DESIGN CURVES FOR THE REUSE OF STORMWATER

BY

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The concept for this report developed over the past two years and emerged at a time when the need for additional pollutant removal from stormwater and preservation of water within the State became a important goal expressed by State water policy and demanded by local economic conditions. As such there are many people within in State, regional, and local agencies who helped with this report. All should be given credit for their comments and suggestions. Of specific mention are John Cox and Eric Livingston of The Florida Department of Environmental Regulation. In addition, the financial support of the State Department of Environmental Regulation, the Environmental Protection Agency, and the University of Central Florida are appreciated.

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The Problem

Within the State of Florida, the pollutants associated with stormwater and the volume of stormwater discharges pose significant impacts to the natural and man-made environments of the State. As watersheds are made more impervious due to paving and other construction activities, the volume of runoff and pollutant mass discharged to surface waters increases relative to pre-developed conditions.

Impacts from uncontrolled runoff are loss of water from an area where the rainfall occurred, decreased rates and volumes of evapotranspiration, additional fresh water discharges to estuaries, increased pollutant mass loadings, decreased river base flows, a reduction of wetland areas, and an economic loss associated with the need to replace discharged fresh water.

Water Policy in the State requires a stormwater pollutant annual average load reduction of 80% for discharges to most waters and 95% for those discharging into outstanding Florida waters. Of the currently used stormwater management methods, off-line retention can achieve the stated pollutant removal efficiencies. However wet detention ponds that discharge to adjacent surface waters do not. If some of the detained water can be used within the watershed and not discharged to surface waters, the wet detention ponds may also meet the standards.

A Possible Solution

A stormwater reuse pond is proposed to retain runoff water within a watershed and to reduce the mass of pollutants in the discharges to surface water bodies. The difference between a wet detention pond and a reuse pond is the operation of the temporary storage volume. A wet detention pond is designed to discharge the runoff water and possibly some groundwater to adjacent surface waters, while a reuse pond is designed to reuse a specific fraction of the runoff volume and not discharge that fraction. In this report, mathematical relationships are developed between the reuse volume (temporary storage volume), the rate at which stormwater is reused, and the percentage of annual surface runoff that is reused. The procedures for the design of stormwater reuse systems are presented.

The traditional design of pond temporary storage volume for a wet detention pond has been based on the consideration of water quality and uses a design storm. The design storm, however, usually ignores the preceding rainfall record and assumes that there is an antecedent dry period long enough to ensure that the pond is at some control elevation. The usual assumption is a zero temporary storage.

To address the sensitivity of the temporary storage volume to inter-event dry periods, long term rainfall records were used from 25 Florida rainfall stations in a model that simulates the behavior of a reuse pond over time. A spreadsheet was used to build a 15 year mass balance for a pond. After each rainfall event, surface runoff and reuse volumes were respectively added to and subtracted from the previous pond storage volume. If the temporary storage volume exceeded the available storage volume, discharge occurred. If the temporary storage volume was less than zero (the permanent pool volume was used for reuse water), supplemental water was used to replenish the pond and maintain the permanent pool. Both the rate of reuse from the pond and the reuse volume were varied. The reuse efficiency, defined as one minus the total volume of surface discharge divided by the total volume of runoff times one hundred, was calculated for each combination.

The results of the simulation are presented in Rate-Efficiency-Volume (**REV**) charts. Curves reflecting several efficiencies track the appropriate combinations of reuse rates and reuse storage volumes. The REV charts are generalized for application to watersheds of any size or runoff coefficient. A computer program was developed to execute the design technique.

Recommendations

The reuse of stormwater within a watershed from which it came should be encouraged and in some areas required. Reuse ponds can be designed to conserve water within a watershed and to reduce the mass of pollutants entering the surface waters of the State. Specific design and operating recommendations are:

The effective impervious area for a watershed should include the area of the pond when using the **REV** curves. The effective impervious area calculation is necessary for the use of the **REV** curves. More than one **REV** curve for a location is expressed in a figure called a **REV** chart.

There are 25 **REV** charts for the State. The designer should use the one closest to the site for design. When doubt exists as to the station to use, pick the one within the NOAA Climatic Division area that is closest to the site (see Figure 3.5).

For an average annual pollutant mass removal of 80% in a wet detention pond, at least 50% of the runoff volume should be reused when the **REV** charts are used for design. For a 95% annual pollutant mass removal, at least 90% of the runoff volume should be reused. The reuse percentages assume a wet detention pond will remove an annual average 60% of the incoming runoff pollution mass before surface discharge, which may over estimate the actual efficiency.

The control elevation for surface water discharge from the pond should be set near the seasonal high groundwater table elevation. Thus, the resulting design is conservative with respect to the percentage of runoff discharged. Also. flood control reliability can be increased if some of the permanent pool is reused.

CHAPTER 1

INTRODUCTION

Philosophy

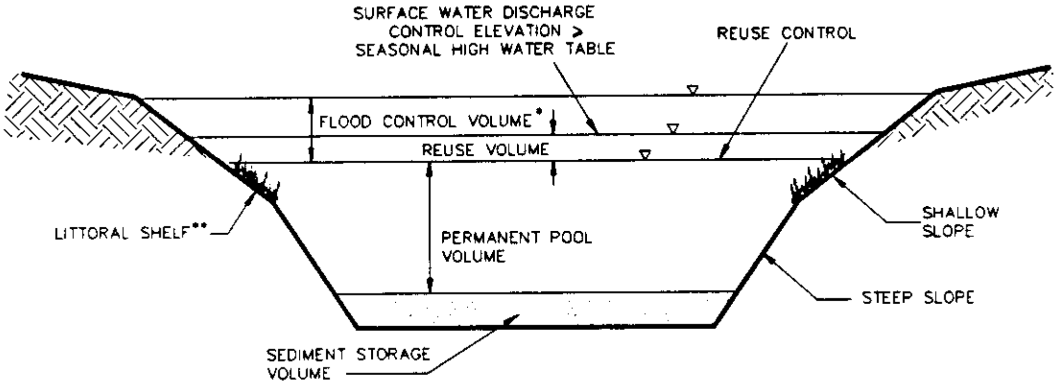
Most stormwater management is determined, both technically and financially, by the needs of society. Many times, the need is the result of past social changes, such as, the construction of the first paved parking lots which protected our shoes. Since the early 1970's, however, we have seen a growing concern for the effects of the runoff from these and other impermeable areas which are, literally, gaining new ground every day. Our lakes and rivers are experiencing accelerated eutrophication and stormwater is being wasted as it is flushed out to sea. This is not desirable. Consequently, there is a need to control the quantity and quality of discharges from these areas.

Today, the idea that runoff must be managed is uncontested. All new developments must include stormwater management systems that function to reduce the rate and volume of surface discharge from watershed areas and to improve the water quality of this discharge and, consequently, the receiving waters. The State has established design and performance criteria to satisfy these goals but there is continuous debate concerning which stormwater management methods and design criteria best satisfy the current standards. The State does stress the importance of the reuse of stormwater (Cox, 1990).

This report proposes two ideas. The first focuses on the concern for the quality of our receiving waters: a way in which to design and operate the temporary storage volume of a detention pond so that a desired level of treatment is reasonably maintained. The second addresses the problem of wasted stormwater and proposes the inclusion of a reuse component into the stormwater system.

Wet Detention versus Reuse

Wet detention can be implemented in areas where the groundwater table can help maintain the permanent pool volume (Figure 1-1). For a pond at equilibrium, the top surface of the permanent pool will rest at the elevation of the groundwater table and there will be no net groundwater movement. The temporary storage volume lies above the permanent pool. For wet detention, the runoff from a storm event is temporarily stored in this space and generally released at a controlled rate by a bleed down orifice or weir and sometimes by infiltration of ponded water through the pond banks above the groundwater table. The surface discharge structure may be replaced by a mechanical reuse system which draws down the temporary storage volume at a comparable rate. Thus a reuse pond is created and the temporary storage volume is termed "reuse volume". A flood control structure must remain.



*Can be measured above permanent pool, however some regulatory agencies measure above the reuse volume.

**The reader should consult local water management districts and other regulatory agencies to determine specific geometric and littoral zone design requirements.

Figure 1-1. Schematic of a Stormwater Reuse Pond.

Benefits of Reuse

The reuse of stormwater is not a new concept. In agricultural areas ponds have been built to provide an economical source of water. However, the size of the ponds have generally been built to occupy available land area and are not designed with a target level of reuse, or for a percent reduction in pollutant mass. A design with predicted performance levels can be related to related to benefits.

Ecological Benefits

No-impact stormwater management practice has become an increasingly important professional goal and is more often publicly demanded. Although the term "reuse" alone implies environmental benefits, there are tangible arguments supporting the benefits of reusing stormwater.

Foremost is the reduction of volume and pollution discharges to surface waters: water reused is water that is not discharged. Typical detention ponds draw down the temporary storage volume using control devices that discharge into adjacent natural water bodies. However, the temporary storage in reuse ponds is reused in the watershed or in some other productive way. Because water above the temporary storage is directly discharged and the temporary storage is reused, the reuse pond will discharge less than a similarly sized detention pond.

Reuse is a good practice in the wise management of groundwater resources. As urbanization increases there is a change in the hydrologic balance of the region (Wanielista, 1990a). An increase in watershed discharges will decrease the amount of water that had previously infiltrated into the ground and evaporated from the watershed. However, as the stormwater is reapplied to the watershed there is greater potential for groundwater replenishment. Also, when reuse systems replace irrigation systems dependent on groundwater, there is decreased use of groundwater, whether the original source for irrigation was potable water or pumped on site.

Stormwater ponds usually receive nutrients (nitrogen, phosphorus, etc.) from surrounding watershed areas. Dissolved nutrients can be recycled back to the landscape by reuse systems that irrigate the stormwater.

Economic Benefits

The concept of reuse may be ecologically sound, but unless the inclusion of reuse is monetarily profitable it would not become widely implemented into design. There are several economic advantages to reusing stormwater.

A significant monetary savings will result from not using and paying for potable water. This fact is exaggerated for large land users, such as golf courses. The annual cost of potable water for a 100 acre golf course irrigating at a rate of 2 inches per week can be estimated. The average cost of treated groundwater is about $1.00 per thousand gallons.

$$\$/yr = \frac{2\ in}{wk} \times 100\ ac \times \frac{1\ ft}{12\ in} \times \frac{325{,}828\ gal}{ac\text{-}ft} \times \frac{52\ wk}{yr} \times \frac{\$1.00}{1000\ gal} = \$282{,}385/yr$$

The golf course would pay about $300,000 per year for water.

This cost could be substantially reduced with a reuse system. A reuse system would use the same irrigation network but would require a pumping system to deliver the water. The initial cost of this is estimated to be between $25,000 and $35,000 with an electrical and maintenance cost of $15,000 to $30,000 per year. An annual cost considering amortization of the equipment over 20 years at 10 percent is

$$\begin{aligned} \$/yr &= P\ (\$35{,}000,\ 10\%,\ 20yr) + \$30{,}000 \\ &= (\$35{,}000 \times .1175) + \$30{,}000 \\ &= \$34{,}112.50/yr \end{aligned}$$

A reuse pond, having comparable land use requirements to a wet detention pond, will save significant money in water costs.

Different water restrictions generally apply to operators of stormwater reuse systems. Most of the water used would come from the storage of stormwater runoff. It is not the intention to encourage the abuse of unregulated watering. Responsible practices should be maintained with any watering system.

Iron and other minerals contained in groundwater will have an opportunity to oxidize and settle in the reuse pond before being distributed by the reuse system. Traditional groundwater irrigation systems may cause rust stains on walls and sidewalks, thus causing an economic impact.

Objective

The objective of this report is to provide a means for the rational design of reuse ponds by producing, using site specific rainfall conditions, relationships between the reuse volume of a pond, the rate at which this stored runoff is reused, and the percentage of runoff that is reused. This is accomplished by generating a long term mass balance of a stormwater reuse pond which considers the stochastic nature of rainfall. Hydrologic parameters include rainfall, runoff volumes, groundwater interactions, and evapotranspiration. Pond design and operation parameters include the rate of reuse, reuse volume, discharge volumes, and control structures. The report is limited to geographic regions within the State of Florida for which long term continuous and accurate rainfall data exist.

CHAPTER 2

THEORY AND BACKGROUND

The Rainfall-Runoff Process

Upon receiving rainfall, a watershed will produce some degree of runoff. Development typically increases the amount of runoff due to an increase in impervious areas that are directly connected to the point of discharge of the watershed. Stormwater systems are constructed to control the amount of runoff and the rate at which runoff is discharged from the watershed. When designing a system to collect, transport, and treat stormwater, the runoff characteristics of the watershed must be determined. The runoff coefficient, designated C, is a most basic parameter for runoff. It is equal to the fraction of rainfall that flows overland to a discharge point, becoming runoff (Wanielista, 1990b).

$$C = \frac{R}{P} \tag{1}$$

where C = runoff coefficient
R = rainfall excess or runoff volume
P = rainfall volume

The runoff coefficient for a watershed varies depending on the quantity and rate of rainfall, the extent of pervious area, the water storage potential of the soil, the permeability and antecedent moisture conditions of the soil, and the degree to which runoff corridors are linked.

When designing stormwater systems, the runoff coefficient must be determined for a specific rainfall event and antecedent conditions. Impervious areas that are directly connected to the point of discharge will contribute almost all of the rainfall that falls on it. For design purposes, the runoff coefficient for impervious areas is generally assumed to be one. Pervious areas may or may not contribute runoff, in which case the runoff coefficient may range from zero for soils with high permeability and low saturation to near one for soils with low permeability and high saturation.

The overall runoff coefficient for an area composed of different surfaces can be determined by weighting the runoff coefficients with respect to the total areas they encompass.

$$C = \frac{C_1\,A_1 + C_2\,A_2 + \cdots + C_N\,A_N}{A_1 + A_2 + \cdots + A_N} \qquad \textbf{(2)}$$

where C_N = runoff coefficient for surface N
A_N = area of surface N

This value is termed the effective runoff coefficient of the watershed and is representative for the entire watershed.

The Equivalent Impervious Area

The equivalent impervious area (EIA) is equal to the product of the total area of the watershed and the effective, or weighted, runoff coefficient for the watershed.

$$EIA = C \times A \qquad (3)$$

This equation is used throughout this report. The area of the EIA is equal to the area of a completely impervious watershed that would produce the same volume of runoff as the actual watershed. As an example, a 20 acre watershed with an effective runoff coefficient of 0.50 would have an EIA of 10 acres. If one inch of rain fell on this 10 acre impervious area, the runoff volume would be 10 ac-in (10 ac x 1 in). If the same amount of rain fell on the actual watershed the runoff volume would not change (20 ac x 1 in x 0.50 = 10 ac-in). The EIA will be expressed in acres throughout this report. The use of the EIA serves to generalize the model so that it can be applied to a watershed of any size and runoff characteristics.

Calculation of EIA

Directly Connected Impervious Area (DCIA) Only

For watersheds in which all runoff is from directly connected impervious areas, the EIA is simply equal to the DCIA. The EIA is calculated as

$$EIA = DCIA = CA \qquad (4)$$

when there is no contribution from other areas. The term CA is commonly called the contributing area and is referenced in hydrology literature (Mulvaney, 1851; Wanielista, 1990c).

DCIA Plus Pervious Area

The runoff from the pervious areas can be calculated using one of following techniques. The effective runoff coefficient can then be calculated using Equation 2.

Rainfall Excess

Soil Conservation Service (SCS) Curve Number

The United States Soil Conservation Service compiles and publishes data concerning the hydrologic characteristics of soils. This information, combined with on-site observations can be used to obtain a measure of the water storing capacity of the soil called the curve number (CN). The curve number ranges from 0 (no runoff) to 100 (complete runoff). The maximum storage of the soil, S′, is related to the curve number by the following equation (Kent, 1973):

$$S' = \frac{1000}{CN} - 10 \qquad \textbf{(5)}$$

where S′ = maximum storage (inches).

The rainfall excess can then be calculated using

$$R_p = \frac{(P - 0.2S')^2}{(P + 0.8S')} \qquad if\ P > 0.2S' \qquad \textbf{(6)}$$

and

$$R_p = 0 \qquad if\ P \leq 0.2S' \qquad \textbf{(7)}$$

where P = rainfall (inches).

Horton Equation

The potential infiltration rate of a soil over time can be approximated by an exponential curve. A description of the curve can be developed from a double ring infiltrometer test. The Horton equation can be used to find the volume of infiltrate (Horton, 1940).

$$F = \int_0^t f(t) = f_c t + \frac{(f_0 - f_c)}{K}(1 - e^{-Kt}) \qquad (8)$$

where F = volume of infiltrate (in)
$f(t)$ = infiltration rate (in/hr)
f_c = ultimate infiltration rate (in/hr)
f_0 = initial infiltration rate (in/hr)
K = recession constant (1/hr)
t = time (hr)

The rainfall excess is equal to the rainfall minus the infiltrate.

$$R_P = P - F \qquad (9)$$

After the rainfall excess for the pervious area is computed by either method, the runoff coefficient for the pervious area can then be calculated as:

$$C_P = \frac{R_P}{P} \qquad (10)$$

Equations 2 and 3 can then be used to calculate the effective runoff coefficient and the EIA, respectively.

Wet Detention Pond Design

Chapter 17-25 of the Florida Administrative Code (F.A.C.), the State Stormwater Rule, was established in 1982 to facilitate responsible management practices concerning the water resources within the State. Similar rules were later adopted by the State's Water Management Districts. These guidelines include articles stipulating that the post-development peak discharge rate and volume of direct runoff must not exceed the pre-development peak rate and volume, that the first flush of runoff which contains the highest concentrations of pollutants must be collected, and a minimum residence time must be provided for the allowance of adequate chemical and biological treatment to occur. Wet detention, which serves to attenuate hydrograph peaks and to reduce discharge volumes through the temporary storage and removal of runoff, is presumed to reasonably meet these guidelines if the following design criteria are observed (Wilkening, 1990):

1. Permanent pool volume must provide a minimum residence time of 14 days. A more empirical approach sometimes used is calculated by taking 2 inches times the impervious area plus 1/2 inch times the pervious area.
2. Wet detention (temporary storage) of the first inch of runoff or 2.5 inches times the percent impervious, whichever is greater. No more than half of this volume should be discharged in the first 60 hours following a storm event.
3. The temporary storage volume should normally be no greater than 18 inches in depth.
4. Additional treatment will be needed for commercial and industrial development and for discharges to Class I, II, and Outstanding Florida Waters (OFW) receiving waters.
5. The control elevation should be set at or

above both the on-site wet season water table and the off-site tailwater elevation. An overflow weir should effectively pass the design storm flood events (25 year - 24 hour).

6. Pond depth should not exceed 12 feet, including the sediment storage depth.

The temporary storage of a reuse pond may be calculated using alternative methods while all other criteria remain the same.

Irrigation Ponds in Florida

From a survey of members of the Florida Irrigation Society, at least 40 sites were identified within the State. Ten of the 40 sites service golf courses, eight were built for commercial development, two provide water for a cemetery, and the others operate in apartment and multi-family developments. None of the pond volumes or irrigation rates were designed considering long-term historical rainfall and other hydrologic data. Essentially, the volumes were either fit to an area or some rough calculations were done using a design storm, ie., the runoff from 4 inches of rainfall. Also, many ponds have been constructed to provide water for agricultural uses.

Design Methods

The Design Storm

Historically, the sizing of detention ponds has been based on the concept of a design storm, a storm of particular volume that is associated with a specific recurrence interval and duration. The volumes vary with geographic location and are presented in Frequency-Intensity-Duration curves. A designed system is expected to fail only when a storm of greater magnitude occurs. For instance, a pond volume might be designed using the 25 year - 6 hour storm event which is equivalent to 6 inches of rainfall over a 6 hour period for Orlando. Ideally, the pond will properly function during this and any smaller storm and will fail on the average of once every 25 years.

The certainty and completeness of using the design storm is being increasingly questioned (James, 1982). A major shortcoming is that the antecedent conditions of the pond, specifically the level of water in the pond at the time of the design storm event, is not considered.

Alternative: Continuous Modeling

Increasing value is being placed on long-term continuous modeling. A continuous model of a reuse pond would use the complete rainfall record of a specific region and simulate the pond's reaction to this and other variables. The time distribution of storm events is known so that both the antecedent conditions and inter-event dry periods, which are being stressed by Wanielista (1990d), are addressed. The cumulative effects of more frequently occurring storms are also considered. Thus with inexpensive but fast microcomputers, complex simulations are both time and cost effective. The results of the continuous model can be used to develop design criteria that meet discharge regulations.

CHAPTER 3

SIMULATION OF A REUSE POND

In order to establish a relationship between the efficiency, the reuse rate, and the reuse volume of a pond, the model used in this research simulates the dynamics of a reuse pond over a period of time. The efficiency of the pond, or percentage of runoff that is reused, was calculated as the reuse volume and reuse rate were varied. The results of this routine were used to create design charts. Charts for different regions were produced by utilizing the local rainfall records of these regions. This chapter includes a description of a reuse pond and of the model that simulates this pond. To be consistent, the term "model" is used to refer to the unchanged skeleton of equations of the mass balance in which different rainfall records were inserted and reuse volumes and reuse rates were varied. "Simulation" is used to refer to one calculation of the model in which there was a defined volume and rate. There is only one model while many simulations were done.

The Structure of a Reuse Pond

Figure 1-1 is the cross-section of a typical reuse pond. The sediment storage volume lies at the bottom to receive settled matter. Above this is the permanent pool volume, which provides a minimum residence time for stormwater. The reuse volume (temporary storage volume), is the volume above the permanent pool and below the flood control structure. The flood control volume includes the reuse volume and is that volume which lies above the permanent pool. The flood volume may exceed the reuse volume, at which time discharge would occur.

The reuse pond differs from a typical detention pond in that instead of the temporary storage volume being depleted by a discharge device (such as a bleed down orifice in an outlet pipe) it is drawn down by a reuse system and is thus called the reuse volume. A bleed down orifice does not deplete the permanent pool because it lies at the top of this layer. A reuse system, however, would continue to deplete the pond volume below the permanent pool boundary, thereby requiring a supplemental component to maintain this volume. A discharge structure is still necessary for flood control. Common practice should be used for the design of sediment storage, permanent pool, and flood control volumes, and their elevations and side slopes. This research provides design criteria for the reuse volume only.

The Behavior of a Reuse Pond

The response of a typical reuse pond to a rainfall event may be summarized. During and following a rainfall event, there is runoff into the pond and the water level rises to some depth above the permanent pool. If this new water level exceeds the level of the surface discharge control, there will be discharge at some rate until the water level drops back below the control structure. The reuse system is incrementally (daily) removing an amount of water from the reuse volume. If the reuse volume is expended, supplemental water, such as groundwater, is used to maintain the permanent pool volume. This could occur as seepage through the sides of the pond or by mechanical pumping using a controller. This scenario was simulated by creating a mass balance, monitoring the inputs and outputs, adding decision statements, and recognizing assumptions.

The Model

The model is based on the continuity equation:

$$INPUTS - OUTPUTS = \Delta S \qquad \textbf{(11)}$$

By considering all potential water movements, a complete hydrologic balance may be expressed in volume units as

$$R_E + G + P \pm F - R - D - ET = \Delta S \qquad \textbf{(12)}$$

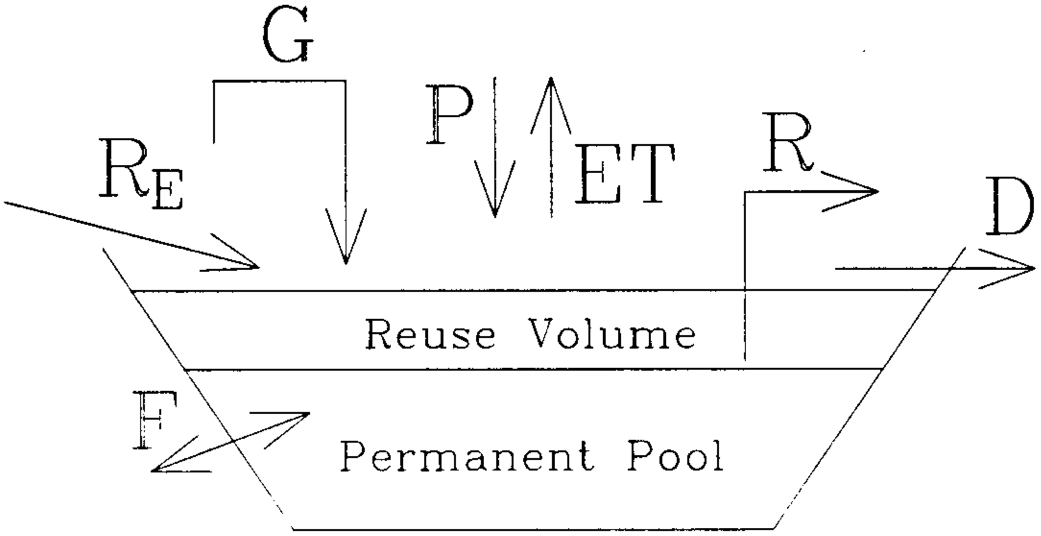
where R_E = rainfall excess or runoff volume
G = supplemental water (groundwater)
P = precipitation directly on the pond
F = water movement through the sides of the pond
R = reuse
D = discharge
ET = evapotranspiration
S = storage in pond

The average evapotranspiration rate for a pond is generally equal to the average precipitation on the pond (approximately 50 inches in Florida). Additionally, evaporation data are only available in mean monthly rates compared to the daily time step of the model making the estimate of evaporation potentially inaccurate. These parameters were dropped from the mass balance. Also, because of its complexity, the flow of groundwater through the sides of the pond was assumed to equal zero, and Equation 12 was further simplified to

$$R_E + G - R - D = \Delta S \qquad (13)$$

Assumptions have been made regarding variables that are not easily quantified. These assumptions are addressed in the chapter on sensitivity analysis and the conclusion.

For modeling purposes, there were two inputs, runoff and supplement, and two outputs, reuse and discharge (Figure 3-1). Runoff was established from known precipitation and watershed data. The reuse rate was a controlled variable. Both supplemental water and discharge were functions of the water level of the pond, or the storage volume. Since groundwater movement was assumed to equal zero, supplemental water will be considered as that which is pumped into the pond mechanically. Supplement will occur at a rate which is necessary to maintain the permanent pool; the maximum required rate would equal that of reuse. Because potential storage capacity is being constantly eliminated by supplement, this may be considered as being conservative. With the previous simplifications, the actual pond may be simulated by the model.



$$R_E + G + \cancel{P} \pm \cancel{F} - R - D - \cancel{ET} = \Delta S$$

$$R_E + G - R - D = \Delta S$$

Figure 3-1. Summary of Mass Balance of Reuse Pond.

The reuse model was generated using Quattro Pro, an electronic spreadsheet. The top and bottom sections of one model simulation can be seen in Figure 3-2. The columns of the upper portion of the model are the incremental registers of the various parameters, which are labeled along the top. The equations for each cell are listed in Appendix A. Each of these variables is defined as follows:

EVENT	a distinct rainfall occurrence; for computational purposes, each day of a multi-day rainstorm is considered a separate event.
DATE	the date on which an event occurs.
DRY	the dry period separating rainfall events (days); if events occur on consecutive days there are no dry days. This value is not used in the basic model but is needed for the sensitivity analysis of the discharge potential.
RAIN	the amount of rainfall recorded during each event (inches). This information was taken directly from NOAA rainfall data and will be discussed further in detail.
RUNOFF	the amount of runoff that enters the pond during an event (inches).
REUSE	the amount of water reused during the day of an event and the dry days following the previous event (inches); the rate of reuse remains constant during a single simulation.
DISCHARGE	
Poten.	the potential amount of discharge for an event (inches); the amount which could, if necessary, physically discharge during the time since the previous event. This was established as 2 inches per day over the EIA.
Actual	the amount that DOES discharge during an event (inches); depends on the water level of the pond but is restricted to the potential discharge.

```
ORLANDO RAINFALL STATION (May 1974 - Dec. 1988) Volume = 3 in, Rate = 0.2 in/day

EVENT    DATE      DRY    RAIN    RUNOFF   REUSE      DISCHARGE     SUPLMNT    NET
                   Days   In.     In.      In.     Poten.Actual     In.      In.
-------------------------------------------------------------------------------------
    0  04-May-74                                                              0
    1  05-May-74    0     0.12    0.12     0.2       2       0      0.08     0.00
    2  06-May-74    0     0.77    0.77     0.2       2       0      0.00     0.57
    3  07-May-74    0     0.04    0.04     0.2       2       0     -0.00     0.41
    4  08-May-74    3     0.33    0.33     0.2       2       0      0.00     0.54
    5  12-May-74    1     0.15    0.15     0.8       8       0      0.11     0.00
    6  14-May-74    0     0.11    0.11     0.4       4       0      0.29     0.00
    7  15-May-74    0     0.46    0.46     0.2       2       0      0.00     0.26
    8  16-May-74    0     0.07    0.07     0.2       2       0      0.00     0.13
    9  17-May-74    5     0.23    0.23     0.2       2       0      0.00     0.16
   10  23-May-74    3     0.35    0.35     1.2      12       0      0.69     0.00
   11  27-May-74    4     0.06    0.06     0.8       8       0      0.74     0.00
   12  01-Jun-74    0     1.19    1.19       1      10       0      0.00     0.19
   13  02-Jun-74    0     0.07    0.07     0.2       2       0      0.00     0.06
   14  03-Jun-74    6     0.05    0.05     0.2       2       0      0.09     0.00
   15  10-Jun-74    0     2.19    2.19     1.4      14       0      0.00     0.79
   16  11-Jun-74    2     0.18    0.18     0.2       2       0      0.00     0.77
   17  14-Jun-74    0     0.05    0.05     0.6       6       0     -0.00     0.22
   18  15-Jun-74    1     0.54    0.54     0.2       2       0      0.00     0.56
   19  17-Jun-74    6     0.09    0.09     0.4       4       0      0.00     0.25
   20  24-Jun-74    0     0.95    0.95     1.4      14       0      0.20     0.00
   21  25-Jun-74    0     1.07    1.07     0.2       2       0      0.00     0.87
   22  26-Jun-74    0     3.47    3.47     0.2       2       0      0.00     4.14
   23  27-Jun-74    0     1.89    1.89     0.2       2    1.14     -0.00     4.69
   24  28-Jun-74    1     3.36    3.36     0.2       2    1.69      0.00     6.16
   25  30-Jun-74    0     0.17    0.17     0.4       4    3.16      0.00     2.77
   26  01-Jul-74    0     0.12    0.12     0.2       2       0     -0.00     2.69
   27  02-Jul-74    0     0.88    0.88     0.2       2       0      0.00     3.37

 1386  23-Dec-88    4     0.04    0.04     1.4      14       0      1.36     0.00
 1387  28-Dec-88          0.05    0.05       1      10       0      0.95     0.00
                       ---------------------------------------------
         Summation:      706.88  706.88  1070.40           75.72   439.24

      % Discharged =    Total Discharge/Total Runoff =          10.71%
          % Reused =    1 - Total Discharge/Total Runoff =      89.29%

      Inputs:
        Runoff:                 706.88 in.          Inputs          1146.12 in.
        Supplement:             439.24 in.        - Outputs        -1146.12 in.
                              ----------------    ---------------------------------
                               1146.12 in.          Storage            0.00 in.
      Outputs:
        Reuse:                 1070.40 in.
        Discharge:               75.72 in.
                              ----------------
                               1146.12 in.
```

Figure 3-2. Example of Computer Model using Rainfall Data from Orlando, FL.

