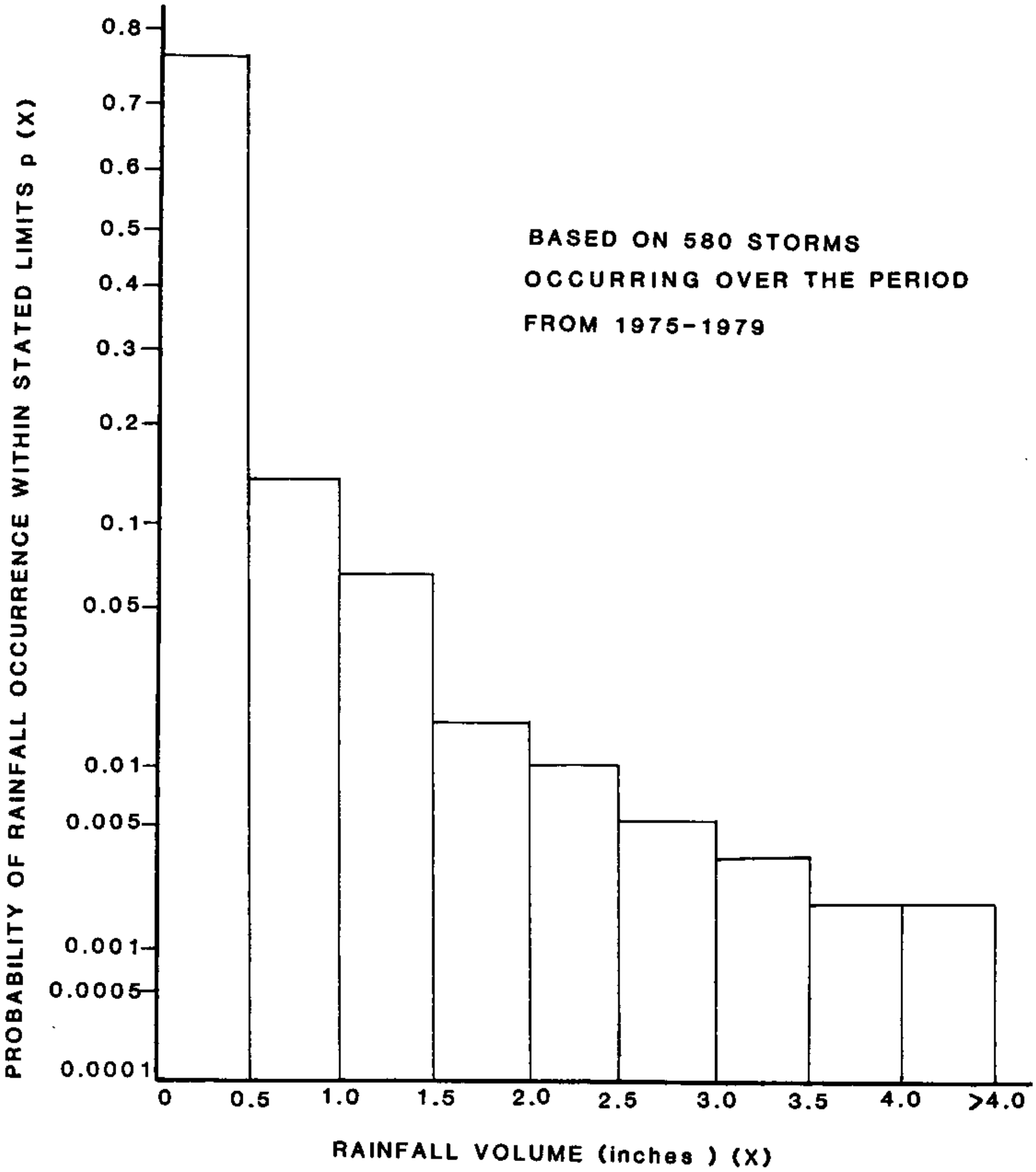


Fig. A-8. Frequency distribution of rainfall at Orlando McCoy Airport over a 5-year period.

