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HYDRAULIC AND HYDROLOGIC ANALYSIS OF THE C-102 BASIN, SOUTH FLORIDA

by

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Lehigh University

May, 1995

IMBT HYDRAULICS LABORATORY REPORT # IHL-142-95

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ABSTRACT

Engineers and environmental scientists model the hydrologic processes of basins to gain valuable insight for managing water resources. The reliability of these models is dependent on the availability and accuracy of the data used to do the analysis. Since rainfall records are one of the most important and repeatedly used parameters, methods have been developed to interpolate missing rainfall records. In this study, five different interpolation methods are implemented on rainfall gauging stations in a coastal region of southeast Florida known as the C-102 basin. The results of the five methods are accurate with respect to each other; however, it is shown that the rainfall gauging station S-194 was inconsistent during two time periods; 1973 - 1975 and 1978 - 1980.

The C-102 basin is one of many basins draining into Biscayne Bay that form a region known as the Lower East Coast (LEC). Due to the transmissivity of the unconfined aquifer lying under this region, hydrologic models have been developed to estimate the seepage out of these coastal basins into Biscayne Bay. In this study, the seepage loss out of the C-102 basin is estimated using a basin water budget technique. The average monthly seepage out of the C-102 basin over a six month period in 1974 is 7.4×10^7 ft^3. The results from this study will be used as support material to the Florida Surface Water Improvement and Management (SWIM) Plan being developed by South Florida Water Management District (SFWMD).

CHAPTER 1 INTRODUCTION

1.1 General Description

1.1.1 Background

The reliability of any hydrologic study is limited by the availability and accuracy of the data used to complete the analysis. Due to the importance and repeated use of rainfall records in these studies, methods have been developed to interpolate missing records. The interpolated records can then be used in a variety of hydraulic and hydrologic models. One parameter that can be estimated is the net seepage out of a basin. In this multifaceted thesis, five different methods of interpolating missing rainfall records at gauging stations located in an area of south Florida known as the C-102 basin are compared. In addition, through the development and implementation of a basin water budget hydrologic model, an estimation of the seepage out of the C-102 basin is obtained. The results from this study will be used as support material to the Florida Surface Water Improvement and Management (SWIM) Plan being developed by South Florida Water Management District (SFWMD).

1.1.2 Study Area

The C-102 basin, with an area of approximately thirty-four square miles, is in the southeast portion of Dade County, Florida, approximately twenty-five miles southwest of Miami (Figures 1.1 & 1.2). The basin boundary, major roadways, canals, and canal flow control structures are represented in Figure 1.3. There are two Central and Southern Florida Flood Control Project (C&SF Project) canals in the basin: C-102 and C-102N. These canals have three primary functions (Cooper and Lane, 1987):

1) to provide drainage and flood protection for the C-102 basin
2) to supply water to the basin for irrigation
3) to maintain a groundwater table elevation adequate to prevent saltwater intrusion

Flow in the basin is to the southeast; therefore during low flow periods, the South Dade Conveyance System (SDCS), specifically the L31N borrow canal, drains water into the basin. As a result, during low flow, the L31N borrow canal provides the necessary water to maintain a stage in the two C&SF Project canals to prevent saltwater intrusion from Biscayne Bay. There are four Project control structures in the C-102 basin (Cooper and Lane, 1987). An aerial photograph of the basin from Biscayne Bay and each structure is represented in Figures 1.4A, B, and C. The four structures have the following characteristics (Cooper and Lane, 1987):

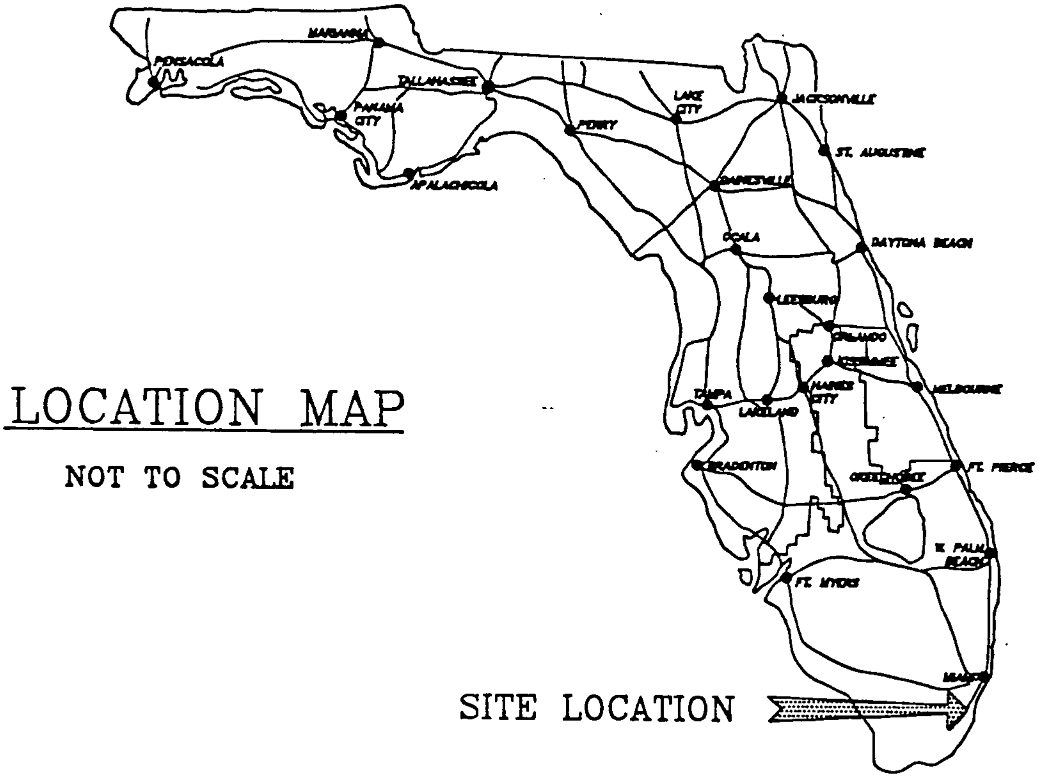


Figure 1.1 Geographic Location Map (SFWMD Technical Support, 1995)

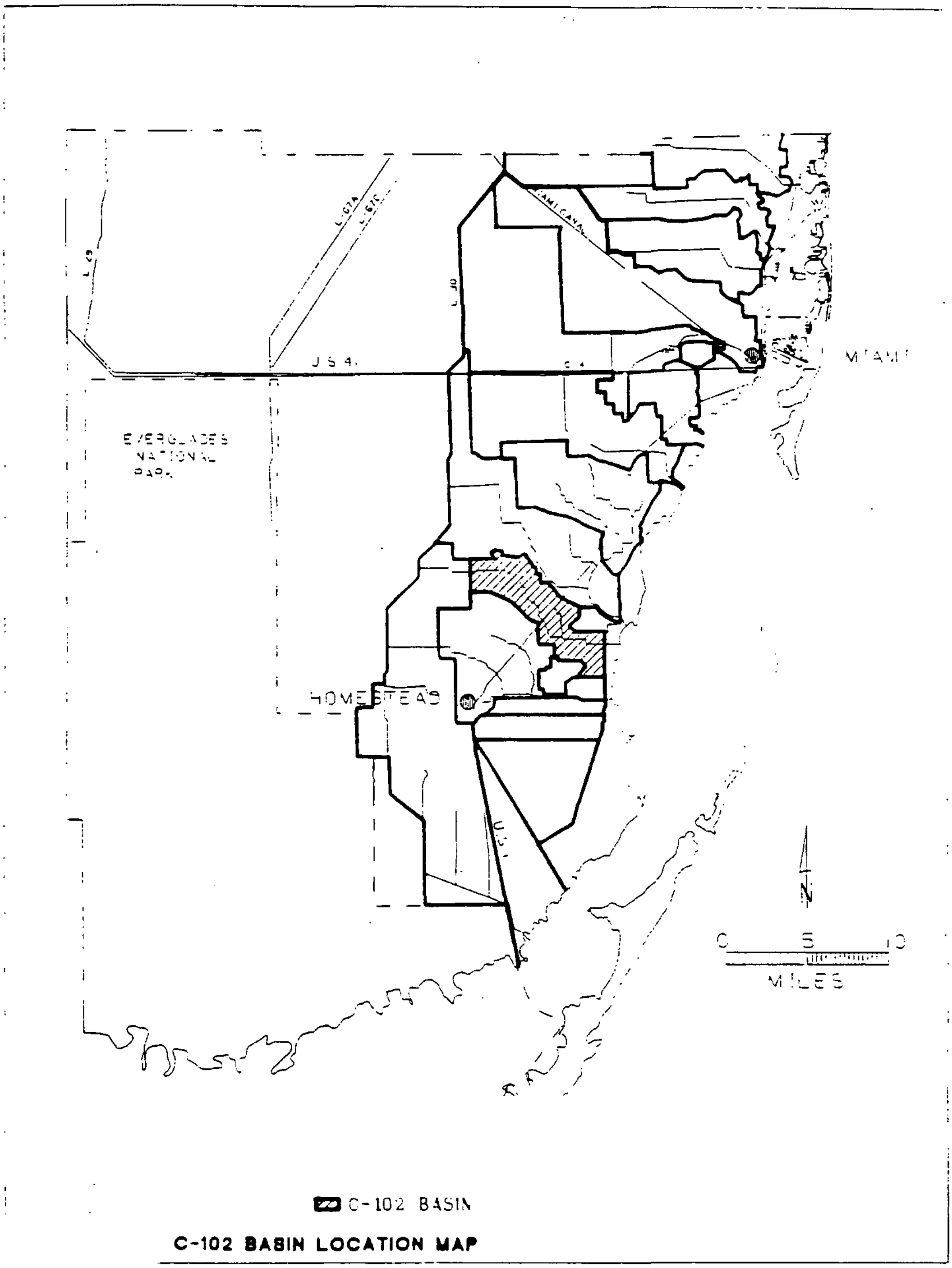


Figure 1.2 Basin Location Map, (Cooper and Lane, 1987)

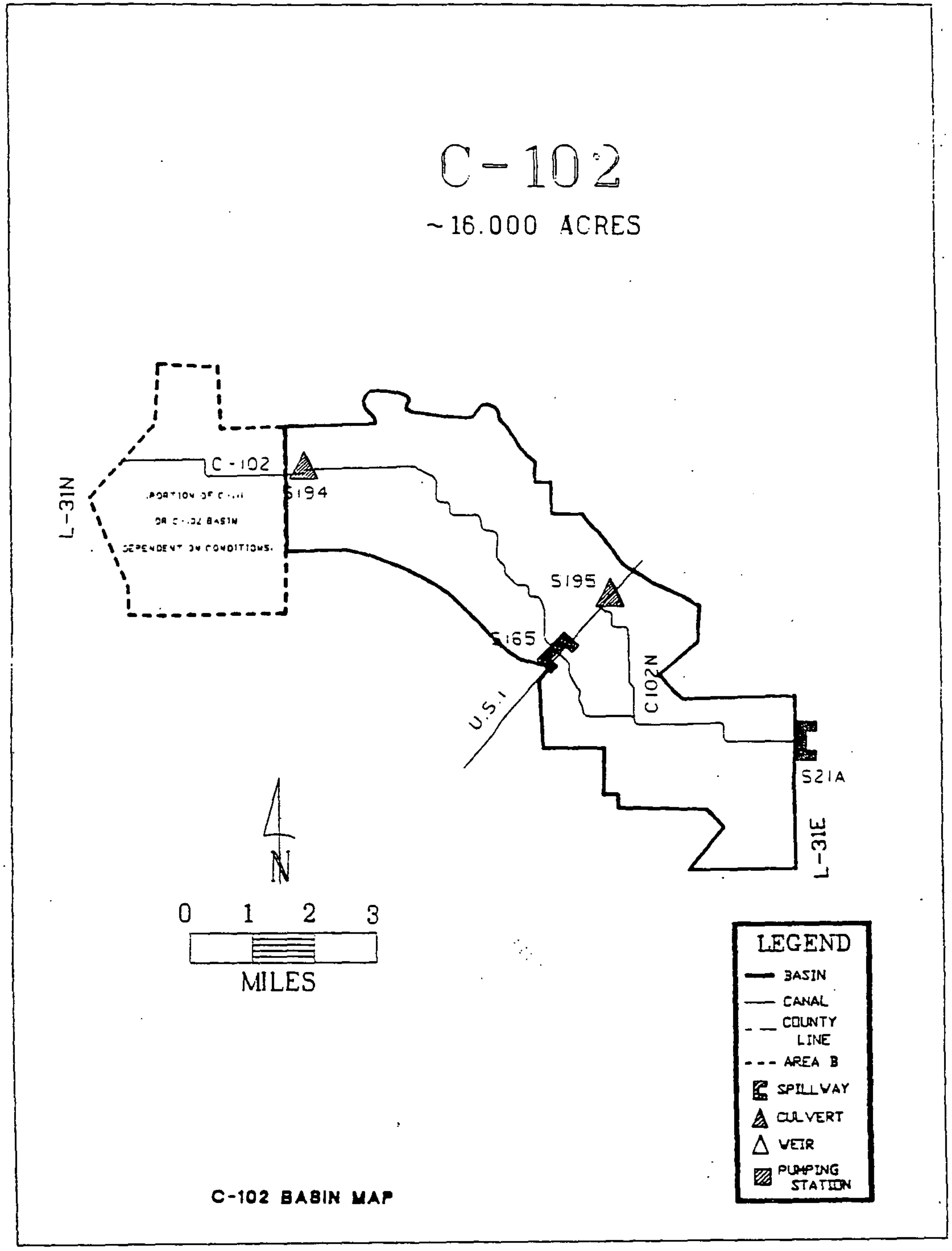
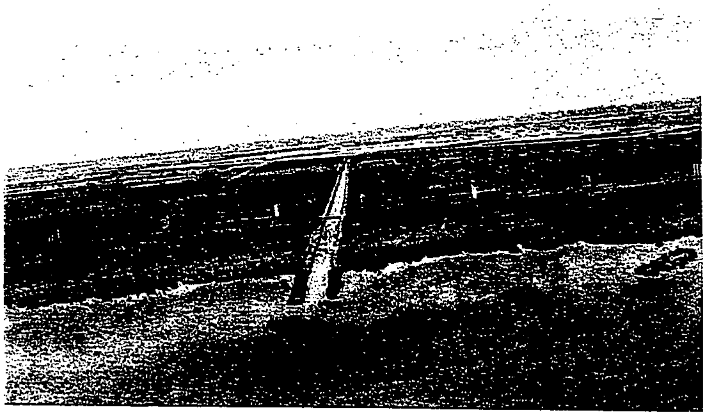
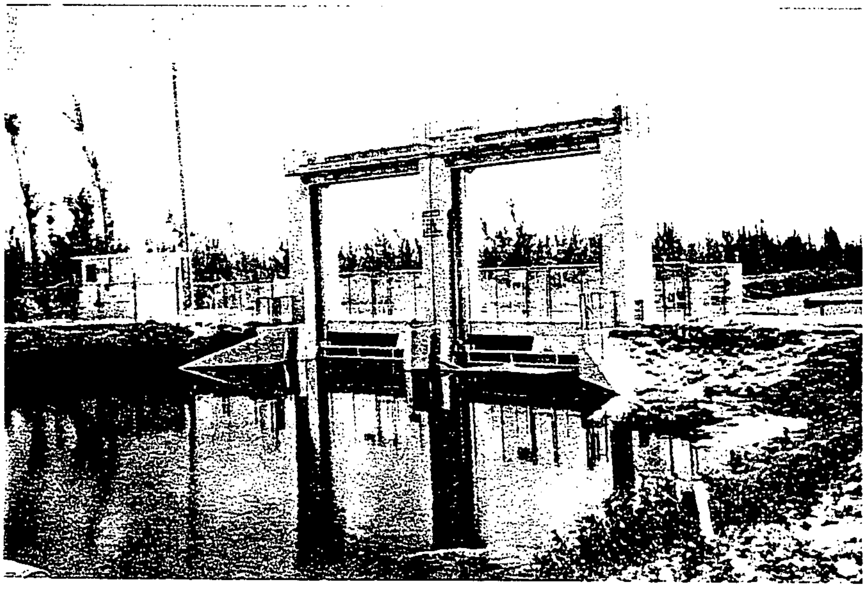


Figure 1.3 C-102 Basin Map (Cooper and Lane, 1987)