SUPLMNT	the amount of water needed between events to maintain the permanent pool volume (inches).
NET	the amount of water above the permanent pool recorded at the end of each event (inches).

Every day in which a rainfall event takes place represents one line in the simulation. This is the fundamental time step of the model. All inputs and outputs occur during this 24 hour period. At the end of the period the net storage value of the pond is calculated. From this value, decisions are made concerning discharge and supplement. The process then repeats itself.

The fifteen year totals for rain, runoff, reuse, actual discharge, and supplement are calculated in Figure 3-2. From these values, the efficiency, or the percentage of runoff reused, can be determined for a particular simulation. The efficiency is equal to one minus the volume of water that is discharged divided by the volume of runoff times 100. The percent discharged, the volume of water discharged divided by the volume of runoff, is also calculated. The percent reused plus the percent discharged equals 100.

At the bottom of Figure 3-2 is a summary of the mass balance for the entire record. Both the inputs and outputs are listed and totaled. The difference between the inputs and outputs, labeled storage, is compared to the final value for NET. The values should be identical. This is used primarily to check the calculations.

This single model was used to predict the behavior of a reuse pond subjected to the rainfall record of 25 different locations around the state of Florida. To simulate a pond in a particular region, the rainfall record of that region was inserted into the DATE and RAIN columns of the model. The model was then lengthened or shortened to match the span of the rainfall record. Otherwise, no changes were made to the model. By using one model and varying only the rainfall record, the consistency of the simulations was assured.

Length of Rainfall Record

An investigative question when examining the random behavior of rainfall is how large a record must be to accurately represent the meteorological characteristics of a region. In other words, how many years of rainfall data must be used to estimate the ultimate dynamics of the pond? Obviously, the greatest accuracy can be obtained by using the most data. But the incremental benefit of each additional unit of data diminishes so that there is a point beyond which it is no longer reasonable to use more. This is the limit for investigation.

Twenty-four individual simulations were run for the Moore Haven and Tallahassee stations using, first, one year of rainfall data (1988) and then incrementally adding the next previous year to the rainfall record. The efficiencies for several combinations of reuse volumes and reuse rates were monitored and then plotted with respect to the number of years of data (Figure 3-3). As can be seen, different volume/rate combinations for each location follow the same general trend. Therefore, two combinations are sufficient to represent each rainfall station.

The combinations plotted are a reuse volume of 1.0 inch over the EIA with a reuse rate of 0.16 inches per day over the EIA and a volume of 2.0 inches over the EIA with a rate of 0.08 inches per day over the EIA. As expected, initially the efficiencies fluctuated widely but then leveled out as more years of data were added. As the size of the database increased, each additional year had less impact.

The trends seem to reach a fairly constant efficiency at about a fifteen year record. This may be somewhat subjective, however, the change in efficiencies between fifteen and twenty four years (the maximum used) is not significant, and the percent difference for the trends shown range between less than 0.3% and 2.1%.

Volume Units

The runoff, discharge, reuse, supplement, and net storage are volumes of water that are expressed in units of inches. Volumes are commonly expressed as inches over a defined area and, likewise, the parameters of this model are based on a variable unit area which the user defines. Rates are merely volumes delivered over a period of time and thus can be

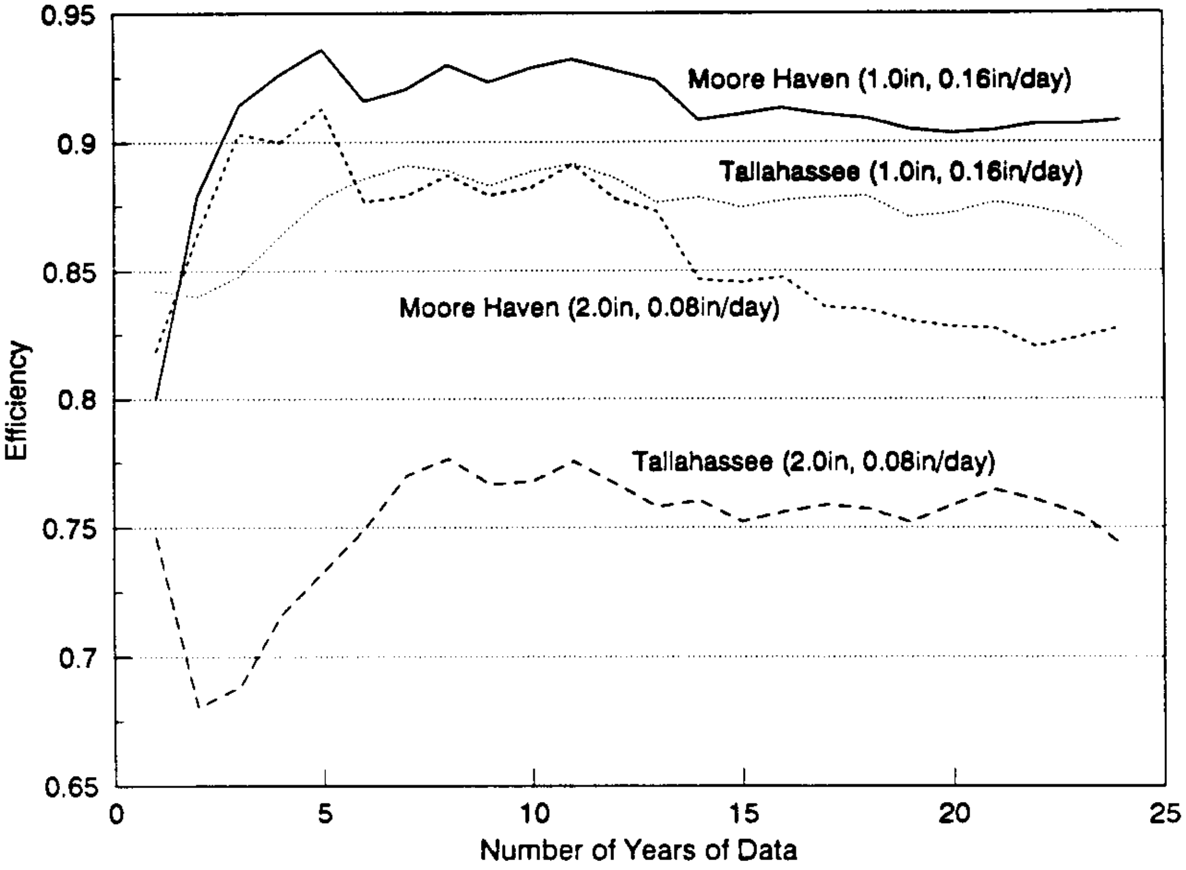


Figure 3-3. The Efficiencies of two Combinations of Volume and Rate as a Function of the Number of Years of the Rainfall Data for two Regions.

expressed in the same manner. This unit area is the equivalent impervious area of the watershed as explained in Chapter 2. The volumetric unit of inches on the EIA is a way in which the charts are generalized for any runoff coefficient and contributing area. Once the EIA is known, the values can be converted to more practical units using simple conversions.

Example Execution of Model

A step-by-step explanation of the first two lines of the simulation (Figure 2-3) will increase the understanding of the model. As the heading points out, this particular simulation used rainfall data from the Orlando rainfall station, the reuse volume was 3 inches on the EIA, and the reuse rate was 0.2 inches per day on the EIA. These values remained constant throughout this simulation but were changed for other simulations. It is assumed, for computational purposes, that a fictional rainfall event, Event 0, with zero volume occurred on the day before the first event. The first line shows that Event 0 occurred on May 4, 1974 and the initial net storage volume above the permanent pool was zero. Since the simulation spans a 15 year period, any reasonable number for initial net storage will not alter the results.

Event 1 occurred on May 5, 1974. The number of dry days between Event 0 and Event 1 was zero. Event 1 was 0.12 inches of rainfall. The runoff resulting from this event was 0.12 inches on the EIA. Because this unit area (EIA) is completely impervious, the runoff will always equal the rainfall. This is one of the simplifications of basing the mass balance on the EIA. The volume of reuse was 0.2 inches on the EIA and was equal to the product of the reuse rate (0.2 in/day) and the number of days since the last event (1 day). The daily potential discharge is the maximum amount of water that can be released and is based on the 25 year, 24 hour storm volume. The storm volume is about 8-10 inches and must be removed in about 5 days or at a rate of 2 inches per day. The potential discharge for Event 1 was 2 inches on the EIA. Actual discharge will have occurred only if the net storage value from the previous period was greater than the reuse volume, which for this simulation was 3 inches on the EIA. Since the net value was zero, there was no need to discharge water from the pond; the actual discharge was zero.

If the net storage were to be calculated at this point it would be -0.08 inches on the EIA.

Event 0 Net	0.00
+ *Runoff*	+0.12
- *Reuse*	-0.20
-*Discharge*	-0.00
Event 1 Net	-0.08

Because the reuse system is not supposed to draw from the permanent pool, supplemental water must be mechanically added to maintain the permanent pool volume (to raise the net storage value from a negative value to zero). Therefore, the supplement for Event 1 was 0.08 inches on the EIA. The mass balance for Event 1 now looks like this:

Event 0 Net	0.00
+ Runoff	+0.12
- Reuse	-0.20
-Discharge	-0.00
+Supplement	+0.08
Event 1 Net	0.00

As shown, the net storage for Event 1 was zero.

An explanation of Event 25 might also be helpful. The event took place on June 30, 1974 and was 0.17 inches of rainfall which produced 0.17 inches on the EIA of runoff to flow into the pond. The reuse volume was 0.4 inches on the EIA because there were two days of reuse, June 29 and June 30. Likewise, the potential discharge was 4 inches on the EIA. The actual discharge was determined from the previous net storage (6.16 inches). This exceeded the reuse volume (3 inches) and, if possible, the pond would have discharged 3.16 inches. This value did not exceed the potential, therefore the actual discharge was 3.16 inches on the EIA. Since the net storage at this point was still positive (2.77 inches) there was no need for supplement.

Model Output

The basic function of the model was to determine a relationship between the reuse rate, the reuse volume, and the efficiency. This was done by varying the reuse rate and the reuse volume and then calculating the efficiency. Thus, a simulation was done for each combination of reuse rate and reuse volume. Quattro Pro contains a routine which automatically varies two parameters within a spreadsheet and creates a table for the selected output parameter. The output table for Orlando is Figure 3-4. The reuse volumes are the top row and vary between 0.25 and 7.0 inches on the EIA. The reuse rate, which varies between 0.04 and 0.30 inches per day on the EIA, are the left column. The respective efficiencies are shown as fractions. From this table, the Orlando **REV** chart was produced.

Rainfall Data

Historical rainfall records are an important part of this research. The developed design charts are the product of the manipulation of these data. While the structure and dynamics of the pond model remained constant, rainfall records from each location were, in turn, placed within the model. Therefore, each design chart owes its individuality to the rainfall behavior that is specific to the particular region it represents. Because of the importance of the role of rainfall in this research, this section is devoted to the explanation of its usage.

The source of rainfall data was the database of the National Climatic Data Center (NCDC). The National Oceanic and Atmospheric Association (NOAA) collects and compiles meteorological information at approximately 50 locations throughout the state of Florida. The data are distributed in

```
ORLANDO RAINFALL STATION (May 1974 - Dec. 1988)  --  Original Model


      | 0.25  0.5 0.75    1  1.5    2  2.5    3  3.5    4  4.5    5  5.5    6  6.5    7
------| -------------------------------------------------------------------------------
 0.04 | 0.25 0.27 0.29 0.29 0.30 0.30 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31 0.31
0.045 | 0.28 0.30 0.31 0.32 0.33 0.34 0.34 0.34 0.34 0.35 0.35 0.35 0.35 0.35 0.35 0.35
 0.05 | 0.30 0.32 0.34 0.35 0.36 0.37 0.38 0.38 0.38 0.38 0.38 0.38 0.39 0.39 0.39 0.39
0.055 | 0.32 0.34 0.36 0.37 0.39 0.40 0.41 0.41 0.42 0.42 0.42 0.42 0.42 0.42 0.42 0.43
 0.06 | 0.34 0.36 0.38 0.40 0.42 0.43 0.44 0.45 0.45 0.45 0.46 0.46 0.46 0.46 0.46 0.46
0.065 | 0.35 0.38 0.40 0.42 0.44 0.46 0.47 0.48 0.48 0.49 0.49 0.49 0.50 0.50 0.50 0.50
 0.07 | 0.37 0.40 0.42 0.44 0.47 0.48 0.49 0.50 0.51 0.52 0.52 0.52 0.53 0.53 0.53 0.54
0.075 | 0.39 0.42 0.44 0.46 0.49 0.50 0.52 0.53 0.54 0.54 0.55 0.56 0.56 0.56 0.57 0.57
 0.08 | 0.40 0.44 0.46 0.48 0.51 0.53 0.54 0.55 0.56 0.57 0.58 0.58 0.59 0.60 0.60 0.60
0.085 | 0.41 0.45 0.48 0.50 0.53 0.55 0.56 0.58 0.59 0.60 0.60 0.61 0.62 0.62 0.63 0.63
 0.09 | 0.43 0.47 0.50 0.52 0.54 0.57 0.58 0.60 0.61 0.62 0.63 0.64 0.64 0.65 0.66 0.66
0.095 | 0.44 0.48 0.51 0.53 0.56 0.59 0.60 0.62 0.63 0.65 0.65 0.66 0.67 0.68 0.69 0.69
  0.1 | 0.45 0.50 0.53 0.55 0.58 0.60 0.62 0.64 0.65 0.67 0.68 0.69 0.70 0.70 0.71 0.72
0.105 | 0.47 0.51 0.54 0.57 0.60 0.62 0.64 0.66 0.67 0.69 0.70 0.71 0.72 0.73 0.74 0.75
 0.11 | 0.48 0.52 0.56 0.58 0.61 0.64 0.66 0.68 0.69 0.71 0.72 0.73 0.74 0.75 0.76 0.77
0.115 | 0.49 0.54 0.57 0.60 0.63 0.65 0.67 0.69 0.71 0.72 0.74 0.75 0.76 0.77 0.78 0.79
 0.12 | 0.50 0.55 0.58 0.61 0.64 0.67 0.69 0.71 0.73 0.74 0.75 0.77 0.78 0.79 0.80 0.81
0.125 | 0.51 0.56 0.60 0.62 0.66 0.69 0.71 0.72 0.74 0.76 0.77 0.78 0.79 0.81 0.82 0.83
 0.13 | 0.52 0.57 0.61 0.64 0.67 0.70 0.72 0.74 0.76 0.77 0.79 0.80 0.81 0.82 0.83 0.84
0.135 | 0.53 0.58 0.62 0.65 0.69 0.72 0.74 0.75 0.77 0.79 0.80 0.81 0.82 0.83 0.85 0.86
 0.14 | 0.53 0.59 0.63 0.66 0.70 0.73 0.75 0.77 0.79 0.80 0.81 0.83 0.84 0.85 0.86 0.87
0.145 | 0.54 0.60 0.64 0.67 0.71 0.74 0.76 0.78 0.80 0.81 0.83 0.84 0.85 0.86 0.87 0.88
 0.15 | 0.55 0.61 0.65 0.68 0.73 0.76 0.78 0.80 0.81 0.83 0.84 0.85 0.86 0.87 0.88 0.89
0.155 | 0.56 0.62 0.66 0.69 0.74 0.77 0.79 0.81 0.83 0.84 0.85 0.86 0.88 0.89 0.90 0.91
 0.16 | 0.57 0.62 0.67 0.70 0.75 0.78 0.80 0.82 0.84 0.85 0.86 0.88 0.89 0.90 0.91 0.92
0.165 | 0.57 0.63 0.67 0.71 0.76 0.79 0.81 0.83 0.85 0.86 0.87 0.89 0.90 0.91 0.92 0.92
 0.17 | 0.58 0.64 0.68 0.72 0.77 0.80 0.82 0.84 0.86 0.87 0.89 0.90 0.91 0.91 0.92 0.93
0.175 | 0.59 0.65 0.69 0.72 0.77 0.81 0.83 0.85 0.87 0.88 0.89 0.90 0.91 0.92 0.93 0.94
 0.18 | 0.60 0.66 0.70 0.73 0.78 0.82 0.84 0.86 0.88 0.89 0.90 0.91 0.92 0.93 0.94 0.95
0.185 | 0.60 0.66 0.71 0.74 0.79 0.82 0.85 0.87 0.89 0.90 0.91 0.92 0.93 0.94 0.95 0.95
 0.19 | 0.61 0.67 0.71 0.75 0.80 0.83 0.86 0.88 0.90 0.91 0.92 0.93 0.94 0.95 0.95 0.96
0.195 | 0.62 0.68 0.72 0.75 0.80 0.84 0.86 0.89 0.90 0.92 0.93 0.94 0.94 0.95 0.96 0.97
  0.2 | 0.62 0.68 0.73 0.76 0.81 0.85 0.87 0.89 0.91 0.92 0.93 0.94 0.95 0.96 0.97 0.97
        -------------------------data intentionally left out-------------------------
 0.25 | 0.68 0.73 0.77 0.81 0.86 0.90 0.92 0.94 0.96 0.97 0.98 0.98 0.99 0.99 0.99 1.00
0.255 | 0.68 0.74 0.78 0.81 0.86 0.90 0.93 0.95 0.96 0.97 0.98 0.98 0.99 0.99 1.00 1.00
 0.26 | 0.68 0.74 0.78 0.82 0.87 0.90 0.93 0.95 0.97 0.97 0.98 0.98 0.99 0.99 1.00 1.00
0.265 | 0.69 0.74 0.79 0.82 0.87 0.91 0.93 0.95 0.97 0.98 0.98 0.99 0.99 0.99 1.00 1.00
 0.27 | 0.69 0.75 0.79 0.82 0.87 0.91 0.94 0.96 0.97 0.98 0.98 0.99 0.99 1.00 1.00 1.00
0.275 | 0.70 0.75 0.79 0.83 0.88 0.91 0.94 0.96 0.97 0.98 0.98 0.99 0.99 1.00 1.00 1.00
 0.28 | 0.70 0.76 0.80 0.83 0.88 0.92 0.94 0.96 0.97 0.98 0.99 0.99 0.99 1.00 1.00 1.00
0.285 | 0.70 0.76 0.80 0.83 0.88 0.92 0.94 0.96 0.97 0.98 0.99 0.99 0.99 1.00 1.00 1.00
 0.29 | 0.71 0.76 0.80 0.84 0.88 0.92 0.95 0.96 0.98 0.98 0.99 0.99 0.99 1.00 1.00 1.00
0.295 | 0.71 0.77 0.81 0.84 0.89 0.92 0.95 0.97 0.98 0.98 0.99 0.99 0.99 1.00 1.00 1.00
  0.3 | 0.72 0.77 0.81 0.84 0.89 0.92 0.95 0.97 0.98 0.98 0.99 0.99 1.00 1.00 1.00 1.00
```

Figure 3-4. Output Table: Efficiency as a Function of Reuse Rate (column) in inches/day on EIA and Reuse Volume (row) in inches on EIA.

a publication by NOAA and are maintained by the NCDC. The data were obtained in digital format on Compact Disc-ROM through a private company called EarthInfo, Inc. of Boulder, CO, in a package called ClimateData. This source includes the complete rainfall record, in hourly recordings, for all NOAA stations and processing/interaction software.

By using ClimateData, daily rainfall totals were transferred directly from the compact disc to a spreadsheet, eliminating mistakes associated with manual input. Of these daily totals, any value of less than 0.04 inches was deleted from the record. This is a common procedure which reflects the usual condition that small amounts of rainfall will not produce runoff and can be ignored. A listing of dates and respective rainfall totals were obtained for each station to be introduced into the model.

Rainfall data from Twenty-Five stations throughout the State of Florida were chosen for modeling and are listed in Table 3-1. They were selected on four qualities: the completeness of record, the length of record, the years associated with each record, and their location.

Almost all station records are, to some degree, incomplete due to power loss, mechanical failure, foreign objects blocking the collection drum, etc.. The completeness of record is represented by the percent coverage value offered by ClimateData which is equal to the number of days in which observations were reported divided by the number of all

Table 3-1. Listing of Rainfall Stations Used with Model and Rainfall Record Characteristics.

Station	Mean Annual Rainfall (inches)		Coverage Value (%)	Number of Event Days
	Model Record	Complete Record		
Apalachicola	55.59	54.42	97	1280
Belle Glade	37.93	47.57	96	1131
Daytona Beach	48.69	49.23	99	1365
Fort Myers	50.55	52.82	95	1251
Gainesville	43.23	52.32	92	1210
Grady	52.65	54.49	95	13.47
Homestead	53.49	58.60	93	1361
Inglis	49.43	50.00	96	1232
Jacksonville	48.85	51.95	97	1382
Key West	38.51	40.24	95	1188
Lakeland	49.58	48.94	98	1375
Lisbon	43.91	45.78	93	1288
Marineland	44.34	46.11	94	1196
Melbourne	40.82	46.15	94	1170
Miami	54.51	57.60	97	1619
Moore Haven	43.18	45.25	98	1220
Niceville	65.69	60.36	93	1443

Figure 3-1. Continued

Station	Mean Annual Rainfall (inches)		Coverage Value (%)	Number of Event Days
	Model Record	Complete Record		
NNR Canal 2	39.13	50.17	94	1095
Orange City	41.70	53.78	87	1142
Orlando	48.20	48.21	94	1387
Parrish	51.01	52.00	92	1352
Tallahassee	64.31	64.51	97	1438
Tampa	44.56	46.30	95	1292
Vero Beach	48.33	47.22	97	1357
West Palm Beach	61.51	60.91	99	1637

possible days of the record. Because the most recent rainfall record was desired, stations were selected that were presently operating. It was also necessary to have records of sufficient length. All of the stations have a 15 year record, extending from January 1974 through December 1988. The Orlando rainfall station started keeping records in May of 1974 and so has a slightly shorter record. The selected stations are well distributed and provide good geographic coverage of the State (see Figure 3-5). Also shown on Figure 3-5 are the NOAA Climatic Division Areas.

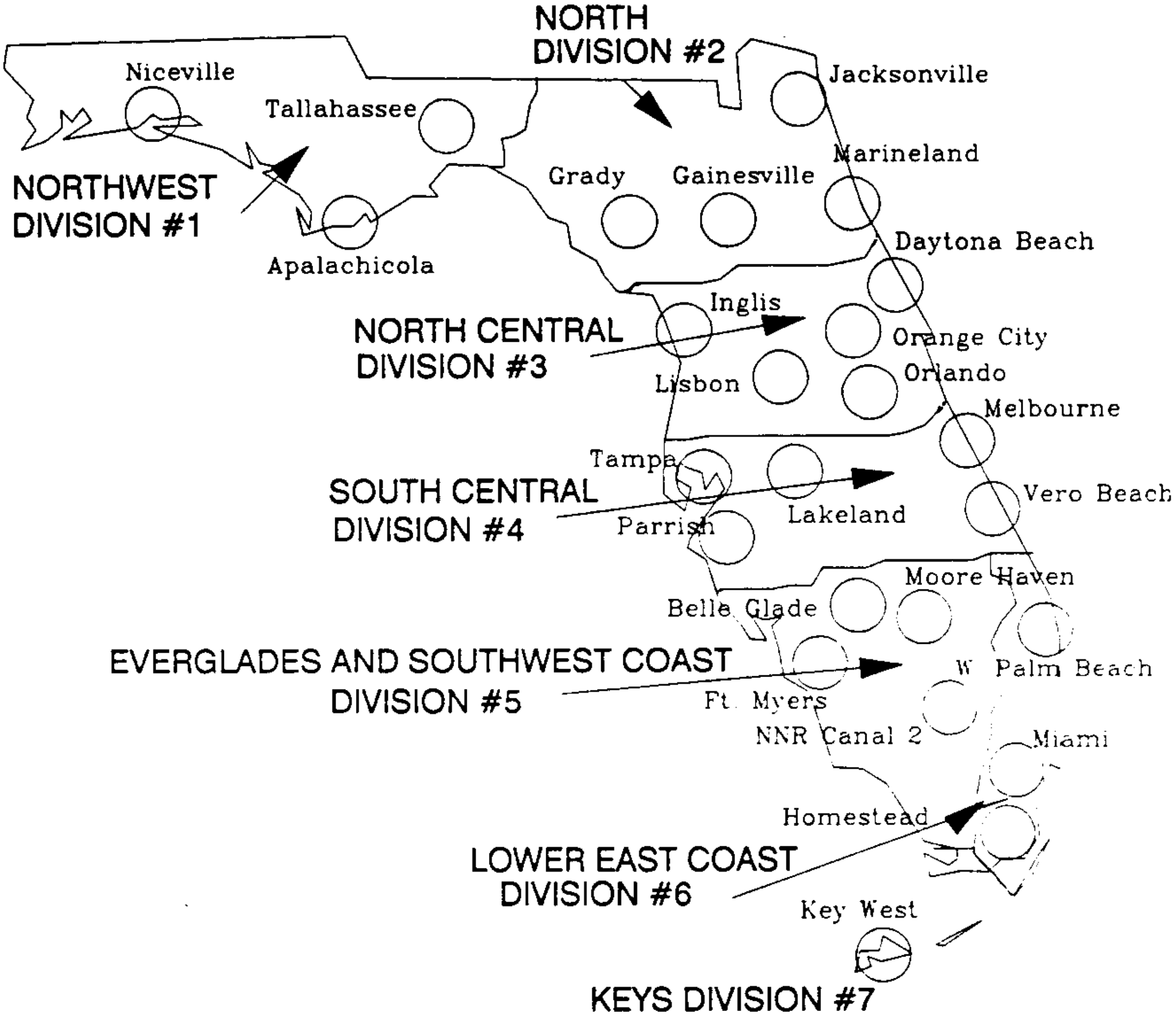


Figure 3-5. Geographic Distribution of Rainfall Stations with NOAA Defined Climatic Division Areas

CHAPTER 4

RESULTS

The ultimate functional product of the reuse pond model is the Rate-Efficiency-Volume (**REV**) chart. The **REV** chart for Orlando is Figure 4-1. Appendix B contains **REV** charts for each of the 25 locations used in this report. Individual **REV** charts are specific to geographical regions with similar meteorological characteristics. This chapter contains a description of the development of the **REV** charts from the model output, an explanation of the use of **REV** charts, and the introduction of several applications including examples.

The Development of REV Charts

The **REV** charts were derived directly from the output table produced by the spreadsheet model (Figure 3-4). The output table is a matrix of efficiency values generated by the model which correspond to respective reuse volumes (top row) and reuse rates (left column). The charts incorporate curves representing specific efficiency levels (95%, 90%, etc.). In order to plot these curves, multiple volume and rate coordinates for each efficiency level (each curve) must be determined. This was done by computing a reuse rate necessary to achieve each desired efficiency at each reuse volume.

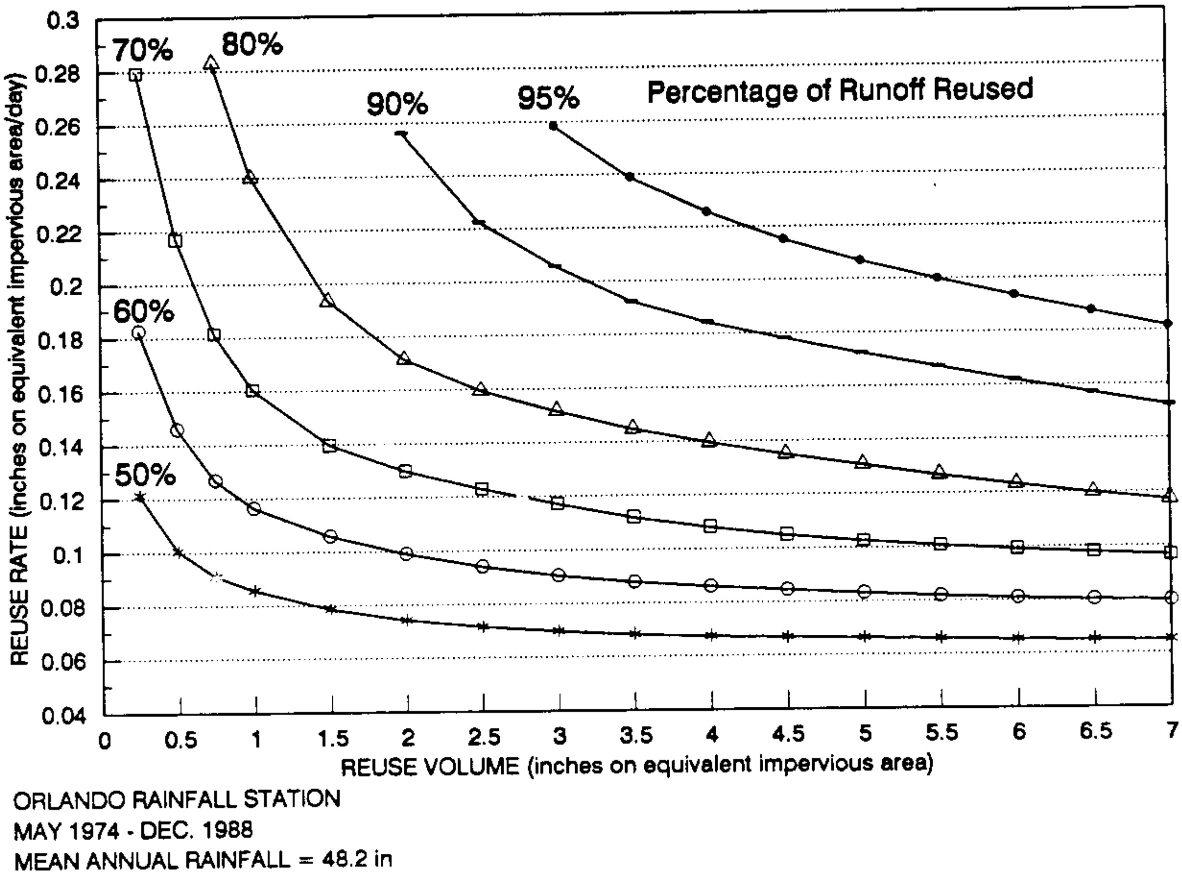


Figure 4-1. Rate-Efficiency-Volume (**REV**) Chart for Orlando, FL.

