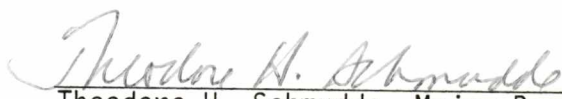


To the Graduate Council:

I am submitting herewith a dissertation written by Jacqueline Pryce-Harvey entitled "Estimating Recharge to the Liguanea Aquifer of Kingston, Jamaica." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.


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We have read this dissertation
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Accepted for the Council:


Vice Provost and
Dean of the Graduate School

ESTIMATING RECHARGE TO THE LIGUANEA AQUIFER OF
KINGSTON, JAMAICA

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Jacqueline Pryce-Harvey

August 1985

DEDICATION

I would like to dedicate this work to my husband, Errol St. John Harvey, who gave me unwavering moral support and whose faith in my ability kept me working even in the worst times. I also dedicate this work to my wonderful parents, Mr. and Mrs. Aubrey Pryce and to my sister, Deanne Pryce, all of whom cared for my daughter during the busiest times of my program.

Finally I dedicate this work to my daughter, Natalie Celeste Harvey, who inspired me to aim for a better future for all of us.

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Finally, I would like to thank my typist, Georgia Bunn, and cartographer, Kurt Butefish, for doing great jobs under severe time constraints.

ABSTRACT

Kingston, Jamaica, is situated on the Liguanea aquifer and draws a substantial portion of its water supply from underground source. The purpose of the study is to estimate the volume of groundwater stored during dry, average, and wet years, as a basis for determining whether additional water can be withdrawn as an alternative to proposed expensive, large-scale, inter-basin water transfer.

The study area includes four lithologic subdivisions of which the Liguanea alluvial surface is the largest. Each subdivision is treated separately because of differences in infiltration and runoff rates as well as subsurface storage capacities. The hydrology of the study area is simulated using the Thornthwaite water balance procedure based on climatic data for 16 stations. The allocation of surplus to either runoff (overland flow, streamflow, gullyflow) or recharge (baseflow or groundwater storage) considers regional differences in lithology, urban build-up, and seasonal rainfall and its intensity.

The simulated volumes of runoff and recharge are tested for validity using observed values of streamflow and change in height of the water table based on well records. Matching observed streamflow at Gordon Town to simulated runoff for the comparable drainage area for the average year of 1971 shows that the volume of simulated runoff and the volume of observed runoff are in close agreement

(less than 5% difference). Likewise the volume of simulated recharge for the Liguanea aquifer in the dry year of 1977 and the wet year of 1979 and the observed change in volume of groundwater have similarly close agreements.

The close correspondence between simulated and observed runoff and recharge in the study area strongly suggests that the water budget analysis and the procedure for allocating surplus to runoff and recharge used in this study is a workable model of the general hydrology of the study area. The results show that approximately 400 million gallons of water would go to recharge in dry years compared to 9000 million gallons in wet years. The primary recharge area is the northern boundary of the Liguanea alluvial surface. Coefficients based on rainfall totals for each lithologic subdivision and for wet, average, and dry years have been prepared. These coefficients, calibrated to conform to the estimates using the more elaborate procedure of this study, provide a quick way to estimate recharge for any year. Caution, however, should be exercised in applying such coefficients outside the study area where the rainfall and surface conditions may be quite different.

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CHAPTER I

INTRODUCTION

Overview

At the base of the Blue Mountains in eastern Jamaica, the city of Kingston is sited on the sloping alluvium of the Liguanea aquifer, a primary source of its water supply. At present the aquifer supplies over one-half of the municipal water for Kingston but is threatened by excess withdrawal. The quantity and timing of ground-water recharge, zones of recharge, and the extent and location of water outflows, however, are uncertain.

The demand for water in Kingston is influenced by a rapidly growing urban population with ever-increasing per capita needs and the expanding requirements of industrial uses. The growing demand, when combined with a history of periodic shortfall, has caused planners to propose large-scale importation of water from surrounding basins as well as a detailed analysis of the water available in the vicinity. As the projected cost of importing water has risen so has the willingness to investigate the potential of locally available supplies. Consequently, it is timely to investigate all possible local water sources including groundwater resources.