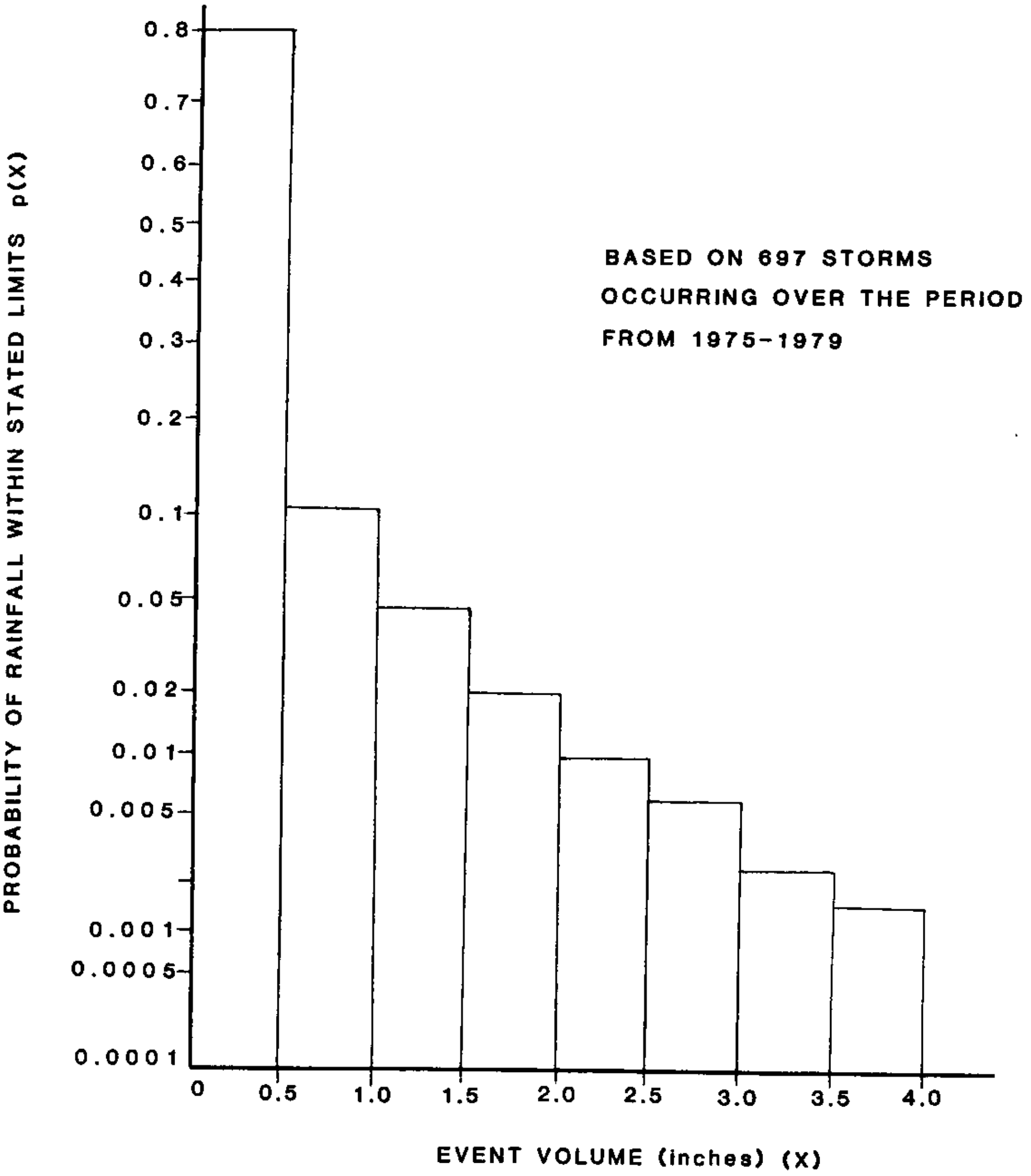


Fig. A-9. Frequency distribution of rainfall at Orlando McCoy Airport over a 5-year period.