For instance, from Figure 4-1 it can be seen that the smallest reuse volume for which there are points on the chart is 0.25 inches on the EIA. From Figure 3-4, the first column of efficiency values, which corresponds to the 0.25 inch reuse volume, was used to determine the reuse rate values by which the 50, 60, and 70 percent efficiency lines were plotted. By moving down this first column it can be seen that the efficiency values of 0.4972 and 0.5069 correspond to reuse rates of 0.120 and 0.125 inches per day, respectively. By linear interpolation, the reuse rate corresponding to an efficiency of 0.500 can be calculated to be 0.1214 inches per day. Therefore, the left most point on the 50 percent efficiency curve is located at a reuse volume of 0.25 inches and a reuse rate of 0.1214 inches per day.

Note that the bottom number in the column is 0.7151, which implies that for a reuse volume of 0.25 inches, an efficiency of greater than 71.5% will exceed the reuse rate of 0.30 inches per day and therefore will not be shown on the chart. This agrees with the **REV** chart in which only the 50, 60, and 70 percent efficiency curves pass through the imaginary vertical line representing a volume of 0.25 inches on the EIA.

The process is repeated until all possible points are obtained. The range of these points, like the limits of the chart, are restricted by practical applicability. A reuse rate of greater than 0.30 inches per day on the EIA would require such huge quantities of supplement that the pond would act as no more than a large reservoir in the piping network of a groundwater irrigation system. And the cost of the land needed to store a volume exceeding 7.0 inches on the EIA would not be economical. In observance to the law of diminishing returns, the incremental benefits for increasing the rate or volume at either extreme is small.

Direct Use

REV charts relate the reuse rate, the efficiency, and the reuse volume of a pond. Information concerning any two of these three variables is necessary for the determination of the third.

The use of a **REV** chart requires an understanding of the concept of the EIA. The units of both the reuse rate and the reuse volume are based on this area. The EIA is discussed in Chapter 2 and can be determined by using Equation 3.

The efficiency is defined as the average percentage of runoff that is reused over a period of time, specifically 15 years. A pond that discharges to surface waters 10% of the runoff that flows into the pond must reuse the remaining and so is 90% efficient. It may be sometimes desirable to determine the efficiency of an existing pond. More often it will be necessary to achieve a required efficiency established by local regulations, thus making the efficiency one of the known values. On every **REV** chart there is a curve for each of the following efficiency levels (in percentage): 50, 60, 70, 80, 90, and 95.

Examples of Direct Use

Example Problem 1

A watershed in Orlando must reuse 80 percent of the annual runoff from a 10 acre impervious area. The pond area is included in the impervious area. The maximum reuse storage volume available for the pond is equal to the runoff from a 3 inch rainfall event. At what rate must the runoff be reused?

Since the entire watershed is impervious, the EIA is equal to 10 acres. Because runoff equals rainfall on impervious areas, the storage volume is equal to 3 inches on the EIA. The reuse rate is a function of the efficiency and the reuse volume:

$$\begin{aligned} R &= f\,(\,E\,,\,V\,) \\ &= f\,(80\%,\ 3\ inches) \\ &= 0.152\ inches/day \end{aligned}$$

By referring to the Orlando **REV** chart (Figure 4-1) we see that the necessary reuse rate is 0.152 inches per day on the EIA. The rate and volume can be expressed in other units:

$$\begin{aligned} V &= 3\ inches \times EIA \times \frac{10\ ac}{EIA} \\ &= 30\ ac\text{-}in \times \frac{43{,}560\ ft^2}{ac} \times \frac{ft}{12\ in} \\ &= 109{,}000\ ft^3 \end{aligned}$$

and

$$
\begin{aligned}
R &= 0.152\ \frac{in}{day} \times EIA \times \frac{10\ ac}{EIA} \\
&= 1.52\ \frac{ac\text{-}in}{day} \times \frac{43{,}560\ ft^2}{ac} \times \frac{ft}{12\ in} \\
&= 5{,}520\ \frac{ft^3}{day}
\end{aligned}
$$

Example Problem 2

An apartment complex located in Tallahassee needs to reuse 90 percent of the runoff from their parking lots. The EIA is equal to the directly connected impervious area and is 4 acres. They want to use 0.26 inches of water per day over the EIA. What must the reuse volume be in order to maintain these conditions?

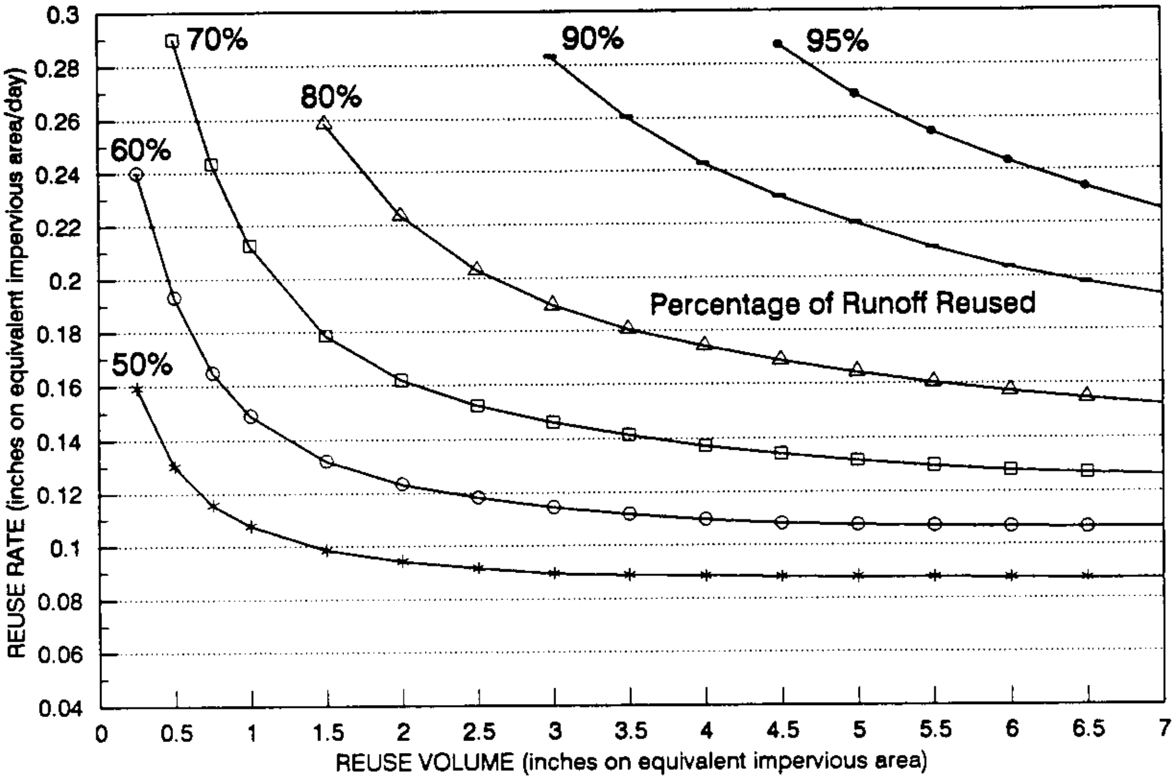
From the **REV** chart for Tallahassee (Figure 4-2), the required reuse volume is determined to be 3.5 inches on the EIA.

$$
\begin{aligned}
V &= f\ (\ E\ ,\ R\ ) \\
&= f\ (90\%,\ 0.26\ inches/day) \\
&= 3.5\ inches
\end{aligned}
$$

Again the volume and rate can be expressed in other units.

$$
\begin{aligned}
V &= 3.5\ inches \times EIA \times \frac{4\ ac}{EIA} \\
&= 14\ ac\text{-}in \times \frac{43{,}560\ ft^2}{ac} \times \frac{ft}{12\ in} \\
&= 50{,}800\ ft^3
\end{aligned}
$$

and



TALLAHASSEE RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 64.3 in

Figure 4-2. Rate-Efficiency-Volume (**REV**) Chart for Tallahassee, FL.

$$\begin{aligned} R &= 0.260\ \frac{in}{day} \times EIA \times \frac{4\ ac}{EIA} \\ &= 1.04\ \frac{ac\text{-}in}{day} \times \frac{43{,}560\ ft^2}{ac} \times \frac{ft}{12\ in} \\ &= 3{,}780\ \frac{ft^3}{day} \end{aligned}$$

The previous examples illustrate the most simple application: the watershed being impervious and the volume and rate given in terms of the EIA. However, much more complex design problems can be solved using the same technique. The following steps can be used in any design situation:

1) Select the appropriate chart.
2) Compute the EIA of the watershed.
   (EIA = total area x effective C), see Equation 2
3) Determine known variables in terms of the EIA.
4) Reference the chart to obtain a solution.
5) Convert the answer to desired units.

Variations in Application

The sections that follow present different types of design problems and methods which can be used to address these problems.

Irrigation Area and Rate

Many reuse applications will involve an area suitable for irrigation. For instance, an apartment complex may want to water grass and other landscaped common areas. The rate of delivery in these areas will vary with the time of the year and the type of plants. Recommended rates for Florida vary from 0.38 inches per week in the winter season to 2.25 inches per week in the summer season (Augustin, 1991).

<u>Example Problem 3</u>

An Orlando apartment complex must reuse, through irrigation, 90 percent of the annual runoff from a 3.5 acre impervious parking lot. The maximum reuse storage volume available for the pond is equal to the runoff from a 3 inch rainfall event. If the development wants to irrigate at a rate of 1.75 inches per week, how much area must be incorporated into the irrigation system?

The **REV** chart for Orlando, Figure 4-1, will be used. Because all rainfall will result in runoff, the pond volume is 3 inches on the EIA, or 3 inches times 3.5 acres (10.5 ac-in). The required reuse efficiency is 90 percent. From the chart a reuse rate of 0.205 inches per day on the EIA is obtained.

$$\begin{aligned} R &= f\ (90\%, 3\ \mathit{inches}) \\ &= 0.205\ \mathit{inches/day} \end{aligned}$$

This is equal to 0.205 inches per day times 3.5 acres, or 0.72 ac-in/day. The irrigation area can be obtained by a mass balance of the volume of reuse:

$$\begin{aligned} \mathit{Volume\ on\ Local\ Area} &= \mathit{Volume\ on\ EIA} \\ A_L \times R_L &= EIA \times R \\ A_L &= \frac{EIA \times R}{R_L} \end{aligned} \tag{14}$$

where A_L = local area for irrigation (ac)
R = reuse rate (inches/day on EIA)
R_L = local reuse rate (inches/day)

By using Equation 14 with a time conversion we obtain

$$A_L = \frac{0.72\ ac\text{-}in/day}{1.75\ in/wk} \times 7\ \frac{days}{wk}$$
$$= 2.87\ acres$$

Thus, 2.87 acres are needed for local irrigation to ensure that 90 percent of the water entering the pond will be reused. If the irrigation area had been designated instead of the irrigation rate, the rate could have been calculated using the same method.

Runoff Coefficient of less than One

In almost all cases, a watershed will contain some areas which do not contribute runoff and therefore the effective runoff coefficient of the watershed will be a value of less than one. If there is complete runoff from an impervious area only, the EIA is simply the area of the impervious zone. Otherwise, the effective runoff coefficient can be used to calculate the EIA.

Example Problem 4

A 10 acre apartment complex in Tallahassee must reuse 90 percent of the runoff from their watershed. Forty percent of the rainfall results in runoff. Determine the size of the reuse volume if the reuse rate will be 0.26 inches per day on the EIA.

The EIA is 4 acres.

$$\begin{aligned} EIA &= 10\ ac \times 0.40 \\ &= 4\ acres \end{aligned}$$

Using the Tallahassee chart, the required reuse volume is 3.5 inches on the EIA.

$$\begin{aligned} V &= f\ (\ E\ ,\ R\ ) \\ &= f\ (90\%,\ 0.26\ inches/day) \\ &= 3.5\ inches \end{aligned}$$

Note that this problem is identical to Example Problem 2; a 4 acre impervious watershed is equivalent to a 10 acre watershed with a runoff coefficient of 0.40. The reuse volume and reuse rate are calculated in the same way to be 50,800 cf and 3,780 cf/day, respectively.

Example Problem 5

A detention pond is to be designed for a new community of multi-family condominiums in the Orlando, Florida area. The watershed information is as follows:

40 acres total area
24% directly connected impervious area
No runoff contribution from pervious area for rainfall up to 5.5 inches
80% reuse efficiency criteria
Maximum reuse storage is 4 inches on equivalent impervious area
1.5 inches/week of reuse by irrigation

How much land area is needed for irrigation and what is the volume of the reuse storage?

Since the intensity of local irrigation is given, the area to be used for irrigation can be found by knowing the reuse rate. This is a function of the reuse volume and the reuse efficiency and can be obtained from the **REV** chart. From the Orlando chart, Figure 4-1, for a volume of 4 inches on the EIA and an efficiency of 80%, a reuse rate of 0.14 inches/day on the EIA is obtained.

$$\begin{aligned} R &= f\ (4\ \mathit{inches},\ 80\%) \\ &= 0.14\ \mathit{inches/day} \end{aligned}$$

The EIA is equal to 40 acres times 0.24, or 9.6 acres. Therefore, the irrigation area can be calculated using Equation 14.

$$\begin{aligned} A_L &= 9.6\ ac \times \frac{0.14\ in/day}{1.5\ in/wk} \times 7\ \frac{days}{wk} \\ &\approx 6.3\ acres \end{aligned}$$

The reuse storage volume is stated in the problem as being 4 inches on the EIA or

$$\begin{aligned} V &= 9.6\ ac \times 4\ in \times \frac{ft}{12\ in} \\ &= 3.2\ ac\text{-}ft \end{aligned}$$

Therefore, the area needed for irrigation is approximately 6.3 acres and the reuse storage volume is 3.2 ac-ft.

Runoff from both Impervious and Pervious Areas

If the pervious area of a watershed contributes runoff when rainfall is equal to the reuse volume, then the size of the EIA impervious area will be influenced by the pervious portion as well as the impervious portion of the watershed.

Example Problem 6

Solve Example Problem 5 except with the pervious area having an SCS curve number (CN) of 80.

The same procedure is followed. To find the reuse rate the efficiency and the reuse volume must be known. The efficiency has remained at 80% and although the actual reuse volume has changed due to the increase in EIA, it is still 4 inches on the EIA. Therefore, the **REV** chart can be used in the same way and the reuse rate remains at 0.14 inches/day on the EIA. To find the EIA we must determine the effect of the pervious area in response to a 4 inch rainfall event. The curve number method will be used to calculate the resulting runoff. From Equation 5, the infiltration storage at saturation, S′, is calculated to be

$$\begin{aligned} S' &= \frac{1000}{CN} - 10 \\ &= \frac{1000}{80} - 10 \\ &= 2.5\ in \end{aligned}$$

The resulting rainfall excess from the pervious area for a rainfall of 4 inches is calculated using Equation 6,

$$\begin{aligned} R_p &= \frac{[4 - 0.2(S')]^2}{4 + 0.8(S')} \\ &= \frac{[4 - 0.2(2.5)]^2}{4 + 0.8(2.5)} \\ &\approx 2.0\ inches \end{aligned}$$

and the runoff coefficient using Equation 10.

$$C_p = \frac{R_p}{P} = \frac{2\ in}{4\ in}$$
$$= 0.50$$

The effective runoff coefficient can then be calculated using Equation 2.

$$C = \frac{1.0(40\ ac \times 0.24) + 0.50(40\ ac \times 0.76)}{40\ ac}$$
$$= 0.62$$

The EIA is then computed as 24.8 acres.

$$EIA = 0.62 \times 40\ ac$$
$$= 24.8\ ac$$

We can now calculate the local irrigation area by using Equation 14.

$$A_L = \frac{24.8\ ac \times 0.14\ in/day}{1.5\ in/wk} \times 7\ \frac{days}{wk}$$
$$\approx 16.2\ acres$$

The land area needed for irrigation is 16.2 acres. As expected, this is considerably more area than what was needed in Example Problem 5 due the significant runoff from the pervious area. The reuse volume can be calculated in the same way as before.

$$V = 24.8\ ac \times 4\ in \times \frac{ft}{12\ in}$$
$$= 8.3\ ac\text{-}ft$$

Likewise, the reuse volume is greater because the overall imperviousness of the watershed has been increased.

Reuse Resulting in Runoff

The reuse of stormwater may be accomplished using a variety of practices. One of the most useful is the irrigation of local landscaped or natural areas. However, some irrigated water may return to the storage pond resulting in a decrease in the reuse efficiency of the pond. The return of reused water may be minimized by the design of the irrigation system or the proximity of the irrigation area.

The effect of reuse return can be considered by decreasing the reuse rate by some factor. For instance, if we are using stormwater to irrigate landscaping surrounding a shopping center parking lot, some of the water may fall on the parking lot and return to the pond. If the irrigation rate is actually 0.2 inches per day, a value smaller than 0.2 must be used for design purposes. The reduction is related to the effective runoff coefficient of the irrigated area by the following equation:

$$R = R_L \ (1 - C_r) \qquad \textbf{(15)}$$

where R = Reuse Rate to be used with **REV** chart
R_L = Reuse Rate to be applied to reuse area when reused water returns to pond
C_r = Fraction of reuse water that returns to the pond (estimated by observation).

<u>Example Problem 7</u>

An Orlando shopping center is reusing stormwater, through irrigation, at the rate of 0.2 inches per day on the EIA. It is estimated that 40% of the irrigated water returns to the pond. If local criteria specifies a maximum of 20% discharge of annual runoff (80% efficiency), what size volume is needed for reuse storage?

The reuse rate to be used with the **REV** chart must be reduced.

$$\begin{aligned} R &= R_L\ (1 - C) \\ &= 0.2\ \frac{in}{day}\ (1 - 0.4) \\ &= 0.12\ \frac{in}{day} \end{aligned}$$

From the Orlando **REV** chart

$$\begin{aligned} V &= f\ (0.12\ in/day,\ 80\%) \\ &= 2.75\ inches \end{aligned}$$

The required reuse volume is 2.75 inches on the EIA. If none of the irrigated water returned to the pond, the reuse volume is approximately 1.40 inches on the EIA (from Figure 3-1).

Calculation of Supplement Rate

One of the benefits of reusing stormwater is the cost savings of not having to buy water. A reuse pond sometimes requires the use of groundwater or other sources to supplement the reuse storage volume. Since reuse rates may average as high as 2.0 inches per week over 52 weeks, a reuse volume of 104 inches per year is required, but runoff may only supply half of the reuse needed. The designer should be interested, for economic and conservation considerations, in how much supplemental water is necessary for a certain design. This can easily be done using a **REV** chart.

The procedure is based on a mass balance of the reuse pond. By equating the inputs and outputs to the pond using units of inches/year we obtain

$$\begin{gathered} Inputs = Outputs \\ Rainfall\ Excess + Supplement = Reuse + Discharge \\ R_E + G = R + D \end{gathered}$$

and

$$G = R + D - R_E$$

However,

$$D = (1 - E) R_E$$

where E = reuse efficiency of the pond. Therefore,

$$\begin{aligned} G &= R + (1 - E) R_E - R_E \\ &= R - [R_E - (1 - E) R_E] \\ &= R - [R_E - (R_E - R_E E)] \end{aligned}$$

$$G = R - (R_E \times E) \qquad \textbf{(16)}$$

This indicates that supplement use is a function of the reuse rate, the amount of rainfall excess, and the efficiency of the system. The rate of supplement use in the above equation is in units of inches per year on the EIA.

Example Problem 8

An economic feasibility study is being done for a reuse pond in a small apartment development in Orlando, Florida. It is necessary to know the quantity of groundwater supplement to a pond per year. The reuse storage shall be 1.5 inches on the EIA and the reuse rate is estimated at 0.2 inches/day on a pervious area equal to the EIA. The average rainfall is 50 inches per year.

From the Orlando **REV** chart we find that the efficiency of the system will be 81%. We can now use Equation 16.

$$\begin{aligned} G &= R - (R_E \times E) \\ &= (0.2\ \frac{in}{day})\ (365\ \frac{days}{year}) - (50\ \frac{in}{year})\ (0.81) \\ &= 32.5\ \frac{in}{year} \end{aligned}$$

This system will use approximately 32.5 inches of groundwater on the EIA per year.

Example Problem 9

The owners of a golf course are considering a water reuse system to decrease the use of county potable water. They will be using an existing water hazard for reuse storage, the volume of which is 6.5 inches on the EIA. They plan to irrigate at a rate of 0.12 inches/day on the EIA. How much water do they need to supplement the reuse volume over one year if the annual rainfall volume is 50 inches?

A reuse efficiency of 80% is obtained from the Orlando **REV** chart. Again from Equation 16,

$$\begin{aligned} G &= R - (R_E \times E) \\ &= (0.12\ \frac{in}{day})\ (365\ \frac{days}{year}) - (50\ \frac{in}{year})\ (0.80) \\ &= 3.8\ \frac{in}{year} \end{aligned}$$

we see that only 3.8 inches/year of supplemental groundwater is needed.

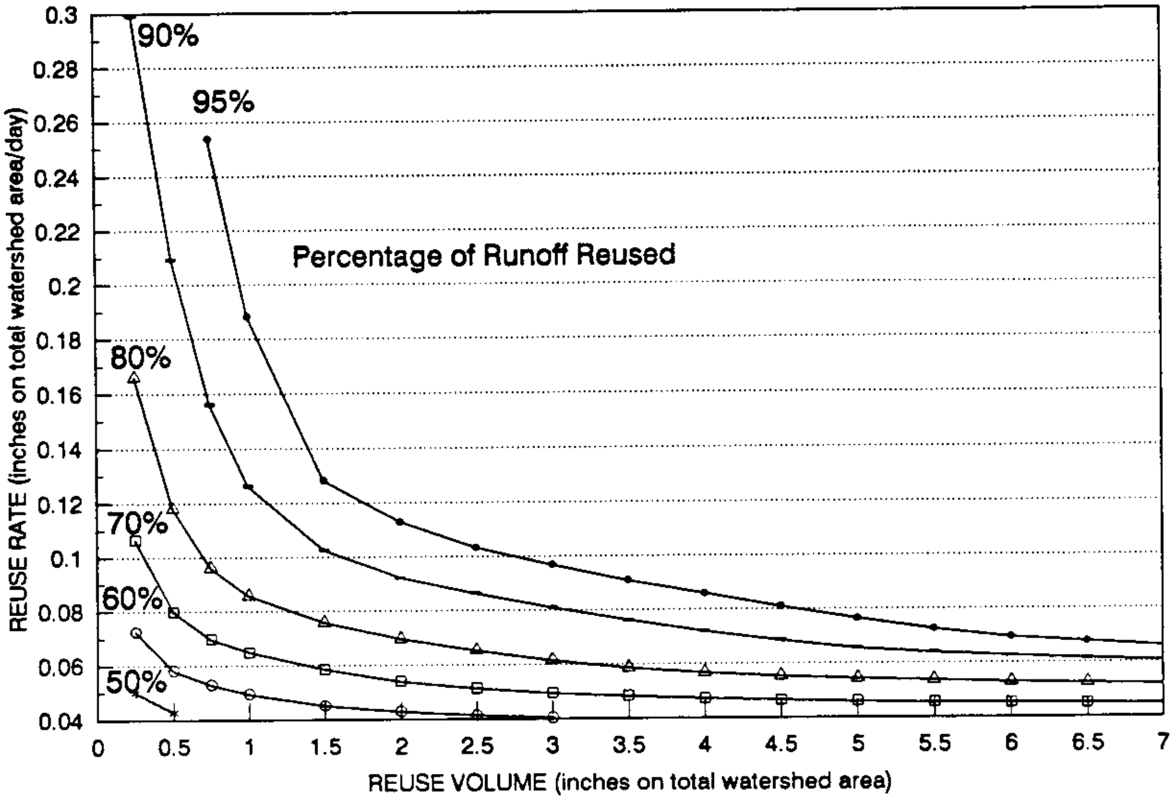
The necessary rate of supplemental water depends on the design of the system. Referring to the mass balance, since runoff will not change, a higher reuse rate (irrigation in this case) will require more groundwater supplement and a larger reuse volume will decrease the intensity of fluctuations in the level of the pond which will decrease the demand for supplement. Thus, there is an economic trade-off between the cost of land for reuse storage and the cost of supplemental water. If a pond is to be designed in an area where the cost of supplemental water is high and a certain efficiency must be maintained, the designer would probably prefer a larger storage volume and a lower reuse rate. On the other hand, in an area where land is relatively expensive a higher quantity of supplemental water might be desirable. Groundwater has been exclusively used as the supplement in previous examples but sources such as greywater and other surface water bodies may also be used.

Support of the Generalized REV

During the initial stages of development, **REV** charts were created to represent specific runoff coefficients (0.40, 0.50, etc.). These were produced from the same computer model by varying the runoff coefficient of the model. The Orlando **REV** charts for runoff coefficients of 0.5 ($REV_{0.5}$) and 0.4 ($REV_{0.4}$) are Figure 4-3 and Figure 4-4, respectively. Pond design required the selection of the chart corresponding to the runoff coefficient of the watershed. The units on the chart are based on the total area of the watershed.

After working with several charts from the same region, it was determined that the charts contained identical information, only based on different units. The result of this realization is the concept of the equivalent impervious area (EIA). The following section is the support of the generalized **REV** charts by the use of the EIA.

The model used in this research is a long-term mass balance of a reuse pond. When the runoff coefficient of the model is changed, the fraction of rainfall entering the pond (runoff) is consequently changed. For instance, if the runoff coefficient is reduced from 1.0 to 0.5, the simulated pond will receive only half of what it had previously received. This reduction in runoff volume can be duplicated by decreasing the size of the contributing watershed to half of its original area and maintaining a runoff coefficient of 1.0; the runoff volume would still be halved. As long as the



ORLANDO RAINFALL STATION
MAY 1974 - DEC. 1988
RUNOFF COEFFICIENT = 0.50

Figure 4-3. **REV** Chart for Orlando, FL based on Runoff Coefficient of 0.50.

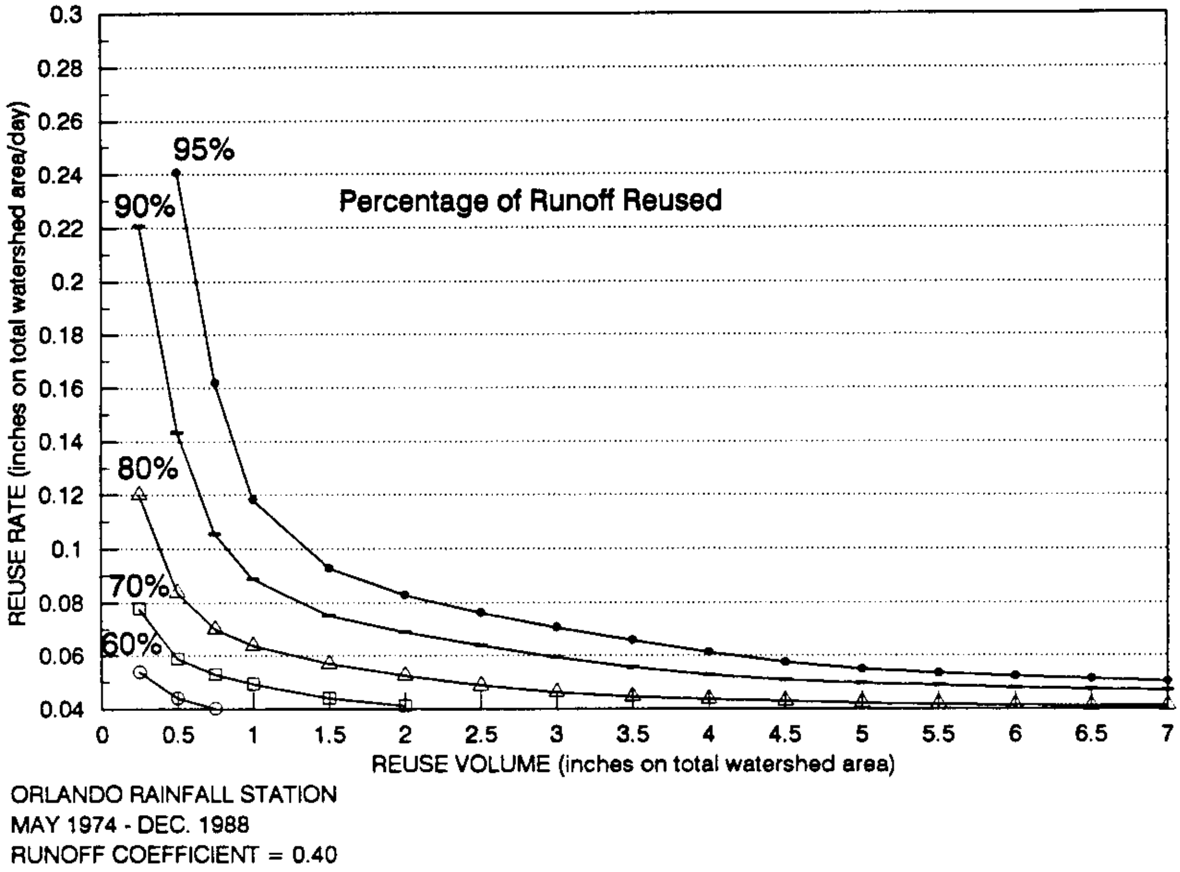


Figure 4-4. **REV** Chart for Orlando, FL based on Runoff Coefficient of 0.40.

original runoff volume is maintained, the total area and the runoff coefficient of the watershed can be complimentarily varied; if one is increased, the other must be decreased. The model, as well as an actual pond, will not "see" this change in the watershed conditions.