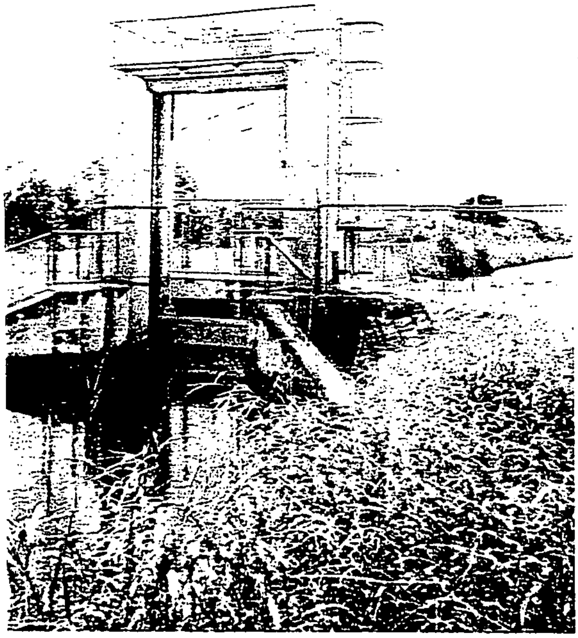


Aerial

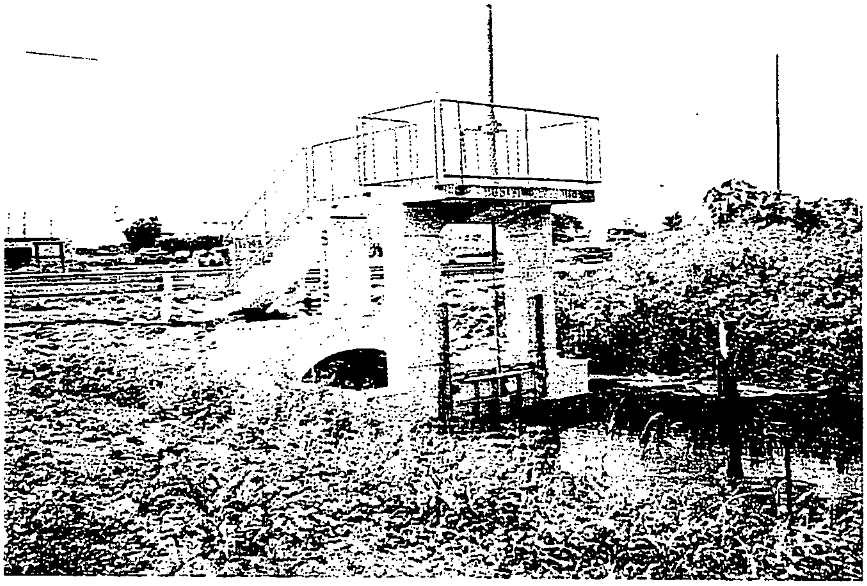


S-21A

Figure 1.4A Aerial and S-21A

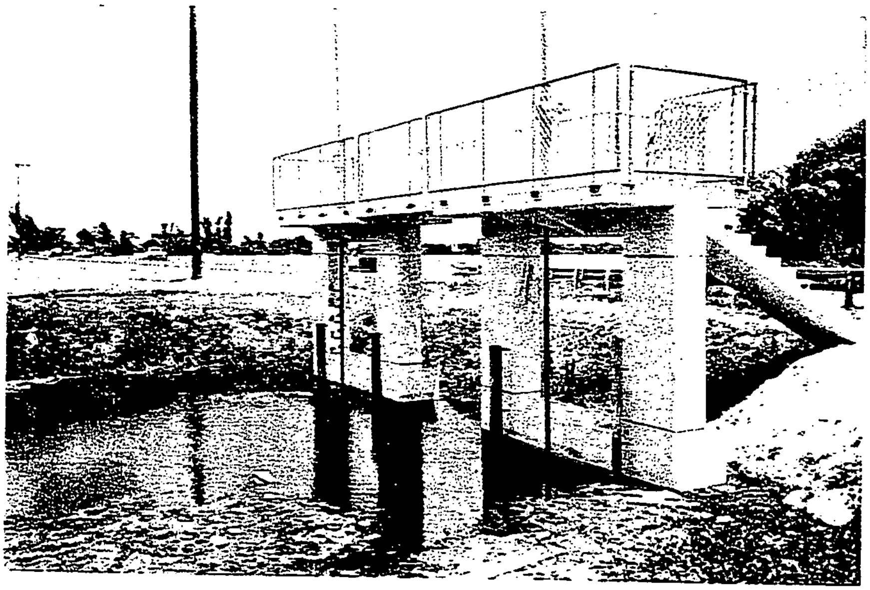


S-165



S-195

Figure 1.4B S-165 and S-195



S-194

Figure 1.4C S-194

1) S-21A, a gated spillway found one mile west of Biscayne Bay is the primary control for the stages in both the C-102 and C-102N canals, providing the head needed in the project canals to prevent saltwater intrusion.

2) S-165, a gated spillway found west of U.S. Highway 1, controls the stages in the upper reaches of C-102 canal and regulates the discharges to the lower reaches.

3) S-195, a gated culvert at the upper end of C-102N canal just west of U.S. Highway 1, controls drainage into the C-102 canal from local drainage systems.

4) S-194, two gated culverts in C-102N just west of Krome Avenue on the divide between the C-111 and C-102 basins, remains open to supply water to the C-102 basin from the L31N borrow canal. During flooding, this structure is closed to prevent water passage between the two basins, causing the 9.2 square mile area west of S-194 to become part of the C-111 basin and to flow to the L31N borrow canal, see Figure 1.3.

To further illustrate the conveyance capability of these structures, Figure 1.5 lists the design criteria used for these structures.

C-102 Basin Structures - Design Criteria

Structure	Type	Design HW Stage (ft NGVD)	Design TW Stage (ft NGVD)	Optimum Stage (ft NGVD)	Design Q (cfs)	Peak Stage (ft NGVD) and Q (cfs)	
S-21A Stage divide	Spillway, 2gates 20ft x 11.8ft Crest lgth = 40ft Crest elev = -7.8ft NGVD	1.9	1.4	1.2 (Dry Season) 2.0 (Wet Season)	1330	HW = 2.87 TW = 2.37 Q = 2454cfs	8/16/81 8/16/81 8/16/81
S-195 Divide structure	Gated Culvert 97in x 152in x 90ft CMP Arch Invert elev = -1.8ft NGVD	5.6	4.8	5.5	180	HW = 7.1 TW = 6.4 Q = 400	
S-194 Divide structure	Culvert 2-84in x 90ft RCP, gated Invert elev = -2.5 to -3.5ft NGVD	3.9 (water supply)	3.7 (water supply)	5.5 (to west)	~190 (water sup)ply divide structure during flood)	HW = 9.23 TW = 9.15 (storm Dennis)	8/18/81 8/18/81
S-165 Stage divide	Spillway, 1 gate 12ft x 7ft Crest lgth = 12ft Crest elev = -0.5ft NGVD	5.6	4.6	5.5	450	HW = 7.55 TW = 6.28 Q = 666	8/18/81 8/18/81 8/19/81

in = inches
ft = feet
elev = elevation
lgth = Length
TW = Tail water
Q = discharge in cfs
CMP = Corrugated metal pipe
RCP = Reinforced concrete pipe
ft NGVD = Feet relative to National Geodetic Vertical Datum
HW = Head water
CFS = Cubic feet per second
ds = downstream
ups = upstream

Figure 1.5 Basin Structures - Design Criteria (Cooper and Lane, 1987)

1.1.3 Catchment Classifications

According to Ponce (1989), small catchments, or watersheds, are those in which runoff can be modeled by assuming constant rainfall in both space and time. A mid-size catchment is one in which runoff can be modeled by assuming that rainfall is constant in space but varying in time. Large catchments, or basins, are those in which runoff can be modeled by assuming rainfall to vary in both space and time. The C-102 basin is considered a large catchment due to the weather patterns in south Florida. These weather patterns, which include isolated thunderstorms, present an area equal to the C-102 basin with both spatially and time varying rainfall.

1.1.4 Hydraulic and Hydrologic Information

1.1.4.1 Groundwater

There are two major aquifer systems in Dade County:

1) The surficial
2) The Floridian (Southeastern Geological Society, 1986)

According to the SFWMD SWIM Plan (1994), the surficial aquifer system is composed of all the sediments from the water table to the low permeability deposits (confining unit) that separate it from the Floridian. The Biscayne Aquifer, which occurs at or near the land surface in most of Dade County, is the principle water bearing unit of the surficial aquifer system and the source of groundwater flow to Biscayne Bay. The Biscayne

Aquifer consists of sandstone and cavity-riddled limestones. It attains depths of sixty to one hundred-sixty feet below sea level along the western coast of Biscayne. Due to its transmissivity, which exceeds 300,000 ft^2/day in southeast Dade County, the Biscayne Aquifer is considered one of the most permeable in the world.

1.1.4.2 Surface Water

According to the SFWMD SWIM Plan (1994), surface drainage from eastern Dade County into Biscayne Bay is primarily controlled by the system of canals, levees, and control structures constructed as part of the C&SF Project known as the primary system. Although the coastal structures prevent saltwater from tidal or storm surge from entering the canals and moving inland, hurricane tides have overtopped every tidal structure (SFWMD SWIM Plan, 1994).

1.2 Scope

1.2.1 Filling Missing Rainfall Records

In this study, data on rainfall, groundwater levels, evapotranspiration, canal stage, and canal discharge are used. When measuring or recording any of these parameters, missed records can occur which can lead to inaccuracies when attempting to model a basin. The scope of this study concentrates only on the replacement of missing rainfall records at gauging stations in the C-102 basin.

1.2.2 Basin Water Budget

A basin water budget refers to an accounting of the various inflows and outflows in a catchment over a specific time period to ascertain their relative magnitudes. In this study, seepage out of the C-102 basin is approximated. The result will be an average daily volume of water lost from the basin due to outflow seepage to Biscayne Bay. SFWMD estimates that the magnitude of this seepage outflow is substantial due to the permeability of the Biscayne Aquifer. Quantifying this loss will greatly aid in understanding the water budget of the C-102 basin. Due to the study area's geographic characteristics, the groundwater table has a very small gradient and is close to mean sea level. As a result, an understanding of the flow around or under the structures will aid in the water management of this area, particularly at low flows when the danger of salt water intrusion is greatest.

CHAPTER 2 FILLING MISSING RAINFALL RECORDS

2.1 Rainfall Records

2.1.1 History and Theory

Missing rainfall records can possibly be attributed to sporadic readings of the rainfall gauge or equipment malfunction making it necessary to estimate the missing records. According to Paulhus and Kohler (1952), since 1948, when the Weather Bureau discontinued the practice of publishing interpolated precipitation data, monthly and annual totals have been omitted from its publications whenever any portion of the record was missing. In view of objections by the users of precipitation data, this policy was reviewed for possible revision. A series of tests involving some twelve hundred storms was conducted to determine if missing records could be satisfactorily estimated by simple procedures. The results from the tests by Paulhus and Kohler showed that the normal ratio method and the station average method are accurate methods to interpolate missing rainfall records. In addition to the above methods, Singh (1992) states that the Inverse Distance Method also accurately interpolates missing rainfall records.

To implement any of the above methods, three index stations, termed A, B, and C, with complete records must be identified. The index stations should be close to and as evenly spaced around the incomplete station, X, as possible. Once the index stations are identified, the following procedures can be used to interpolate the missing records:

1) If the mean annual rainfall at each of the index stations A, B, and C is within 10% of that at station X, then a simple arithmetic average of the rainfall values at the index stations provides the missing value at station X, or:

$$P_X = \frac{1}{3}(P_A + P_B + P_C) \tag{2.1}$$

where P is precipitation over a specific period, from part of a single storm to that of a year (Fetter, 1980). In Equation (2.1), all of the index stations are equally weighted resulting in inaccuracies when the mean annual rainfall of the index stations is greater than 10% of that at station X. When the difference is greater than 10%, the index stations could be exposed to different meteorological processes resulting in an incorrect estimation of the missing record.

Paulhus and Kohler further established that, for coastal stations, two instead of three index stations could be used to accurately interpolate missing rainfall records. As a result, Equation (2.1) simplifies to:

$$P_X = \frac{1}{2}(P_A + P_B) \tag{2.2}$$

2) If the mean annual rainfall at any of the index stations differs by more than 10% of that at station X, the normal ratio method is used (Paulhus and Kohler, 1952). In this method, the missing precipitation value, P_x, is estimated using the following equation:

$$P_X = \frac{1}{3} \left(\frac{N_X}{N_A} P_A + \frac{N_X}{N_B} P_B + \frac{N_X}{N_C} P_C \right) \tag{2.3}$$

where N is the mean annual rainfall and the subscripts X, A, B, C refer to the respective stations. It is apparent when looking at Equation (2.3) that the weighting of the index stations is represented as a proportion of the mean annual rainfall at the missing station to the mean annual rainfall at the index stations. For coastal stations, Equation (2.3) simplifies to:

$$P_X = \frac{1}{2} \left(\frac{N_X}{N_A} P_A + \frac{N_X}{N_B} P_B \right) \tag{2.4}$$

3) Similar to the station average method, the inverse distance method (Singh, 1992) does not use any of the known record at the missing station to interpolate the missing record. Instead, it weights the surrounding index stations according to the distance they lie from station X with the closest station receiving the greatest weighting and the farthest station receiving the least. The reasoning behind this is that the closest station is likely to experience the same meteorological events. The distances are computed by establishing a set of axes running through the missing station, X, as shown in Figure 2.1.

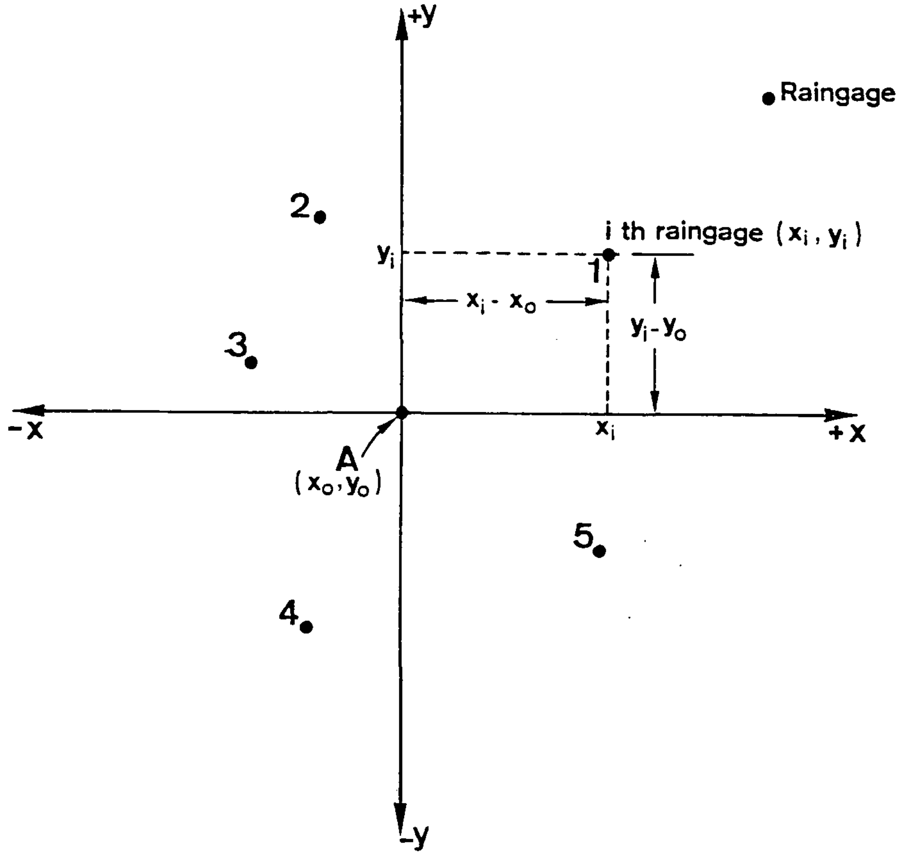


Figure 2.1 Inverse Distance Method (Singh, 1992)

By establishing the missing record ordinates as (x_0,y_0), vertical and horizontal distances to each of the index stations, i, can be measured with respect to the missing record. The weighting variable is dependent on the inverse squared distances as represented in Equation (2.5):

$$a_i = \frac{\frac{1}{(D_i)^2}}{\sum_{i=1}^{n} \frac{1}{(D_i)^2}} \tag{2.5}$$

where $(D_i)^2$ is calculated using the following equation:

$$(D_i)^2 = (x_i - x_o)^2 + (y_i - y_o)^2 \,,\; i = 1, 2, \ldots \tag{2.6}$$

The missing precipitation value, P_x, is estimated using the following equation:

$$P_X = a_A P_A + a_B P_B + a_C P_C \tag{2.7}$$

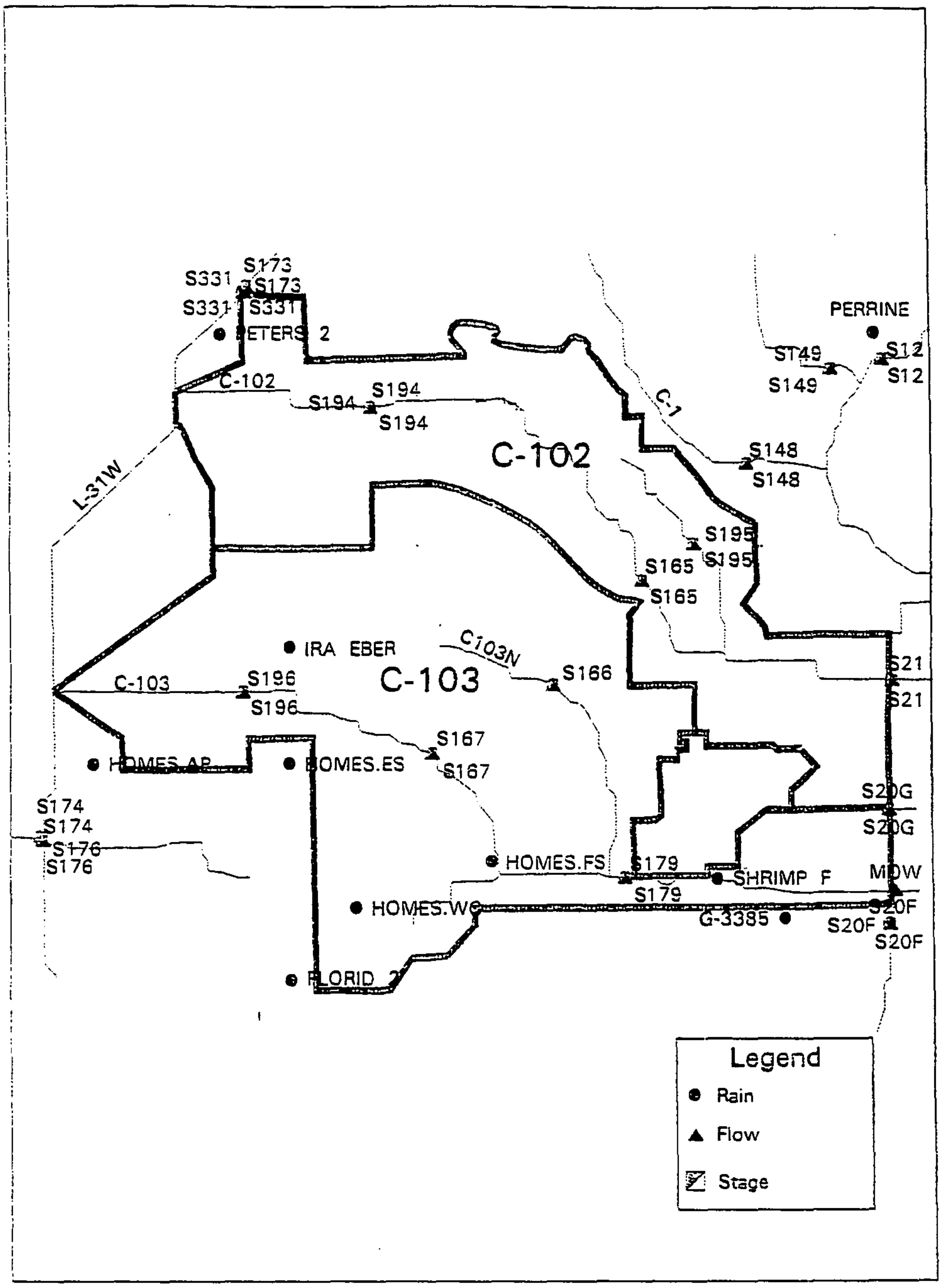
2.2 Methods Applied in This Study

The SFWMD retrieved the entire record, termed the period of record (POR), of the one rainfall station within the C-102 basin. Another station search was done within a fifteen-mile buffer around the C-102 basin which yielded a total of fourteen stations in and around the C-102 basin. This was enough rainfall data to complete the interpolation of missing rainfall records outlined above. These stations' ASCII filenames, Data Base filenames (DBKEY), and period of record are represented in Table 2.1. The data was organized in five year intervals using a spreadsheet. Eleven different intervals were considered: 1940-44, 45-49, 50-54, 55-59, 60-64, 65-69, 70-74, 75-79, 80-84, 85-89, and 90-present. A station location map, Figure 2.2, was obtained from SFWMD.