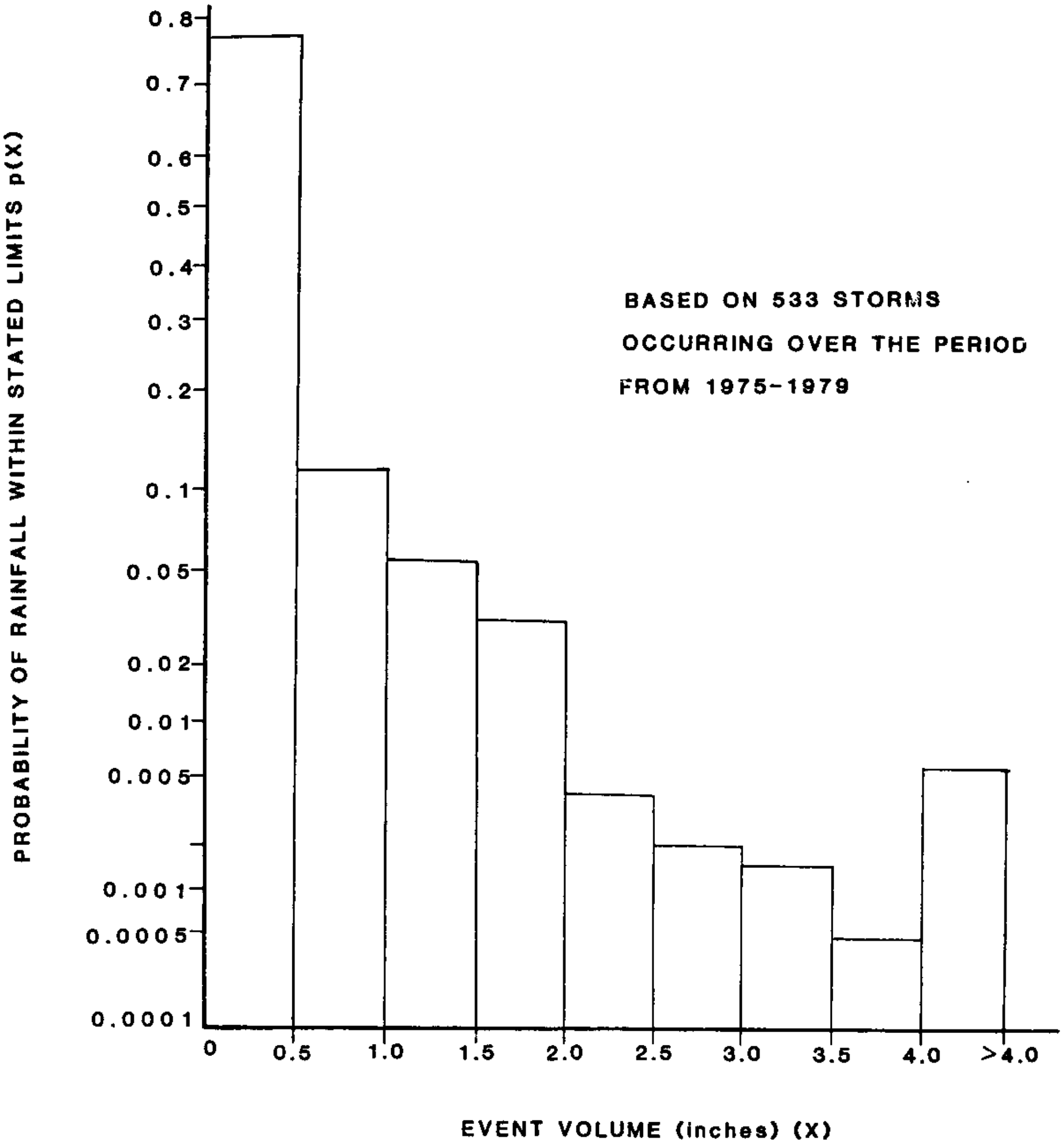


Fig. A-10. Frequency distribution of rainfall at Vero Beach over a 5-year period.

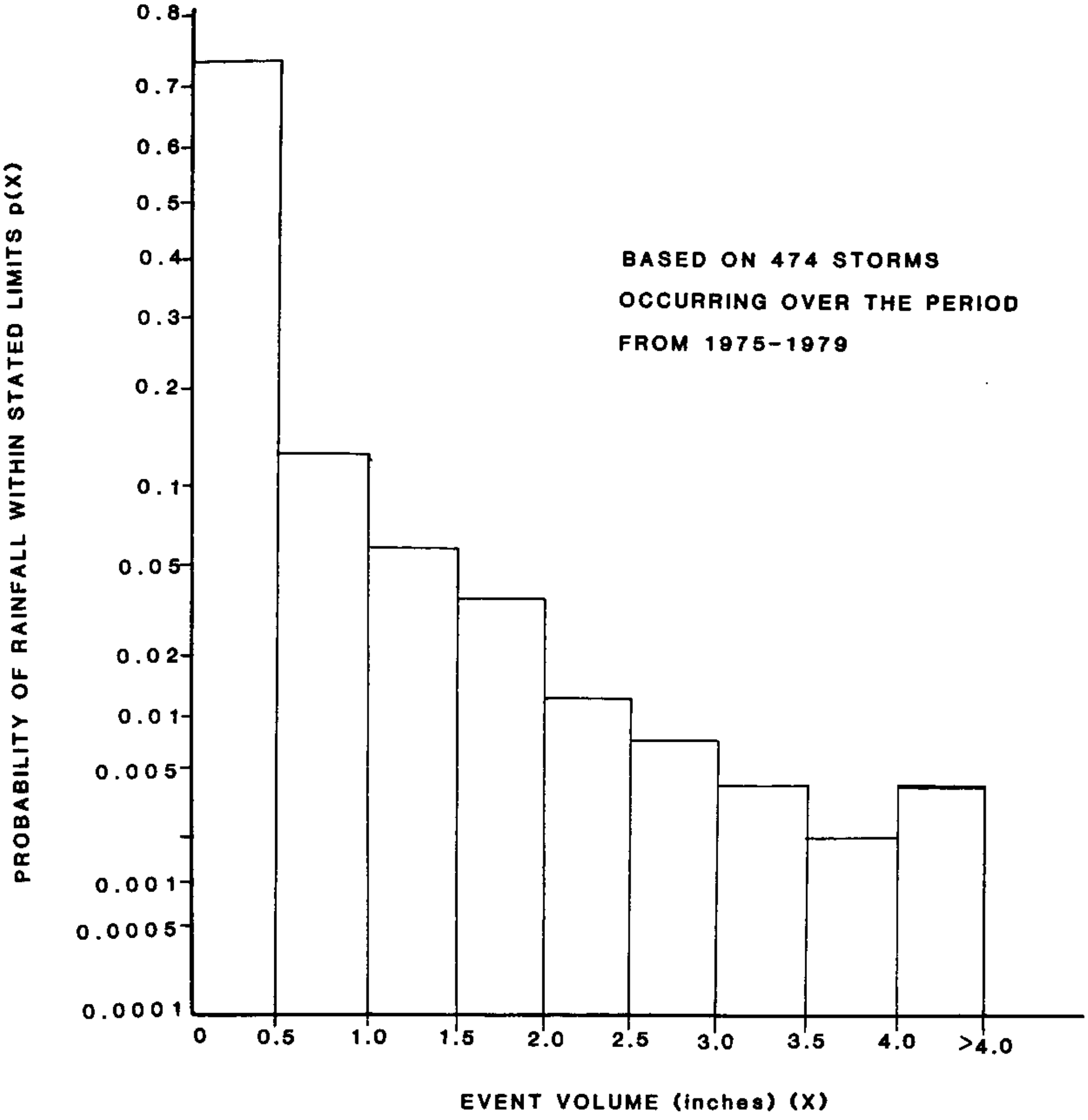


Fig. A-11. Frequency distribution of rainfall at Clewiston over a 5-year period.