If the runoff coefficient for a watershed can be converted to any other runoff coefficient (with an accompanying conversion of the total area) without changing the runoff volume, then only one chart representing a single runoff coefficient is necessary to solve any design problem. For greatest simplicity, a chart representing a runoff coefficient of one, or a completely impervious condition, was chosen. To use this chart with a watershed having a runoff coefficient not equal to one, the area of the actual watershed must be converted such that if it was impervious, it would produce the original volume of runoff. This converted area is called the equivalent impervious area and its formula can be derived from a mass balance of runoff volumes:

$$Volume_{actual\ watershed} = Volume_{equivalent\ watershed}$$
$$A \times C = EIA \times C_{imp.}$$

or

$$EIA = A \times \frac{C}{C_{imp.}} \qquad (17)$$

in which EIA = equivalent impervious area (ac)
A = area of actual watershed (ac)
C = runoff coefficient of actual watershed
$C_{imp.}$ = runoff coefficient of EIA

Since $C_{imp.} = 1$, this can be simplified to

$$EIA = A \times C \tag{3}$$

This is Equation 3.

To compare the use of different charts, the following example will be solved using the Orlando $\mathbf{REV}_{1.0}$, $\mathbf{REV}_{0.5}$, and $\mathbf{REV}_{0.4}$.

Example Problem 10

A 20 acre watershed in Orlando drains into the Wekiva River. Local regulations stipulate that the mass loadings in the runoff from the watershed must be reduced by 95 percent (assume that the discharge loading equals the runoff loading). The runoff coefficient of the watershed is 0.5. What will the reuse volume be if the reuse rate is maintained at a rate of 2 ac-in per day?

First, the basic Orlando **REV** ($\mathbf{REV}_{1.0}$) will be used. The EIA is calculated as

$$\begin{aligned} EIA &= A \times C \\ &= 20\ ac \times 0.5 \\ &= 10\ ac \end{aligned}$$

The reuse rate is calculated in terms of the EIA:

$$R = \frac{2\ ac\text{-}in/day}{10\ ac}$$
$$= 0.20\ in/day\ on\ the\ EIA$$

From the Orlando **REV**$_{1.0}$, the reuse volume can be calculated as

$$V = f\ (95\%,\ 0.20\ in/day)$$
$$= 5.5\ inches\ on\ the\ EIA$$

which is equal to

$$V = 5.5\ inches \times EIA \times \frac{10\ ac}{EIA}$$
$$= 55\ ac\text{-}in$$

The Orlando **REV**$_{0.5}$, (Figure 4-3), is now used. Note that the units of volume and rate are based on the total area of the watershed, in this case 20 acres. This time, the reuse rate is calculated in terms of the watershed area:

$$R = \frac{2\ ac\text{-}in/day}{20\ ac}$$
$$= 0.10\ in/day\ on\ the\ watershed$$

From the Orlando **REV**$_{0.5}$, the reuse volume can be determined to be

$$V = f\ (95\%,\ 0.10\ in/day)$$
$$= 2.75\ inches\ on\ the\ watershed$$

which is equal to

$$V = 2.75\ inches \times watershed \times \frac{20\ ac}{watershed}$$
$$= 55\ ac\text{-}in$$

This matches the value calculated by the **REV**$_{1.0}$.

To reinforce the fact that any **REV** chart can be used, the Orlando **REV**$_{0.4}$ (Figure 4-4) will be used to solve the example problem. To use the **REV**$_{0.4}$, the watershed area must be converted to a size in which the runoff volume from a watershed having a runoff coefficient of 0.4 would be equivalent to the original runoff volume. This can be calculated by using a form of Equation 17:

$$\begin{aligned} A_{0.4} &= A_{0.5} \times \frac{C_{0.5}}{C_{0.4}} \\ &= 20\ ac \times \frac{0.5}{0.4} \\ &= 25\ ac \end{aligned}$$

This implies that a 25 acre watershed with a runoff coefficient of 0.4 will produce the same volume of runoff as a 20 acre watershed with a runoff coefficient of 0.5. The reuse volume is calculated in terms of the 25 acre watershed:

$$\begin{aligned} R &= \frac{2\ ac\text{-}in/day}{25\ ac} \\ &= 0.08\ in/day \text{ on the watershed} \end{aligned}$$

From the Orlando **REV**$_{0.4}$, the reuse volume can be determined to be

$$\begin{aligned} V &= f\ (95\%,\ 0.08\ in/day) \\ &= 2.2 \text{ inches on the watershed} \end{aligned}$$

which is equal to

$$V = 2.2\ inches \times watershed \times \frac{25\ ac}{watershed}$$
$$= 55\ ac\text{-}in$$

Again, this is consistent with the solutions derived from the Orlando $\mathbf{REV}_{0.5}$ and $\mathbf{REV}_{1.0}$.

Mathematical Equations and a Computer Program

The efficiency curves of the **REV** charts were approximated with equations of best fit using a non-linear regression search procedure of software entitled "SYSTAT". It was found that the power equation consistently estimated the curves most accurately. The "fit" was generally very good. Out of the 150 equations (6 for each station), only two had R-squared values of about 0.98 and of the remaining, all had R-Squared values above 0.99.

The equation is of the form

$$y = a \cdot x^b$$

or

$$R = a \cdot V^b \tag{18}$$

where R = reuse rate (inches on EIA/day)
V = reuse volume (inches on EIA)
a,b = descriptive variables

The variables vary for each geographic region and level of efficiency. They are listed in Appendix C.

The equations were used in a computer program, written to execute the design calculations. Information concerning two of the three **REV** parameters (rate, efficiency, volume) is required. The input of watershed data (area, runoff coefficient, area for irrigation) is an option that allows the program to express the **REV** parameters in more meaningful units, ie., cubic feet and acre-inches as opposed to inches on the EIA.

CHAPTER 5

SENSITIVITY OF PARAMETERS AND OTHER ANALYSES

Sensitivity Analysis

When a model is used to simulate or predict the behavior of a natural dynamic system, the model should be tested to see how it reacts to variations in the parameters of the model. For example, if a small change in some parameter produces a large change in what the model is trying to predict, the model is said to be sensitive to that parameter, in which case greater precautions should be made concerning the usage of that parameter. In producing **REV** charts there was concern for the sensitivity of both the characteristics of the rainfall data and the assumptions of the model. Although many of the assumptions made are widely utilized or intuitively safe, the influence of the following parameters on the model will be addressed:

1) how periods of missing rainfall data affect the results of the simulation
2) the difference between using rainfall data recorded to the tenth of an inch and recorded to the hundredth of an inch
3) the consideration of evapotranspiration as a variable output versus the assumption that it is balanced by rainfall directly on the pond
4) whether allowing discharge on the same day as it rains results in different efficiencies as holding the water till there is a day with no rain
5) the effect of not irrigating during periods of heavy rainfall

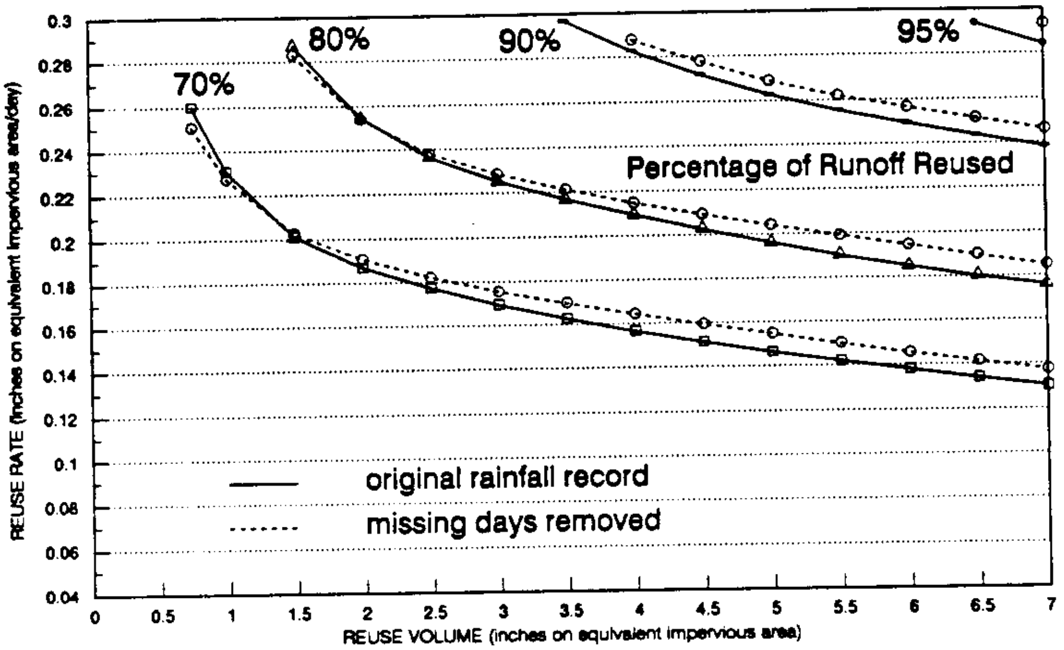
These five concerns were examined by making modifications or additions to the existing model. Only the variable in question was changed while all other factors remained the same. The results of the altered model were then compared to the original model. The model was considered sensitive to the parameters that, when varied, caused significant change. Extra care must be used when modeling these variables so that they are represented as accurately as possible. If the variable caused little change the model was considered insensitive to that parameter.

Missing Data

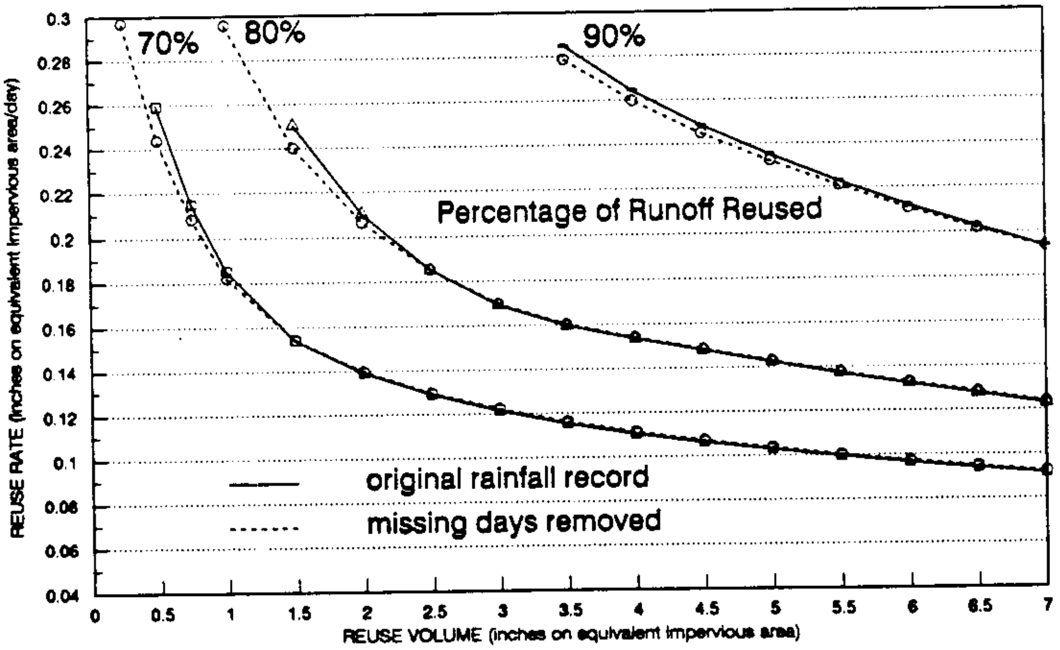
Most of the 25 Florida rainfall stations used in this experiment were, to varying degrees, subject to broken or incomplete records. These were noted in the database by single letter "flags", one at the beginning of the affected period and one at the end. An "A" signified accumulation where the distribution of the rain is not known and so is totaled at the end of the period. A "D" represented data that had been deleted due to a question of its validity. Data that had been estimated was tagged with a "E". An "M" marked periods where the data was missing, usually caused by a malfunctioning station.

It was important to see how these inaccuracies influenced the simulation results. The Ft. Myers and Moore Haven rainfall stations were selected for a comparison of using untouched data and data that had been adjusted. An inspection of the 15 years of the untouched data revealed that, for Ft. Myers, 356 days were affected by either deleted or missing data. 108 days were affected in the Moore Haven database. Accumulated data did not pose a problem because it almost always involved only one day and so the daily totals were unaffected. Estimated data were never encountered. The intervals in which data were unavailable ranged from one day to two months. To make the adjustments, periods with incomplete data were excluded from the record and the dates directly preceding and following where brought together as if they were consecutive. For instance, if the data from the month of April were missing, the days would be removed from the record and May would immediately follow March.

A comparison of the **REV** charts showed that there was very little difference between the resulting efficiencies of each of the records (Figure 5-1). In general, the difference ranged from 0.1% to 0.2% for different combinations of reuse rates and reuse volumes. The small difference can be explained in that the only time the efficiency would be influenced is during heavy rainfall events when there is discharge potential. Dry periods of even just a day would allow some time for reuse to occur, thereby decreasing the amount discharged. Extended periods of unknown rainfall activity actually have little more effect on the efficiency as a single day. Because they don't yield any rain, the reuse



FT. MYERS RAINFALL STATION
356 DAYS MISSING



MOORE HAVEN RAINFALL STATION
108 DAYS MISSING

Figure 5-1. The Sensitivity of Missing Rainfall on the Model Results of Ft. Myers and Moore Haven.

rate is balanced by supplemental inputs. Since efficiency is a function of discharge and runoff volumes, it is not changed.

Rain Gauges

Of the twenty-five rainfall stations used in this report, fourteen employ the Universal Rain Gauge, which records precipitation to the hundredth of an inch, and eleven use the Fisher-Porter rain gauge, which records rainfall in increments of tenths of an inch. Because a difference in recording hardware should not have an influence on pond design, it was necessary to check whether the resulting efficiencies of the simulation were significantly different when comparing both types of measurement.

Rainfall data from Orlando and Tallahassee, which are reported in hundredths of an inch, were converted to data in tenths of inches. Since both types of rain gauges accumulate precipitation until the incremental amount (tenth or hundredth inch) is collected, the conversion can be made by counting only complete units of tenths of inches and passing the hundredths values as remainders to the next record. As in the actual gauges, no rainfall is lost, only held until a full tenth of an inch of rain is accumulated.

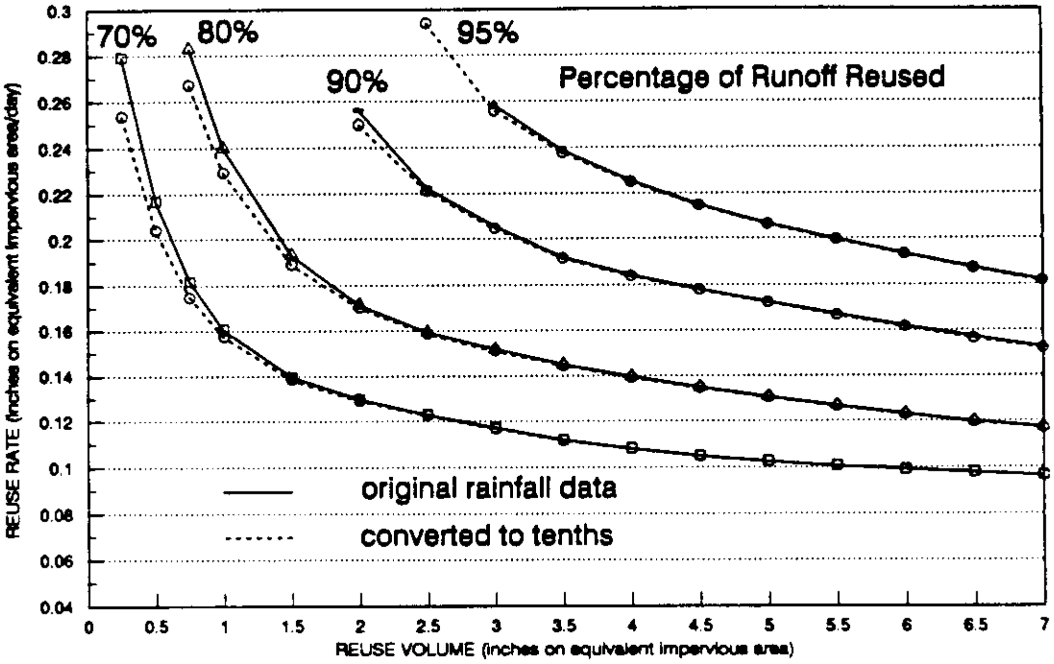
Sometimes the rainfall event plus the accumulated rainfall did not total a tenth of an inch and there was a zero recorded for that day. These zeros were deleted from the record, thereby decreasing the size of the database. The original 15 year record for Orlando contained 1387 events while the modified record had 1266. An interpretation of this is that there were fewer but larger storm events. The total volume of rainfall over the 15 years, however, remained at 706.9 inches for the Orlando station.

The results, shown in Figure 5-2, support that there is almost no difference between using data recorded to the tenth of an inch and that recorded to the hundredth of an inch. The distinction between efficiencies is small because the simulation, as actual retention ponds, are not sensitive to such small amounts of rainfall (hundredths of an inch).

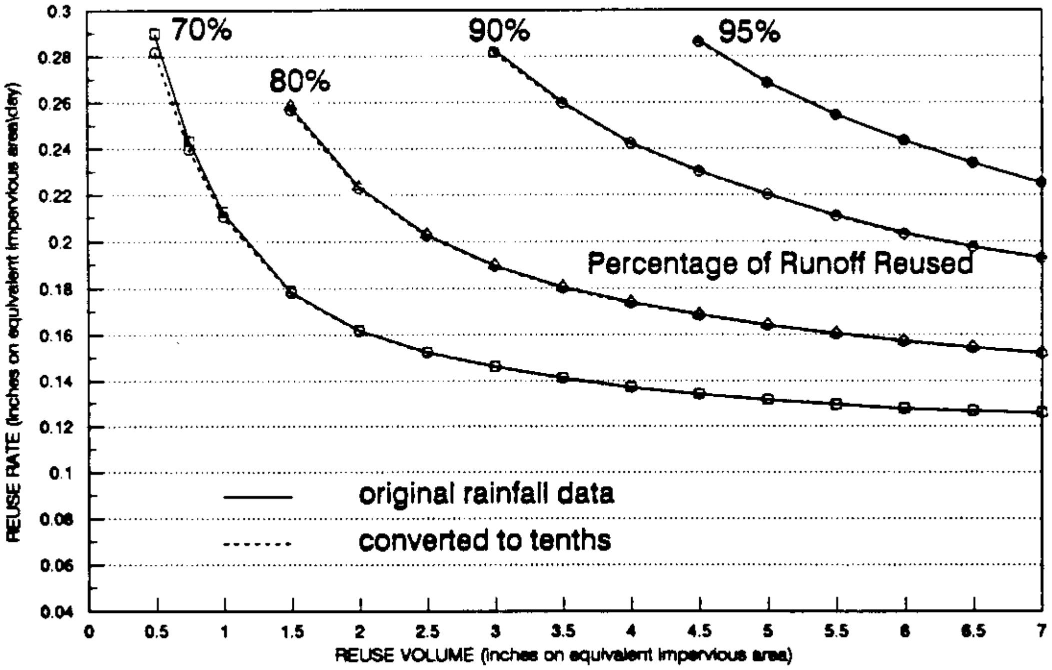
Evaporation and Rainfall on Pond

One of the initial simplifications of the pond mass balance was the assumption that the mean annual evaporation from the pond is equal to the mean annual rainfall on the pond. The evaporation totals in Florida may range from 40 to over 60 inches per year. Precipitation rates range from 37 inches per year in Key West to 64.5 in Tallahassee.

While evaporation and direct rainfall rates are based upon the size of the pond, all other model parameters were based on the EIA. Therefore, a ratio was established between the size of the pond and the EIA. Since detention ponds usually require no more than 5% of the total area of the watershed, depending on the impervious area, a conservative estimate of pond area to a completely impervious area was



ORLANDO RAINFALL STATION



TALLAHASSEE RAINFALL STATION

Figure 5-2. The Sensitivity of Rain Gauges on the Model Results of Orlando and Tallahassee.

chosen as 1:10. As an example, a one inch rainfall event, through direct precipitation, would add one inch of rainfall to the pond or 0.10 inches over the EIA.

Evaporation data were obtained from NOAA Climatological Data publications for the years 1985 through 1989. Since the locations of climatological stations match those of precipitation stations in only a few instances, evaporation data from nearby stations were used with selected model locations. Evaporation data from Lisbon and Lake Alfred were introduced into the models of Orlando and Parrish, respectively.

Evaporation data for Florida are available in monthly pan evaporation totals. The five years of record were used to obtain mean monthly total evaporation rates for each location. These were converted to surface water evaporation rates by multiplying by a pan coefficient of 0.7. The mean annual total evaporation for the three locations is 56.46 inches for Lake Alfred and 41.07 inches for Lisbon.

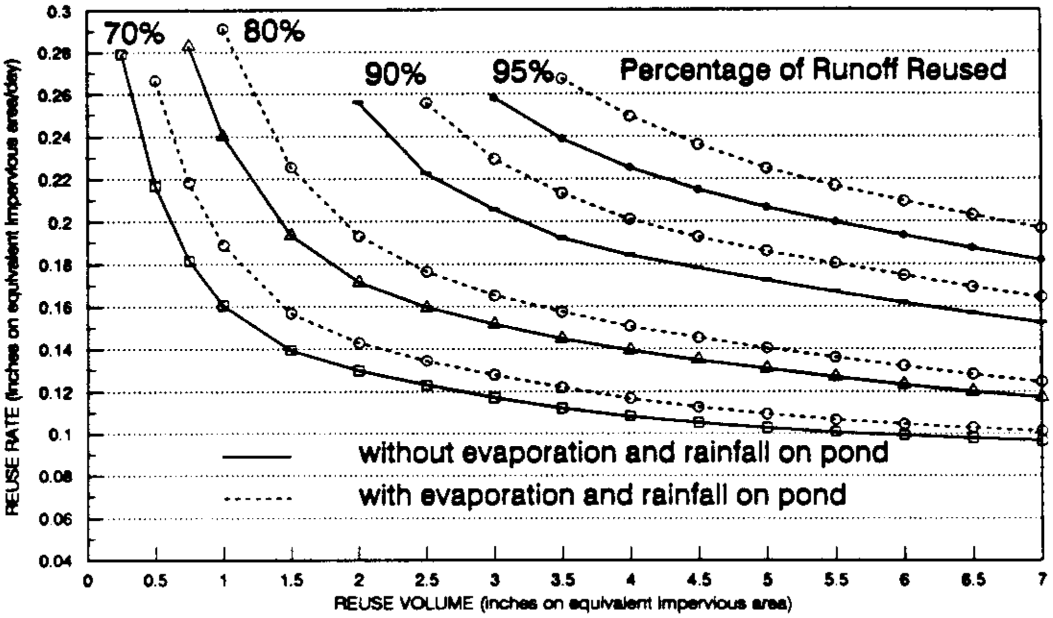
The evaporation function was added to the models by distributing evaporation depths in inches for each time interval. The amount of evaporation for each interval is the product of the number of days in that interval and mean daily evaporation rate for the month in which the first day of the interval falls. This distribution approximates what would happen in an average year. To ensure the distribution did not affect the total evaporation volume, the mean annual evaporation volumes for the 15 year simulations were compared to the mean volumes obtained from NOAA. The totals were almost identical.

The resulting **REV** charts are presented in Figure 5-3. As shown, the model ponds are less efficient when evaporation and rainfall on the pond are considered. The 80% efficiency curve calculated without pond rainfall and evaporation (solid line) is approximately the 76% efficiency curve when pond rainfall and evaporation are considered (broken line). When pond evaporation and direct rainfall are considered, generally the efficiency will be between four and two percent less.

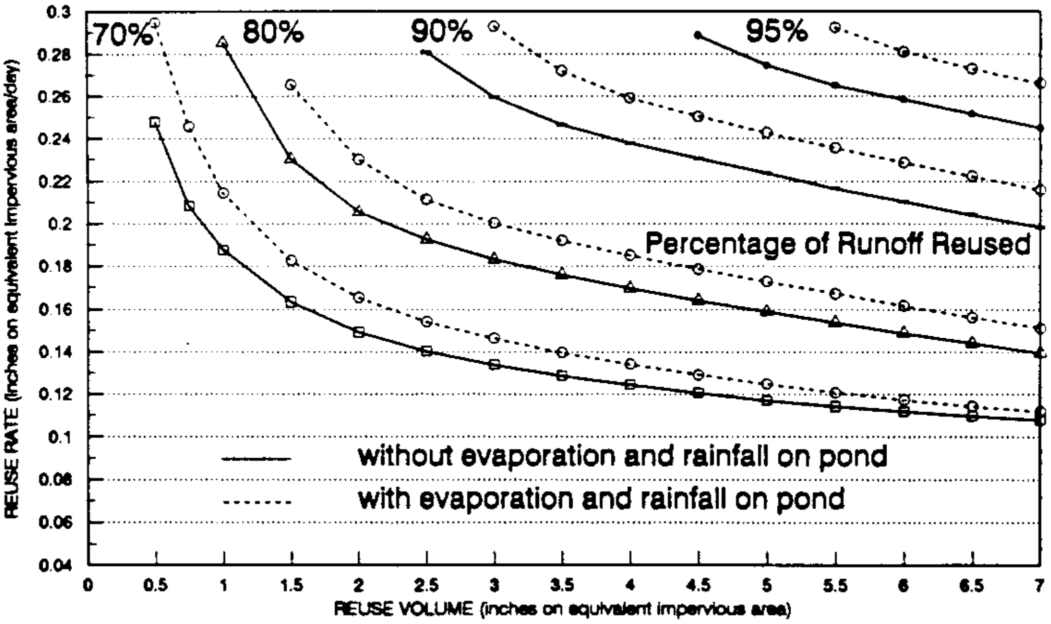
To use the **REV** charts, rainfall on the pond must be included in the calculation of the EIA. When the area of the pond (approximated at 15% of the EIA) was added to the EIA, the pond reuse volume increased and for a fixed reuse rate, the average annual efficiency increased by at least 2.5%. Since rainfall on the pond reflects an impervious condition (all rainfall yields rainfall excess) it must be added to the EIA while maintaining consistent units (depth on an impervious area).

Discharge

The original model allowed discharge (up to 2 inches over the equivalent impervious area) to occur on any day. However, it may be desirable, for quality considerations, to hold stormwater for a given time period to allow settlement before discharging. This could be done using a depth detector and a



ORLANDO RAINFALL STATION
PRECIPITATION = 48.2 in/yr
EVAPORATION = 41.1 in/yr



PARRISH RAINFALL STATION
PRECIPITATION = 51.0 in/yr
EVAPORATION = 56.5 in/yr

Figure 5-3. The Sensitivity of Evaporation and Rainfall on the Pond on the Model Results of Orlando and Parrish.

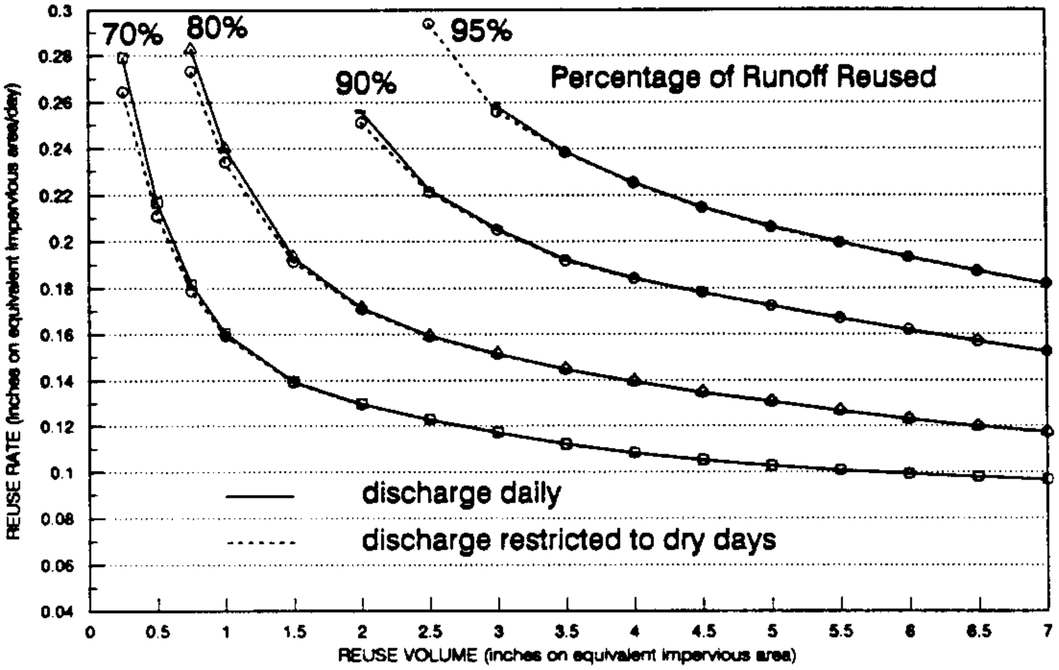
timer that activates a control valve. A 24 hour minimum holding time was introduced into the Orlando and Parrish models. Therefore, discharge could not occur on any day in which there was rainfall. If there was rainfall on consecutive days, there would be no allowable discharge until the first day in which there was no rainfall.

This variation in the model produced little differences in the results (Figure 5-4). Only in the range of higher reuse rates and lower reuse volumes were there any difference at all, and then the differences were slight.