Table 2.1 Rainfall Stations Used in Analysis

FILE NAME	**DBKEY**	**PERIOD of RECORD**
FLORID2R	06418	01 SEP 1982-31 JAN 1983
HOMES_R.FS	05815	27 JAN 1968-30 MAY 1994
HOMES_R.ES	06268	01 JAN 1942-31 JUL 1991
HOMES_R.AP	06316	26 JUN 1969-31 JAN 1985
G3385_R	07084	26 JUN 1986-13 OCT 1987
S331_R	05967	31 JUL 1980-13 JUN 1994
S20F_R	05816	22 MAY 1968-13 JUN 1994
S194_R	05814	17 JUN 1966-30 JUL 1980
PETERS2_R NR*	06291	01 JAN 1942-31 DEC 1952
PETERS_R	06201	01 MAY 1942-30 SEP 1958
PERRINE_R	06167	01 DEC 1958-31 MAY 1972
IRA_EBER	06315	19 JUN 1969-31 DEC 1984
HOMES_R.WC	06417	01 SEP 1982-28 FEB 1985
SHRIMPF_R	06952	18 JAN 1977-30 JUL 1980

* NR - no record



Rain, Flow and Stage Stations for the C102 and C103 Basins.

Figure 2.2 Rain, Flow, and Stage Stations (SFWMD Technical Support, 1995)

The period of record for S-194, the only rain gauge in C-102, is from June 17, 1966 to July 30, 1980. Since this station and any possible index stations are within 20 miles of the coastline of Florida, the assumption is made that all of the stations can be considered coastal stations, leaving only two index stations to be selected. These index stations were selected based upon their completeness of record and data available coinciding with S-194's period of record. Stations HOMES_R.ES, HOMES_R.FS, PERRINE_R, and IRA_EBER were selected. Their location and period of record is portrayed in Figure 2.2 and Table 2.1, respectively. The remaining stations and time intervals were not required for this analysis.

2.2.1 Partitioning of Data

A spreadsheet was created that contained the period of record for S-194 and any records at the index stations corresponding to the same time. When the periods of records for some stations were retrieved from SFWMD's database, several different types of numeric and alphabetic flags existed in the records. These flags were either next to, in place of, or next to and in place of a daily rainfall value. Table 2.2 is a hypothetical illustration of the flags observed during this analysis.

Table 2.2 Hypothetical Flags

Daily Rainfall	Flags
.1	
-900 series	X
2.01	A
0.2	
1.2	P
1.2	M
1.2	P

In this table, the X next to a numeric -900 series flag represents a missed day. This X is followed by an A which represents the accumulated two day total. These X flags can occur as a series depicting a number of missed days followed by the accumulated total over the missed time, A. The X flags generally occurred on weekends because the person charged with recording data did not go to the station on an individual day, but recorded the total catch over two or more days. Although the X records are missing, the value found next to the A allows the missing record to be partitioned over the missed time. Evaporation from the rain gauge adds error to the accumulation number A, but that error is small because the time of missed recording is generally only one or two days. To verify this, the missing X and A records were totaled from June 17, 1966 to March 01, 1974 for station S-194 and the average of the surrounding index stations. Table 2.3 illustrates the number of missing A and X records at station S-194, the rainfall average of the surrounding stations, and the total of the accumulated A values in S-194's record.

It can be observed from Table 2.3 that over nine years approximately the same amount of rain fell on the index stations, 20.08 inches, and S-194, 25.10 inches, over the missed X and A days so the assumption is made that the A values accurately represent rain that fell over the missed time. Based on this assumption, no interpolation was done on any A or X record. Instead, the accumulated A values were partitioned over the missed time. This was first done on the index stations. In this analysis, partitioning of the index stations used the available data at the surrounding index stations. The partitioning was performed using the following equation (Sculley, 1995):

$$P_p = \frac{(\sum_{i=1}^{n} C_i)A}{\sum_{i=1}^{n} S_i} \tag{2.8}$$

where P_p is the missing value at station X, C is the surrounding station values, A is the accumulation value associated with the alphabetic letter A, and $\sum S_i$ is the accumulated rainfall of a surrounding station over the time of missing record including the accumulation day. This method is illustrated in Table 2.4 which is a hypothetical representation of partitioning accumulated values over missed time. The following parameters are applied to Equation (2.8) to partition the X and A records:

Table 2.3 Missing A and X Records (in)

Year	Number of Missing A and X Records	Surrounding Stations Average	S-194 Accumulated (A) Value
June 17,1966- February 29, 1968	38	5.62	5.69
March 01, 1968- March 01, 1969	0	0	0
March 02, 1969- March 01, 1970	6	6.63	10.15
March 02, 1970- March 01, 1971	1	.1	.35
March 02, 1971- March 01, 1972	3	.62	2.56
March 02, 1972- March 01, 1973	2	.86	1.74
March 02, 1973- March 01, 1974	0	0	0
March 02, 1974- March 01, 1975	40	6.25	4.61
Total	90	20.08	25.10

Table 2.4: Partitioning Missing Records

Date	Station A	Station B	Station X		
			Record	Flag	Final Record
May 1, 1990	0	1	1		1
May 2, 1990	1	0	-901	X	.33
May 3, 1990	1	1	-901	X	.667
May 4, 1990	1	1	-901	X	.667
May 5, 1990	0	1	2	A	.33

1) $\sum S_i = 6$; the total amount of rain accumulated at the index stations over the period of missing record plus the next day associated with the A value.

3) A = 2; the total amount of rain accumulated over the missing days.

4) $\sum C_i$ for the first missing day, May 2, 1990, is 1; the sum of the surrounding index stations rainfall values on the missing day.

By substituting these values into Equation (2.8), the missing record, P_p, can be computed for the first missing day, May 2, 1990, to be 0.33. This value along with the rest of the missing values are summarized in Table 2.4 under the title, final records. After partitioning the index stations, station S-194 was partitioned similarly.

In Table 2.2, page 23, the P flag represents a partial record. An M flag following the P represents a missing record. As illustrated in this table, the value associated with the M is usually the same as the value associated with the P. The missing, M, and partial, P, records are the records that require interpolation. However, these records can not be partitioned because there is no accumulated rainfall value, A.

2.2.2 Interpolation of Missing Rainfall Records

In Equations (2.1 - 2.4), the mean annual rainfall at the index stations and S-194 is a key variable. However, a question arises as to how to calculate the mean annual rainfall, particularly when there is an insufficient amount of data prior to or after any missing records to establish this value. Station S-194 in the C-102 basin has a period of record approximately fourteen years long. Unfortunately, the first missing records appears only a couple months into S-194's period of record. To address this question, five different methods of interpolation were implemented. The first three use the normal ratio method. However, three techniques were used to compute mean annual rainfall. To draw a comparison between the accuracies of these methods, two other methods, the inverse distance method and the station average method, were used that are not dependent on the existing rainfall values at S-194.

2.2.2.1 *The Normal Ratio Method, Period of Record*

This first method involves taking the period of record for each of the index stations and S-194 and computing a mean annual rainfall using the following equation:

$$P = \left(\frac{1}{n}\sum_{i=1}^{n} R_i\right) 365 \qquad (2.9)$$

In this equation, R is the rainfall at day i, and n is the total number of days considered. Table 2.5 shows the time frame available for each station along with the total number of missing records. HOMES_R.ES was the only station not completely used because of the number of missing records it had after February 29, 1968.

Table 2.5 Entire POR Time Interval and Missing Records

Station	Time Period Used	Number of Missing Records (M & P flags)
HOMES_R.ES	June 17, 1966 - February 29, 1968	4
HOMES_R.FS	January 27, 1968 - July 30, 1980	0
IRA_EBER	June 19, 1969 - July 30, 1980	0
PERRINE_R	June 17, 1966 - May 31, 1972	32
S-194	June 17, 1966 - July 30, 1980 (POR)	162

The resultant mean annual rainfall using Equation (2.9) for each station is represented in Column (1), Table 2.6. Using Equations (2.3) and (2.4) with the mean annual average in Column (1) of Table 2.6 for the period of record described in Table 2.5, interpolation of the missing rainfall records was done for the period of record of station S-194. The results of this analysis are shown in Column (2), Table 2.6. The annual average after-interpolation for station S-194 is considerably lower than the index stations with the exception of HOMES_R.ES which is considered to be the least accurate due to the period of record available and because its period of record covers what is considered to be one of Florida's below average rain periods. The results also illustrate that the change in the mean annual precipitation at S-194 was small because there are one hundred sixty-nine missing records in the fourteen year period of record.

Table 2.7 was created to compare the results with the other methods described in sections 2.2.2.2 thru 2.2.2.5. This table shows the average yearly rainfall in inches of the index stations in addition to the before-interpolation and after-interpolation of missing rainfall records at S-194 for thirteen different time periods that are used in the following methods. In this table, the yearly average for the first time period and the last time period were computed using Equation (2.9). Yearly totals for the remaining eleven time periods were computed by summing the individual rainfall amounts during the associated time period. Table (2.7) also illustrates that station S-194 might be inconsistent, especially in the last two time intervals. This problem will be addressed in section 2.4, Gauge Consistency.

Table 2.6 Mean Annual Rainfall for Entire POR Method

Station	(1) Mean Annual Before-Interpolation (in)	(2) Mean Annual After-Interpolation (in)
HOMES_R.ES	51.12	51.12
HOMES_R.FS	59.82	59.82
IRA_EBER	60.12	60.12
PERRINE_R	64.02	64.02
S-194	49.37	50.67

Table 2.7 Before and After Interpolation of Yearly Averages, Entire POR Method

Time Frame	Station with Yearly Average Rainfall (in)					
	HOMES_ R.ES	HOMES_ R.FS	IRA_ EBER	PERRINE _R	S-194	
					Before	After
June 17,1966- February 29, 1968	51.12	NA	NA	61.92	53.77	54.81
March 01, 1968- March 01, 1969	NA	89.96	NA	74.80	86.33	86.80
March 02, 1969- March 01, 1970	NA	79.30	NA	77.69	78.18	78.18
March 02, 1970- March 01, 1971	NA	49.58	44.36	46.40	37.7	37.70
March 02, 1971- March 01, 1972	NA	50.34	46.77	60.97	49.1	49.26
March 02, 1972- March 01, 1973	NA	53.51	60.95	NA	54.58	54.58
March 02, 1973- March 01, 1974	NA	53.26	58.72	NA	40.68	41.67
March 02, 1974- March 01, 1975	NA	44.49	50.39	NA	28.89	35.00
March 02, 1975- March 01, 1976	NA	52.92	51.11	NA	50.46	51.09
March 02, 1976- March 01, 1977	NA	59.24	68.59	NA	53.74	54.95
March 02, 1977- March 01, 1978	NA	67.50	69.80	NA	54.08	60.30
March 02, 1978- March 01, 1979	NA	56.00	66.01	NA	26.91	27.02
March 02, 1979- July 30, 1980	NA	64.36	65.21	NA	27.34	27.34

2.2.2.2 *Normal Ratio Method, Yearly Averages*

In this method, missing rainfall records at S-194 are interpolated by implementing Equations (2.3) and (2.4). The difference between this method and the previous method is that the mean annual rainfall is taken as the yearly total at each station rather than using Equation (2.9). By comparing the results of this method with the results from the previous method, conclusions can be made as to how sensitive the normal ratio method is to the two methods of computing the mean annual rainfall.

The period of record was divided into thirteen different periods, represented in Column (1), Table 2.8. Because the period of record cannot be divided into equal yearly intervals, the first time period was picked based on the availability of records. As a result, the yearly average for the first time period and the last time period were computed using Equation (2.9). Yearly totals for the remaining eleven time periods were computed by summing the individual rainfall amounts during the associated time period. For this method, any yearly time interval can be used, whether it is from a dry season to dry season or a wet season to wet season, as long as the same time interval is used on the index stations. For instance, yearly totals from March 2, 1970 to March 01, 1971 can be used to interpolate any missing records within that time period as long as the same time period is used for the index station.

The accuracy of this methodology depends on the number of missing rainfall records in the time interval. Because there is a total of one hundred and sixty-three missing records from June 17, 1966 to July 30, 1980 at S-194, and these records are scattered fairly uniformly over the period of record, the number of missing records in any given time interval is assumed to be small relative to the total number of records in any time interval. Therefore, the missing records do not change the yearly average at S-194 significantly. Based on this hypothesis, Equation (2.3) and (2.4) were used to interpolate the missing records for the given time frames shown in Table 2.8 with their respective yearly averages as previously explained. The results are illustrated in Table 2.8. When comparing the values of the parameters in Table 2.7 with Table 2.8, the conclusion is made that the normal ratio method is not very sensitive to the method of computing the mean annual precipitation. The greatest difference is 1.64 inches of rain in the time interval of March 02, 1974 to March 01, 1975. Similar to the previous method, the yearly average method also illustrates that station S-194 might be inconsistent in the last two time intervals.

2.2.2.3 *Normal Ratio Method, Three Time Periods*

The third method combines the first and second method of computing the average annual rainfall at the index stations and S-194. In this method, the period of record was divided into three large time periods which are shown in Columns (1), Table 2.9. Column (2) shows the corresponding stations used. Columns (3) and (4) show the average annual rainfall computed using Equation (2.9) for the index stations and for S-194. Equations (2.2) and (2.4) were used to carry out the analysis. The average annual rainfall comparison chart for this analysis is illustrated in Table 2.10. When comparing the values in Table 2.9 with the previous two methods, it is apparent that normal ratio method is not very sensitive to the method of computing the mean annual precipitation.