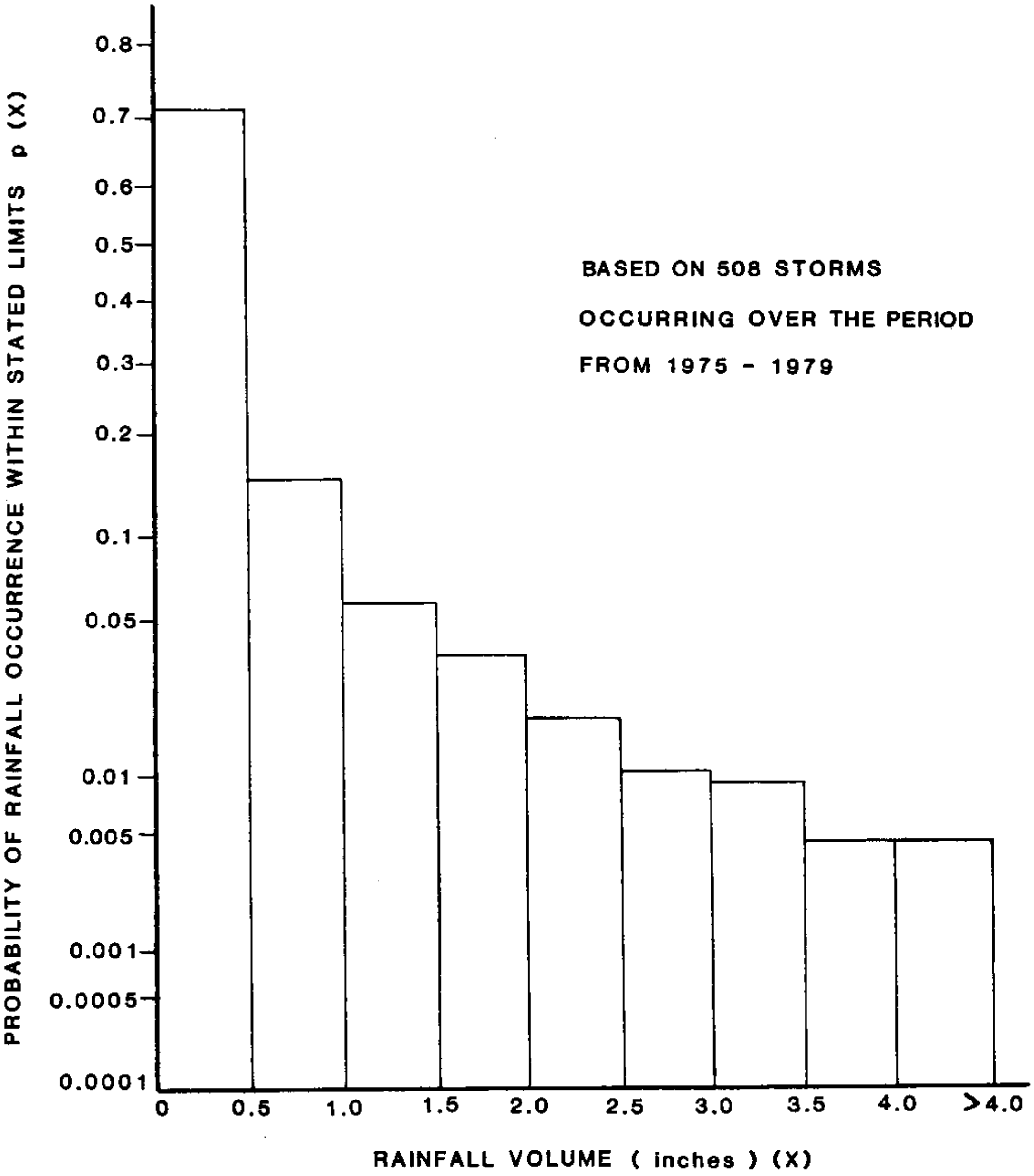


Fig. A-12. Frequency distribution of rainfall at Fort Myers over a 5-year period.