In a tropical environment, groundwater storage is valuable because evapotranspiration from it is minimal, which permits water to be stored for long periods of time. The alluvial fan of the Liguanea aquifer is such a storage reservoir, but its hydrological

boundaries and sources of recharge are ill-defined. Although precipitation records exist for over 100 years, only a few recent studies have attempted to estimate the proportion of precipitation that may go to recharge. Under these circumstances, calculating the quantity of water which can be extracted on a sustained basis while avoiding saline intrusion is difficult.

Calculating recharge to the Liguanea aquifer is complicated because the alluvial plain is surrounded by three separate and hydrologically different areas of higher elevation. All of these areas are oriented in such a way that subsurface interbasin flow from each could reach the aquifer and thus increase significantly the volume of groundwater in the Liguanea basin.

The alluvial surface of the basin slopes toward the sea and its southern boundary is the coastline which could allow easy subsurface flow into the sea. Estimating the rate of such outflow from the alluvium is necessary in assessing the safe yield of water from the aquifer without salt water intrusion.

It is logical to assume that the aquifer responds to the periodic drought as well as hurricane-induced flooding that is characteristic of the climate of the region. Knowledge of net changes in recharged storage both annually and monthly is needed to determine the safe yield from the aquifer. There is extreme variability in both the monthly and annual precipitation of the region. Preventing flooding, however, has received most attention with little regard for the effects preventive measures may have on groundwater volumes.

Presently, the Liguanea aquifer, although a major supplier of municipal water, is not an integral part of the long-term water planning strategy of the Kingston Metropolitan Area. Passing mention is made of its potential utility in only three of the several existing feasibility studies of the water supply for Kingston into the next century. It is desirable that before the Liguanea aquifer is completely rejected as unsuitable as a long-term storage facility for Kingston, an attempt be made to understand the groundwater dynamics of the alluvial fan, its interaction with its borders, and its response to the pattern of climatic variability of the region.

Problem Definition

This work is an assessment of groundwater resources of the Liguanea aquifer. It recognizes the diverse hydrological characteristics of the region as a critical factor in such an assessment. The major objective is to determine the timing and quantity of the recharge to subsurface storage. Along with this major goal are three other objectives. One is to assess the hydrological boundaries of the alluvial fan, another is to evaluate the potential of artificial recharge to the aquifer, and the third is to assess the need for more localized water balance analysis to supplement the "extensive" approach to water planning currently being used. Each objective is discussed in detail below.

Timing of Groundwater Recharge

The metropolitan area of Kingston now receives 63% of its water supply from groundwater sources; 27% is pumped from wells

located in two limestone areas, and 36% of which is pumped from wells located in alluvium. During the period of analysis, 1971-1979, the remaining 37% was supplied by the Mona and Hermitage reservoirs, both of which are surface storage facilities on the Hope and Wag-water rivers, respectively. During the study period there were two years of below-average rainfall (Table 1) and over 600 days of water restrictions during periods of low water levels in both reservoirs. Increased pumpage of groundwater occurred at these times. During the same period, nine tropical storms passed within 175 miles of the island, bringing large quantities of high-intensity precipitation, excessive runoff, and non-destructive flooding during five of the nine years. This haphazard pattern of periodic wet and dry years is replicated on a monthly basis, with May and October having the greatest chance of high rainfall totals. These alternative dry and wet spells are the basis for suspecting substantial potential recharge during years or months of excessive precipitation that compensates for the lack of recharge during dry years or months.

Quantity of Recharge

In a drainage basin system several factors influence the amount of precipitation that can be allocated to groundwater recharge. Assuming that a set fraction of the precipitation goes to recharge in dry and wet years alike and to all the various lithologic subdivisions of the Liguanea basin would underestimate the recharge of wet years, overestimate recharge in built-up areas

TABLE 1
RANKING OF RAINFALL YEARS

Average Rainfall (in.)	Year	Classification
22	1976	Dry
33	1977	Dry
42	1975	Normal
42	1978	Normal
45	1972	Normal
46	1971	Normal
49	1973	Normal
61	1974	Wet
71	1979	Wet

and during storms, and would not represent the difference in recharge in areas with different lithologies. An important part of the present work involves adjusting for rainfall intensity, geologic variability, and degree of urbanization, in addition to the usual adjustments for change in soil moisture storage and potential evapotranspiration when calculating recharge.