Table 2.8 Before and After Interpolation of Yearly Averages, Yearly Average Method

Time Frame (1)	Station with Yearly Average Rainfall (in)					
	HOMES_ R.ES	HOMES_ R.FS	IRA_ EBER	PERRINE _R	S-194	
					Before	After
June 17,1966- February 29, 1968	51.12	NA	NA	61.92	53.77	55.04
March 01, 1968- March 01, 1969	NA	89.96	NA	74.80	86.33	87.08
March 02, 1969- March 01, 1970	NA	79.30	NA	77.69	78.18	78.18
March 02, 1970- March 01, 1971	NA	49.58	44.36	46.40	37.7	37.70
March 02, 1971- March 01, 1972	NA	50.34	46.77	60.97	49.1	49.30
March 02, 1972- March 01, 1973	NA	53.51	60.95	NA	54.58	54.58
March 02, 1973- March 01, 1974	NA	53.26	58.72	NA	40.68	41.57
March 02, 1974- March 01, 1975	NA	44.49	50.39	NA	28.89	33.36
March 02, 1975- March 01, 1976	NA	52.92	51.11	NA	50.46	51.21
March 02, 1976- March 01, 1977	NA	59.24	68.59	NA	53.74	55.02
March 02, 1977- March 01, 1978	NA	67.50	69.80	NA	54.08	60.07
March 02, 1978- March 01, 1979	NA	56.00	66.01	NA	26.91	26.96
March 02, 1979- July 30, 1980	NA	64.36	65.21	NA	27.34	27.34

Table 2.9 Yearly Averages, Three Time Periods Before Interpolation

Time Period Used Column 1	Stations Used Column 2	Average Annual Rainfall (in) Column 3	S-194 Average Annual Rainfall (in) Column 4
June 17, 1966 - February 29, 1968	HOMES_R.ES, PERRINE_R	51.12 61.92	53.77
March 01,1968- March 19, 1972	HOMES_R.FS, PERRINE_R	68.21 66.42	63.62
March 22, 1972- July 30, 1980	HOMES_R.FS, IRA_EBER	56.75 60.19	41.96

Table 2.10 Before and After Interpolation of Yearly Averages, Three Time Periods

Time Frame	Station with Yearly Average Rainfall (in)					
	HOMES_ R.ES	HOMES_ R.FS	IRA_ EBER	PERRINE _R	S-194	
					Before	After
June 17,1966- February 29, 1968	51.12	NA	NA	61.92	53.77	55.04
March 01, 1968- March 01, 1969	NA	89.96	NA	74.80	86.33	86.97
March 02, 1969- March 01, 1970	NA	79.30	NA	77.69	78.18	78.18
March 02, 1970- March 01, 1971	NA	49.58	44.36	46.40	37.7	37.70
March 02, 1971- March 01, 1972	NA	50.34	46.77	60.97	49.1	49.27
March 02, 1972- March 01, 1973	NA	53.51	60.95	NA	54.58	54.58
March 02, 1973- March 01, 1974	NA	53.26	58.72	NA	40.68	41.54
March 02, 1974- March 01, 1975	NA	44.49	50.39	NA	28.89	34.18
March 02, 1975- March 01, 1976	NA	52.92	51.11	NA	50.46	51.01
March 02, 1976- March 01, 1977	NA	59.24	68.59	NA	53.74	54.80
March 02, 1977- March 01, 1978	NA	67.50	69.80	NA	54.08	59.42
March 02, 1978- March 01, 1979	NA	56.00	66.01	NA	26.91	27.00
March 02, 1979- July 30, 1980	NA	64.36	65.21	NA	27.34	27.34

2.2.4 *Inverse Distance Method*

This method differs from the previous three methods because it does not put any weight on the known precipitation at S-194. Instead it weights the index stations according to their distance to S-194, with the closest receiving the greatest weighting. Before doing the inverse distance method, distances must be measured from the index stations to S-194. These distances are illustrated in Column (1) and Column (2), Table 2.11. The same time periods were used in this method as in method one (normal ratio method, entire period of record). Refer to Table 2.5 for the time periods used. By using Equation (2.7) along with the time periods illustrated in Table 2.5, the inverse distance method was executed for the period of record at gauging station S-194. Table 2.11 illustrates the weighting of the index stations. This table illustrates a hypothetical situation because all of the stations are used in determining the weighting variable, a_i. In the analysis, the same procedure is employed, but only using two and three index stations. However, the distances shown in Column (1) and Column (2) are the ones used to determine weighting. It can be seen from the D^2 that IRA_EBER is the closest station, and therefore receives the greatest weighting.

The results of this analysis are shown in Table 2.12. Because this method does not put any weight on the known precipitation at S-194, the results are generally greater than the previous three methods because all of the index stations have a greater mean annual precipitation value than S-194.

Table 2.11 Hypothetical Inverse Distance Method

Station	(1) $(x_i - x_o)$	(2) $(y_i - y_o)$	D^2	D^{-2}	a_i
HOMES_R.ES	0.63	2.50	6.64	.15	.24
HOMES_R.FS	0.75	3.19	10.74	.09	.15
PERRINE_R	3.50	0.50	12.5	.08	.13
IRA_EBER	0.50	1.75	3.12	.30	.48
				Σ 0.63	Σ 1.0

2.2.2.5 *Average Station Method*

This method is similar to the inverse distance method in that it does not put any weighting on the known rainfall values at S-194. Of the five methods, the average station method is the easiest to implement because it is simply the average of the surrounding index stations. As previously explained in section 2.1, each index station is given equal weighting. The index stations and time periods used are the same as for method three, (Table 2.9, Column (1)). The results of the average station method are summarized in Table 2.13. The results of this method are similar to the inverse distance method because the known precipitation at S-194 is not used to calculate the missing precipitation value.

Table 2.12 Before and After Interpolation,
Inverse Distance Methods

Time Frame	Station with Yearly Average Rainfall (in)					
	HOMES.ES	HOMES.FS	IRA_EBER	PERRINE_R	S-194	
					Before	After
June 17,1966-February 29, 1968	51.12	NA	NA	61.92	53.77	55.10
March 01, 1968-March 01, 1969	NA	89.96	NA	74.80	86.33	86.97
March 02, 1969-March 01, 1970	NA	79.30	NA	77.69	78.18	78.18
March 02, 1970-March 01, 1971	NA	49.58	44.36	46.40	37.7	37.70
March 02, 1971-March 01, 1972	NA	50.34	46.77	60.97	49.1	49.33
March 02, 1972-March 01, 1973	NA	53.51	60.95	NA	54.58	59.18
March 02, 1973-March 01, 1974	NA	53.26	58.72	NA	40.68	41.79
March 02, 1974-March 01, 1975	NA	44.49	50.39	NA	28.89	36.88
March 02, 1975-March 01, 1976	NA	52.92	51.11	NA	50.46	51.30
March 02, 1976-March 01, 1977	NA	59.24	68.59	NA	53.74	55.09
March 02, 1977-March 01, 1978	NA	67.50	69.80	NA	54.08	62.64
March 02, 1978-March 01, 1979	NA	56.00	66.01	NA	26.91	27.08
March 02, 1979-July 30, 1980	NA	64.36	65.21	NA	27.34	27.34

Table 2.13 Before and After Interpolation,
Three Station Average Method

Time Frame	Station with Yearly Average Rainfall (in)					
	HOMES. ES	HOMES. FS	IRA_EB ER	PERRINE _R	S-194	
					Before	After
June 17,1966- February 29, 1968	51.12	NA	NA	61.92	53.77	55.09
March 01, 1968- March 01, 1969	NA	89.96	NA	74.80	86.33	87.01
March 02, 1969- March 01, 1970	NA	79.30	NA	77.69	78.18	78.18
March 02, 1970- March 01, 1971	NA	49.58	44.36	46.40	37.7	37.7
March 02, 1971- March 01, 1972	NA	50.34	46.77	60.97	49.1	49.28
March 02, 1972- March 01, 1973	NA	53.51	60.95	NA	54.58	54.58
March 02, 1973- March 01, 1974	NA	53.26	58.72	NA	40.68	41.89
March 02, 1974- March 01, 1975	NA	44.49	50.39	NA	28.89	36.39
March 02, 1975- March 01, 1976	NA	52.92	51.11	NA	50.46	51.24
March 02, 1976- March 01, 1977	NA	59.24	68.59	NA	53.74	55.23
March 02, 1977- March 01, 1978	NA	67.50	69.80	NA	54.08	61.77
March 02, 1978- March 01, 1979	NA	56.00	66.01	NA	26.91	27.04
March 02, 1979- July 30, 1980	NA	64.36	65.21	NA	27.34	27.34

2.3 Results

A summary of the methods is shown in Table 2.14. This table also includes the number of missing records in a given time interval. As previously mentioned, these records are scattered over S-194's period of record. The missing records also occur during dry seasons. This is apparent due to the small change of the pre- and post- interpolation in the yearly totals of S-194. If the missing records occurred over the wet season, or the number of missing records were large in proportion to the time interval, there would have been a more significant change in the interpolation methods due to the weighting parameter. All of the methods give consistent results with respect to one another. The index stations had a period of record average of 59.82, 60.12, 64.02, and 51.12 inches for HOMES_R.FS, IRA_EBER, PERRINE_R, AND HOMES_R.ES, respectively, for the period of record as shown in Table 2.5. IRA_EBER and HOMES_R.FS are considered the more accurate of the two averages due to the availability of complete records. Table 2.15 shows the standard deviation of the five methods using the equation:

$$\sigma = \left(\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1} \right)^{\frac{1}{2}} \qquad (2.10)$$

where the average, $\bar{x}$, is calculated as the average of the five methods in any given time period, x_i is the yearly value of a given method i, and n is the total number of methods, five.

When comparing the standard of deviation of the methods, it can be seen that the five interpolation methods give consistent results with respect to each other. Therefore, interpolation of missing rainfall records can accurately be calculated whether or not the weighting function used includes the known rainfall values at S-194. In addition, accuracy is independent of the method of determining the mean annual rainfall at S-194.

Table 2.14 Results of Interpolating Missing Rainfall Records

Time Frame	S-194 Yearly Average Rainfall (in)						
	(1) # of Missing Records	Without Inter-polation	Method				
			1	2	3	4	5
June 17,1966-February 29, 1968	10	53.77	54.81	55.04	55.04	55.10	55.09
March 01, 1968-March 01, 1969	31	86.33	86.80	87.08	86.97	86.97	87.01
March 02, 1969-March 01, 1970	0	78.18	78.18	78.18	78.18	78.18	78.18
March 02, 1970-March 01, 1971	0	37.70	37.70	37.70	37.70	37.70	37.70
March 02, 1971-March 01, 1972	1	49.10	49.26	49.30	49.27	49.33	49.28
March 02, 1972-March 01, 1973	0	54.58	54.58	54.58	54.58	54.58	54.58
March 02, 1973-March 01, 1974	30	40.68	41.67	41.57	41.54	41.79	41.89
March 02, 1974-March 01, 1975	67	28.89	35.00	33.36	34.18	36.88	36.39
March 02, 1975-March 01, 1976	5	50.46	51.09	51.21	51.01	51.30	51.24
March 02, 1976-March 01, 1977	3	53.74	54.95	55.02	54.80	55.09	55.23
March 02, 1977-March 01, 1978	10	54.08	60.30	60.07	59.42	62.64	61.77
March 02, 1978-March 01, 1979	5	26.91	27.02	26.96	27.00	27.08	27.04
March 02, 1979-July 30, 1980	0	27.34	27.34	27.34	27.34	27.34	27.34
POR Average (in)	162 (total)	49.37	50.67	50.57	50.54	51.07	50.98

Table 2.15 Standard Deviation of the Five Methods of Interpolation

Time Frame	S-194 Yearly Average Rainfall (in)						
	Without Interpolation	Method					Std. Dev.
		1	2	3	4	5	
June 17,1966- February 29, 1968	53.77	54.81	55.04	55.04	55.10	55.09	0.12
March 01, 1968- March 01, 1969	86.33	86.80	87.08	86.97	86.97	87.01	0.10
March 02, 1969- March 01, 1970	78.18	78.18	78.18	78.18	78.18	78.18	0
March 02, 1970- March 01, 1971	37.70	37.70	37.70	37.70	37.70	37.70	0
March 02, 1971- March 01, 1972	49.10	49.26	49.30	49.27	49.33	49.28	0.03
March 02, 1972- March 01, 1973	54.58	54.58	54.58	54.58	54.58	54.58	0
March 02, 1973- March 01, 1974	40.68	41.67	41.57	41.54	41.79	41.89	0.12
March 02, 1974- March 01, 1975	28.89	35.00	33.36	34.18	36.88	36.39	1.47
March 02, 1975- March 01, 1976	50.46	51.09	51.21	51.01	51.30	51.24	0.12
March 02, 1976- March 01, 1977	53.74	54.95	55.02	54.80	55.09	55.23	0.16
March 02, 1977- March 01, 1978	54.08	60.30	60.07	59.42	62.64	61.77	1.32
March 02, 1978- March 01, 1979	26.91	27.02	26.96	27.00	27.08	27.04	0.04
March 02, 1979- July 30, 1980	27.34	27.34	27.34	27.34	27.34	27.34	0
POR Average (in)	49.37	50.67	50.57	50.54	51.07	50.98	0.24

When comparing the yearly average results in Table 2.14 with the yearly averages of the index stations (Table 2.13), it is observed that even though the methods are apparently consistent with respect to each other, they are not consistent with respect to the index stations. For that reason, the consistency of the rainfall gauging station S-194 is questioned.

2.4 *Gauge Consistency*

Besides estimating missing rainfall data, the catch at rain gauges is occasionally inconsistent over a period (McCuen, 1989). Possible sources of inconsistency in a record include observation procedures, changes in exposure, and changes in the land use. Station S-194 might be inconsistent due to the development of the surrounding area. If reconstruction of Krome Avenue, which is located close to the structure (see Figure 1.4C) occurred during these time periods, inconsistencies could have occurred. A double mass curve is a graph of the cumulative catch at the rain gauge of interest, S-194, versus the cumulative catch of one or more gauges in the region exposed to similar hydrometeorological occurrences (McCuen, 1989). If the gauge is consistent, the slope of the line will be constant. If there is a change in slope, the following equation can adjust the record:

$$Y_1' = \frac{S_2}{S_1} Y_1 \tag{2.11}$$

where Y_1' is the new rainfall average, S_2 is the correct slope of the line as calculated by the previous records, S_1 is the incorrect slope as calculated by the inconsistent records, and Y_1 is the inconsistent rainfall value. Both Column (1), Table 2.16, and Figure 2.3 illustrate that two time periods are inconsistent: 1973-1975 and 1978-1980. A double mass curve was done twice, first to correct the earlier time and then to correct the later time.

Figures 2.3 illustrates the initial double mass curve. Figure 2.4 illustrates the initial double mass curve, the double mass curve after correcting the first inconsistency, and the final double mass curve which includes correcting for the second period of inconsistency. To correct the first inconsistency shown in Table 2.4, the values of S_2 and S_1 used in Equation (2.11) are 0.97 and 0.72, respectively. To correct the second inconsistency, the values of S_2 and S_1 used in Equation (2.11) are 0.95 and 0.43, respectively. The results of the double mass analysis are in Column (2), Table 2.16. After completing the double mass balance curve, the new average annual rainfall values were used in method 2 to compute new daily average rainfall values. Before the double mass analysis, the mean annual rainfall for the period of record at S-194 was close to 50 inches (see Table 2.16), and after the analysis, the mean annual rainfall was 57.42 inches which is more consistent with the surrounding index stations.

Table 2.16 Mass Balance Results

Time Frame	S-194 Annual Rainfall	
	(1) Method 2 Before Mass Balance	(2) Method 2 After Mass Balance
June 17,1966- February 29, 1968	55.04	55.04
March 01, 1968- March 01, 1969	87.08	87.08
March 02, 1969- March 01, 1970	78.18	78.18
March 02, 1970- March 01, 1971	37.70	37.70
March 02, 1971- March 01, 1972	49.30	49.30
March 02, 1972- March 01, 1973	54.58	54.58
March 02, 1973- March 01, 1974	41.57	56.00
March 02, 1974- March 01, 1975	33.36	44.05
March 02, 1975- March 01, 1976	51.21	51.21
March 02, 1976- March 01, 1977	55.02	55.02
March 02, 1977- March 01, 1978	60.07	60.07
March 02, 1978- March 01, 1979	26.96	59.25
March 02, 1979- July 30, 1980	27.34	60.08
POR Average (in)	50.57	57.51