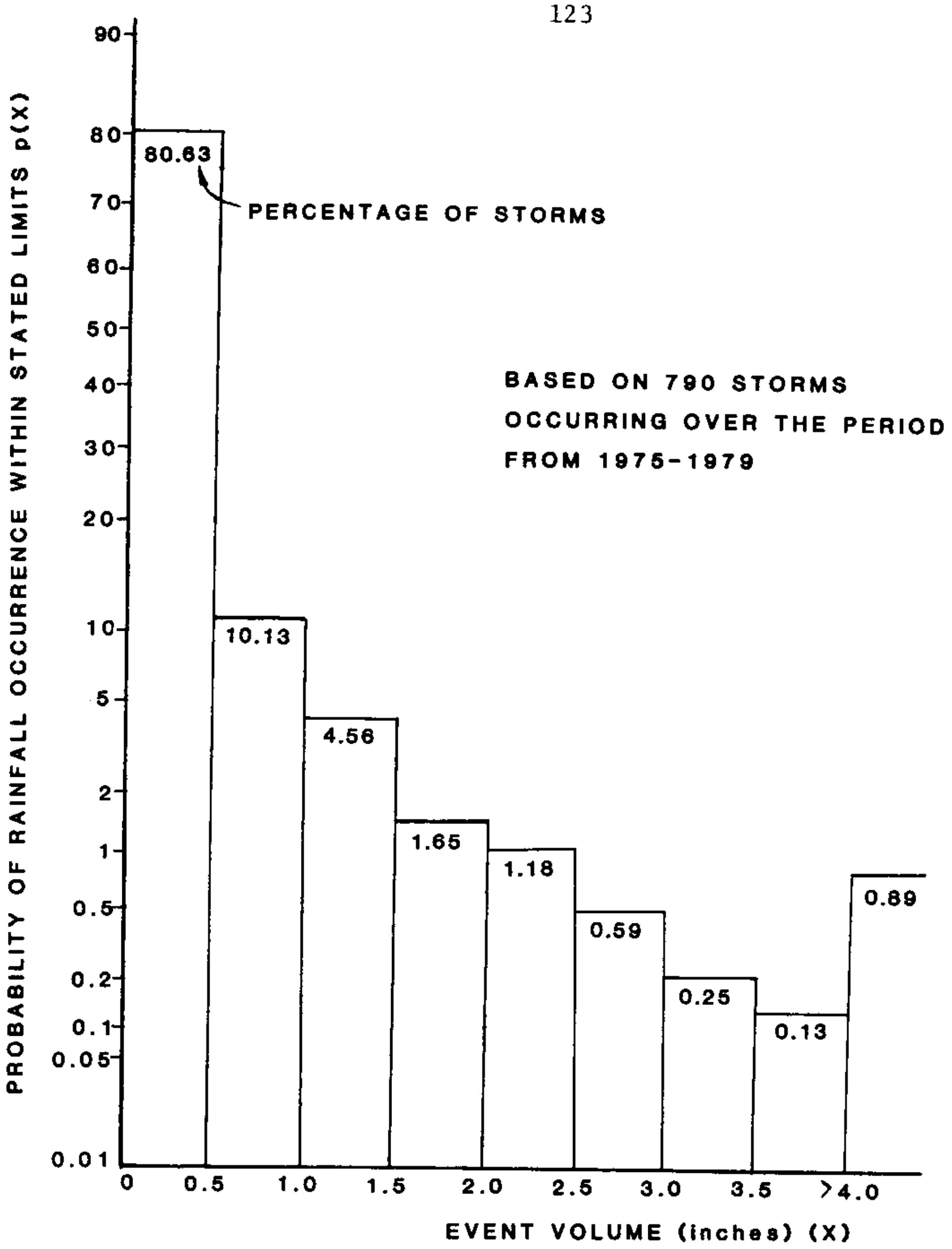


Fig. A-13. Frequency histogram for storms at West Palm Beach WSO Airport over the 5-year period.