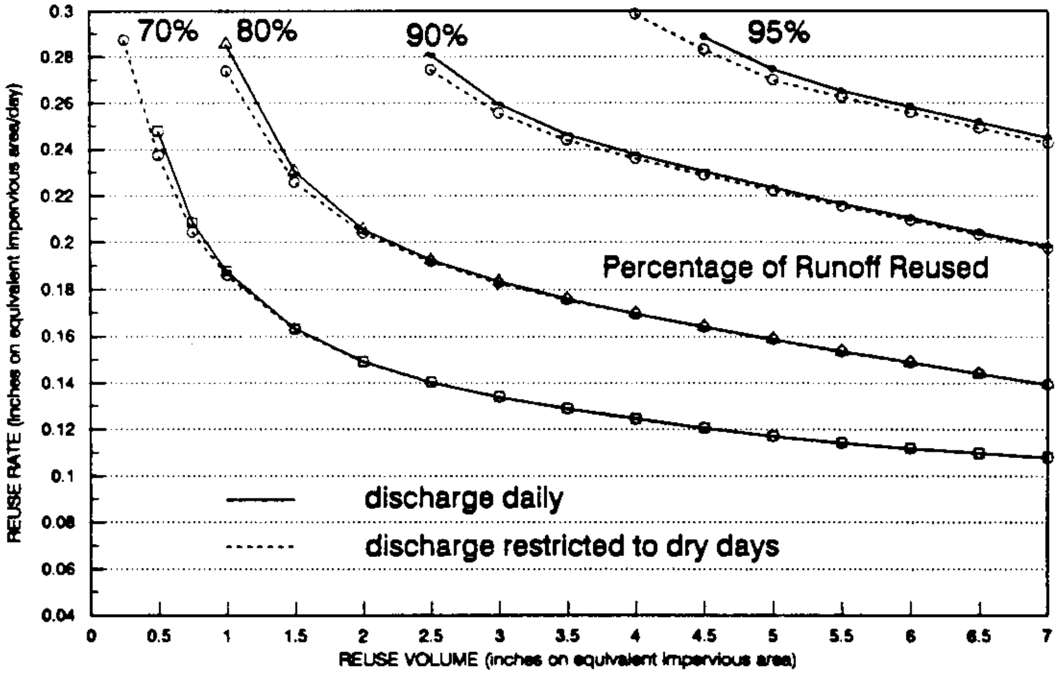
No Irrigation During Heavy Rainfall

Depending on the reuse application and circumstances, it may be desirable or necessary to prohibit reuse during heavy periods of rainfall. However, only about one in one hundred systems operate with restrictions (Hessenauer, 1990), and there are no specific limiting guidelines. An extreme limit to restrict irrigation was assumed to be five days of cumulative rainfall exceeding 3 inches. The Orlando and Tallahassee models were modified to assess this limit. The rainfall records from these regions were analyzed to determine the days on which this restriction was violated. For the 15-year Orlando and Tallahassee records, irrigation could not be done on 122 and 203 days, respectively.

The resulting **REV** charts are Figure 5-5. The difference in calculated efficiencies between the original and the

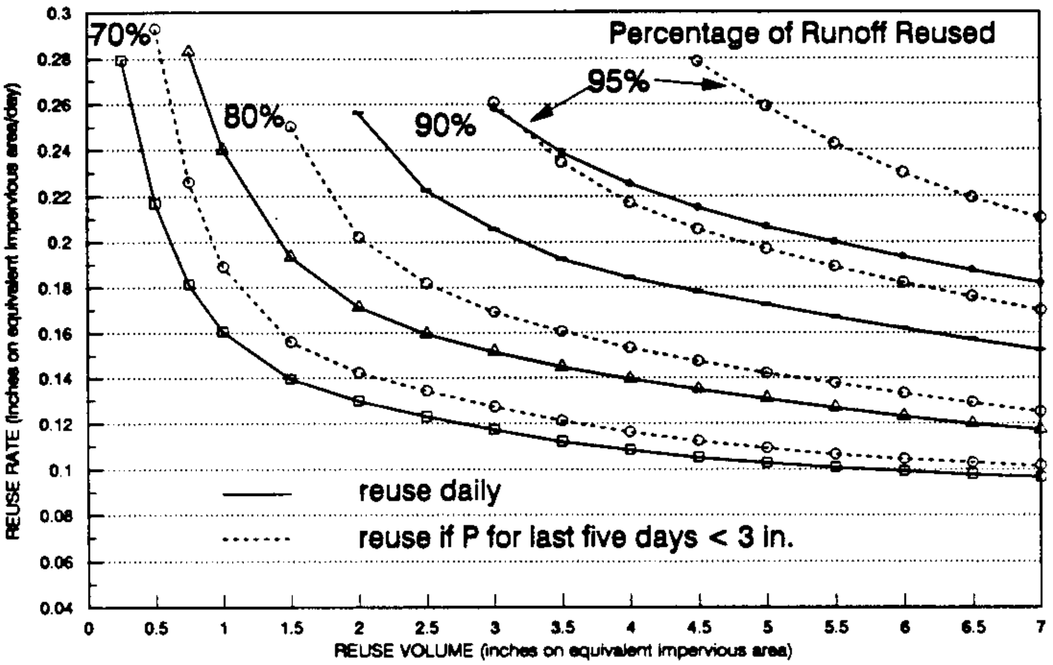


ORLANDO RAINFALL STATION

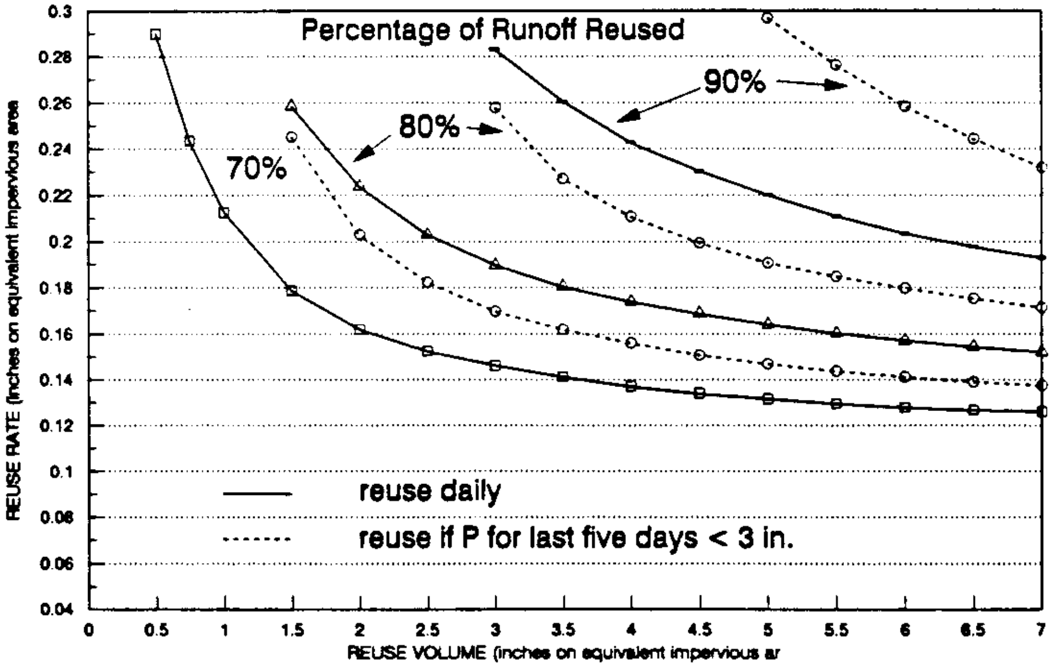


PARRISH RAINFALL STATION

Figure 5-4. The Sensitivity of the Timing of Discharge on the Model of Orlando and Parrish.



ORLANDO RAINFALL STATION



TALLAHASSEE RAINFALL STATION

Figure 5-5. The Sensitivity of Reuse Restrictions on the Model Results of Orlando and Tallahassee.

modified models is generally about 3 to 8 percent. The 80% curve calculated with daily reuse (solid line) for Orlando is approximately the 75% curve (doted line) when reuse is limited. When limitations for reuse are developed, they can be assessed using the model of this work. The use of a 5 day 3 inches limitation would require a larger reuse pond and greater irrigation rates for a fixed EIA.

Alternative Applications

The following two sections involve modifications made to the original model that resulted in charts of different form. Although they are not true **REV** charts, they could prove to be useful in related applications.

Storage Tanks

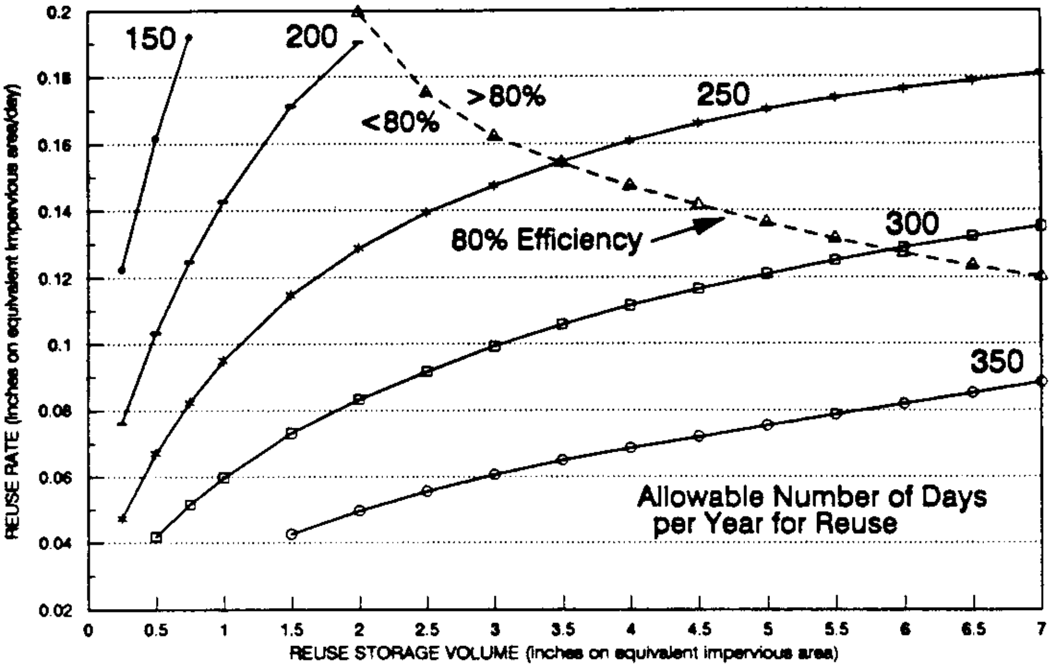
Supplemental recharge, usually groundwater, is a significant source of water in pond designs having low reuse volumes or high reuse rates. For these ponds, the amount of reuse exceeds the runoff into the pond at times and other water sources are necessary to maintain the reuse rates. In some geographical regions it would be impossible or uneconomical to use great quantities of groundwater. The models were modified, therefore, to exclude supplement input.

The new systems would, in effect, have impervious boundaries since there would be nothing passing through the walls or the surface of the pond and could be regarded as underground storage tanks with stormwater runoff as the only input and reuse and discharge as the outputs. Tanks such as these are presently in use in mostly coastal regions which lack feasible groundwater sources. Because of limited reuse water (no supplement) it would be important for designers to know the quantity of water available for use. This can be determined using charts such as Figure 5-6.

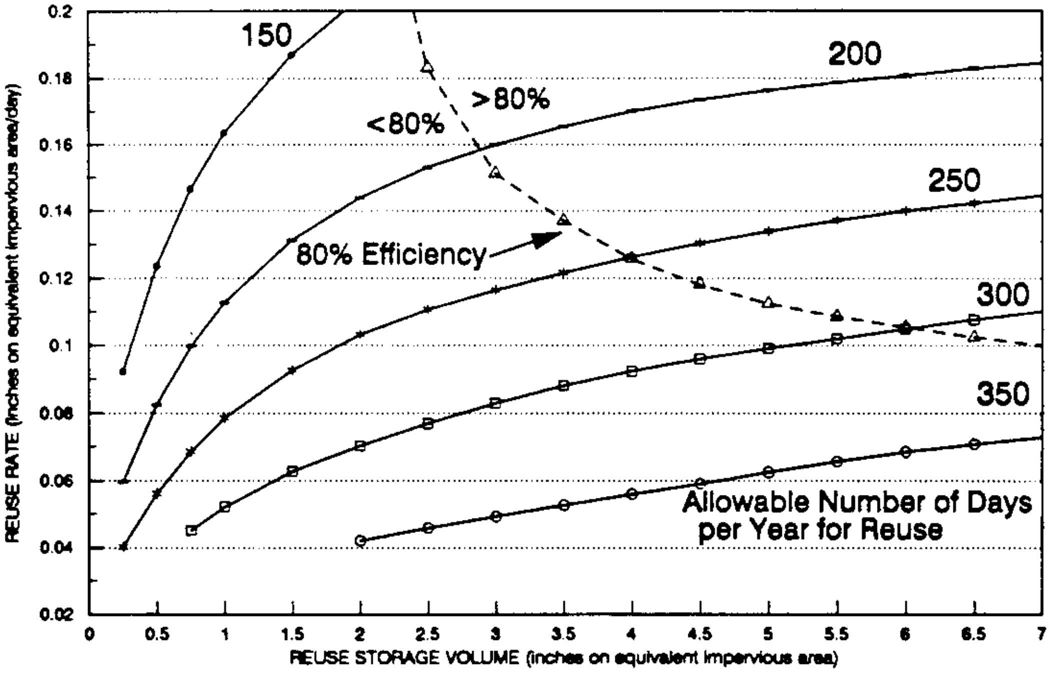
Curves are shown indicating the amount of reuse that can be done at corresponding reuse rates and reuse volumes. The values, 150 through 350, represent the equivalent number of days per year that reuse is possible. "Equivalent" is meant to relate that reuse did not occur for the exact number of days at the precise rate desired. On some days, the storage might have been depleted before the full volume was used. If only half of the water was available, it would have been equivalent to one half of a day of reuse.

Bank Infiltration of Reuse Volume

The movement of water through the sides of a pond can have a significant effect on its operation. There are many factors effecting this variable. The direction of flow will depend on the depth of the pond relative to the groundwater table. The rate of movement will depend upon the soil characteristics and the magnitude of the pressure difference across the wall of the pond. In the original model, the outward movement of water into the soil was prohibited and water as an input was included with the supplement parameter.



ORLANDO RAINFALL STATION



KEY WEST RAINFALL STATION

Figure 5-6. Derivation of REV Chart for Determination of Number of Days per Year of Reuse for a Storage Tank.

To better understand the effects of bank infiltration, the model was modified by replacing the reuse function with the infiltration of water through the sides of the pond. Infiltration rates were derived from an operating research pond. From a mass balance of a residential pond in Orlando, FL (Yousef, 1991), it was determined that a bank infiltration rate of approximately 4 inches per hour (in^3/in^2-hr) existed when the pond depth was 1 foot above the groundwater table.

To express the rate of exfiltration from a pond in terms of the EIA, parameters regarding the size of a pond and the EIA were established. A 1.1 acre pond services a 14 acre watershed with a runoff coefficient of 0.7, or an EIA of 9.8 acres. If the pond is assumed to be circular (lowest perimeter for any pond shape), the circumference can be calculated.

$$\begin{aligned} C &= \pi D \\ &= \pi \sqrt{\frac{4\ Area}{\pi}} \\ &= \pi \sqrt{\frac{4\ (1.1\ ac)(43560\ ft^2/ac)}{\pi}} \\ &= 775\ ft \end{aligned}$$

The volume removed by bank infiltration at a depth of 1 foot above the groundwater table can then be calculated as

$$\begin{aligned} F &= \frac{4\ in}{hr} \times 775\ ft \times \frac{ft}{12\ in} \times \frac{24\ hr}{day} \\ &= 6200\ ft^3/day \end{aligned}$$

If the relationship between the bank infiltration rate and the pressure head (H) is linear, the equation can be generalized for any depth.

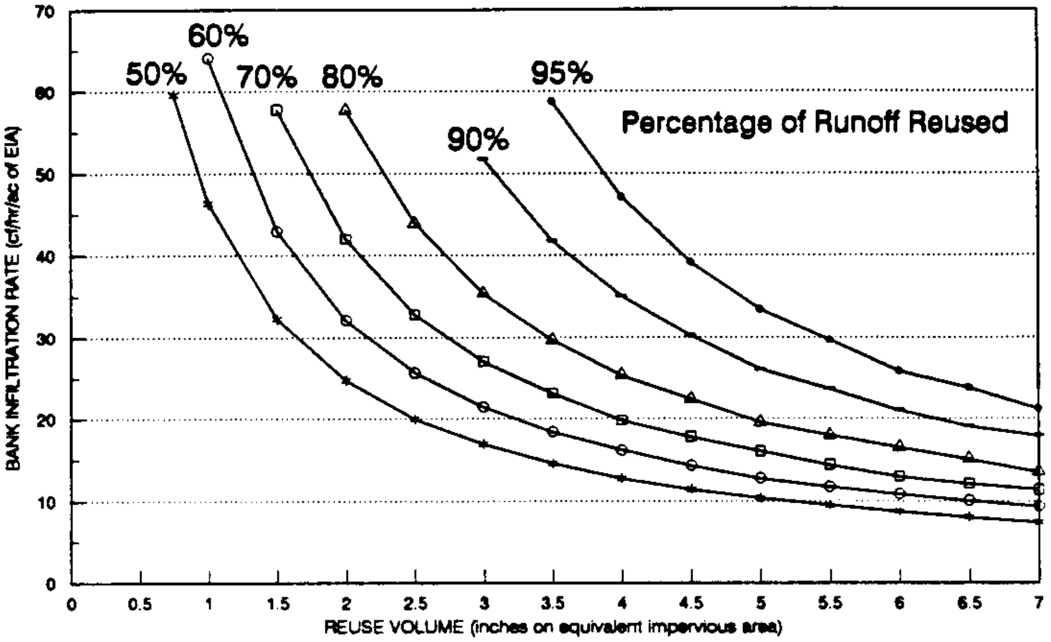
$$F = \frac{6200\ ft^3/day}{1\ ft} \times \frac{1}{9.8\ ac} \times \frac{ac}{43560\ ft^2} \times \frac{12\ in}{ft} \times H$$
$$= 0.17(H)\ in/day\ on\ the\ EIA$$

where H = depth of pond above groundwater table (feet). This equation produces an bank infiltration rate in terms of the EIA for a given pond water depth over the groundwater table. The water depth was monitored by the spreadsheet in terms of inches on the EIA but could be converted to actual inches on the pond by multiplying by the ratio of EIA to pond area (9.8/1.1). Thus, the model was able to estimate the loss of water through the pond banks.

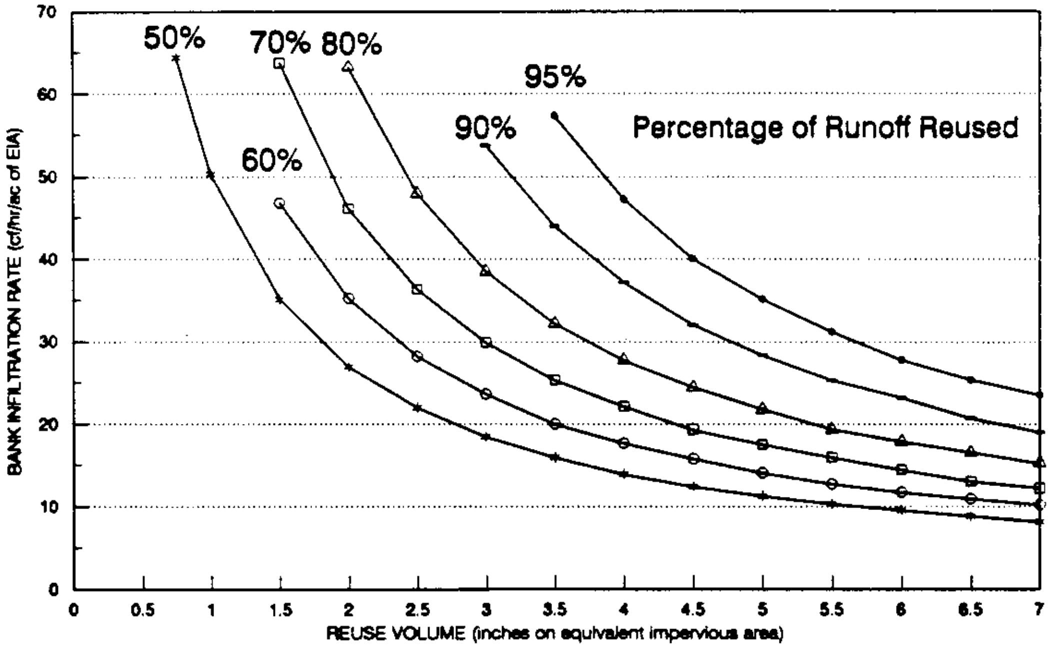
By varying the reuse volume and the rate of infiltration, the charts in Figure 5-7 were produced. The reuse rate from the **REV** chart was replaced by the bank infiltration rate, in terms of cubic feet per hour per equivalent impervious acre. These charts could be used in the same way as the REV charts.

Probability Frequency Distribution for Pond Level

To increase an understanding of the pond storage level characteristics, a frequency distribution for the pond level was developed for several simulations using the Orlando data. The analysis was done for ponds with reuse volumes of 2.5 and 4.5 inches on the EIA that operated at 80 and 95 percent efficiency levels. Figures 5-8 and 5-9 show the percentage of



ORLANDO RAINFALL STATION
RATIO OF IMPERVIOUS AREA TO POND AREA = 9 : 1



PARRISH RAINFALL STATION
RATIO OF IMPERVIOUS AREA TO POND AREA = 9 : 1

Figure 5-7. Derivation of REV Chart with Reuse Replaced by Bank Infiltration through the Soil.

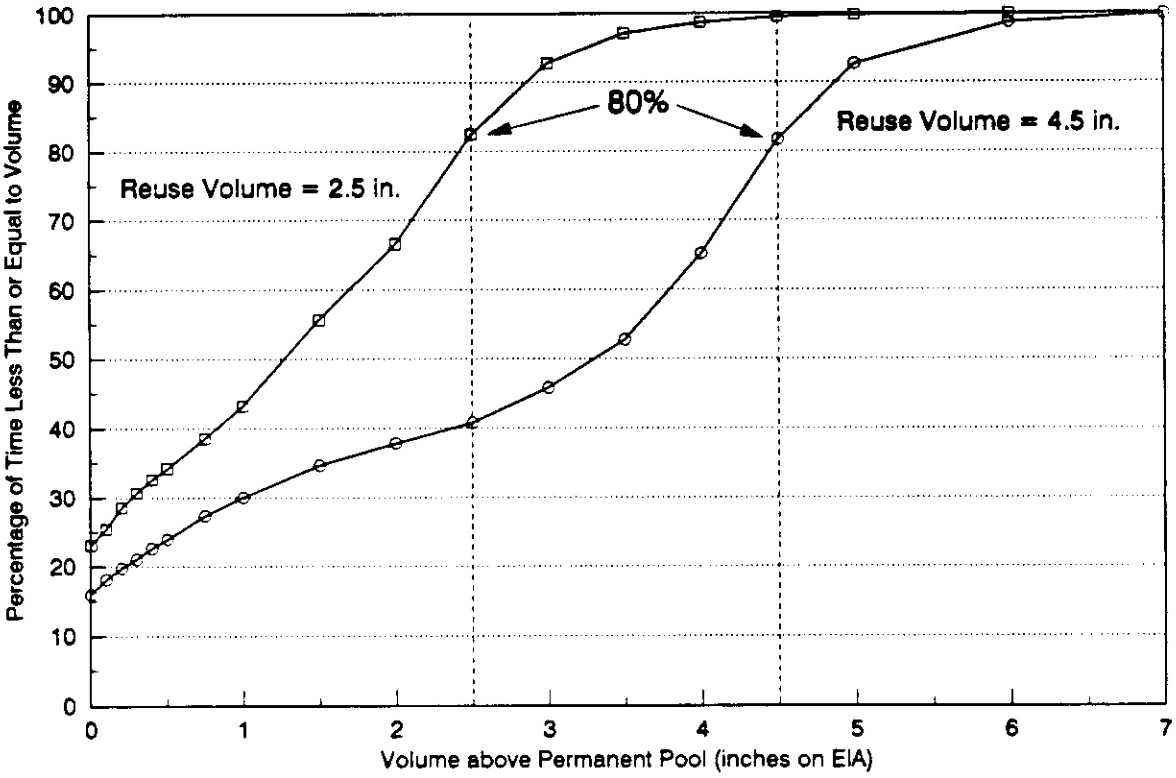


Figure 5-8. Frequency Distribution of Net Pond Level for 80 Percent Efficient Pond in Orlando, FL.

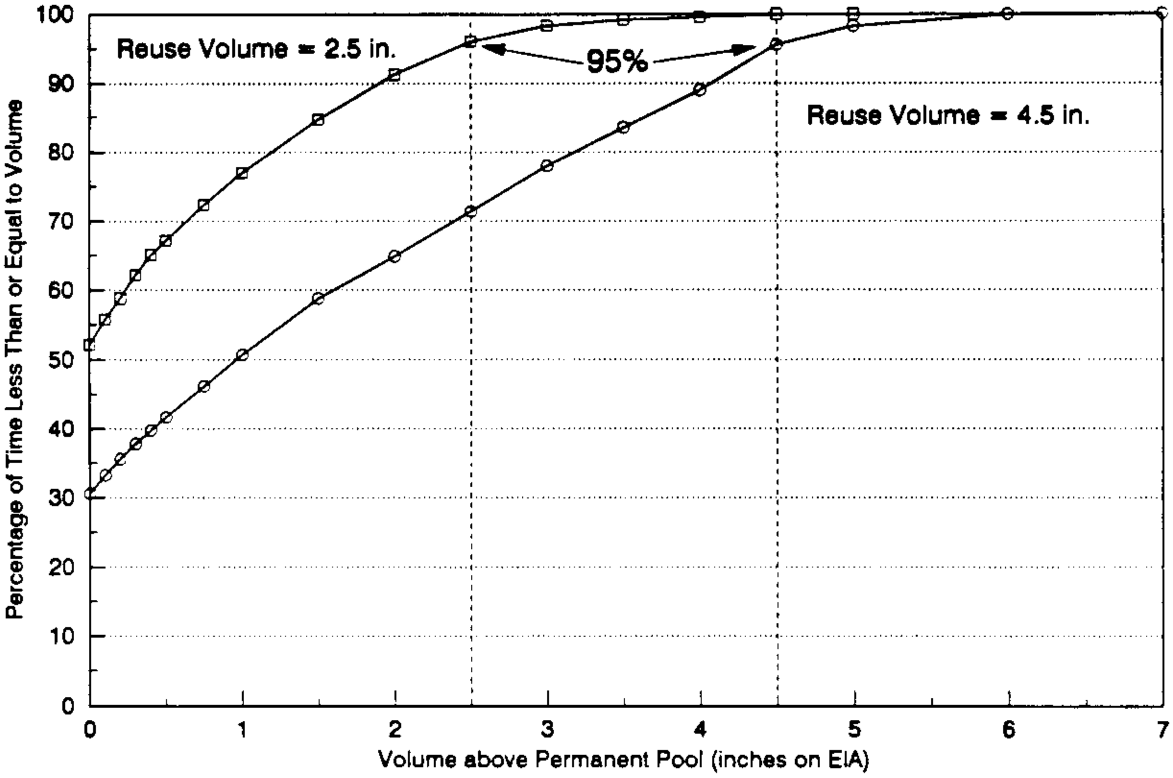


Figure 5-9. Frequency Distribution of Net Pond Level for 95 Percent Efficient Pond in Orlando, FL.

time that the volume above the permanent pool was less than or equal to a particular volume for ponds maintaining 80 and 95 percent efficiency, respectively. Since only four designs are illustrated, only general conclusions about pond designs in the Orlando area can be developed.

It can be seen that the volume above the permanent pool will be less than the reuse volume for the fraction of time approximately equal to the efficiency of the pond. For instance, a pond which discharges 20 percent of the volume of annual runoff will be in the act of discharging this volume less than or equal to 20 percent of the time.

As the reuse volume of a pond is increased, the percentage of time the volume above the permanent pool will be less than or equal to a particular volume is reduced. In other words, when a greater reuse volume is provided a greater volume above the permanent pool is generally maintained. The pond level does not exist near the permanent pool much of the time. For an 80 percent design efficiency the pond will be at the permanent pool level less than 25 percent of the time (Figure 5-8) and for a 95 percent efficiency, less than 55 percent (Figure 5-9). These relative frequencies may be a common occurrence with wet detention systems. A reuse volume of 2.5 inches on the EIA corresponds to a recommended standard for wet detention treatment volume (Wilkening, 1990). When using a design storm for sizing the flood control volume, the antecedent temporary storage volume is assumed to equal zero.

These conclusions assume that the permanent storage volume is not depleted.

By allowing the reuse system to utilize part of the permanent pool volume, a greater capacity would be available for the capture of large storm events and the efficiency would be enhanced. This could be visually expressed by shifting the x-axis on the graphs to the right by the amount of permanent pool being utilized for reuse, in inches on the EIA. For instance, to represent a pond in which the permanent pool can be depleted by one inch on the EIA, Figure 5-9 has been modified by shifting the axis in the amount of one inch on the EIA, thereby producing Figure 5-10. As a result, the time in which the pond volume was less than or equal to the permanent pool (zero temporary storage) rose from approximately 30 percent to 50 percent for the pond with a reuse volume of 2.5 inches. Thus, the probability of the pond level being at or near the permanent pool when a flood occurs has increased when water can be drawn from the permanent pool.