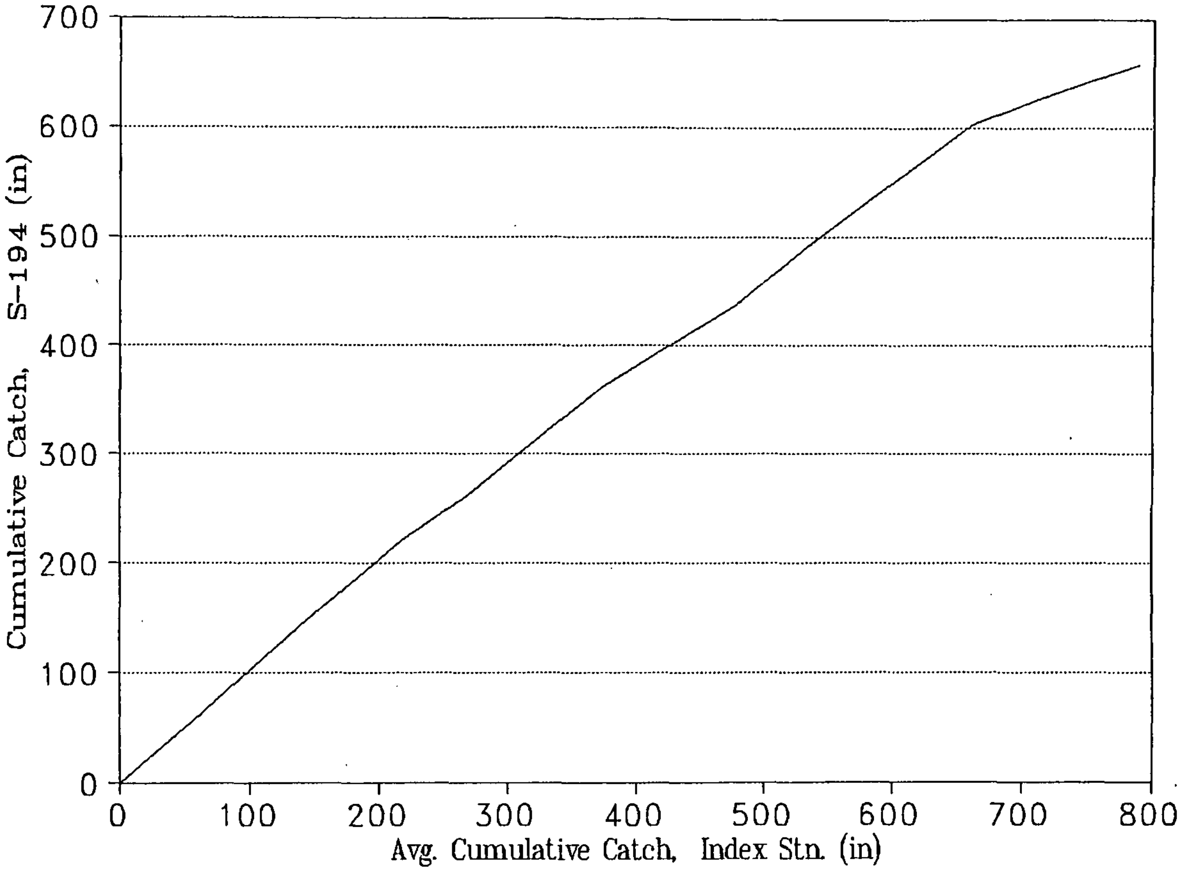


Figure 2.3 Initial Double Mass Curve

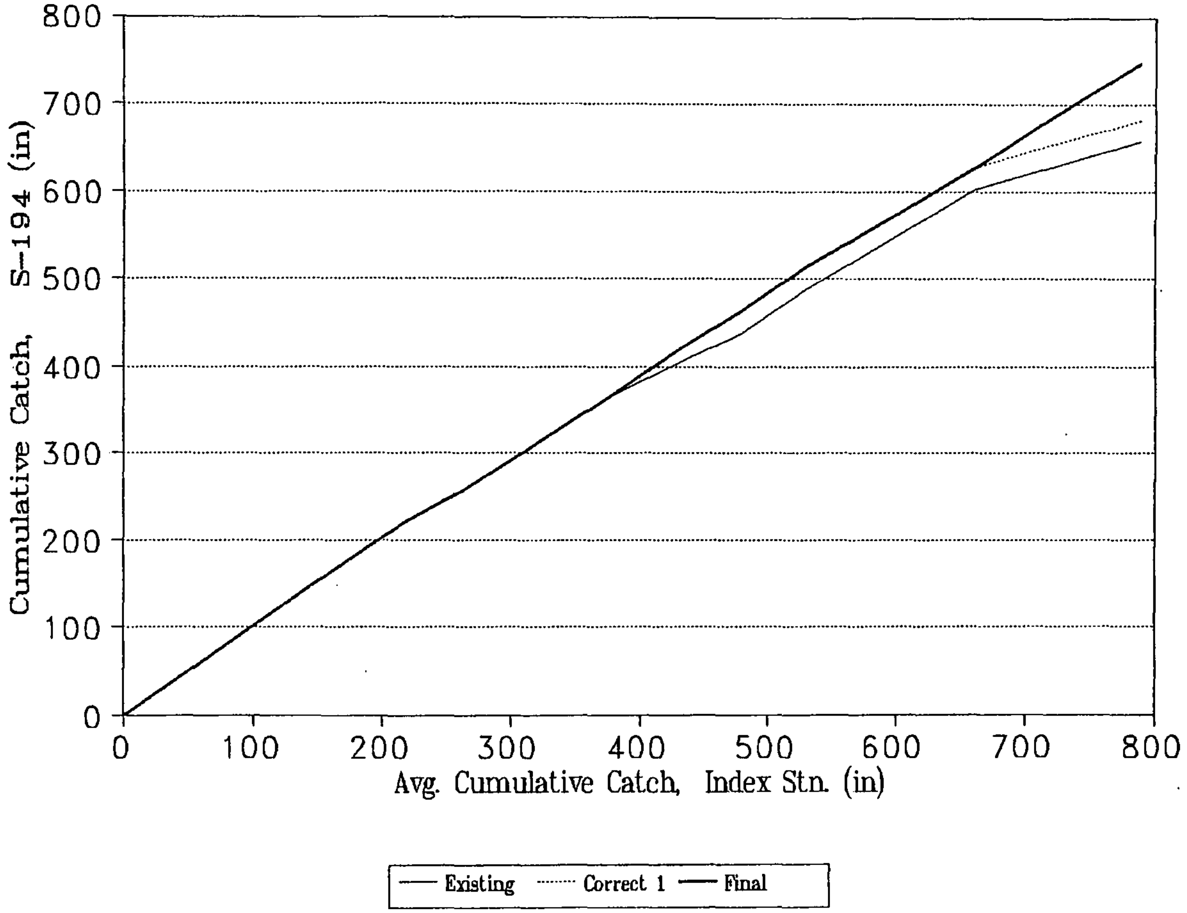


Figure 2.4 Final Double Mass Curve

2.5 *Seasonal Analysis*

To verify that the rainfall gauging station at S-194 has been interpolated correctly and consistently, a seasonal analysis was done computing the accumulated rainfall in each wet and dry season for S-194, HOMES_R.FS, PERRINE_R, and IRA_EBER. A comparison is made between the results in this study and the results in MacVicar (1983) which used all of the stations within or near the SFWMD for which a minimum of twenty years of data were available. In MacVicar's study, the period of record at individual gauges varied from twenty to one hundred years with an average of about thirty-five years of record at each gauge. The number of stations used to produce Figures 2.5 through 2.11 varied from on hundred forty-one to one hundred sixty-five. According to MacVicar, Figures 2.5 through 2.7 were taken directly from the District Publication 81-3, <u>Frequency Analysis of Rainfall Maximums for Central and South Florida</u>. Figures 2.8 through 2.11 were produced by creating a square grid system with a spacing of 3.5 miles over the entire District area. The grid points were then calculated using a reciprocal distance squared (RDS) interpolation scheme among the closest stations (MacVicar, 1983). The wet season includes May 1 through October 31 and the dry season is November 1 through April 30 (MacVicar, 1983). In addition to computing the seasonal dry and wet values, average wet and dry values were calculated for S-194's period of record. Tables 2.17 and 2.18 illustrate the individual seasonal results along with an average dry and wet season value.

Table 2.17 Dry Season (in)

Period	HOMES R.FS	PERRINE R	IRA EBER	S-194
1966-1967	NR	8.14	NR	8.88
1967-1968	NR	9.81	NR	10.33
1968-1969	15.73	14.79	NR	15.47
1969-1970	9.70	10.19	9.98	8.72
1970-1971	2.57	3.60	3.04	2.32
1971-1972	19.44	19.78	15.23	18.65
1972-1973	10.08	NR	12.82	13.33
1973-1974	7.73	NR	7.38	7.41
1974-1975	8.11	NR	6.44	7.05
1975-1976	10.09	NR	9.88	7.34
1976-1977	8.72	NR	10.99	8.03
1977-1978	19.57	NR	19.13	16.13
1978-1979	8.58	NR	10.73	18.70
1979-1980	14.81	NR	14.20	13.45
Average	11.26	11.05	10.89	11.13

Table 2.18 Wet Season (in)

Period	HOMES_R.FS	PERRINE_R	IRA_EBER	S-194
1967	NR	53.79	NR	42.54
1968	80.16	69.06	NR	77.78
1969	64.32	60.77	NR	64.58
1970	44.92	40.26	39.95	32.93
1971	40.26	50.17	38.21	37.58
1972	35.60	NR	44.53	36.23
1973	46.43	NR	50.53	48.5
1974	33.84	NR	42.73	35.43
1975	45.52	NR	43.30	45.28
1976	49.32	NR	57.49	46.52
1977	52.48	NR	54.51	48.60
1978	42.07	NR	52.17	45.67
1979	41.28	NR	38.83	37.16
Average	48.02	54.81	46.23	46.06

The maps produced by MacVicar (1983) show an average annual rainfall of 56 to 62 inches over the study area (Figure 2.5). This value coincides with the result obtained from this study, 57.42 inches. This studies average wet and dry seasonal values of 48 to 54 inches and 10.89 to 11.26, respectively, also coincide with MacVicar's results seen in Figures 2.6 and 2.7. The reason the station PERRINE_R has a higher wet season average is due to the wet season of 1968. Because PERRINE_R has such a short record, this wet season increased its average. Figure 2.8 illustrates the map developed by MacVicar for the 1968 wet season. The averages obtained from this study accurately fall in the isohyetes of this map. The final three figures developed by MacVicar illustrate the following:

1) dry season of 1969 - 1970, Figure 2.9, in which northern and central Florida experienced a drought, but the Lower East Coast was not significantly affected

2) 1970 wet season, Figure 2.10, which experienced a significant shortage of rainfall

3) dry season of 1970 - 1971, Figure 2.11. This was a very dry season. South Florida experienced droughts due to the combined effects of low rainfall in the wet season of 1970 (Figure 2.10) and low rainfalls in the dry season of 1970-1971 (Figure 2.11). The dry season of 1970 - 1971 had an extensive impact on

> the perception of south Florida's water management needs and the institutional requirements necessary to meet them (MacVicar, 1983).

All of the calculated data at S-194 and the index stations coincide with the isohyetal maps developed by MacVicar (1983).

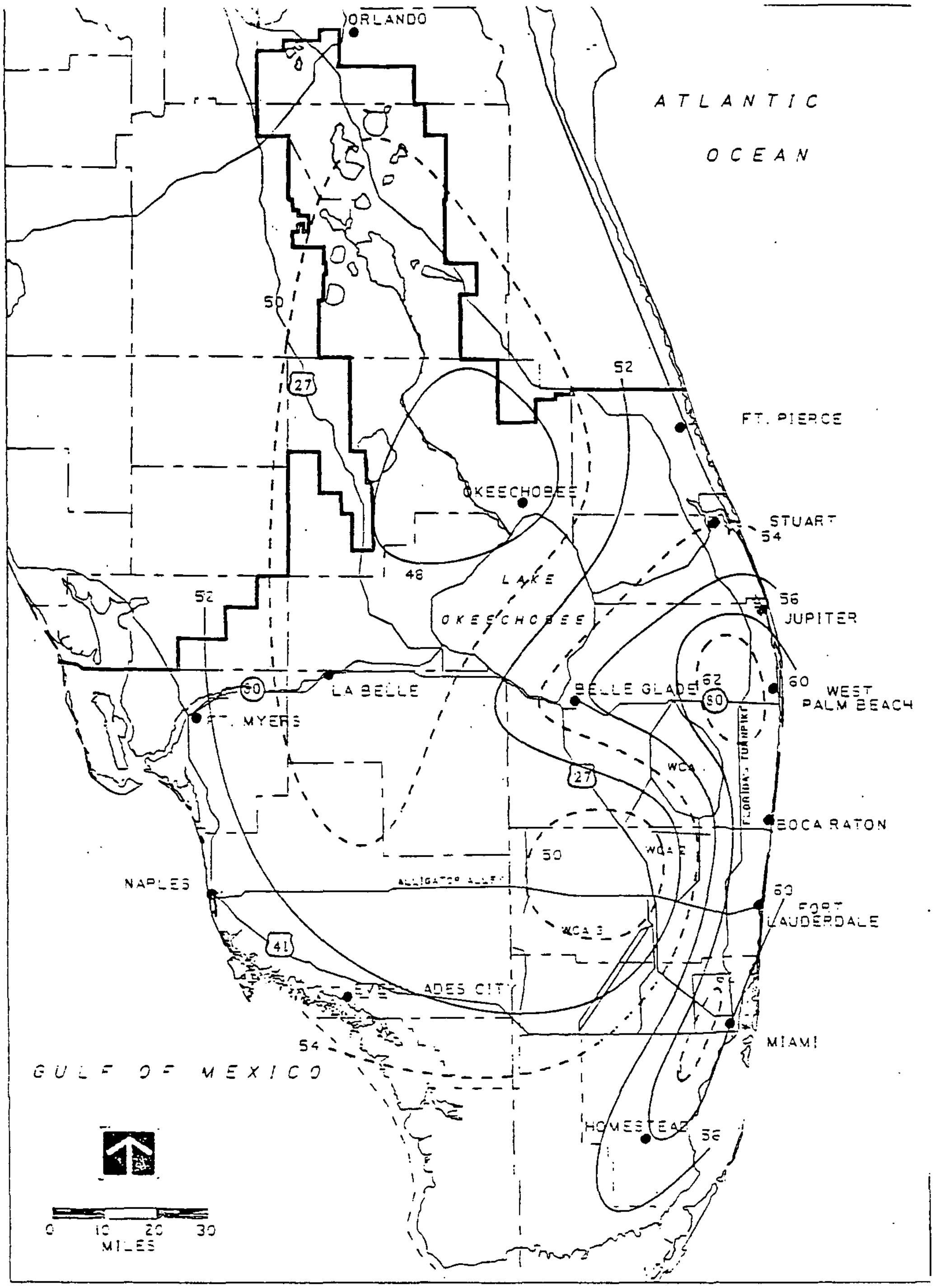


Figure 2.5 Average Annual Rainfall (MacVicar, 1983)

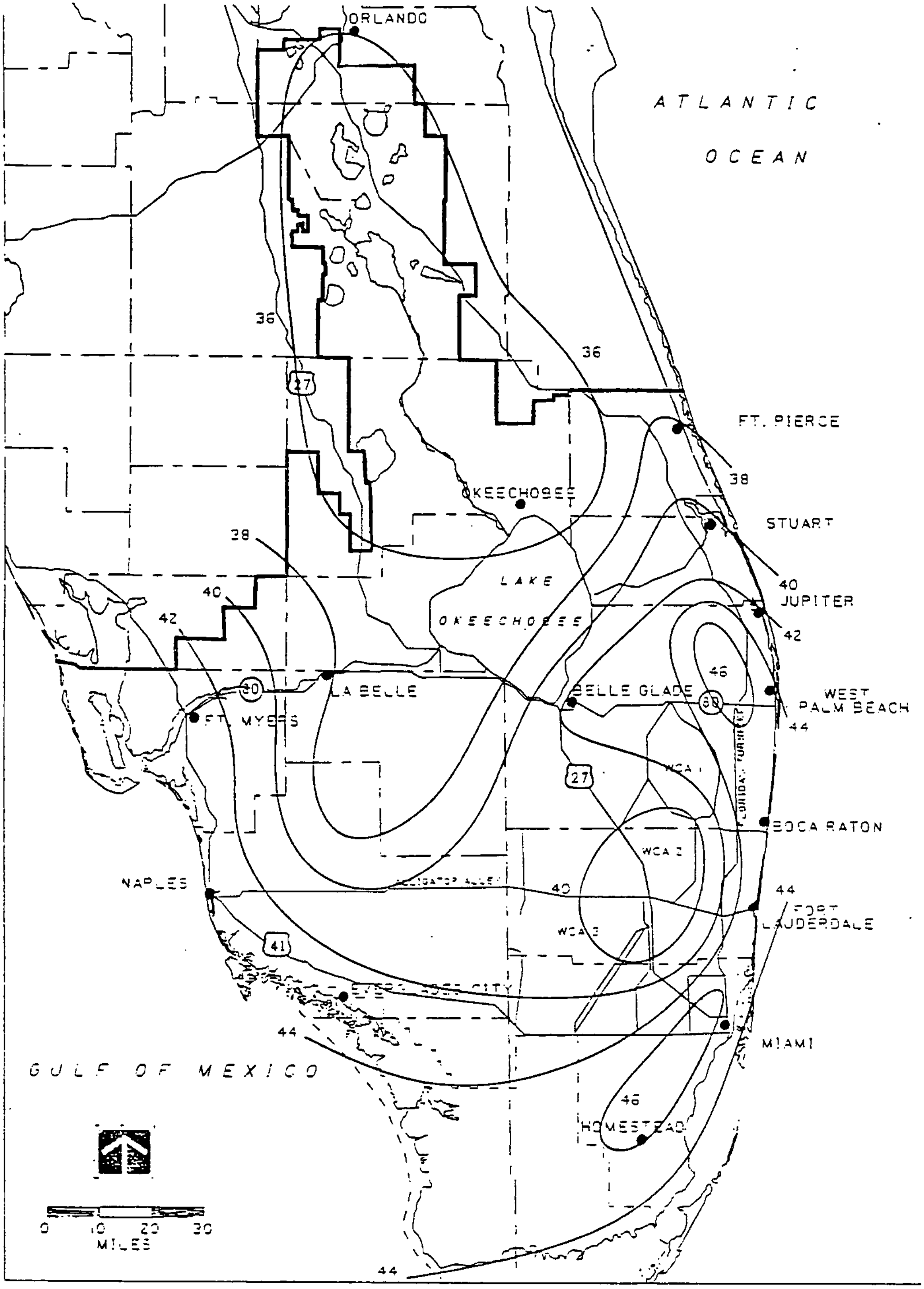


Figure 2.6 Average Wet Season (MacVicar, 1983)