Hydrological Boundaries

Establishing the Hydrological boundaries of the Liguanea aquifer is difficult because of the elevation and lithology of the surrounding areas. To the south it is bordered by 10.4 miles of coastline with no obvious obstruction to water flow. Surplus water from the limestone areas to the northwest and east may be recharging the alluvial fan. The volcanic hills of the northeast have a well-developed surface drainage system with streamflow data for some years, but the water which goes underground could be a substantial amount in wet years, and it is uncertain whether this subsurface flow follows the surface drainage pattern or flows into the Liguanea aquifer along their mutual boundary. No measured observations have been made of any of these subsurface outflows and inflows.

Artificial Recharge

A strategy to store flood water during periods of excessive precipitation could add substantially to the water supplies of the basin. For artificial recharge it is necessary to know, among other things, the amount, timing, and location of surplus water and the availability of storage space underground.

The Localized Approach to Water Planning

The basic objective in all water resource management plans for Kingston is to make available, on a reliable basis, water of sufficient quantity and quality to meet demand. The objective is subject to various physical, environment, and economic constraints, but the prevalent solution has been to adopt engineering technology as the first and probably the only option. White (1964)¹ identified this trend for flood management, but it is increasingly apparent that water planners are responding to increasing demand by simply developing increasingly large-scale storage and transport facilities to meet expected future needs. This approach is used especially in urban areas, and Sewell (1966)² describes it as the "extensive" strategy, whereby: "as local sources become exhausted, progressively larger volumes of water have to be imported from ever more distant sources" (Smith, 1979).³ This strategy is represented in Jamaica by the Blue Mountain scheme, which provides for large-scale transfer of water via tunnels at high cost to satisfy the urban water needs. Increasing competition for investment funds and the high cost of servicing loans from agencies such as the World Bank have led policy makers to seek less expensive water supplies and

¹G. F. White. "Choice of Adjustment to Floods." Univ. of Chicago, Dept. of Geog. Research Paper No. 93, 1964.

²W. R. D. Sewell. "The New York Water Crisis," Journal of Geography, November 1966, 384-9.

³K. Smith. "Trends in Water Resource Management," Progress in Physical Geography, Vol. 3, No. 2, June 1979.

more efficient use of water. By investigating the groundwater hydrologic system of the Liguanea aquifer, it might be possible to demonstrate that more efficient use of this groundwater reservoir may enable deferment of large capital expenditure.

Further, in the last decade, hydrological efficiency has increasingly come to mean the conjunctive manipulation of surface and groundwater sources. Maknoon and Burgess (1978)¹ related that yield advantages of such combined operations were first explicitly recognized in 1953, but it was not until 1972 that the dynamic interaction between a stream and an aquifer was satisfactorily modeled. Optimization of yield usually includes some element of artificial groundwater recharge (Farquhar, 1973;² Nightingale and Bianchi, 1973).³ The environmental background against which such engineering operations take place is of special interest to geographers (Smith, 1979).⁴

A strategy for long-term water supply planning for Kingston must involve integration of the resources of the Liguanea aquifer, the limestone aquifers, and presently tapped surface supplies. In

¹R. Maknoon and S. I. Burgess. "Conjunctive Use of Ground and Surface Water," *Journal of the Am. Water Works Assoc.*, 70, 1978.

²D. C. Farquhar. "Diversion of Flood Flows from the Connecticut River and the Effect on Groundwater Supplies," *Journal of the New England Water Works Assoc.*, 87, 1973.

³H. I. Nightingale and W. C. Bianchi. "1973: Groundwater Recharge for Urban Use: Leaky Acres Project," *Ground Water*, 11, 1973.

⁴K. Smith. "Trends in Water Resource Management," *Progress in Physical Geography*, Vol., 3, No. 2, June 1979.

sum, "the chief alternative to exploiting remote and costly new sources, striking in its comparative simplicity, is to use the water already harnessed more efficiently" (Smith, 1979).¹

Previous Research on the Liguanea Aquifer

The previous work done on the hydrology of the study area provides valuable information about the physical characteristics, climate and lithology of the Liguanea aquifer. The earliest works concentrated on the "extensive" approach, using statistical techniques of trend analysis to present a generalized view of the amount of water available to the Kingston Metropolitan Area. In the more recent studies, there is a conceptual and methodological shift to analysis of real data, using small-scale subdivisions and close examination of the varieties of physical processes of the region.