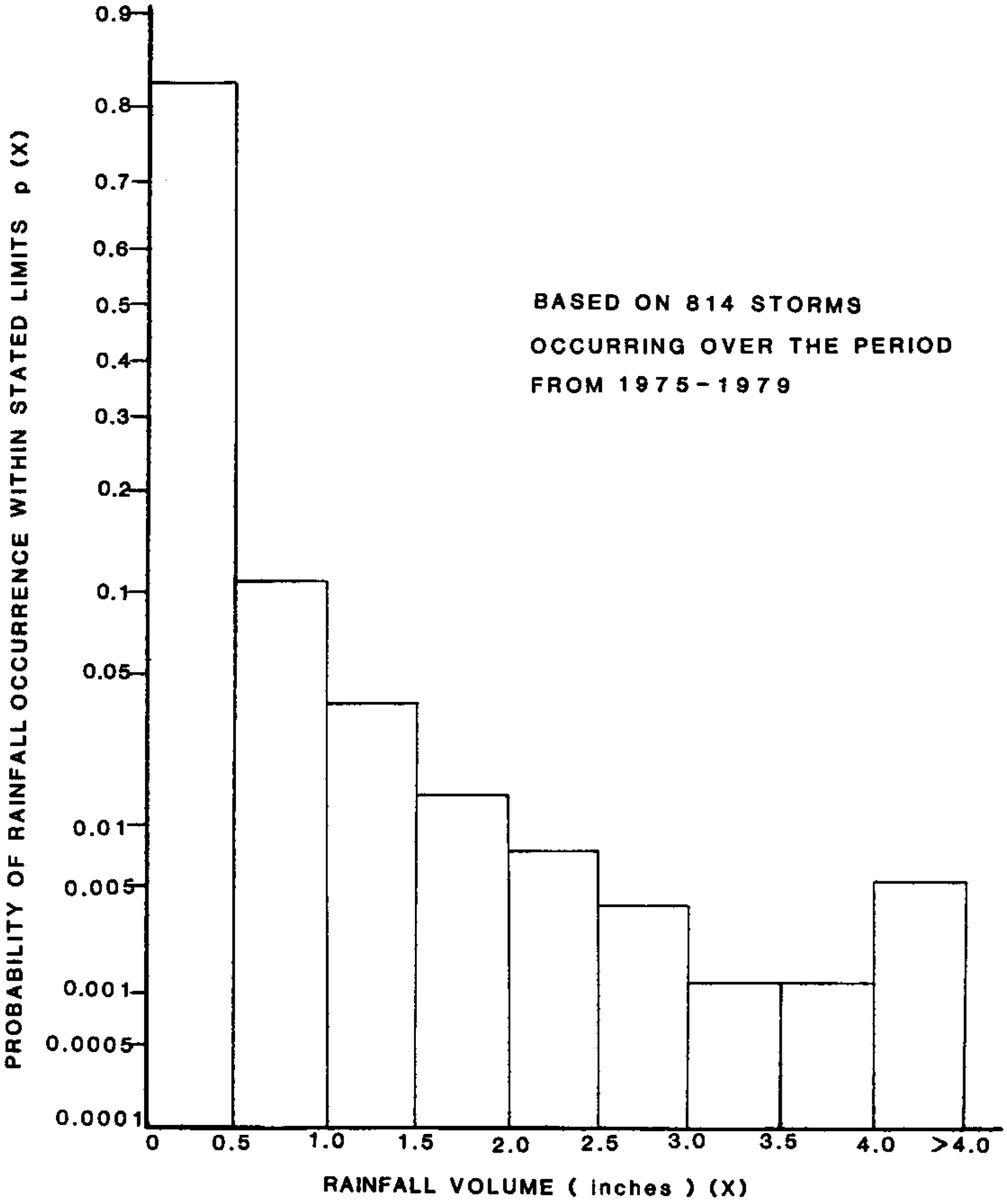


Fig. A-14. Frequency distribution of rainfall at Miami WSO Airport over a 5-year period.

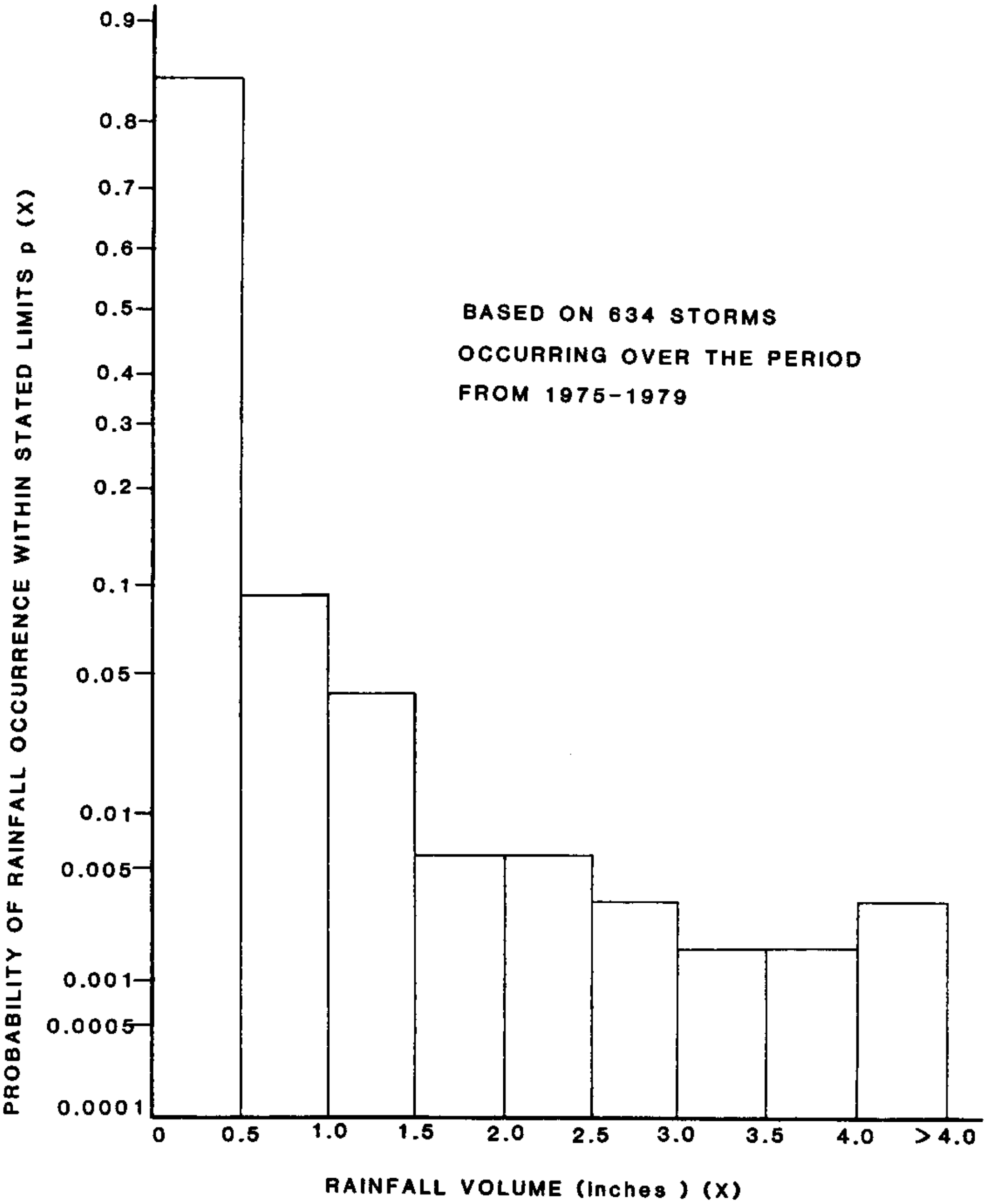


Fig. A-15. Frequency distribution of rainfall at Key West WSO Airport over a 5-year period.

REFERENCES

Alexander, K. "Determination of Rainfall Duration for Rainout Models Using Daily Records." Water Resources Research 17 (June 1981): 521-528.

American Society for Testing and Materials Annual Book of ASTM Standards. Philadelphia, PA: American Society for Testing and Materials, 1980.

Anderson, Melvin W., and Giovanelli, Ronald F. "A Digital Overlay Technique for Evaluation of Potential Infiltration and Recharge." Water Resources Bulletin 16 (February 1980): 93-99.