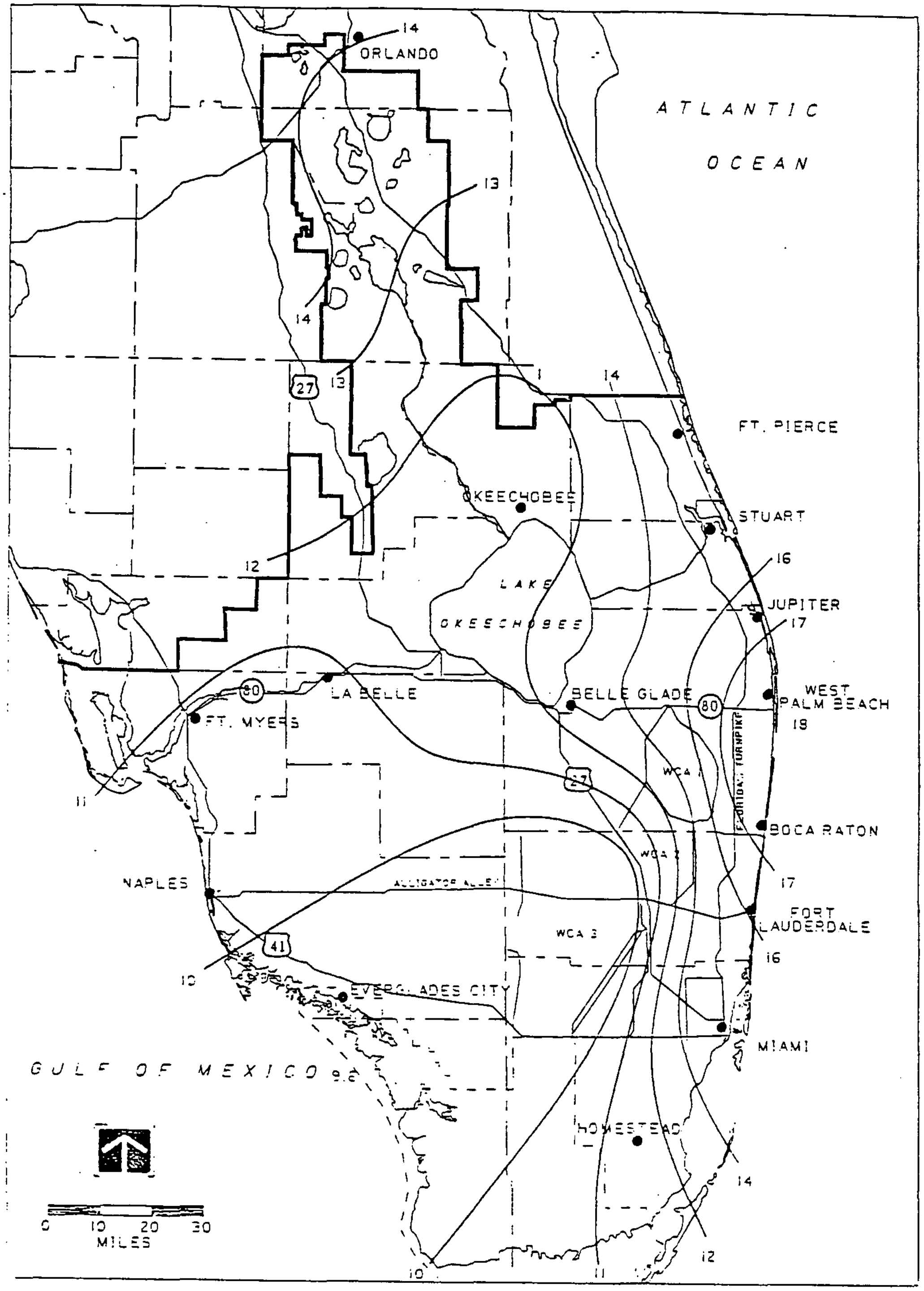


Figure 2.7 Average Dry Season (MacVicar, 1983)

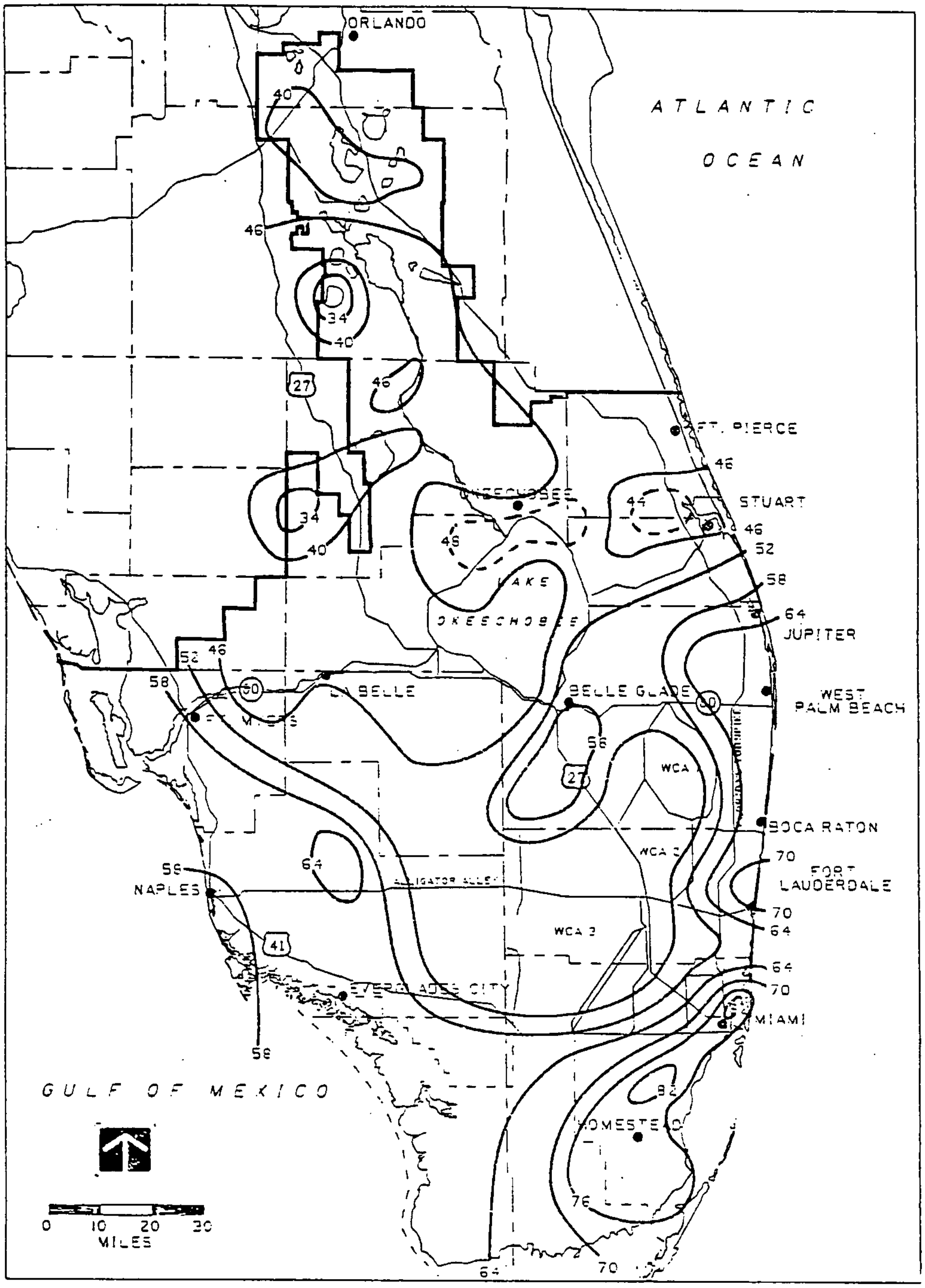


Figure 2.8 1968 Wet Season (MacVicar, 1983)

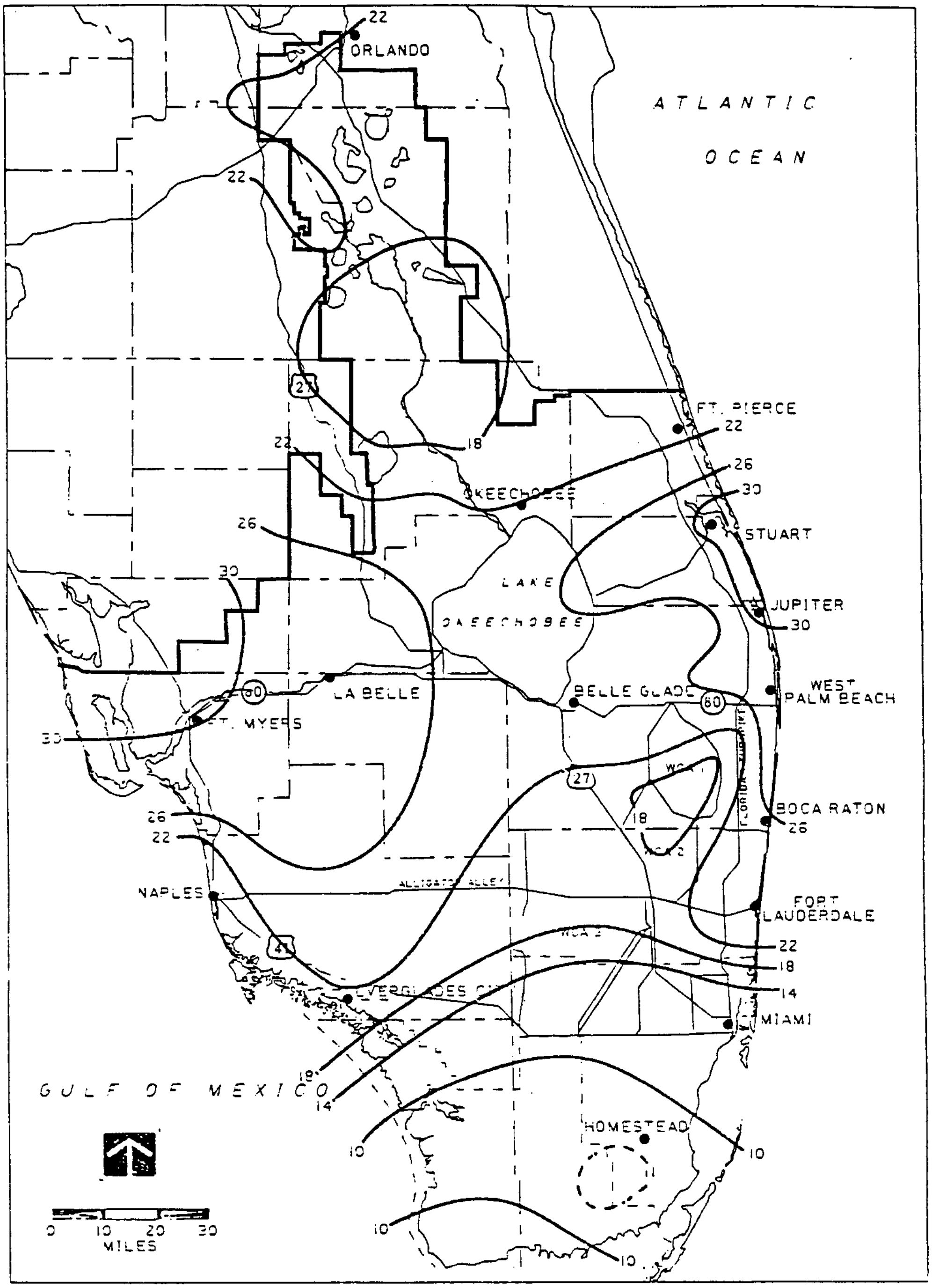


Figure 2.9 1969-1970 Dry Season (MacVicar, 1983)

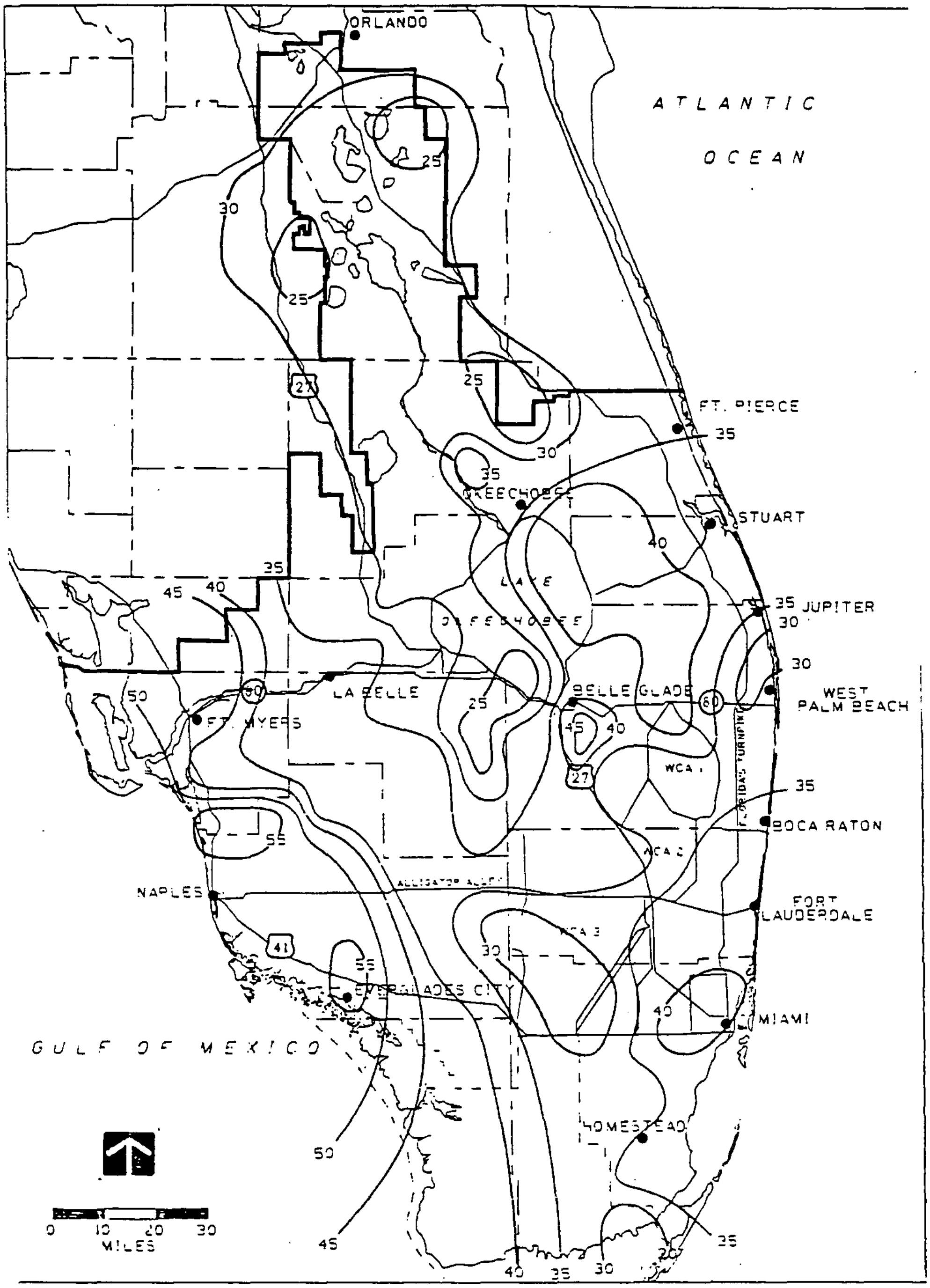


Figure 2.10 1970 Wet Season (MacVicar, 1983)

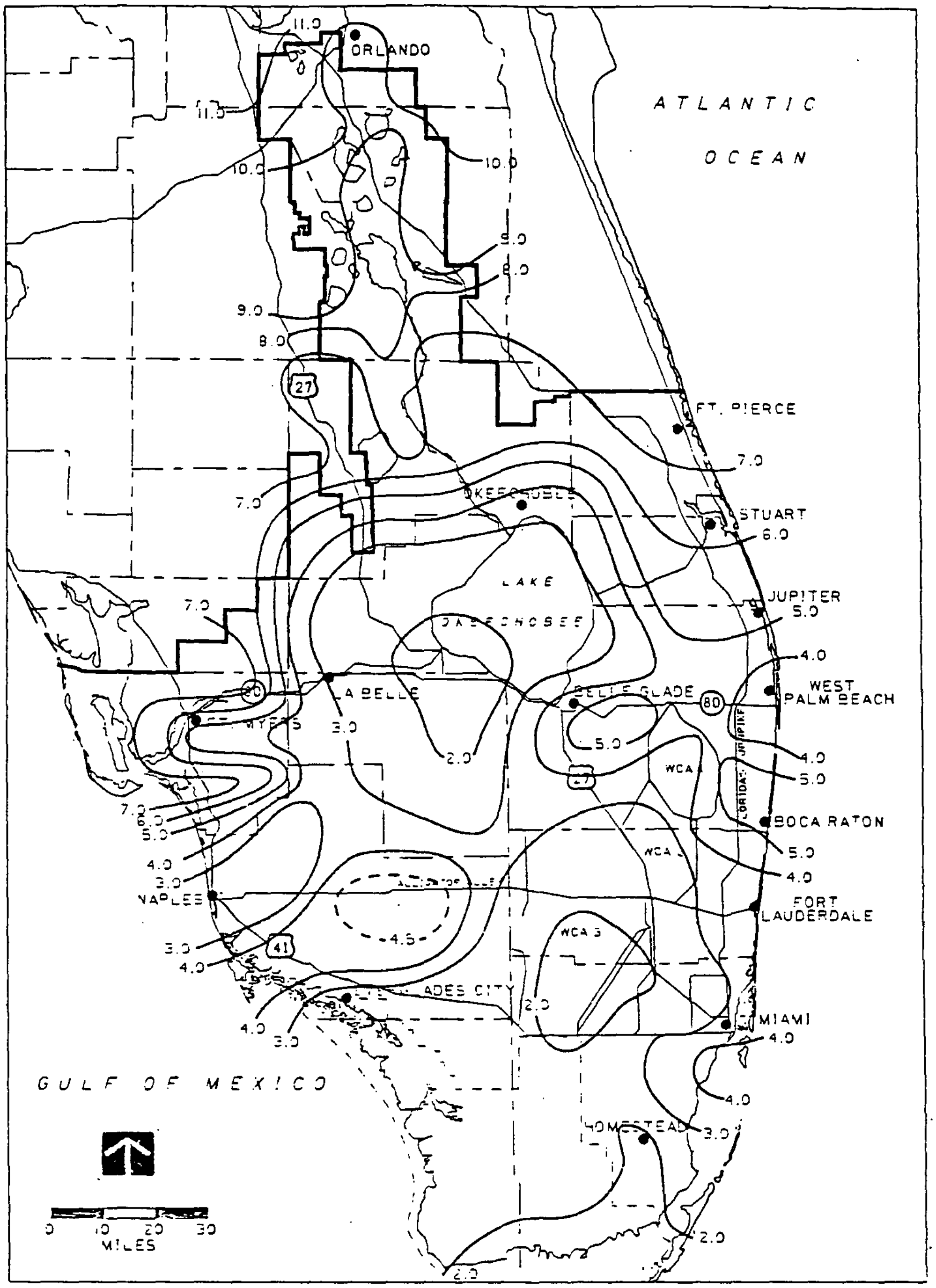


Figure 2.11 1970-1971 Dry Season (MacVicar, 1983)

CHAPTER 3 BASIN WATER BUDGET

3.1 Theory

A basin water budget refers to an accounting of the various transport phases of the hydrologic cycle within a catchment. Figure 3.1 illustrates the various water transport variables in the hydrologic cycle of a coastal area of Florida. In a basin water budget, the flow rate into the basin minus the flow rate out of the basin is equal to the rate of change in storage in the basin, or:

$$Q_{in} - Q_{out} = \frac{\Delta S}{\Delta t} \tag{3.1}$$

where Q is flow, S is storage, and t is time. Over a specified time period, Equation (3.1) simplifies to the volume into the basin minus the volume out of the basin is equal to the change in storage.

$$V_{in} - V_{out} = \Delta V_S \tag{3.1}$$

where V is volume and ΔV_s is the change in storage.