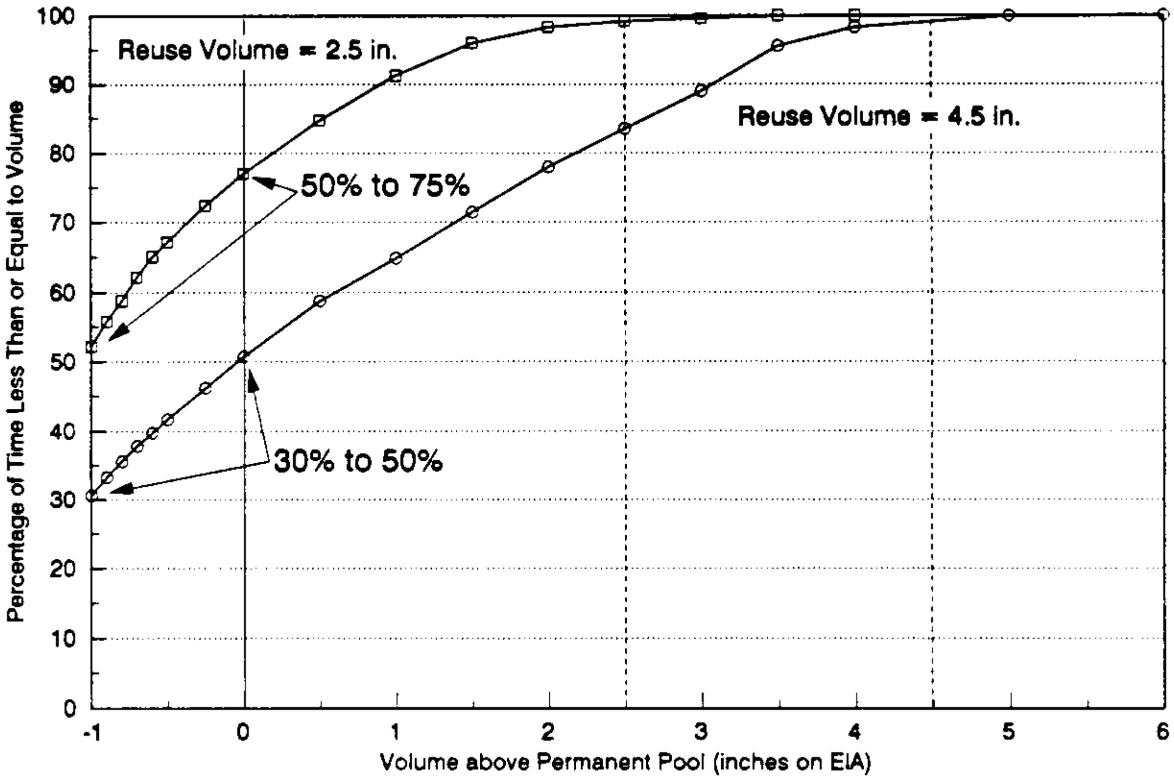


Figure 5-10. Frequency Distribution of Net Pond Level for 95 Percent Efficient Pond with Permanent Pool Reduced by Reuse in Orlando, FL.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The reuse of stormwater is both an environmentally and economically sound management practice. The current common practice is to release stormwater to adjacent surface waters from detention ponds using weirs and orifices. Frequently, if not all the time, this detained volume of water is greater than the volume of water released from the land in its natural condition. A fraction of this detained water can be reused within the watershed to (1) irrigate open areas, (2) recharge groundwater, (3) supplement water used for cooling purposes, (4) supplement car wash water, (5) enhance and create wetlands, and (6) supply water for agricultural users.

Currently, the most popular reuse method has been the irrigation of relatively open spaces, ex., golf courses, cemeteries, recreation areas, citrus groves and common areas of apartment complexes. The primary reason for these reuse systems is economics. Most irrigation systems use treated groundwater. An alternative to the use of groundwater is detained stormwater. Treated groundwater cost on the average about $1.00/thousand gallons. A golf course of 100 acres using treated groundwater at a cost of $1.00/thousand gallons and irrigating at 2 inches per week would pay over

$300,000/year for the irrigation. Using detained stormwater, the irrigation system yearly cost is less than $40,000.

In this report,continuous modeling for reuse ponds was completed and was based on a mass balance using area specific rainfall data to develop design criteria for stormwater reuse ponds. The design procedure relates pond temporary storage (reuse volume) to reuse rate and a percent reuse of the runoff water and is expressed as a **REV** curve. The mathematical equations for the curves have been computer coded.

The **REV** curves can be utilized for various watershed sizes or runoff coefficients. They may be used to determine the reuse rate, the reuse volume, or the efficiency of a pond. Supplemental water needs in a hydrologic balance also can be estimated. The **REV** charts presented in this report will facilitate the rational design of stormwater reuse systems throughout the State of Florida.

Geographic Variability

Table 6-1 indicates the geographic variability of the reuse rates necessary to achieve stated efficiencies and reuse volumes. For example, an efficiency of 80% and a reuse volume of 3.0 inches on the EIA produced reuse rates ranging from 0.126 to 0.226 inches per day on the EIA which were for the regions of Lisbon and Fort Myers, respectively. The results are functions of the site specific rainfall characteristics.

Table 6-1. Comparison of Reuse Rates for given Reuse Volumes and Efficiencies.

Station	Reuse Rate			
	3.0[a]/80%	4.5/80%	4.5/95%	6.0/95%
Apalachicola	0.173[b]	0.151	-	0.291
Belle Glade	0.135	0.120	0.200	0.180
Daytona Beach	0.143	0.127	0.228	0.196
Fort Myers	0.226	0.202	-	-
Gainesville	0.130	0.113	0.221	0.185
Grady	0.152	0.136	0.220	0.190
Homestead	0.216	0.191	-	-
Inglis	0.171	0.147	0.277	0.241
Jacksonville	0.138	0.124	0.240	0.204
Key West	0.132	0.111	-	0.293
Lakeland	0.171	0.152	0.261	0.231
Lisbon	0.126	0.114	0.180	0.162
Marineland	0.127	0.115	0.194	0.162
Melbourne	0.128	0.115	0.195	0.159
Miami	0.190	0.173	-	0.273
Moore Haven	0.170	0.149	-	0.212
Niceville	0.197	0.176	-	0.278

[a] Volume in inches on EIA.
[b] Rate in inches on EIA per day.

Table 6-1. Continued

Station	Reuse Rate			
	3.0[a]/80%	4.5/80%	4.5/95%	6.0/95%
NNR Canal 2	0.152	0.133	0.231	0.202
Orange City	0.170	0.151	0.250	0.228
Orlando	0.152	0.136	0.215	0.194
Parrish	0.183	0.159	0.290	0.259
Tallahassee	0.191	0.169	0.288	0.243
Tampa	0.152	0.136	0.263	0.231
Vero Beach	0.160	0.142	0.293	0.227
West Palm Beach	0.198	0.172	-	0.256

[a] Volume in inches on EIA.
[b] Rate in inches on EIA per day.

Design Goals

When using **REV** charts it must be understood that an 80 percent efficiency translates into an 80 percent reduction in annual discharge volume. This information may be used with two goals in mind: 1) the preservation of an existing water budget, and 2) the reduction of pollutant mass loading to receiving surface waters.

Recommendations

Water Budget

Stormwater systems are constructed to maintain the pre-existing runoff characteristics of a watershed. The increase of runoff rate is immediately recognized as a problem but a reduction in total volume to receiving waters should also be avoided. **REV** charts should be used to control the average annual volume discharged from the watershed.

For example, the flow rate recorded in a stream from an undisturbed watershed that receives 52 inches of annual rainfall may be estimated to be 1.0 $ft^3/s/mile^2$. This is equivalent to 13.6 inches/year. A developed area that is 50% EIA with no stormwater controls and assuming there is no contribution from pervious areas, would produce 26 inches/year of runoff, or half of the rainfall. This value must be reduced by approximately 50 percent to meet the pre-condition and may be done so by obtaining a 50 percent efficiency.

Pollutant Mass Standards

REV charts may be used for the design of reuse systems that meet the 80 and 95 percent reduction of annual pollutant mass loadings. The average annual mass removal associated with wet detention may be assumed to be about 60 percent (USEPA, 1983). A pond which reuses 50 percent of annual runoff will remove from discharge all of the mass in the volume that is reused. If the remaining stormwater has a 60 percent mass reduction before discharge, the overall average annual mass reduction is equivalent to 80 percent.

$$0.50\ (1.0) + 0.50\ (0.60) = 80\%$$

Likewise, a pond operating at a 90 percent volume efficiency will treat 100 percent of the volume reused and 60 percent of the volume discharged. This amounts to an overall removal of 96 percent:

$$0.90\ (1.0) + 0.10\ (0.60) = 96\%$$

Thus, average annual mass pollutant removal standards may be met, depending on the degree of treatment by detention, by achieving significantly lower discharge volumes.

Pond Control Elevations

The surface water discharge elevation of the pond is the top of the reuse volume and it must be above the average groundwater table elevation. If the control is below the groundwater table, groundwater will be drained from the watershed. The groundwater level for a region changes throughout the year. Thus, for a conservative design with respect to percentage of runoff discharged using the **REV** charts, it is recommended that designers follow the guidelines of the Water Management Districts in placing the top of the permanent pool at or near the seasonal high water table (Wilkening, 1990). Also, flood control reliability can be improved if part of the permanent pool is reused.

Addition of Pond Area to EIA

The approximate area of the reuse pond should be included in the calculation of the equivalent impervious area of the watershed when using **REV** charts. This action considers the rainfall on the pond and produces more conservative design results.

Bank Infiltration

A reuse pond was modeled such that there was a daily output from the pond in the form of reuse water. However, this output could actually be in a different form or a combination of outputs. A practical use of this idea is the consideration of bank infiltration as being part of the regulated output (reuse). If infiltration is expected to occur at a known rate, this rate can be converted to the units of inches per day on the EIA. This value can then be subtracted from the required reuse rate for a design to obtain the portion of output that must be done mechanically.

Quantity of Groundwater Supplement

Most ponds may require some degree of storage supplement during periods of low rainfall if the reuse rate remains constant. The choice of pond size and reuse rate will have an affect on the volume of groundwater, or other sources, needed for supplement. Generally, a greater reuse rate will require more supplement. Efforts should be made to minimize to the use of groundwater.

Timing Controls

An irrigation system will operate on a timer, most likely switching the pumps on and off at an established interval of time. During periods when excessive rain and rainfall excess is common, it might be desirable not to irrigate. During other times of the year, irrigation should occur in the early mornings or late evenings when there is minimum evaporation and transpiration. The reuse rate may also be reduced to conserve water.

Use of The **REV** Curves

The **REV** curves provide the designer with many options for the reuse pond size and the rate of reuse that can be examined in relation to economic considerations. It is recommended that the **REV** charts be used for stormwater reuse systems design. The **REV** chart at the location closest to your project location should be used. When doubt exists as to the **REV** chart to use, pick the one within the NOAA climatic division which is closest to the site of your project (see Figure 3-5).

Implementation

A stormwater detention pond with an irrigation system designed according to the Orlando **REV** chart is being constructed in Winter Park, Florida. Instrumentation will monitor all aspects of the water budget. The results will enhance the present understanding of reuse systems and provide data for verification of the design approach.

APPENDICES

APPENDIX A

CELL EQUATIONS OF MODEL

CELL EQUATIONS OF MODEL

(refer to Figure 3-2)

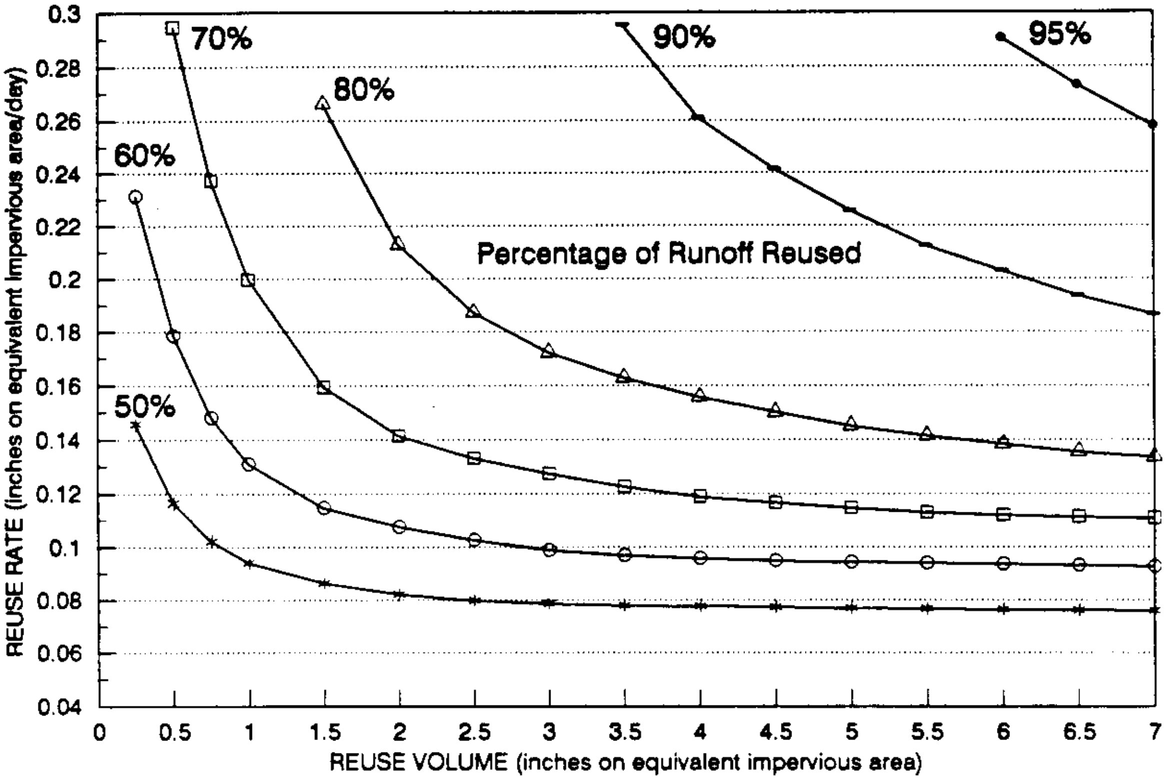
CELL ADDRESS (column/row)	TITLE	FORMULA
A6	EVENT	2
B6	DATE	27155 (# days since 01/01/1900)
C6	DRY	(B7-B6-1)
D6	RAIN	0.77
E6	RUNOFF	(D6)
F6	REUSE	(N$4*(C5+1))
G6	Poten.	(2*(C5+1))
H6	Actual	@IF(J5>N$5,@IF(E6>J5-N$5,J5-N$5,E6),0)
I6	SUPLMNT	(J6-(J5+E6-F6-H6))
J6	NET	@IF(J5+E6-F6-H6<0,0,J5+E6-F6-H6)

N$4 = reuse rate (varied)
N$5 = reuse volume (varied)

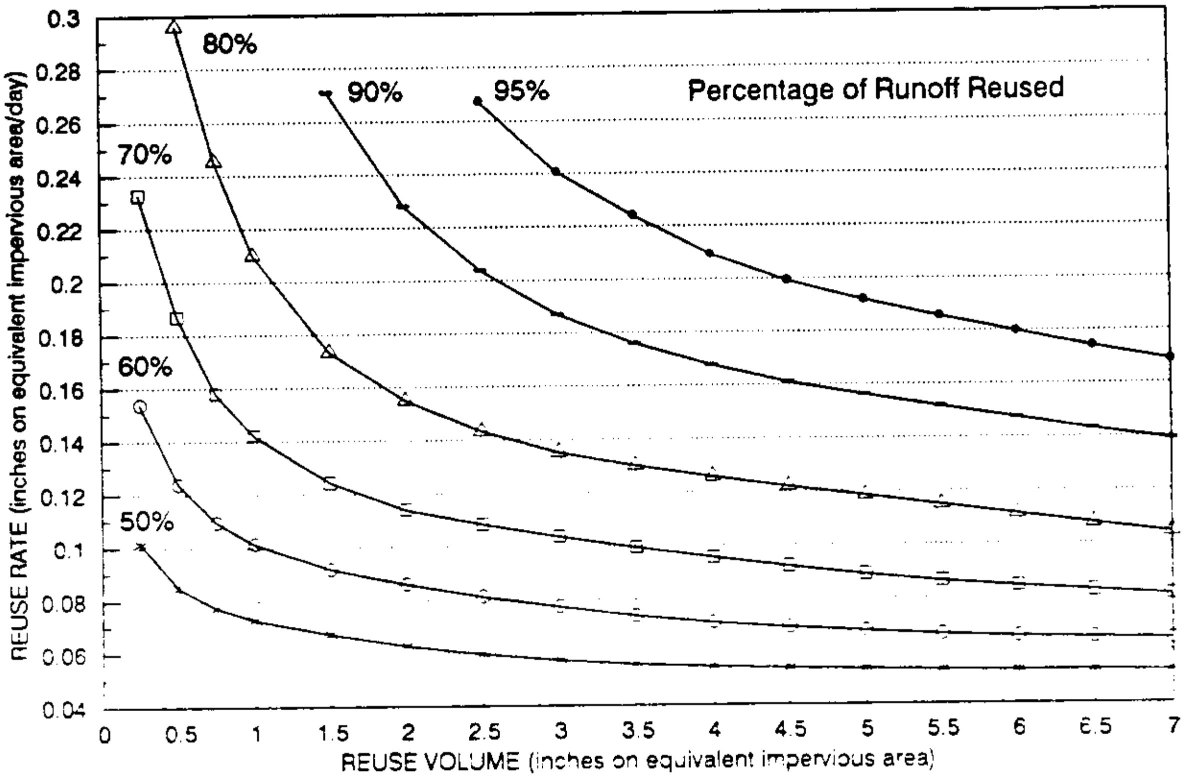
FORMAT: @IF(condition,then,else)

APPENDIX B

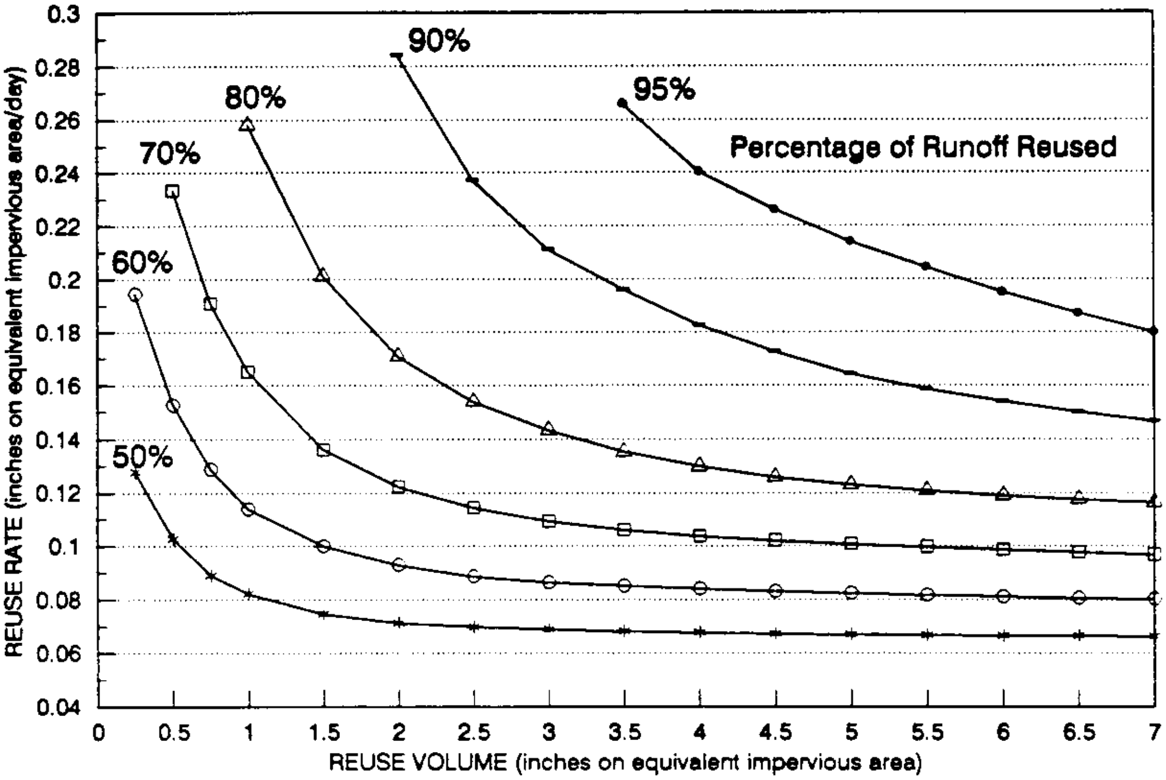
REV CHARTS FOR FLORIDA



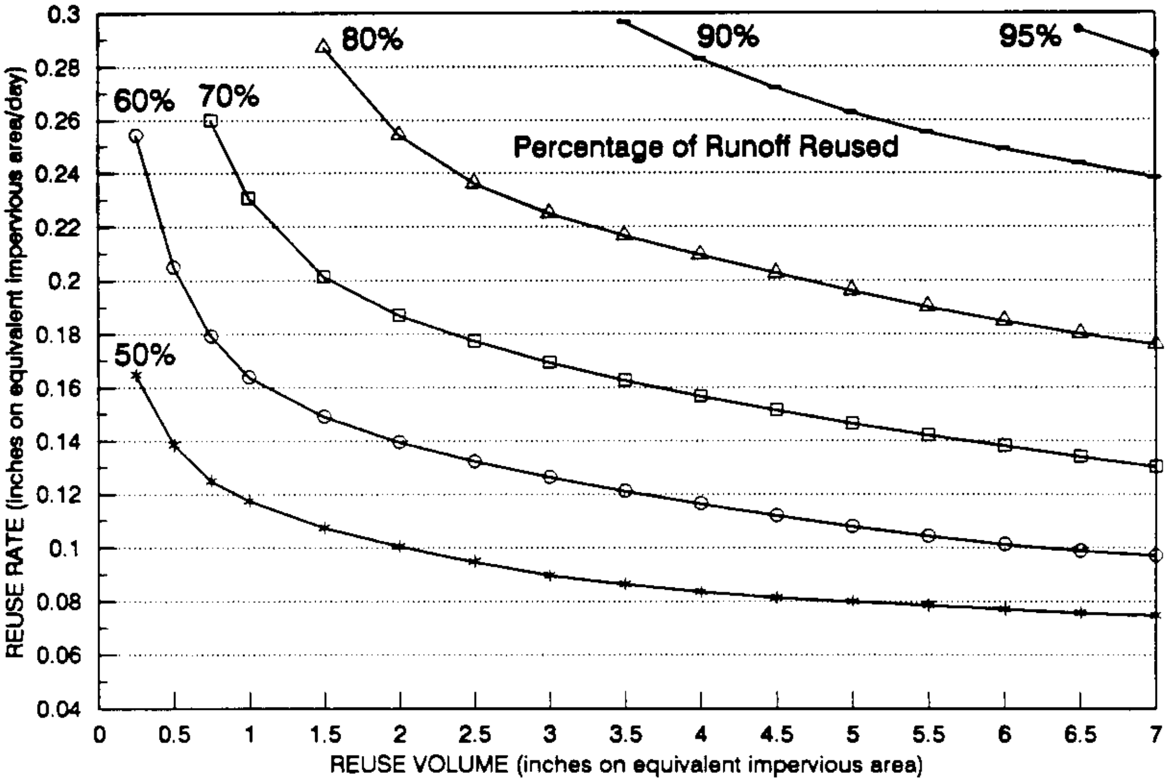
APALACHICOLA RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 55.59 in



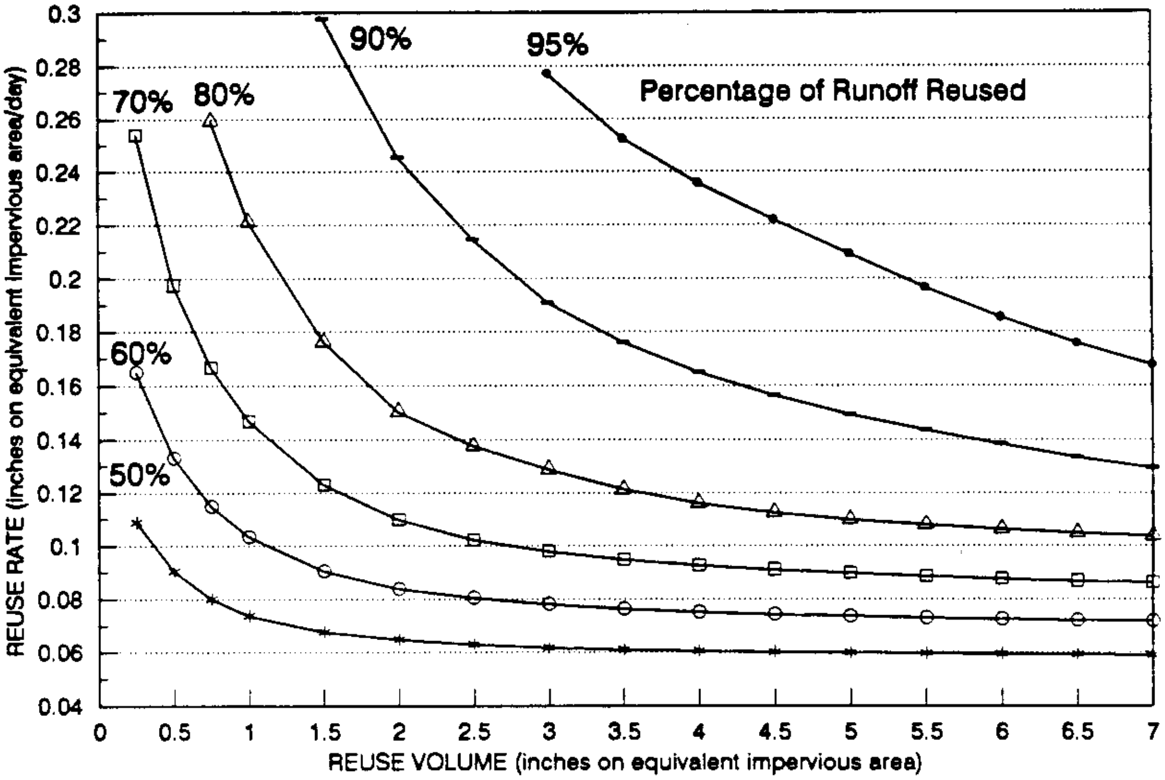
BELLE GLADE RAINFALL STATION
MAY 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 37.9 in.



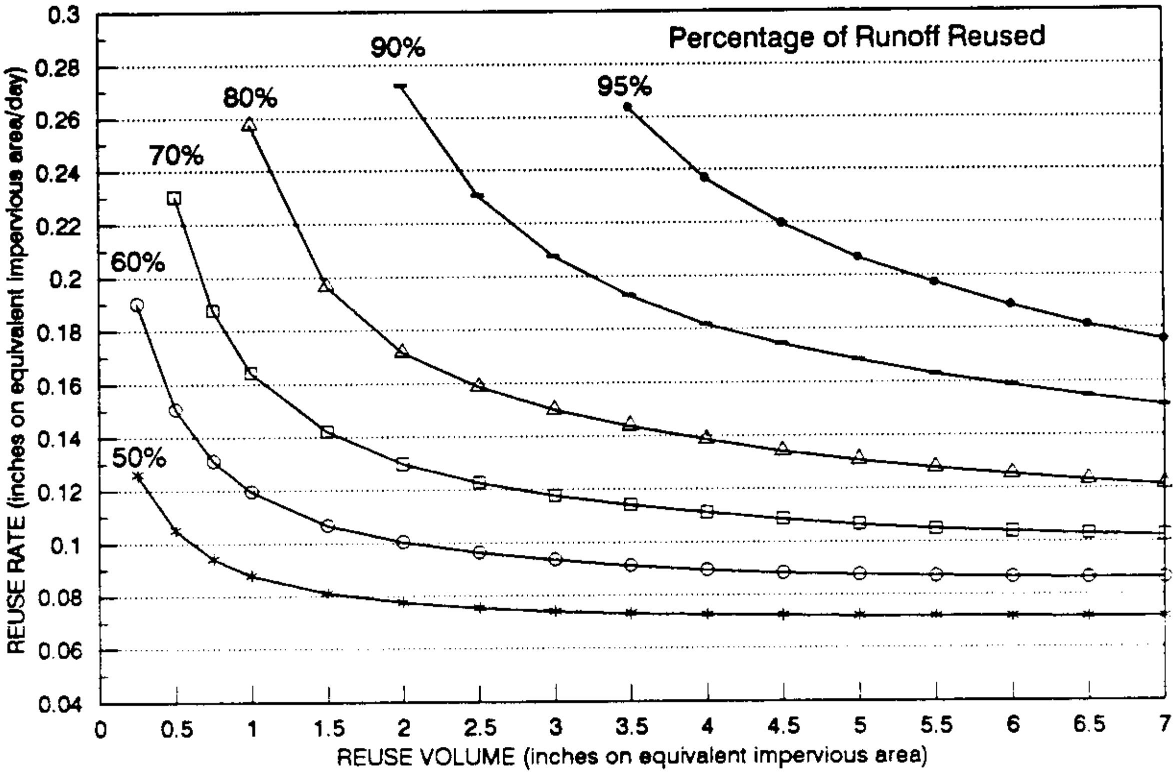
DAYTONA BEACH RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 48.69 in



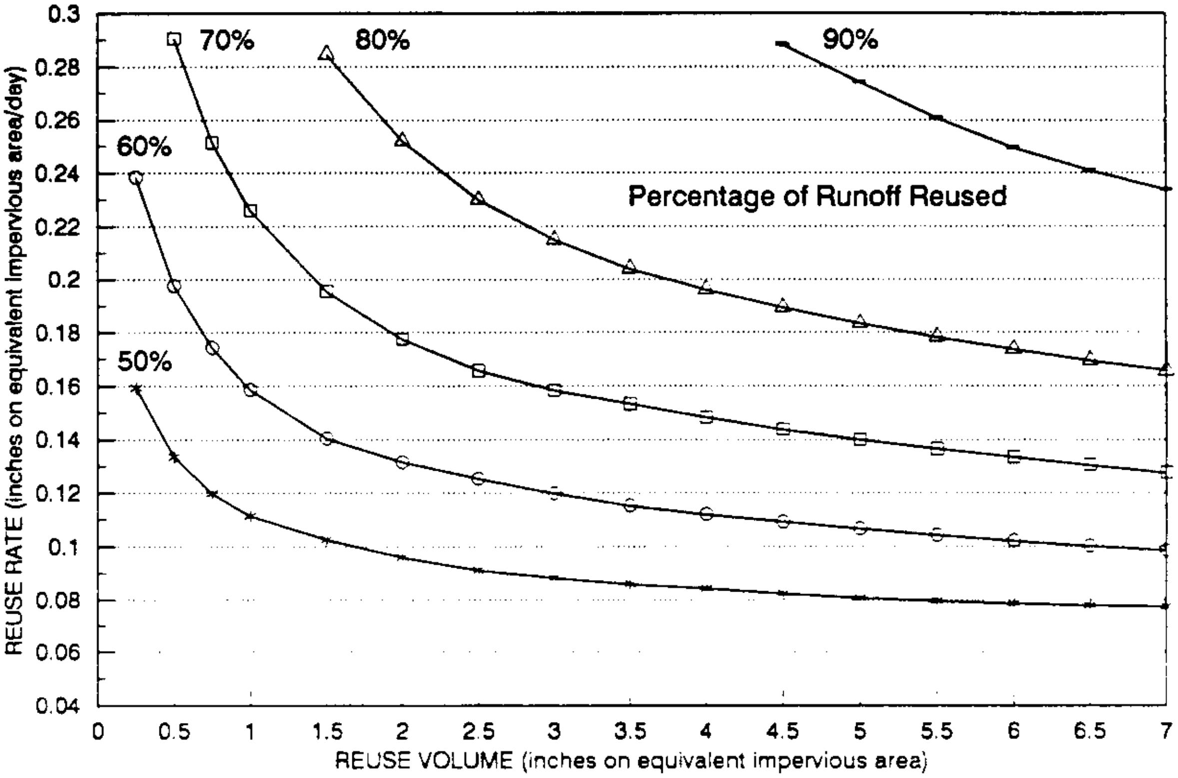
FT. MYERS RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 50.55 in