Barry, R.G. "Precipitation." In Water, Earth and Man, pp. 113-166. Edited by R.J. Chorley. London, England: Methuen and company, Ltd., 1969.

Beard, Leo R.; Weiss, Arden O.; and Austin, T.L. "Alternative Approaches to Water Resources Simulation." In Modeling of Water Resources Systems II, pp. 580-589. Edited by A. Biswas. Ontario, Canada: Crown Copyright, 1972.

Beaver, Robert D. "Infiltration in Stormwater Detention/Percolation Basin Design." Research report, Florida Technological University, Orlando, Florida, 1977.

Bouwer, H. "Rapid Field Measurement of Air-Entry Value and Hydraulic Conductivity of Soil as Significant Parameters in Flow Systems Analysis." Water Resources Research 2 (April 1966): 729-738.

Bouwer, H. "Infiltration of Water Into Non-Uniform Soils." Journal of the Irrigation and Drainage Division ASCE 95 (April 1969): 451-460.

Bowles, J.E. Physical and Geotechnical Properties of Soils. New York: McGraw-Hill, 1979.

Breed, C.B., and Hosmer, G.L. The Principles and Practices of Surveying Volume I - Elementary Surveying. New York: John Wiley and Sons, Inc., 1977.

Calhoun, F.G.; Hammond, L.C.; and Caldwell, R.E. "Influence of Particle Size and Organic Matter on Water Retention in Selected Florida Soils." Soil and Crop Science Society of Florida 32 (May 1973): 111-113.

Childs, E.C. "Soil Moisture Theory." In Advances in Hydroscience, pp. 73-117. Edited by Ven Te Chow. New York: Academic Press, 1967.

Childs, E.C., and Bybordi, M. "The Vertical Movement of Water in Stratified Porous Material, 1. Infiltration." Water Resources Research 5 (April 1969): 446-459.

Childs, E.C., and Poulovassilis, S. "The Hysteresis of Pore Water: The Non-Independence of Domain." Soil Science 112 (May 1971): 301-312.

Chow, Ven Te. Open Channel Hydraulics. New York: McGraw-Hill, 1959.

Chow, Ven Te. Handbook of Applied Hydrology. New York: McGraw-Hill, 1964.

Crane, John. "Porous Pavement to Reduce or Eliminate Stormwater Runoff." Environmental Science and Engineering, Inc., Gainesville, Florida. In Proceedings of the Stormwater Quality Seminar, Daniel K. Shaheen (ed.), June 4, 1973.

Dellour, J.W., and Dendrow, S. "Modeling the Runoff Process in Urban Areas." Critical Reviews in Environmental Control 10 (July 1980): 1-64.

Eagleson, P.S. "Some Limiting Forms of the Poisson Distribution for Annual Station Precipitation." Water Resources Research 17 (June 1981): 752-757.

Egbuniwe, Nnamdi. "Generation of Hourly Rainfall." Water Resources Bulletin 11 (August 1975): 706-713.

Farmer, E.E., and Homeyer, J.W. "The Probability of Consecutive Rainless Days." Water Resources Bulletin 10 (October 1974); 914-924.

Flatt, G. "Sensitivity Analysis of Stormwater Runoff Using the BMP-NONPT Computer Programs." Master's thesis, Florida Technological University, Orlando, Florida, 1978.

Florida State Department of Environmental Regulation. Non-Point Source Management: A Manual of Reference Management Practices for Forest Activities, Tallahassee, Florida, 1980.

Gardner, W.R.; Hillel, D.; and Benyomini, Y. "Post-Irrigation Movement of Soil Water, 1. Redistribution." Water Resources Research 6 (March 1970): 851-861.

Gifford, G.F., and Hawkins, R.H. "Deterministic Hydrologic Modeling of Grazing System Impacts on Infiltration Rates." Resources Bulletin 15 (August 1979): 924-930.

Golding, B.L. "Volusia County 208 Comprehensive Rainfall Analysis." Howard, Needles, Tammen and Bergendoff, Orlando, Florida (February 1977).

Goodrich, R.D. "Rapid Calculation of Reservoir Discharge." Civil Engineering 2 (February 1931): 417-419.

Green, W.H., and Ampt, G.S. "Studies on Soil Physics - I. The Flow of Air and Water Through Soils." Journal of Agricultural Science 4 (June 1911): 1-24.

Hardison, C.H. "Generalized Skew Coefficients of Annual Floods in the United States and Their Application." Water Resources Research 10 (September 1974): 745-752.

Hillel, D., and Gardner, W.R. "Transient Infiltration Into Crust-Topped Profiles." Soil Science 109 (February 1970): 69-76.

Holtan, H.N., and Kirkpatrick, M.H. "Rainfall, Infiltration, and Hydraulics of Flow in Runoff Computations." Transactions of the American Geophysics Union 31 (May 1950): 771-779.

Horton, R.E.; Leach, H.R.; and Vliet, R.V. "Laminar Sheet Flow." Transactions of the American Geophysics Union 15 (June 1934): 393-404.

Horton, R.E. "An Approach Toward a Physical Interpretation of Infiltration Capacity." Proceedings of Soil Science Society of America 5 (July 1940): 399-417.

Hough, B.K. Basic Soil Engineering. New York: Ronald Press Company, 1957.