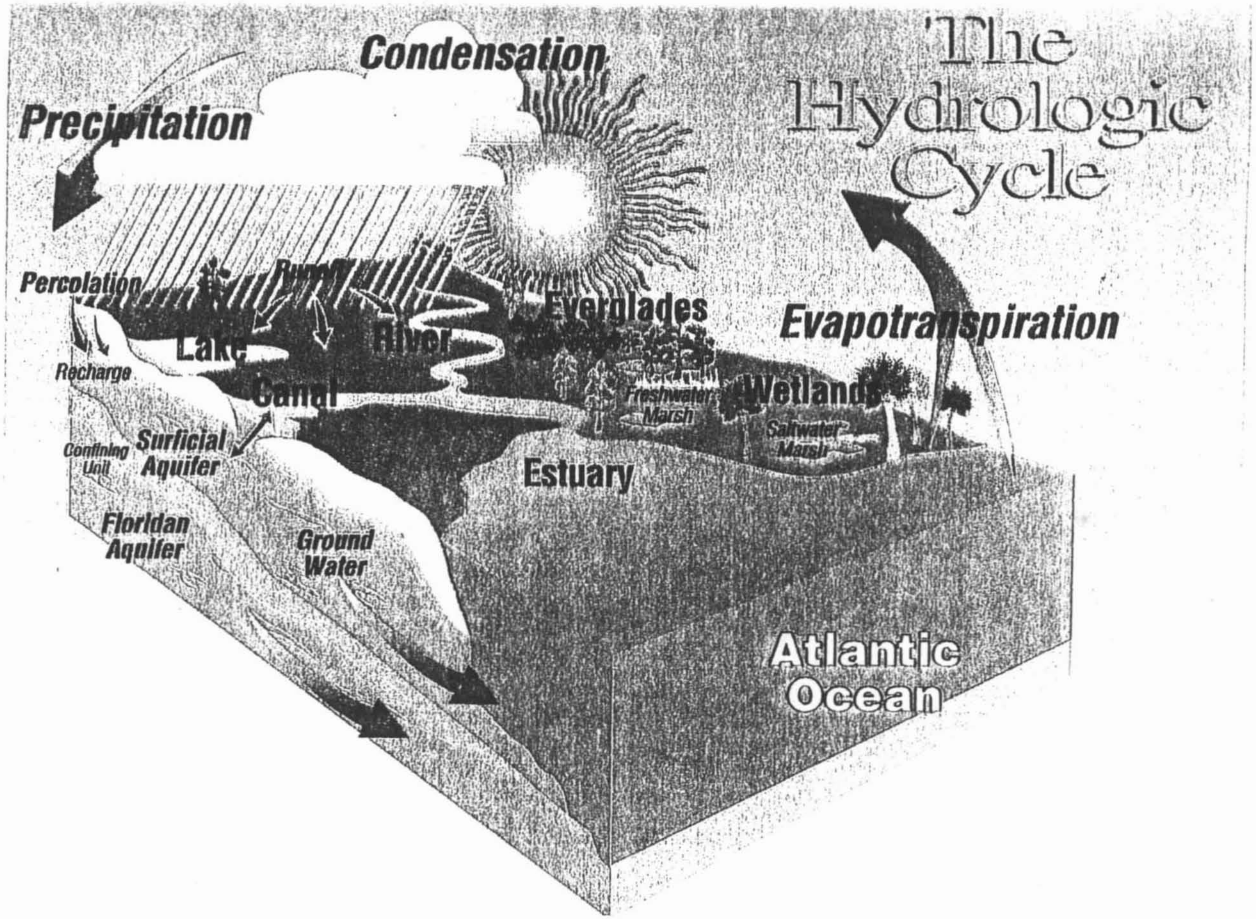


Figure 3.1 Hydrologic Cycle (SFWMD LEC Region Water Supply Plan, 1993)

In this analysis, the flow into a basin is defined by precipitation, surface flow, and groundwater flow. Flow out of the basin is comprised of surface flow, groundwater flow, and evapotranspiration. The change in volume is comprised of the change in volume of groundwater (water table rise or fall), the change in soil moisture in the unsaturated zone of the soil, and the change in volume of surface water bodies (lakes, swamps, etc.). In this study, the change in soil moisture in the unsaturated zone of the soil is neglected due to the shallow water table and sandy nature of the soil. The change in volume of surface water bodies is neglected primarily because the area of surface water bodies, the canals, is small in proportion to the watershed area, approximately 100 out of 16000 acres. Equation (3.2) is rewritten as:

$$(R + P + GW)_{in} - (ET + R + GW)_{out} = \Delta V \tag{3.3}$$

where P is precipitation multiplied by the area of the basin, GW is a net groundwater volume over a period of time, ET is evapotranspiration multiplied by the area of the basin, R is surface flow represented as a volume over a period of time, and ΔV is the change in storage. Equation (3.3) can be rearranged to represent the seepage out of the basin, Z, or:

$$GW_{out} - GW_{in} = Z = P + R_{in} - ET - R_{out} + \Delta V \tag{3.4}$$

which is the equation used to perform the basin water budget in C-102.

The time interval used to perform a basin budget depends on the availability and accuracy of the data for the parameters in Equation (3.4), as well as the purpose of the study. The available data allows the basin water budget in this study to be performed on a daily, weekly, or monthly time interval; however, monthly intervals were selected because it is thought to give the most accurate estimation of seepage out of the basin. Performing a daily or weekly basin water budget introduces errors due to short meteorologic events in the basin and does not allow for ample response time in the basin to meteorological events.

The records used for each parameter must overlap in order to complete the basin budget. In this analysis, only six months of data overlapped in the C-102 basin. Estimation of parameters was avoided as much as possible throughout the analysis; however, evapotranspiration was estimated based on previously documented work (SFWMD LEC Region Water Supply Plan, 1993) as explained in section 3.2.3. The following section describes each of the parameters in Equation (3.4).

3.2 Parameters

3.2.1 Precipitation

Rain is the primary form of precipitation in southeast Florida. Rainfall can be measured over various durations such as: hourly, daily, or monthly. In this study, daily precipitation values were used and summed to obtain monthly values. The daily precipitation values at S-194 were not used as the rainfall on the entire basin. Instead, the spatial average of rainfall over the basin was calculated using the Thiessen polygon method.

3.2.1.1 Thiessen Polygon Method

According to Ponce (1989), to begin the Thiessen polygon method, the station locations are plotted on a scaled map of the basin and the surrounding area. The stations are joined with straight lines to form a pattern of triangles. Perpendicular bisectors to the sides are drawn to enclose each station with a polygon called a Thiessen polygon. The average precipitation over the basin is calculated by weighting each station's rainfall depth in proportion to its area of influence as explained by the following equation (Ponce, 1989).

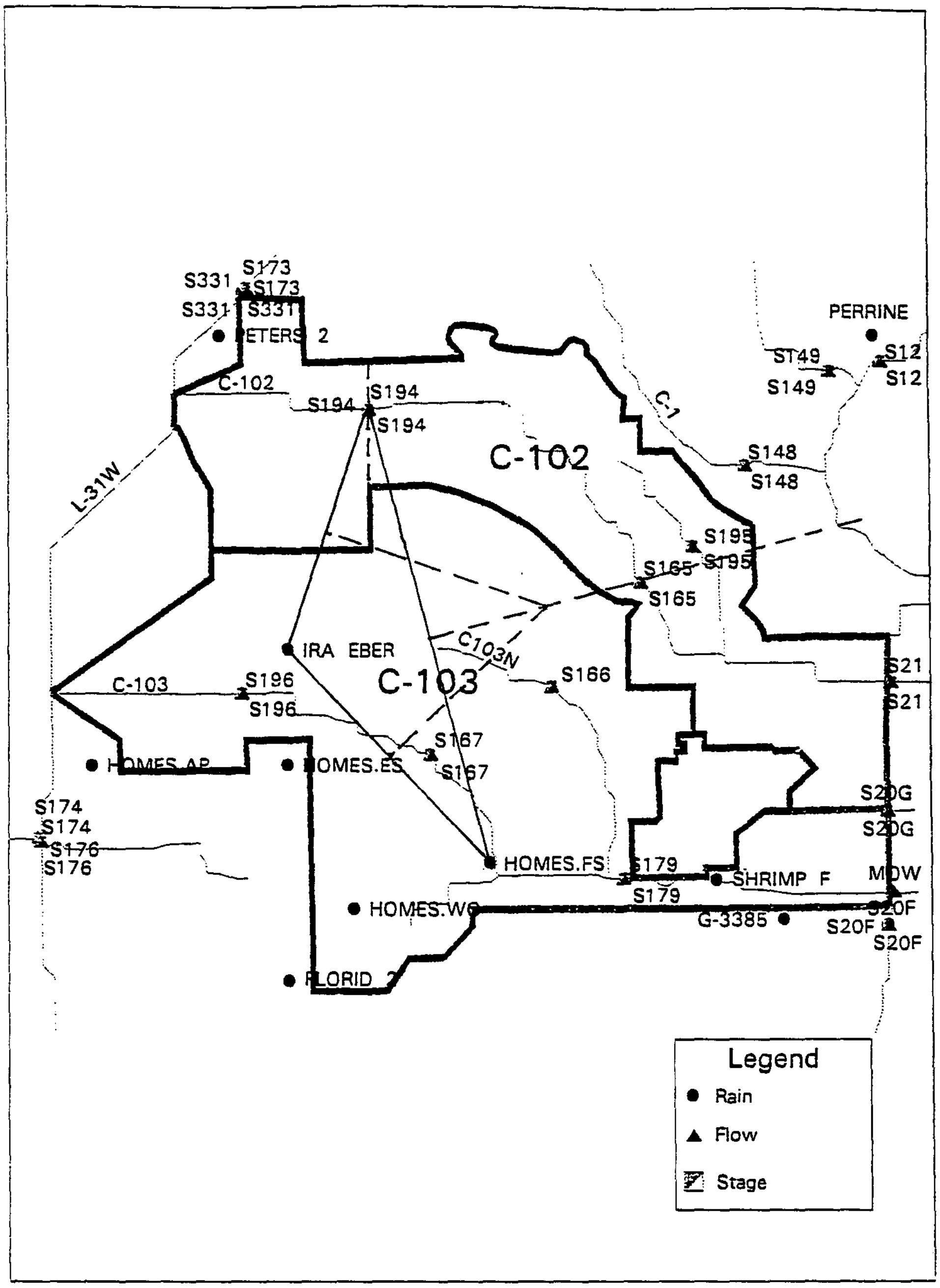
$$P_t = \frac{\sum(PA)}{\sum A} \tag{3.5}$$

where P_t is the resultant daily precipitation in inches, P is the precipitation at the surrounding stations, and A is the area of influence. Figure 3.2 graphically shows the Thiessen polygons. The stations used in the Thiessen polygon method are: HOMES_R.FS, IRA_EBER, and S-194. However, only S-194 and HOMES_R.FS were used to calculate the weighted rainfall over the C-102 basin. IRA_EBER was not used because its Thiessen polygon had no area within the C-102 basin. Table 3.1 shows the weighted areas that were the result of the Thiessen polygon method. These areas were used as the A values in Equation (3.5). A weighted rainfall average was computed using Equation (3.5) with the areas illustrated in Table 3.1.

Table 3.1 Areas of Thiessen Method

Station	Area (mi^2)
Entire C-102 basin	25.4
S-194	15
HOMES_R.FS	10.4

These spatially averaged daily precipitation values were totaled over a month for the period of record at HOMES_R.FS, to attain monthly values. HOMES_R.FS's period of record was used because it was the shorter of the two (refer to Table 2.1, page 20). Figure 3.3 illustrates the difference in the accumulated rainfall at S-194 and the Thiessen Polygon method. There was very little change in the total accumulated rainfall over the basin. The monthly depth totals were then multiplied by the area of the basin to acquire a volume of rainfall, in cubic feet, over the entire basin.



Rain, Flow and Stage Stations for the C102 and C103 Basins.

Figure 3.2 Thiessen Polygon Method

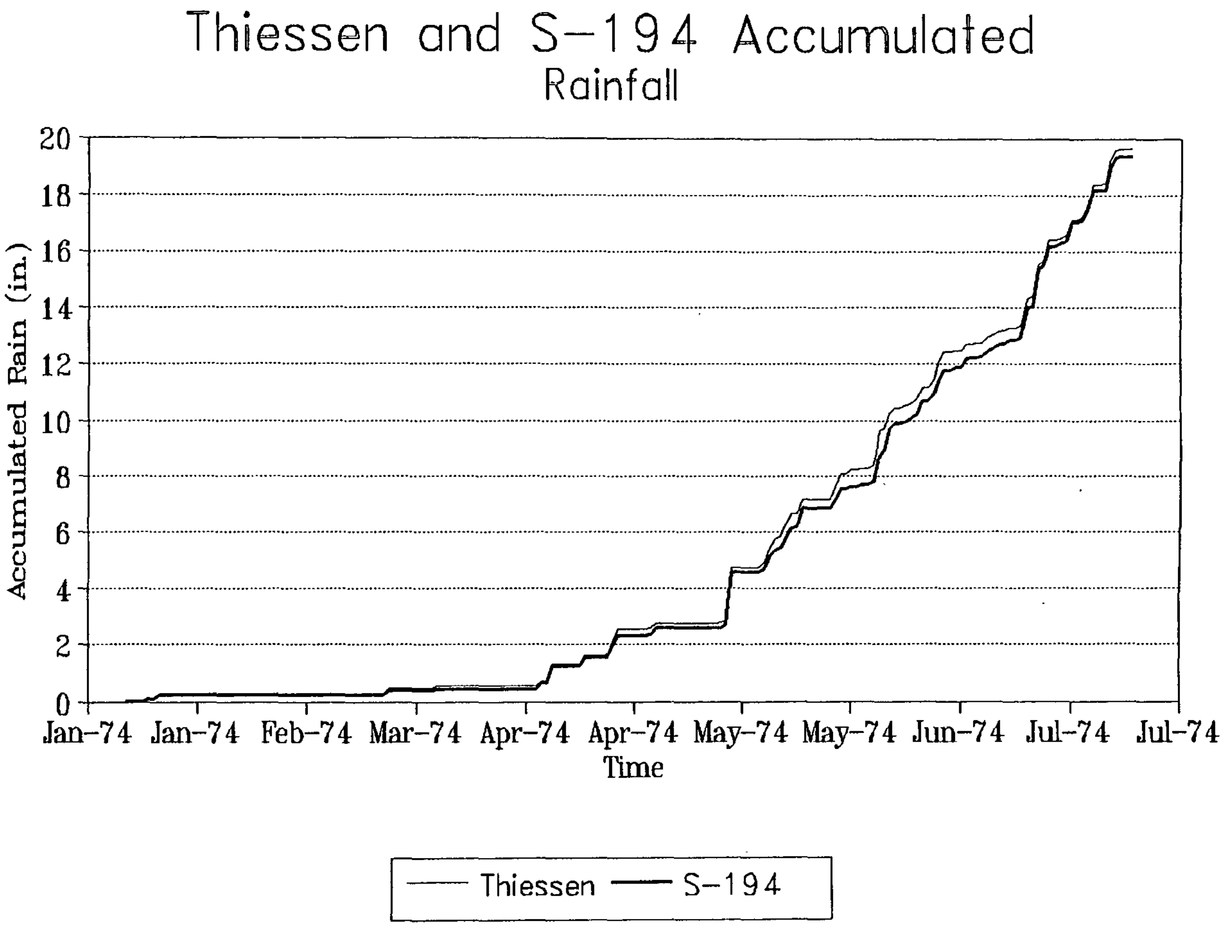


Figure 3.3 Accumulated Rainfall for Thiessen Polygon and S-194

3.2.2 Change in Storage

Groundwater refers to the subsurface water that occurs beneath the water table in soils and geological formations that are fully saturated (Freeze and Cherry, 1979). SFWMD retrieved the period of record for the groundwater stations in the C-102 basin. Similar to precipitation values, groundwater levels can also be recorded in different time intervals such as: hourly, daily, or monthly. Two recording methods exist in the database search acquired from SFWMD. The groundwater values in the first method represent a daily average groundwater elevation. The groundwater values in the second method represent the maximum elevation of the groundwater during a day. From the data acquired from SFWMD, only one station, G757, had a period of record that coincided for a brief time with the rainfall period of record. This station's groundwater levels represent the maximum level of the groundwater during a day.

The groundwater levels at station G757 are used to compute the change in storage, ΔV, over a month. This change in storage was computed by subtracting the end of the month groundwater elevation from the beginning of the month elevation. This results in a positive number if the change in storage over a month decreases and a negative number if it increases. The change in storage was multiplied by the area of the basin to acquire a volume in cubic feet over the entire basin. This volume was used as the input or output value, ΔV, in Equation (3.4).