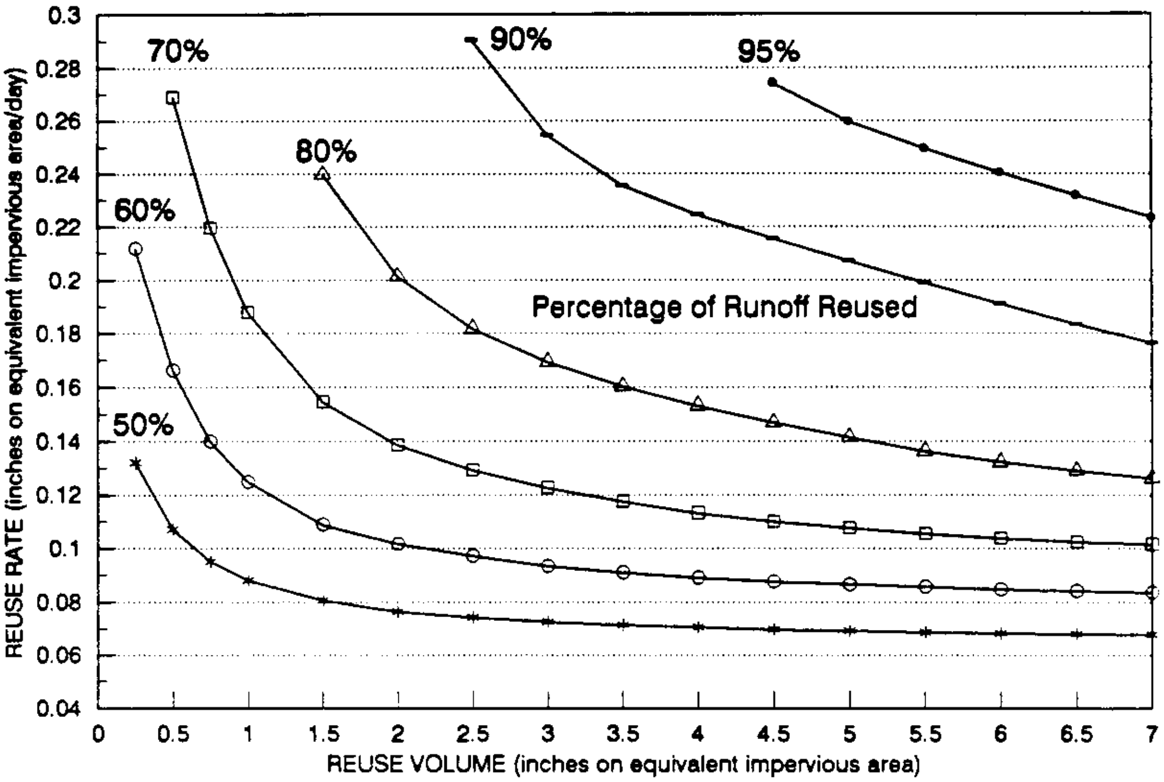
GAINESVILLE RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 43.23 in



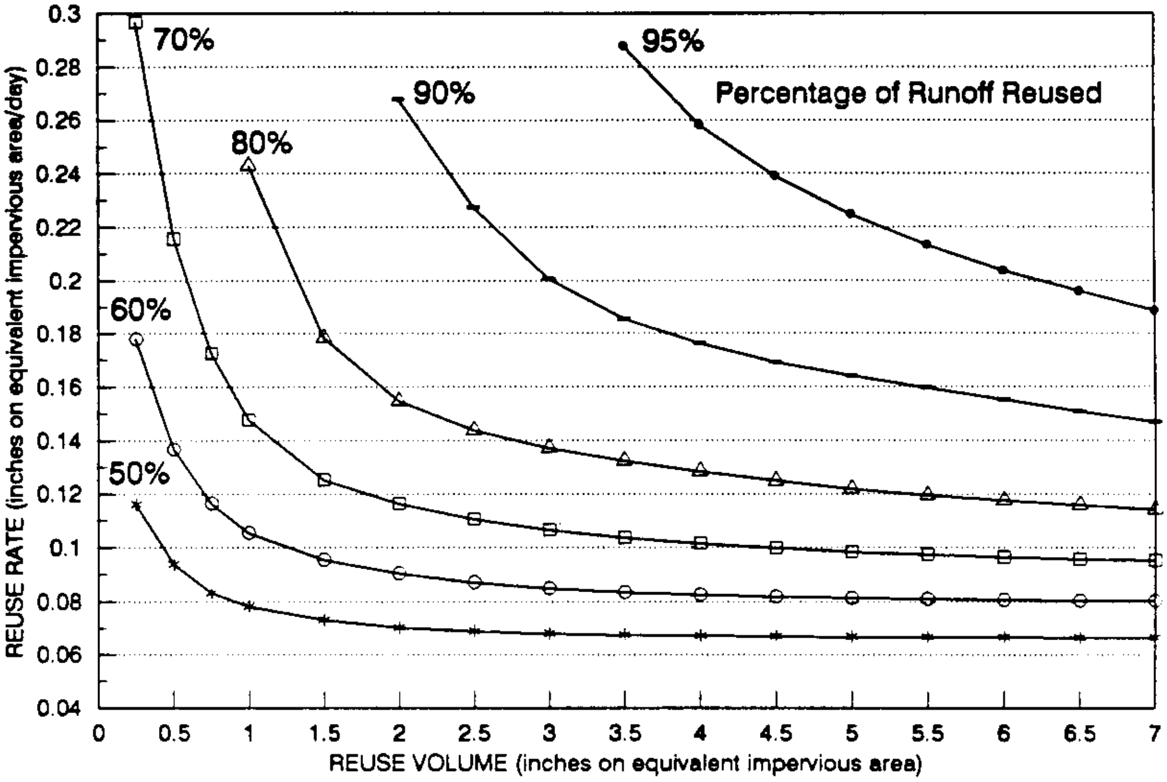
GRADY RAINFALL STATION
MAY 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 52.6 in.



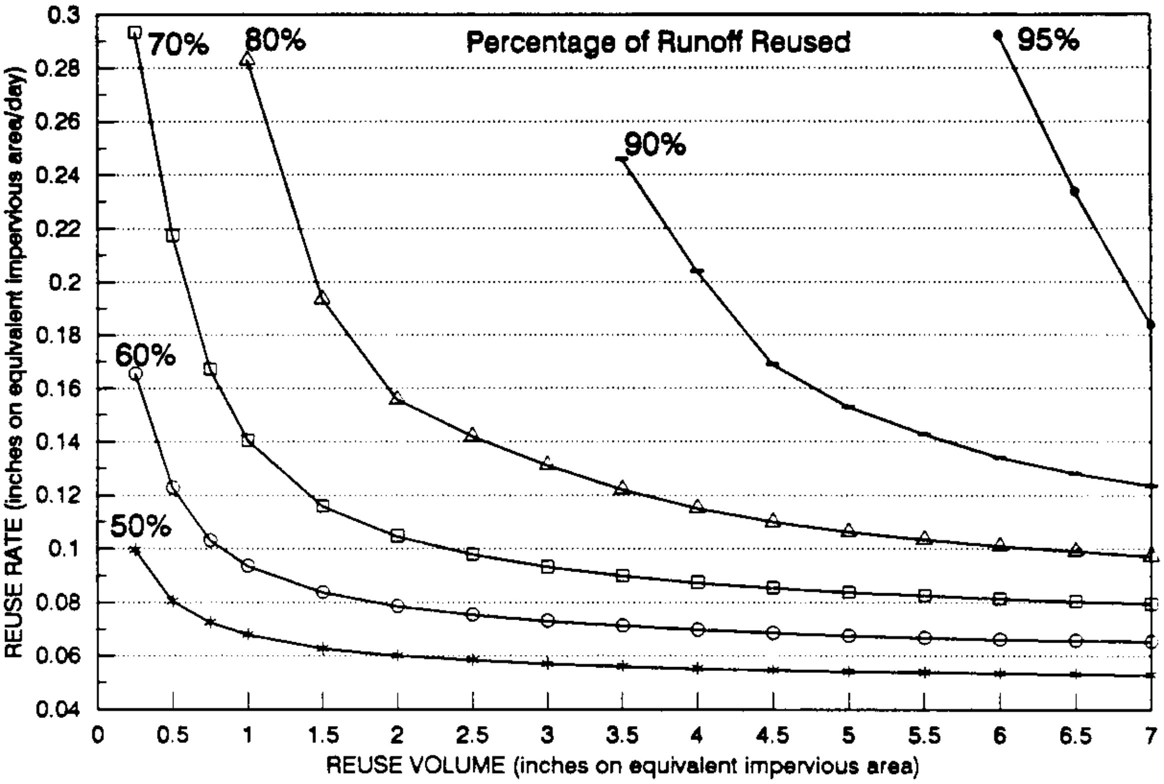
HOMESTEAD RAINFALL STATION
MAY 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 53.5 in.



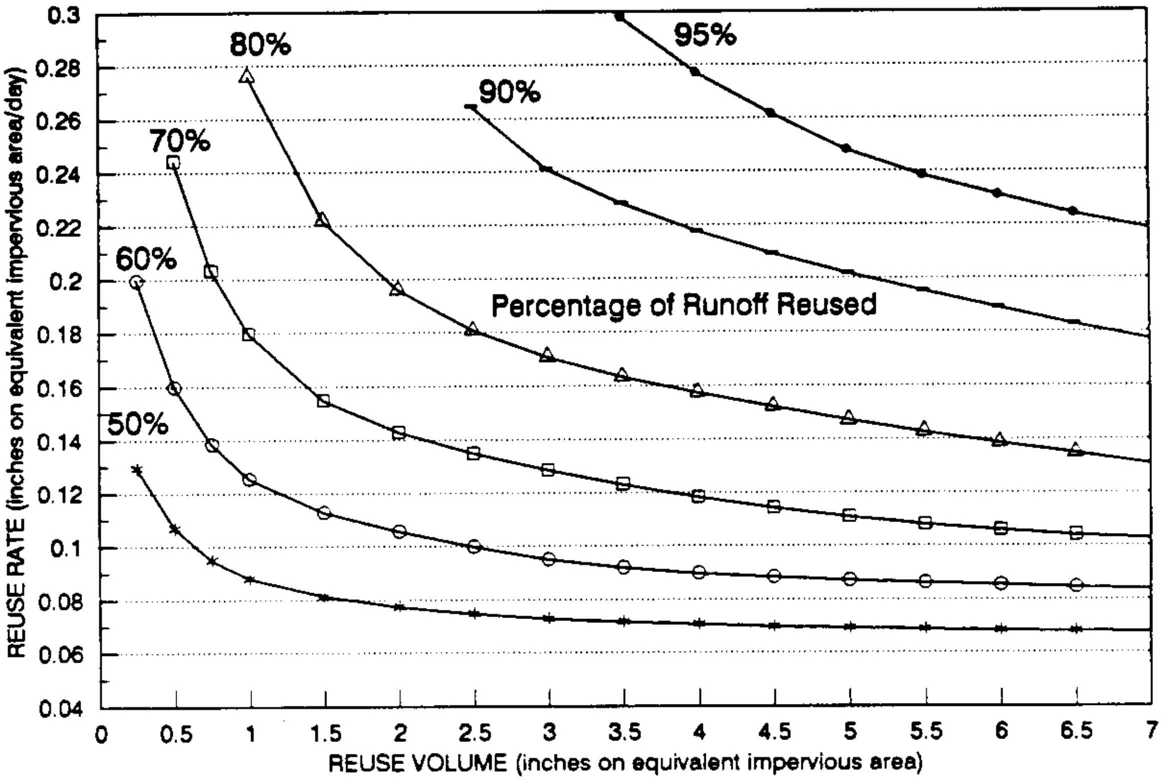
INGLIS RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 49.43 in



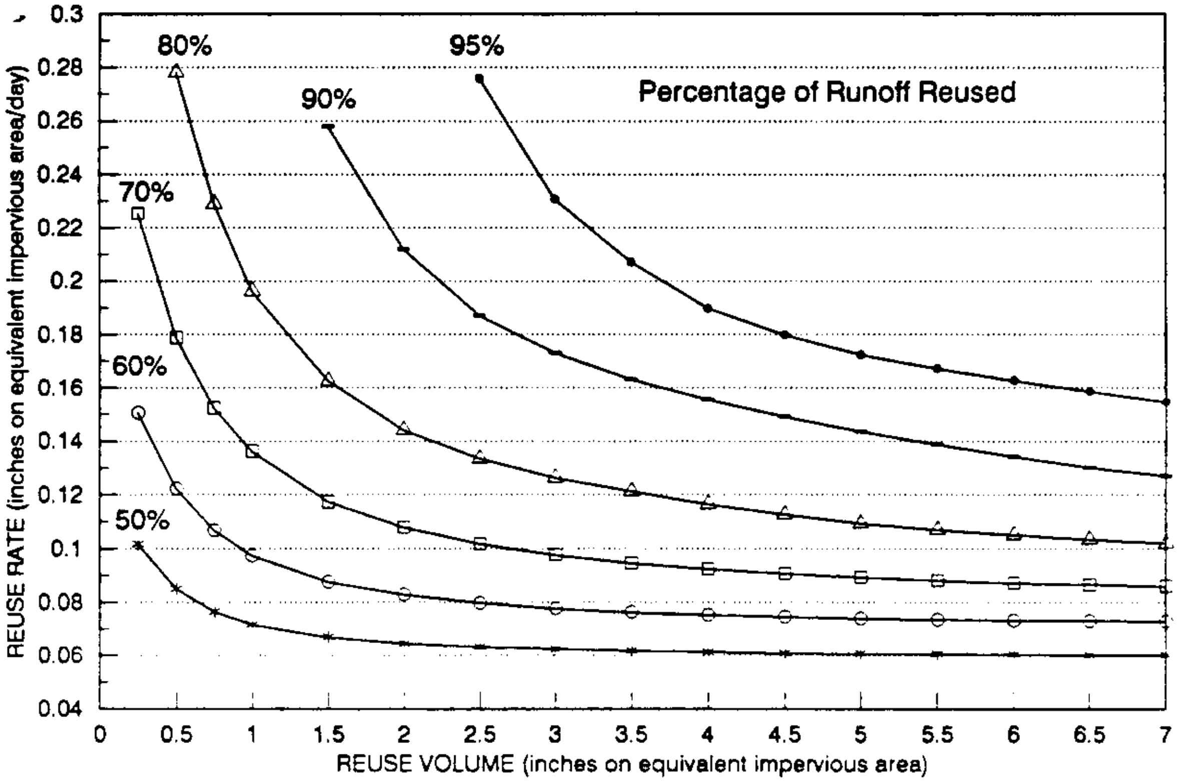
JACKSONVILLE RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 48.9 in



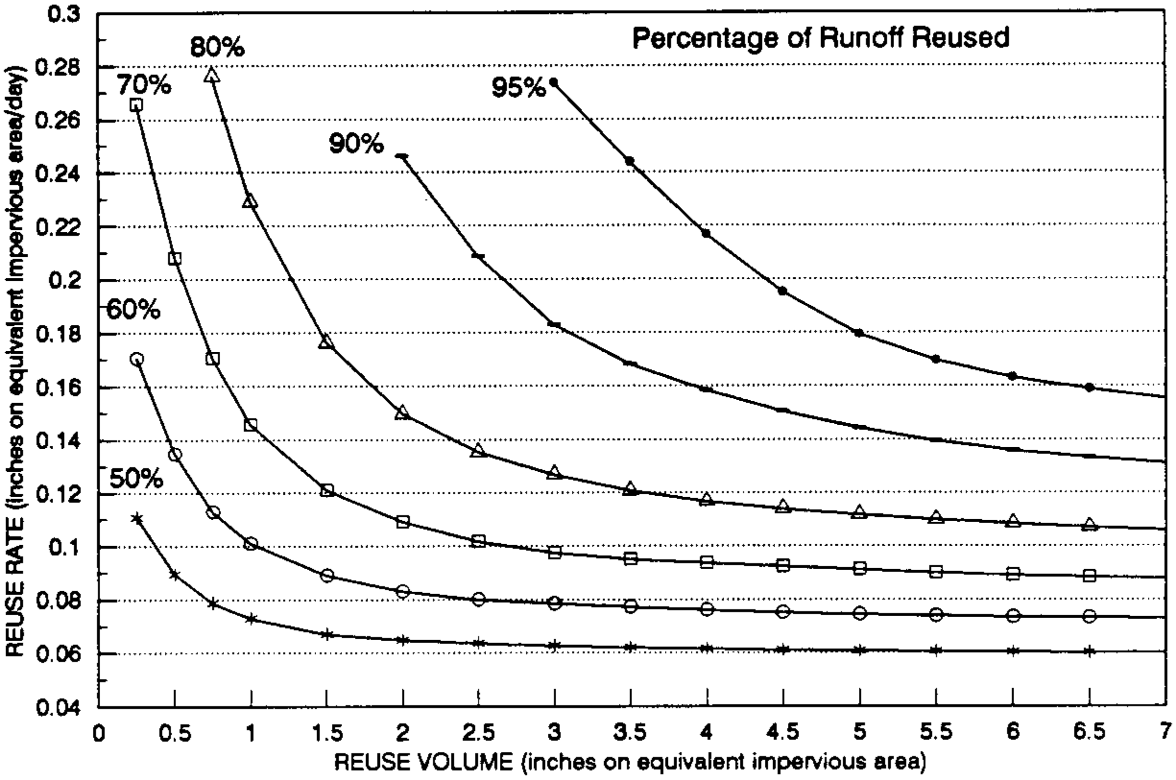
KEY WEST RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 38.51 in



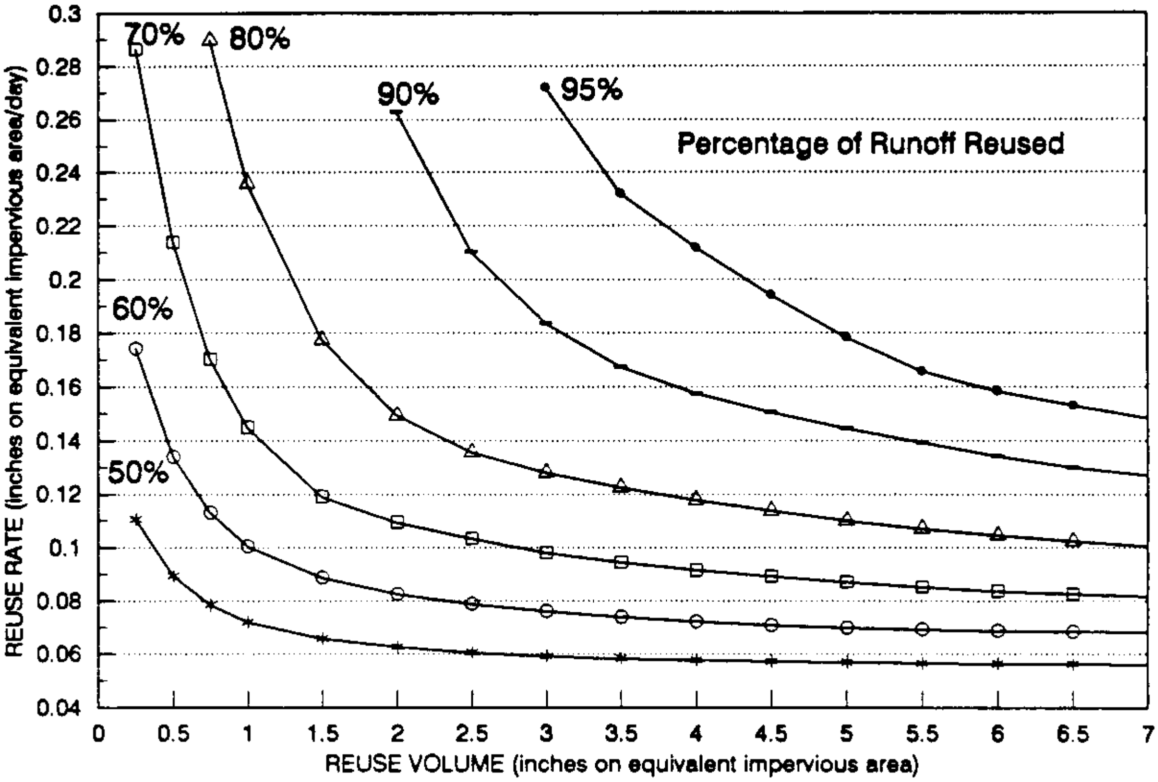
LAKELAND RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 49.58 in



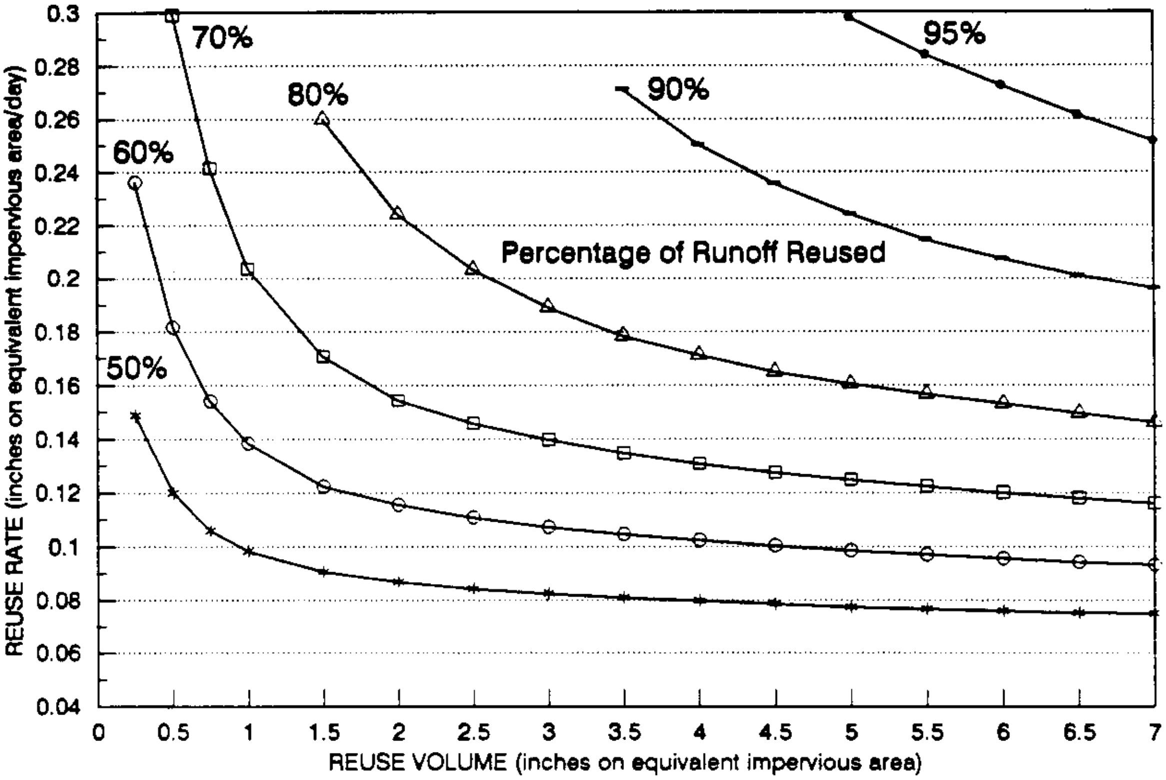
LISBON RAINFALL STATION
MAY 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 43.9 in.



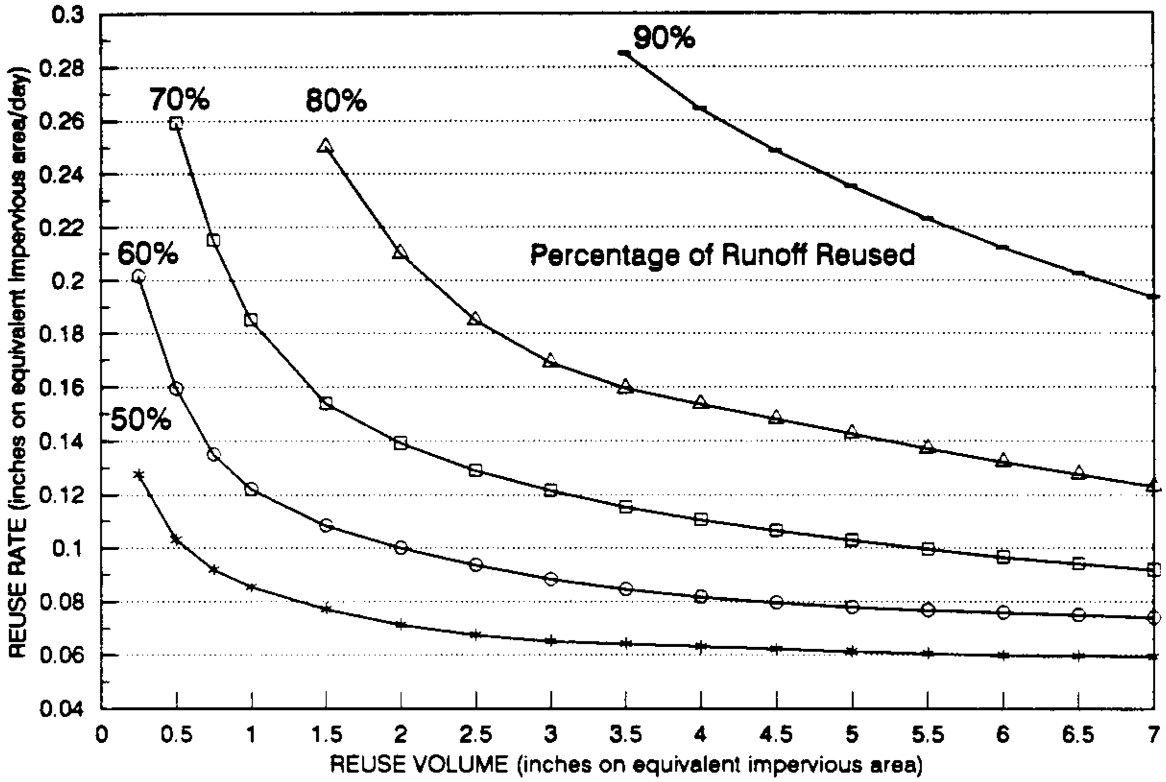
MARINELAND RAINFALL STATION
MAY 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 44.3 in.