Huff, F.A. "Time Distribution of Rainfall Rates." Water Resources Bulletin 6 (April 1970): 447-454.

Johnson, E.R., and Bras, R.L. "Multi-Variate Short Term Rainfall Prediction." Water Resources Research 16 (February 1980): 173-185.

Klute, A., and Heermann, D.F. "Soil Water Profile Development Under a Periodic Boundary Condition." Soil Science 117 (January 1974): 265-271.

Mein, R.G., and Larsen, C.L. "Modeling Infiltration During a Steady Rain." Water Resources Research 9 (April 1973): 384-394.

Morel-Seytoux, H.J. "Application of Infiltration Theory for the Determination of Excess Rainfall Hyetograph." Water Resources Bulletin 17 (December 1981): 1012-1022.

Morel-Seytoux, H.J., and Khanji, J. "Derivation of an Equation of Infiltration." Water Resources Research 10 (June 1974): 795-800.

Musgrave, G.W., and Holtan, H.N. "Infiltration." In Handbook of Applied Hydrology, pp. 12-30. Edited by Ven Te Chow. New York: McGraw-Hill, 1964.

Neuman, S.R. "Wetting Front Pressure Head in the Infiltration Model of Green and Ampt." Water Resources Research 12 (June 1976): 564-571.

Overman, A.R., and Wang, L. "Field Measurement of Hydraulic Conductivity of Lakeland Fine Sand." Soil and Crop Science Society of Florida 33 (1974): 154-156.

Overton, D.E. "Route or Convolute?" Water Resources Research 6 (February 1970): 43-52.

Overton, D.E., and Brakensiek, D.L. "A Kinematic Model of Surface Runoff Response." Paper prepared for International Symposium on the Results of Research on Representative and Experimental Basins, Wellington, New Zealand, December 1-8, 1970.

Packman, J.C., and Kidd, C.H.R. "A Logical Approach to the Design Concept." Water Resources Research 16 (December 1980): 994-1000.

Phillip, J.R. "The Theory of Infiltrations, 4. Sorptivity and Algebraic Equations." Soil Science 84 (March 1957): 257-264.

Phillip, J.R. "Some Remarks on Science and Catchment Prediction." In Prediction in Catchment Hydrology, pp. 16-18. Edited by Chapman and Dunin. Australian Academy of Science, 1975.

Poulovassilis, A. "Hysteresis of Pore Water, An Application of the Concept of Independent Domains." Soil Science 93 (June 1962): 405-412.

Randkivi, A.J., and Lawgun, N. "Synthesis of Urban Rainfall." Water Resources Research 6 (April 1970): 455-464.

Reeder, J.W.; Freyberg, D.L.; Franzini, J.B.; and Remson, I. "Infiltration Under Varying Surface Water Depths." Water Resources Research 16 (February 1980): 97-104.

Rubin, J. "Numerical Method for Analysing Hysteresis Affected Post-Infiltration Re-Distribution of Soil Moisture." Soil Science Society of America Proceedings 31 (1967): 13-20.

Schulze, D. Problems in Applied Hydrology. Fort Collins, Colorado: Water Resources Publications, 1976.

Singh, V.P. "Derivation of Surface Water Lag Time for Converging Overland Flow." Water Resources Bulletin 11 (June 1979): 505-513.

Singh, V.P., and Sherman, A. "A Distributed Converging Overland Flow Model, 2. Effect of Infiltration." Water Resources Research 12 (October 1976): 897-901.

South Florida Water Management District. Permitting Information Manual, Vol. IV. West Palm Beach, Florida, December 1980.

Staple, W.J. "Infiltration and Redistribution of Water in a Vertical Column of Loam Soil." Soil Science Society of America Proceedings 31 (December 1966): 553-558.

Topp, G.C. "Soil Water Hysteresis Measured in a Sandy Loam and Compared with the Hysteretic Domain Model." Soil Science Society of America Proceedings 33 (November 1969): 645-651.

United States Department of Agriculture. Soil Conservation Service. Soil Interpretations for Urban and Recreational Uses, Supplement to the Soils Survey for Orange County, Florida. Gainesville, Florida: University of Florida, Agricultural Experiment Station, July 1973.

United States Department of Agriculture. Soil Conservation Service. Soil Survey Supplement, Seminole County, Florida, Seminole County Board of County Commissioners, 1975.

United States Department of Commerce. National Oceanic and Atmospheric Administration, Environmental Data Service. Hourly Precipitation Data: National Climatic Center, Asheville, North Carolina, 1975-1979.

United States Weather Bureau. Rainfall Frequency Atlas of the United States, TP No. 40. United States Department of Commerce, Washington, D.C. (May 1961).

Van Duin, R.H.A. "Foliage in the Relation to Rainfall Intensity and Infiltration Capacity of Soils." Netherlands Journal of Agricultural Science 3 (May 1955): 182-189.

Vinson, T.S., and Mahr, L. "Soil Percolation Rates from Neutron Probe Measurements." Journal of the Irrigation and Drainage Division, ASCE 107 (December 1981): 343-359.

Wanielista, M.P. Stormwater Management: Quantity and Quality. Ann Arbor, Michigan: Ann Arbor Science Publishers, 1978.

Wanielista, M.P. Personal communication, April 2, 1982.

Wooding, R.A. "An Hydraulic Model for the Catchment Stream Problem, 1. Kinematic Wave Theory." Journal of Hydrology 3 (March 1965): 254-267.