3.2.3 Evapotranspiration

Evapotranspiration (ET) is the combination of evaporation and transpiration and is the process by which water in the soil and vegetation is converted into the vapor state and returned to the atmosphere. SFWMD provided daily average pan evaporation data for the stations seen in Figure 3.4. Although pan evaporation was collected, there was no pan evaporation data available during any of the months used in this analysis. Instead, ET was calculated using information from SFWMD LEC Region Water Supply Plan (1993). The following equation was used to calculate the ET occurring over the basin.

$$ET = 0.46\,(P) \tag{3.6}$$

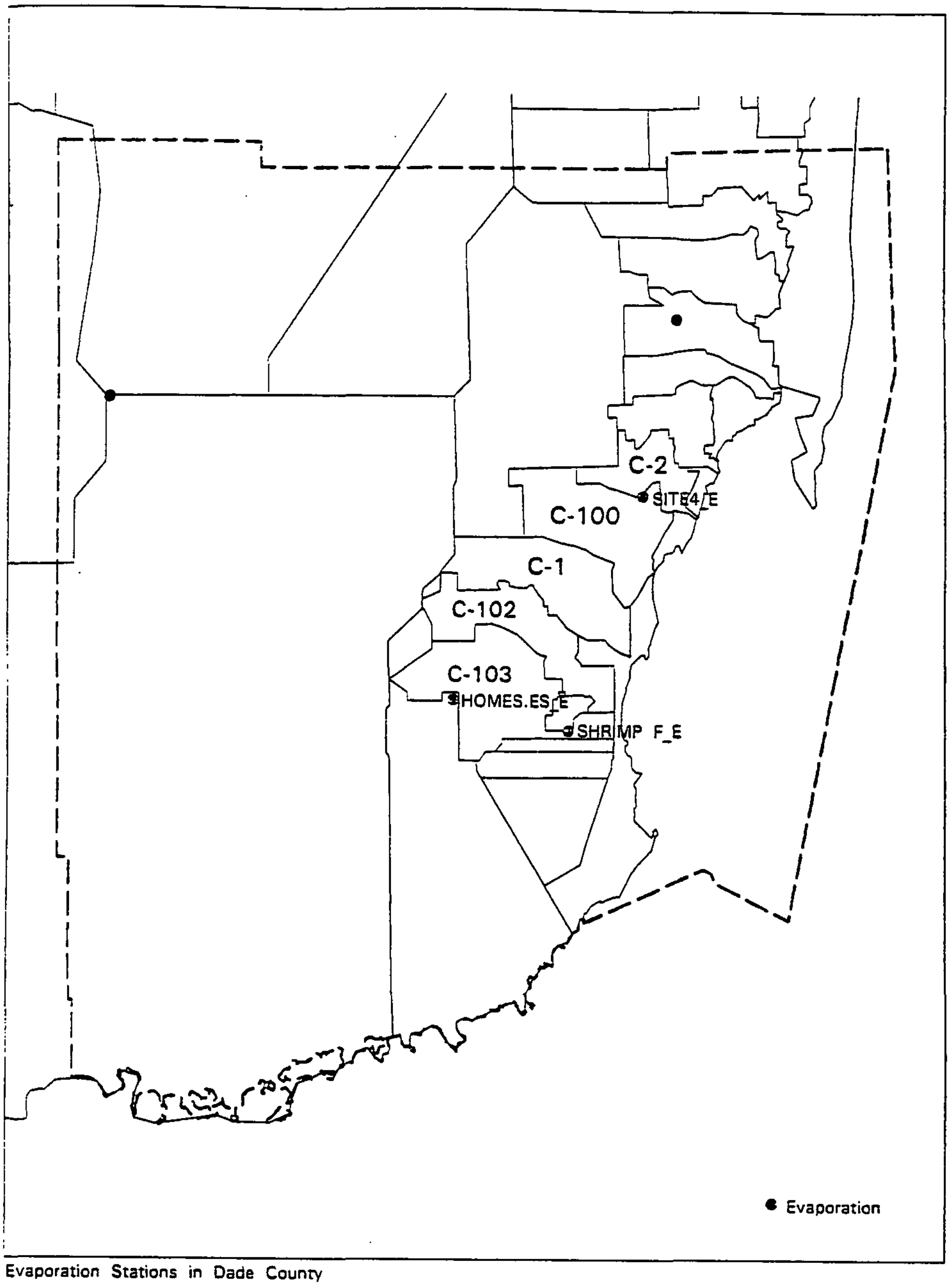
where P is the total precipitation accumulated during the month being analyzed. To verify that this is an accurate estimation of the evapotranspiration in the C-102 basin, the potential evapotranspiration, PET, was calculated using (Ponce, 1989):

$$PET = K_p\,E_p \tag{3.7}$$

where PET is the potential evapotranspiration, K_p is a pan coefficient, and E_p is pan evaporation. According to Ponce (1989), potential evapotranspiration is the amount of evapotranspiration that would take place under the assumption of an ample supply of moisture at all times. In south Florida, ET is approximately equal to PET, even under dry conditions, because of the climate. The pan evaporation data was taken from station HOMES.ES_E, Figure 3.4, which is in the C-103 basin, directly south of the C-102 basin. A pan coefficient of 0.75 is used in Equation (3.7) which, according to Ponce (1989), should be used for regions with the following characteristics:

1) pan surrounded by short green crops
2) the relative humidity is high (70%)
3) the wind speed is moderate (175 - 425 km/d)
4) the upwind distance of green crop is 10 meters

These characteristics, appropriate for Florida, result in a conservative estimate for the PET of the C-102 basin. A plot of the accumulated rainfall at S-194 during February 19, 1968 to May 02, 1969 versus the accumulated PET, as calculated from Equation (3.7), during the same time is illustrated in Figure 3.5. In addition, Figure 3.5 also includes a plot of evapotranspiration versus rainfall using Equation (3.6). The results from this analysis verify that the estimation of ET made by SFWMD, Equation 3.6, is accurate because PET is uniform around ET in Figure 3.7. As a result, ET was calculated using Equation (3.6). The resultant evapotranspiration values were multiplied by the area of the entire basin to acquire a volume in cubic feet over a month of evapotranspiration. This volume was the outflow, ET, in Equation (3.4).



Evaporation Stations in Dade County

Figure 3.4 Pan Evaporation Stations in Dade County
(SFWMD Technical Support, 1995)

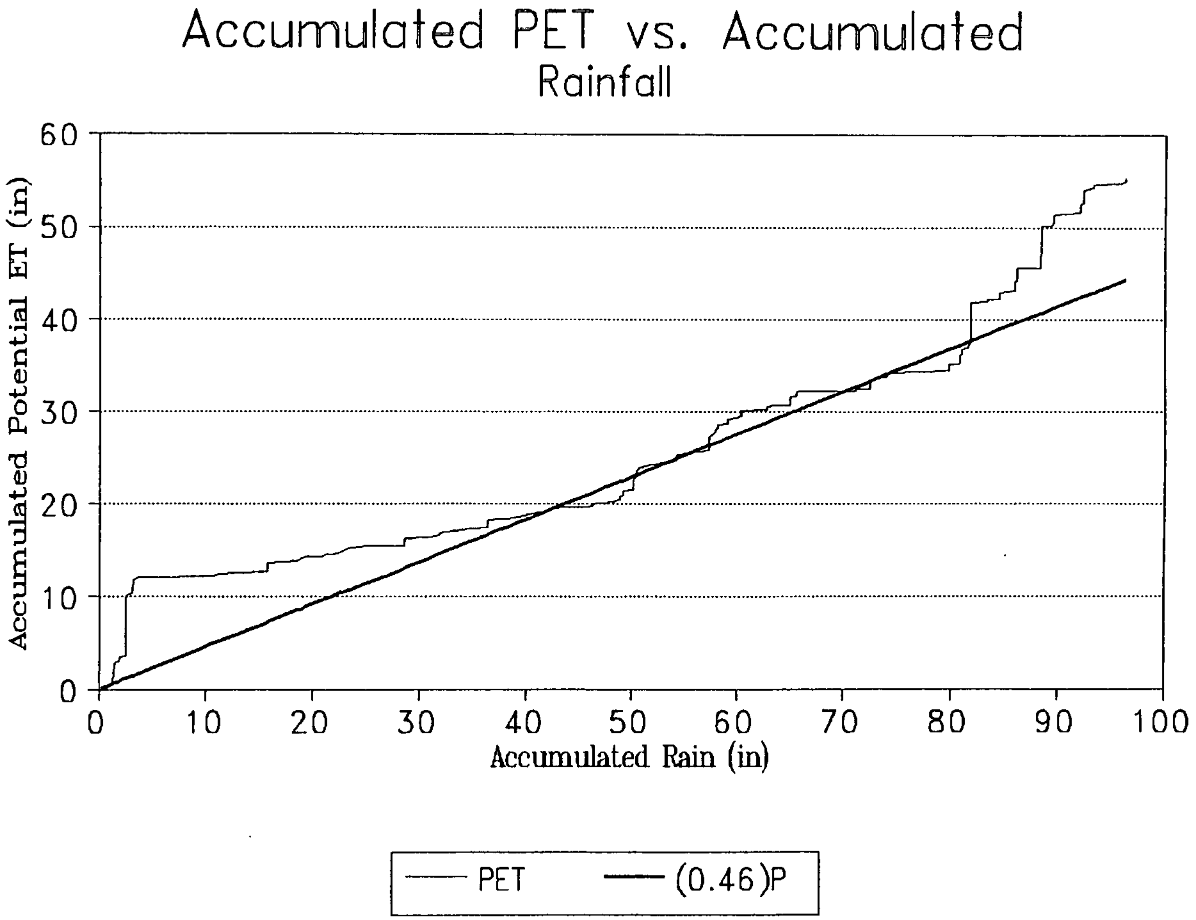


Figure 3.5 Accumulated PET and ET vs. Accumulated Rainfall

3.2.4 Surface Flow

For this analysis, surface flow out of the basin was estimated as the monthly total of the daily average flows at the main tidal structure S-21A located at the confluence with Biscayne Bay. Because there is no available flow data collected at S-194, only months where the flow at the outlet structure S-21A was small were used. The rationale is that, when the flow at S-21A is small, there is an insignificant amount of flow at S-194. The result is that the R_{in} term in Equation (3.4) is negligible. This hypothesis limits the time frame of the basin budget analysis to six months in 1974, when flows at S-21A are relatively small. These months are illustrated in Table 3.2 The volume of flow during a month is calculated by summing the individual daily flow amounts over the month and multiplying by the number of seconds in a day to find a volume of rainfall during the month in cubic feet. This value is the output variable, R_{out}, in Equation (3.4).

3.2.5 Groundwater Flow

Using Equation (3.4), net groundwater flow can either be into or out of the basin; however, in this analysis, only outflow was observed. Because of the groundwater gradients in the study area, seepage is assumed to be to the east, or into Biscayne Bay. However, the seepage could also go into the surrounding basins.

Table 3.2 Months Used For Analysis

Time Interval
January 18, 1974 - February 18, 1974
February 19, 1974 - March 18, 1974
March 19, 1974 - April 18, 1974
April 19, 1974 - May 18, 1974
May 19, 1974 - June 18, 1974
June 19, 1974 - July 18, 1974

3.3 Results

Table 3.3 summarizes the results of Equation (3.4). In this table, the volume of seepage is converted to the equivalent depth of seepage over C-102 in inches. The seepage values range from 0.40 to 2.07 inches over the basin and the average over the six month period is 1.23 inches. Table 3.4 shows each variable in Equation (3.4) and their equivalent depths over the basin. The increase over time of the precipitation values in Table 3.4 illustrate the transition from the dry to the wet season of 1974. This transition is further supported by the change in storage from a positive to a negative number, early spring and late spring, at which the groundwater table began to rise. As illustrated in Table 3.4, the seepage out of the C-102 was greatest during May and June of 1974. However, the seepage decreases significantly during June and July because the flow out of the basin at S-21A was increased significantly probably in preparation for the wet season.

Table 3.3 Summary of Results

Time Interval	Seepage (ft^3)	Seepage (in)
January 18, 1974 - February 18, 1974	4.7×10^7	0.61
February 19, 1974 - March 18, 1974	5.3×10^7	0.91
March 19, 1974 - April 18, 1974	1.0×10^8	1.72
April 19, 1974 - May 18, 1974	9.8×10^7	1.67
May 19, 1974 - June 18, 1974	1.2×10^8	2.07
June 19, 1974 - July 18, 1974	2.4×10^7	0.4
Average	7.4×10^7	1.26

Table 3.4 Depth of Parameters in Basin Water Budget (in.)

Time Interval	P	ΔV	R_{out}	ET	Seepage
January 18, 1974 - February 18, 1974	0.29	0.77	0.32	0.13	0.61
February 19, 1974 - March 18, 1974	0.20	0.80	0.00	0.09	0.91
March 19, 1974 - April 18, 1974	1.91	0.69	0.00	0.88	1.72
April 19, 1974 - May 18, 1974	3.10	0.00	0.01	1.43	1.67
May 19, 1974 - June 18, 1974	6.34	-1.24	0.12	2.92	2.07
June 19, 1974 - July 18, 1974	7.53	-1.93	1.74	3.46	0.40
Average	3.22	-.15	0.36	1.48	1.23

3.3.1 Validation of the Basin Water Budget

The accuracy of the basin budget can be assessed by comparing the groundwater seepage results to results of groundwater modeling. To draw this comparison, the average linear horizontal seepage velocity (V_s) was calculated in addition to the transmissivity of the aquifer. Using the seepage calculated from Equation (3.4), V_s can be calculated by assuming the cross section dimensions of the aquifer. According to Anderson and Shaw (1991), the saturated thickness of the Biscayne Aquifer beneath the west portion of the C-102 basin is forty-five feet. This saturated thickness was assumed to be uniform throughout the entire basin for this analysis. The average width of the C-102 basin is estimated to be 2.25 miles. Thus V_s is calculated by dividing the monthly volume of seepage out of the basin by the saturated thickness and average width, Table 3.5.

To estimate the transmissivity of the aquifer, Darcy's law is used to obtain a value of hydraulic conductivity. The hydraulic gradient of 0.000123 ft/ft, suggested by Anderson and Shaw (1991), and the seepage velocity, V_s, obtained above, give values of hydraulic conductivity. Multiplying hydraulic conductivity by the aquifer thickness, forty-five feet, gives transmissivities shown in Column (2), Table 3.5. Column (3) illustrates the transmissivity multiplied by the effective porosity percent, 0.225, of the aquifer (Anderson and Shaw, 1991).

The study performed by Anderson and Shaw (1991) states that the average linear horizontal groundwater seepage velocity existing within the Biscayne Aquifer is 9.76 ft/day. Anderson and Shaw explain that this is a conservative estimate due to the hydraulic parameters assumed to calculate V_s. In Anderson and Shaw's report, two of the parameters used to calculate the horizontal velocity is the transmissivity of the Biscayne Aquifer which they estimated to be 6,000,000 gal/day/ft (802,139 ft^3/day/ft) and an effective porosity percent of 0.225. The SWIM plan for Biscayne Bay developed in 1994 by SFWMD further estimates the transmissivity of the Biscayne Aquifer to be 300,000 ft^3/day/ft. Both the horizontal velocity and transmissivity values calculated in this study generally agree with previous studies.

Table 3.5 Transmissivity and Horizontal Velocity

Time Interval	Velocity (ft/day)	Transmissivity	
		(2) (ft^3/day/ft)	(3) (ft^3/day/ft)
January 18, 1974 - February 18, 1974	2.73	998780	224725
February 19, 1974 - March 18, 1974	2.68	980487	220609
March 19, 1974 - April 18, 1974	4.59	1679268	377835
April 19, 1974 - May 18, 1974	4.6	1682927	378658
May 19, 1974 - June 18, 1974	5.52	2019512	454390
June 19, 1974 - July 18, 1974	1.11	406097	91371
Average	3.54	1295122	291402

CHAPTER 4 SUMMARY and CONCLUSIONS

The reliability of any hydrologic study is limited by the availability and accuracy of the data used to complete the analysis. Due to the importance and repeated use of rainfall records in these studies, methods have been developed to interpolate missing records. In this thesis, five different methods of interpolating missing rainfall records at a gauging station located in an area of south Florida known as the C-102 basin are compared. The results from this study show the following:

- Accuracy in the normal ratio method is independent of the method of computing the mean annual rainfall.
- The normal ratio method provides accurate results with two methods that were independent of the existing rainfall data at gauging station S-194.
- Rainfall gauging station S-194 was inconsistent with respect to the surrounding stations during two time periods; 1973-1975 and 1978-1980; after performing a double mass analysis on S-194, the seasonal results were accurate compared with work by MacVicar (1983).

By implementing a basin water budget technique, the seepage out of the C-102 basin was estimated at a monthly average of 7.4 x 10^7 ft^3 during the period of January through June, 1974. This value coincides with SFWMD estimates of seepage which further aids in the understanding of how much water is lost to Biscayne Bay.

4.1 Recommendations for Future Work

The next logical step in understanding the hydrology of the C-102 basin should be to develop a hydraulic response model. That way comparisons could be made concerning the effectiveness of surface water management and how it can be improved. To properly calibrate a hydraulic model, more hydrologic information is necessary in the C-102 basin. Therefore, the data collection effort in the area must be intensified. Because the C-102 basin is not urban compared to Miami, it has relatively little hydrologic information about it, and yet the runoff produced by the agricultural area in and around the C-102 basin needs to be monitored to determine its impact on Biscayne Bay.

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ACKNOWLEDGMENTS

The assistance offered by the employees of the South Florida Water Management District, including Mr. Thomas MacVicar, Ms. Sharon Trost, Mr. Thomas Strowd, Ms. Dawn Reid, and Mr. Steve Traver, is appreciated; they not only provided the necessary information and charts to complete the analyses, but also their time and advice.