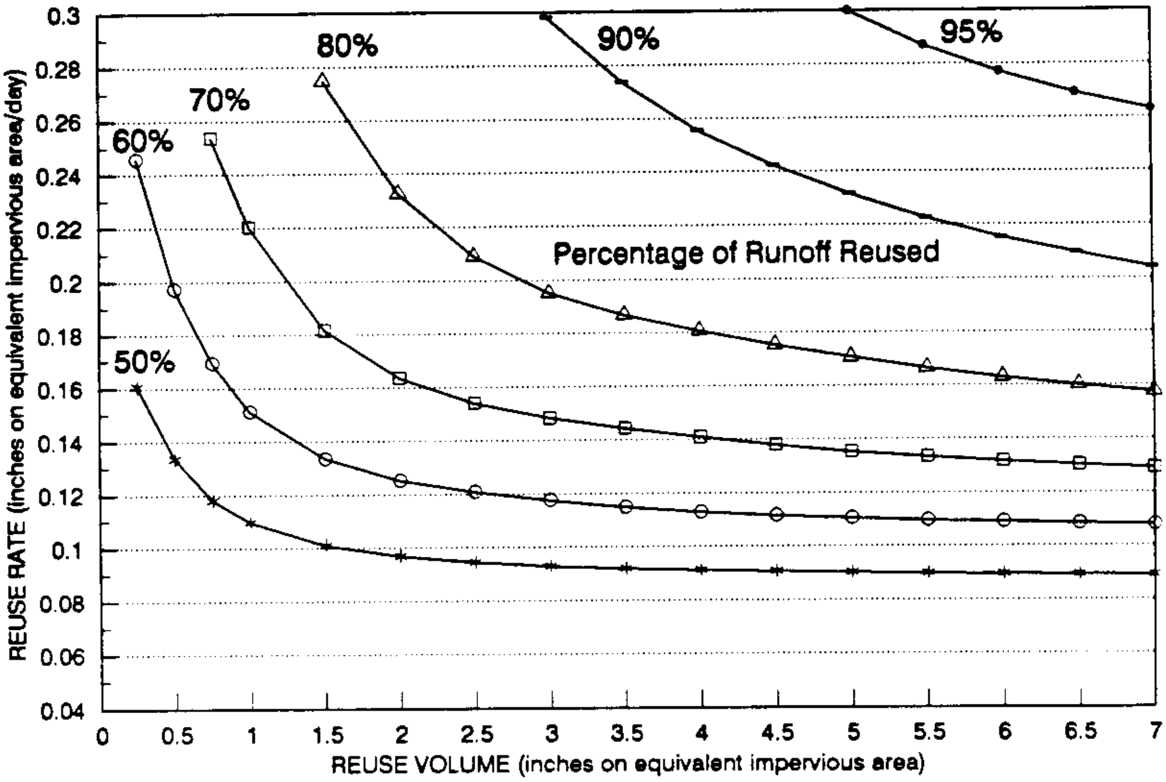
MELBOURNE RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 40.82 in



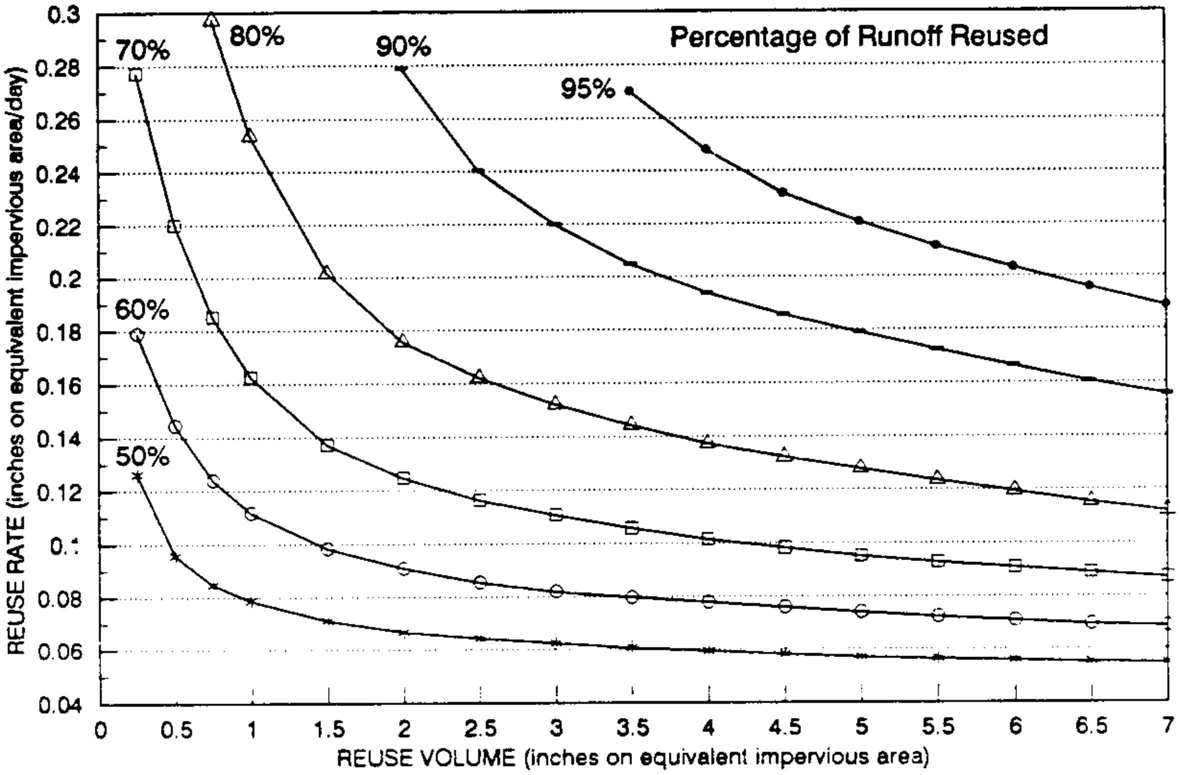
MIAMI RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 54.5 in



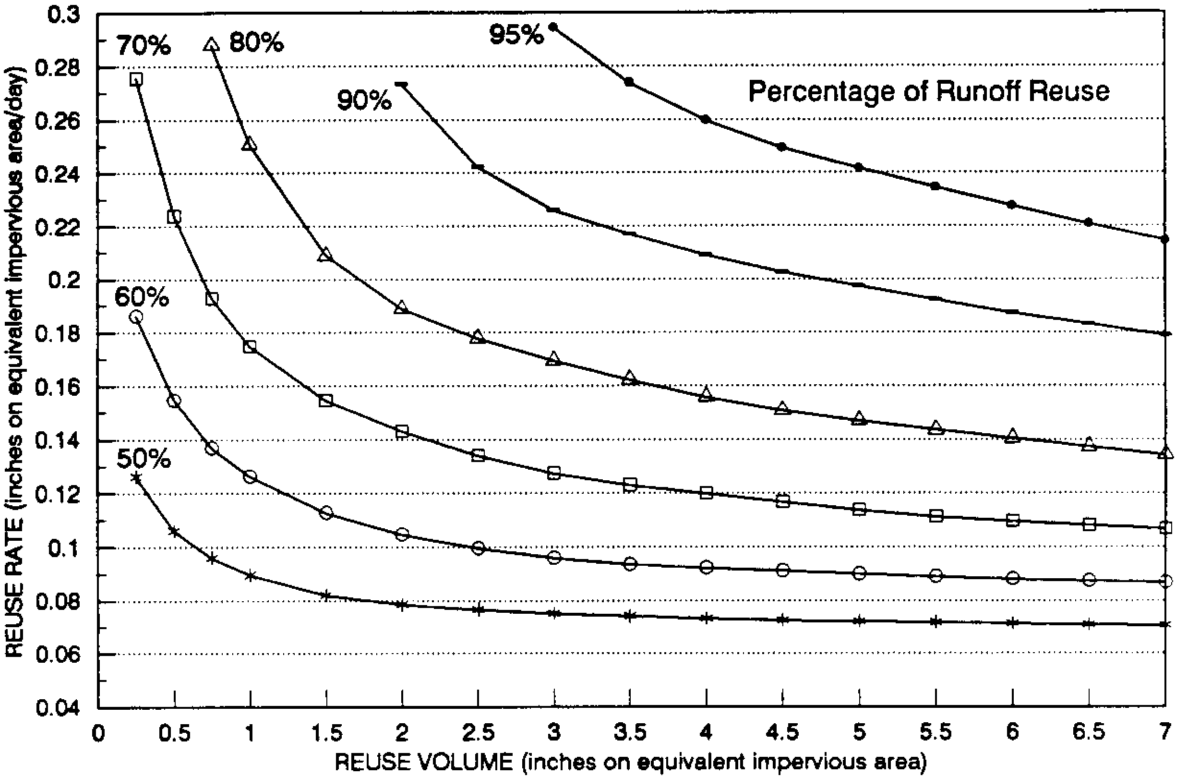
MOORE HAVEN RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 43.18 in



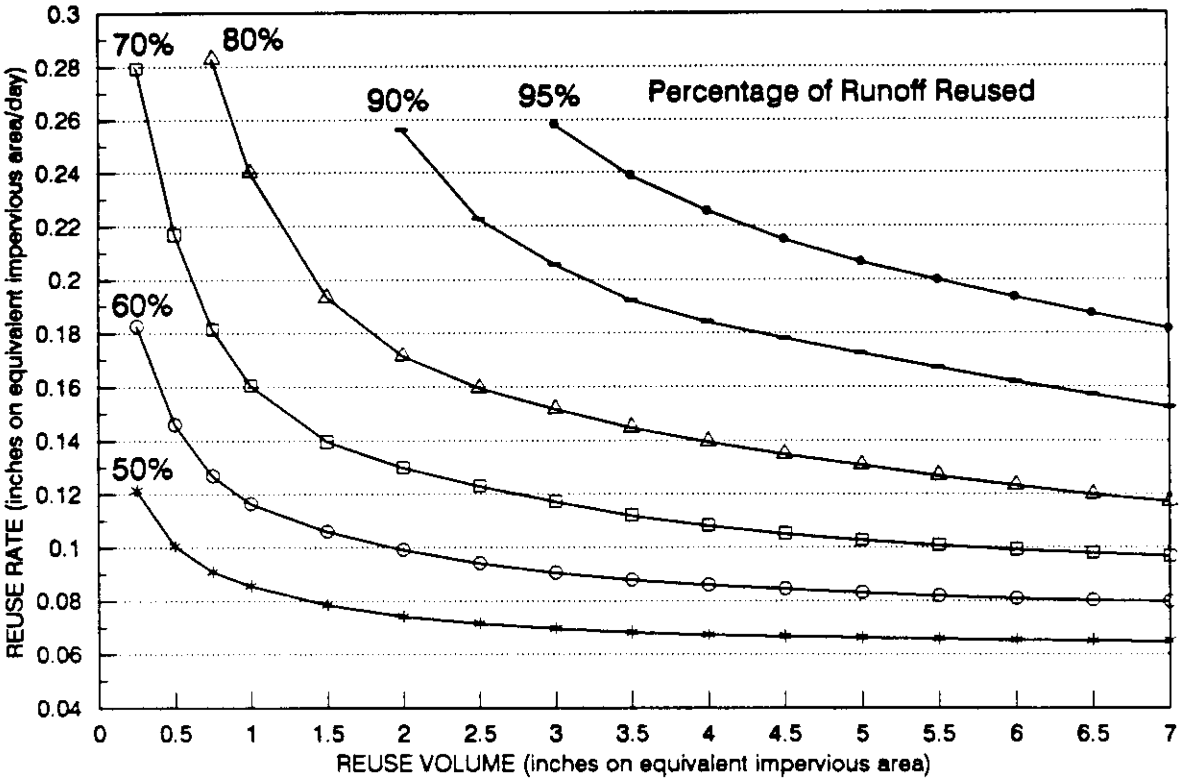
NICEVILLE RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 65.69 in



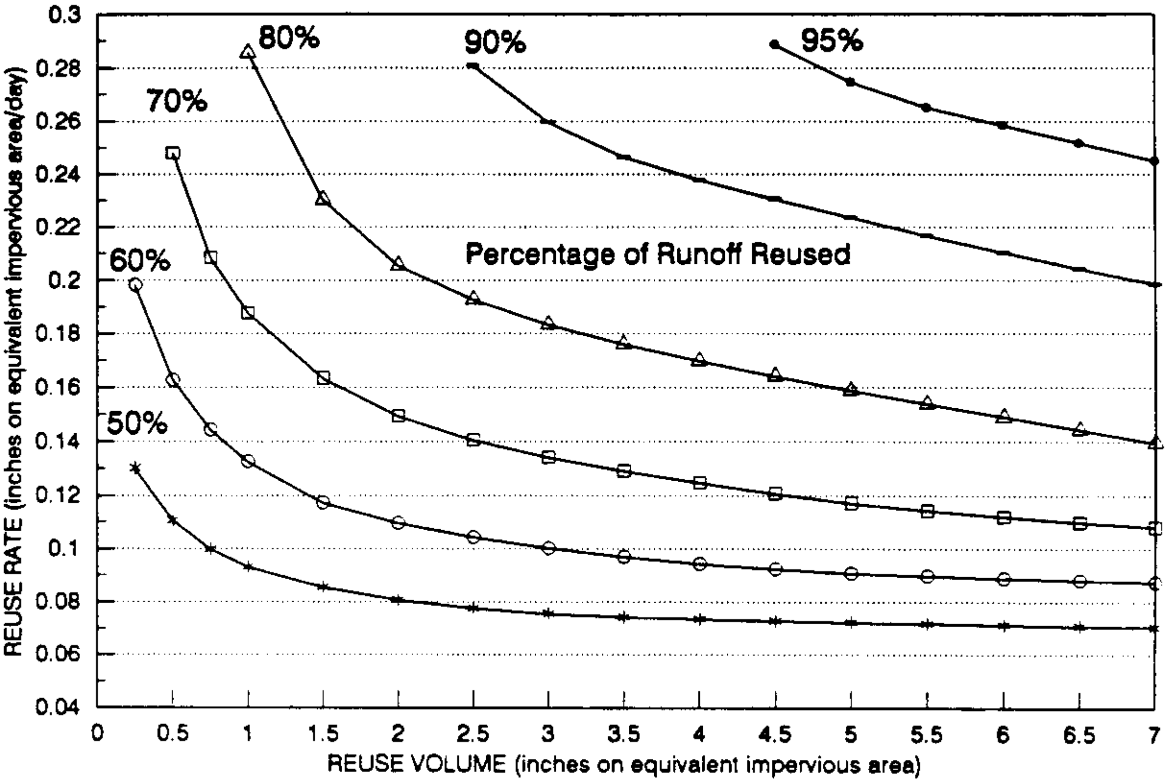
NORTH NEW RIVER CANAL 2 RAINFALL STATION
MAY 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 39.1 in.



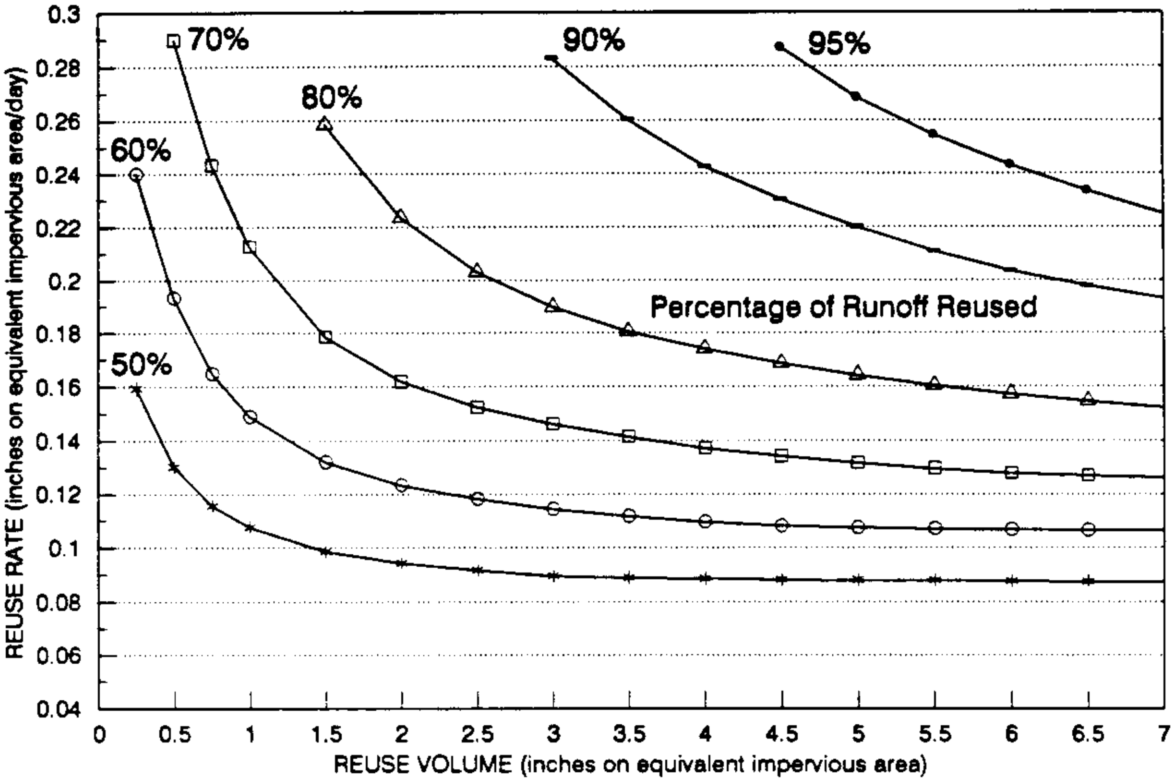
ORANGE CITY RAINFALL STATION
MAY 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 41.7 in.



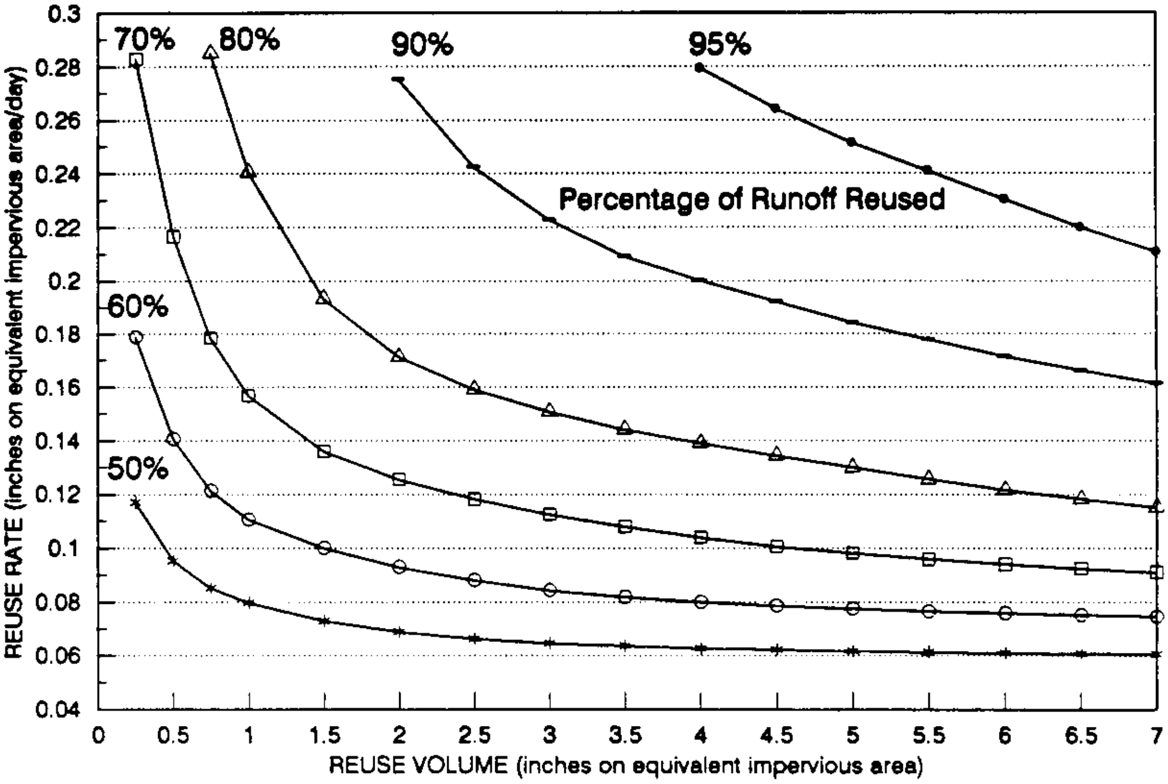
ORLANDO RAINFALL STATION
MAY 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 48.2 in



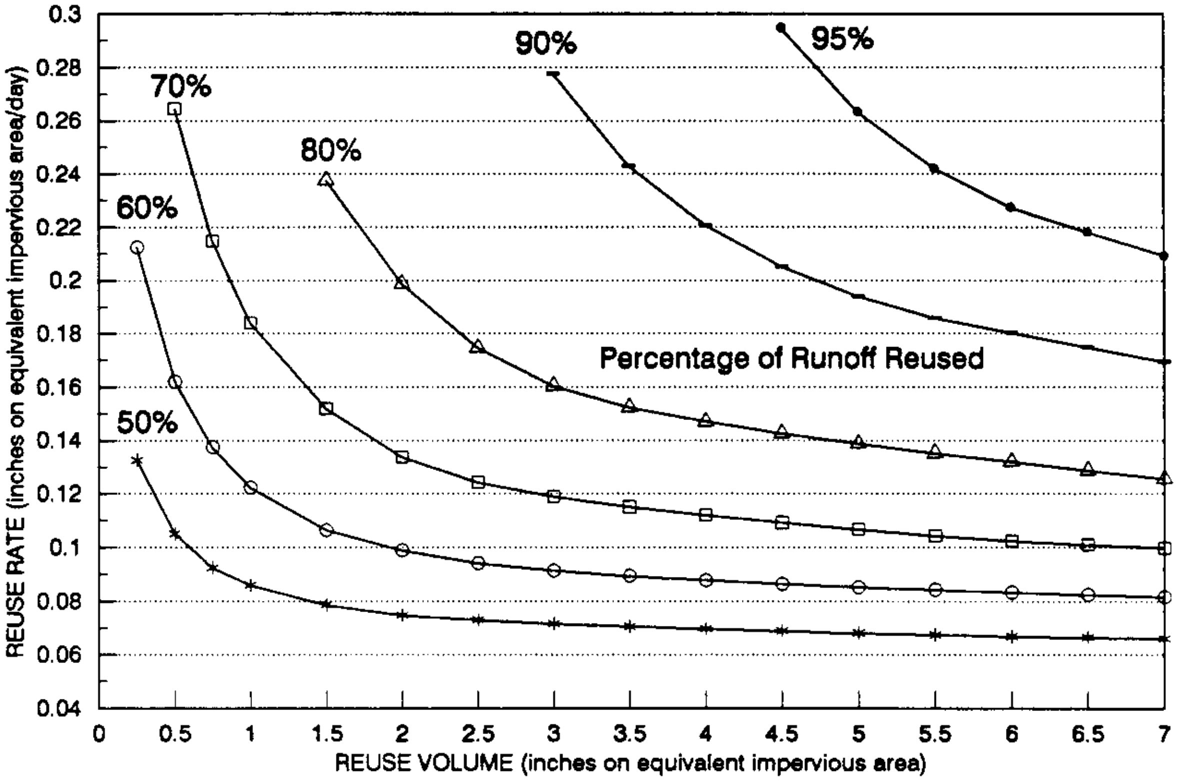
PARRISH RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 51.0 in



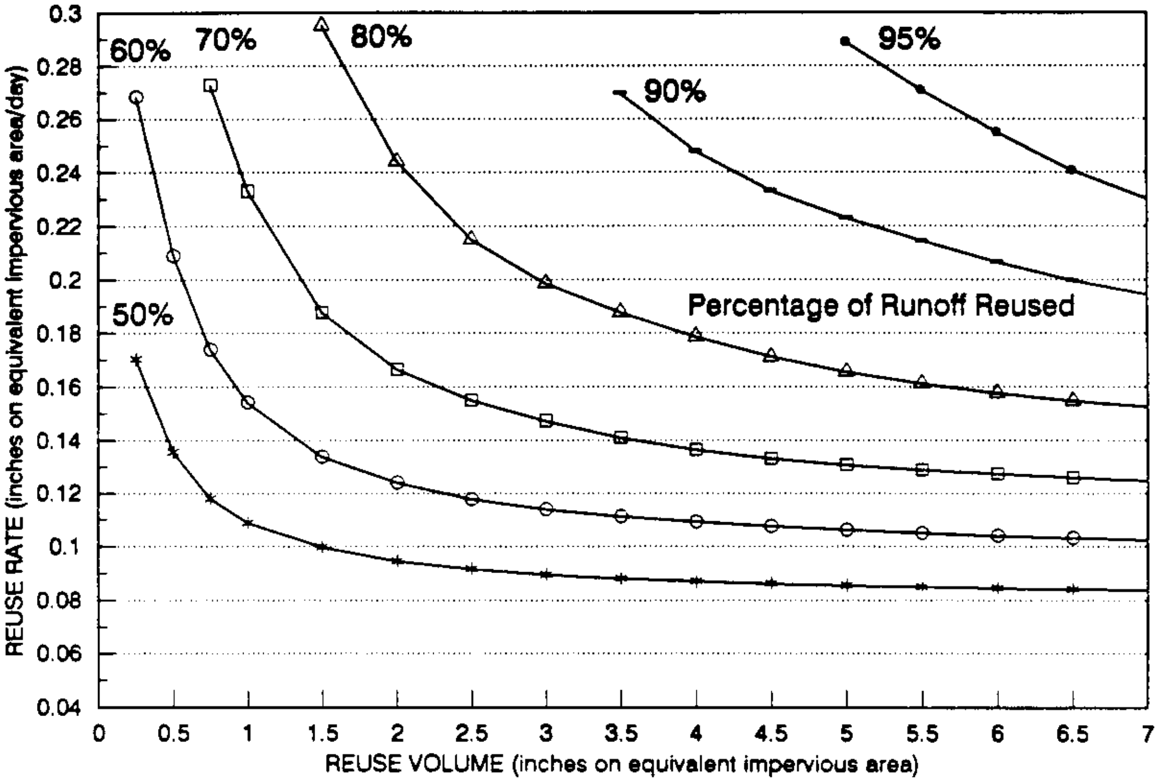
TALLAHASSEE RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 64.3 in



TAMPA RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 44.6 in



VERO BEACH RAINFALL STATION
MAY 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 48.3 in



WEST PALM BEACH RAINFALL STATION
JAN. 1974 - DEC. 1988
MEAN ANNUAL RAINFALL = 61.51 in

APPENDIX C

CONSTANTS FOR POWER EQUATIONS

CONSTANTS FOR POWER EQUATIONS

$$R = a \cdot V^b$$

where R = reuse rate (inches on EIA/day)
V = reuse volume (inches on EIA)
a,b = variables

The format for the non-linear regression constants is:

	a	b	Location	Average yearly rain
95%				
90%				
80%				
70%				
60%				
50%				

The constants in the power equations are listed for each location with average yearly rain and by efficiency:

1.1688426	-.7769124	Apalachicola	55.6 in.
.6661717	-.6652583		
.3045218	-.4869317		
.2091435	-.4038482		
.1437886	-.2969327		
.1016965	-.1993697		

.3940119	-.4432743	Belle Glade	37.9 in.
.3112862	-.4323121		
.2166185	-.4010609		
.1468915	-.3221319		
.1037100	-.2673205		
.0738958	-.2071926		

.5235800	-.5521839	Daytona Beach	48.7 in.
.3956186	-.5386551		
.2437250	-.4327412		
.1713654	-.3560256		
.1235695	-.2851245		
.0889591	-.2008332		

.6739101	-.443528	Ft. Myers	50.6 in.
.4388049	-.3160556		
.3184893	-.3054508		
.2332682	-.2950977		
.1691086	-.2828517		
.1175848	-.2398593		
.5262948	-.5810895	Gainesville	43.2 in.
.3627858	-.5537303		
.2192011	-.4416149		
.1519067	-.3542857		
.1089968	-.2674908		
.0786312	-.1888781		
.5398192	-.5874828	Grady	52.6 in.
.3597611	-.4693062		
.2400658	-.3883559		
.1727518	-.3168517		
.1125716	-.1405530		
.0927719	-.1748439		
.5952260	-.4826946	Homestead	53.5 in.
.5132481	-.5897352		
.3219627	-.3508607		
.2284505	-.3150715		
.1456343	-.2214306		
.1142903	-.2225005		
.5428910	-.4555023	Inglis	49.4 in.
.4314616	-.4615872		
.2736401	-.4139263		
.1952656	-.3909017		
.1337168	-.2970520		
.0932927	-.2043755		
.6069215	-.6094775	Jacksonville	48.9 in.
.3555518	-.4796101		
.2214405	-.3859661		
.1659703	-.3738329		
.1158610	-.2492099		
.0842607	-.1638954		
60.6827945	-2.9760080	Key West	38.5 in.
.8949502	-1.0633921		
.2613503	-.5808729		
.1555503	-.4337518		
.1024584	-.2891565		
.0716231	-.1889729		

.5205609	-.4533424	Lakeland	49.6 in.
.3680180	-.3751234		
.2646949	-.3755870		
.1861202	-.3311885		
.1317641	-.2724208		
.0929244	-.1985931		
.4398261	-.5690305	Lisbon	43.9 in.
.2967522	-.4568937		
.2026906	-.4001071		
.1421575	-.3101034		
.1034458	-.2296417		
.0760092	-.1566994		
.5960653	-.7226874	Marineland	44.3 in.
.3382723	-.5225776		
.2274755	-.4661803		
.1553765	-.3694539		
.1098237	-.2719779		
.789089	-.1837996		
.5981302	-.7403136	Melbourne	40.8 in.
.3704244	-.5865789		
.2358397	-.5031861		
.1574962	-.4083402		
.1087411	-.2998278		
.0771517	-.2105915		
.6644365	-.4982543	Miami	54.5 in.
.4825783	-.4705408		
.2926611	-.3736417		
.2166961	-.3699496		
.1495142	-.2867476		
.1048392	-.2054236		
1.050000	-.632000	Moore Haven	43.2 in.
.5690659	-.5512844		
.2898807	-.4517788		
.1907091	-.3992646		
.1271072	-.3146768		
.0879282	-.2391565		
.7079302	-.5290021	Niceville	65.7 in.
.430838	-.4515618		
.3025706	-.3585497		
.2182495	-.3081039		
.1619282	-.2632204		
.1168778	-.1799934		

.5060788	-.5110864	NNR Canal 2	39.1 in.
.3709197	-.4560263		
.2528176	-.4415159		
.1669285	-.3617027		
.1159926	-.2968920		
.0831104	-.2514974		
.4340635	-.3632859	Orange City	41.7 in.
.3305242	-.3225510		
.2508806	-.3417054		
.1799801	-.2954760		
.1295957	-.2414102		
.0935471	-.1768471		
.3998265	-.4074337	Orlando	48.2 in.
.3262706	-.3995224		
.2405845	-.3962432		
.1707010	-.3305890		
.1224449	-.2567571		
.0884823	-.1927043		
.4944706	-.3620499	Parrish	51.2 in.
.3733839	-.3223833		
.2736866	-.3499228		
.1921202	-.3159180		
.1354184	-.2575308		
.0961427	-.1904141		
.6541850	-.5508202	Tallahassee	64.3 in.
.4627092	-.4579269		
.2863363	-.3456468		
.2191313	-.3335320		
.1586214	-.2630171		
.1144671	-.1845247		
.5560483	-.4942123	Tampa	44.6 in.
.3588074	-.4159919		
.2415717	-.4050487		
.1674422	-.3550230		
.1168560	-.2729188		
.0833187	-.2020971		
.9503040	-.7900547	Vero Beach	48.3 in.
.5132481	-.5897352		
.2665103	-.4117496		
.1912656	-.3899428		
.1316548	-.3029923		
.0919166	-.2087009		

.8683486	-.6837389	**W. Palm Beach 61.5 in.**
.4785317	-.4692543	
.3355087	-.4379572	
.2315740	-.3689613	
.1662192	-.3100779	
.1170520	-.2172371	

APPENDIX D

NOTATION

NOTATION

A	Area of the watershed
A_L	Area over which reuse is delivered (irrigation area)
C	Runoff Coefficient - the fraction of a rainfall that will result in rainfall excess
C_p	Runoff coefficient for a pervious area
C_r	Fraction of reuse water that returns to a pond
D	Discharge of stormwater over control structure
E	Reuse Efficiency - 100 minus the annual percentage of stormwater runoff that is discharged (%)
EIA	Equivalent Impervious Area of the watershed - the size of an impervious area which would produce the same amount of runoff as the actual watershed (acres)
ET	Evapotranspiration
F	Movement of water through the banks of a pond
G	Supplemental water (groundwater) or rate of use on EIA
P	Precipitation directly on the pond
R	Reuse Rate - the rate at which stormwater is reused (inches per day on an area equal to the EIA)
R_E	Rainfall Excess - the volume of rainfall that does not enter the ground but rather flows over or just under the surface to a point of discharge
R_L	Reuse Rate (inches per day on the local area over which reuse is delivered)
R_p	Rainfall excess for a pervious area
REV	Rate-Efficiency-Volume Chart
S	Storage level of pond
V	Reuse Volume - the temporary storage volume for reuse (inches on an area equal to the EIA)

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