Research started in the mid-1960s, when the Government of Jamaica proposed a scheme to store and transport large quantities of water from the well-watered Blue Mountains located northeast of Kingston. In 1966 Humphries² did an initial study of the water yield potential of the Blue Mountains and adjacent areas. In this early work, the Liguanea aquifer was recognized as a water source, but no analysis of its potential water yield was made. Early in the 1970s the World Bank agreed to finance a feasibility study of the groundwater of the Kingston region. In 1971 Howard Humphries and Sons

¹Ibid.

²Howard Humphries and Sons, "Kingston and St. Andrew Water Supply--Future Major Sources." London: Westminster, February 1966.

presented their second report.¹ In this report Humphries concluded that an additional 5 million gallons per day was available for pumping from the alluvium and an undetermined quantity from the limestone hills to the west of Kingston. In 1977, TAMS² also concluded that additional water was available from the Liguanea alluvial aquifer. In addition, TAMS identified an east-west division of the alluvium which they stated would suggest an upper storage facility not subject to subsurface outflow to the sea.

The population of Kingston grew rapidly in the mid-60s, and in 1968 the region experienced its worst drought of the last 30 years.³ By the early 1970s the Blue Mountains region became the target of extensive research and feasibility studies aimed at identifying additional water for the metropolitan area. The rising cost of fuel on the world market in the mid-1970s dramatically increased interest in multi-purpose schemes which would combine the generation of hydropower with provision of reliable sources of freshwater to Kingston. It is unnecessary here to report the various findings

¹Howard Humphries and Sons, Kingston Regional Groundwater Investigations, 1971.

²Tippets-Abbot-McCathy-Stratton and Mattis-Demain-Beckford and Associates. "Comparative Study of Water Supply Projects for Kingston and Surrounding Area," Vols. 1 and 2. New York, USA and Kingston, Jamaica, July 1977.

³Jacqueline Pryce. "Drought in Jamaica." Unpublished thesis, University of West Indies, 1977.

and recommendations. Suffice it to say that fluctuating cost of fuel, scarcity of investment funds, and high projected costs of delivered water to consumers have significantly modified earlier plans. Work began only recently on the first water-provision stage of the Blue Mountains scheme.

Although the Liguanea aquifer was largely ignored or under-investigated as a long-term water storage facility in the mid-1960s and early 1970s, by 1978 the Water Resources Division (WRD)¹ of the Ministry of Mines and Natural Resources undertook an initial investigation of the water yield potential of the aquifer. They were concerned about the large capital expenditure required by the "extensive" approach and were searching for more localized alternatives. They adopted research methods which used less multiple correlations and long-term trends and more analysis of real data.

In June 1980 WRD² published a report, the aim of which was to determine the possibility of further development of the aquifer of the Liguanea basin. This is the most comprehensive research done on the Liguanea/Hope River basin. In this work the recharge to the Liguanea aquifer is estimated using the concept of effective rainfall,

¹Water Resources Division, "Water Potential of the Liguanea Aquifer." Government of Jamaica, Ministry of Mines and Natural Resources, 1978.

²Water Resources Division. "Further Groundwater Development of the Aquifer of the Liguanea (Hope River) Basin." Government of Jamaica, Ministry of Mines and Natural Resources, 1980.

which is the total precipitation minus the percentage which falls on impermeable surfaces within the basin and is lost to the groundwater system. Therefore the percentage of impermeable surfaces relative to total area was determined to be 40% of the total area. This leaves 60% of permeable surfaces and therefore effective rainfall is taken to be 60% of total rainfall. The method continues by calculating the percentage of average rainfall which flowed as baseflow in the adjacent Hope River (52% in 1974 and 54% in 1975) with adjustment for rainfall periodicity WRD arrives at an overall recharge coefficient of 40% of effective rainfall.

There are several problems with this method, most obvious of which is the marked lithologic, relief, and consequent hydrologic differences between the Hope River basin and the Liguanea plain which could produce marked differences in recharge. The method assumes that if you discount for urbanization, then both basins should function almost identically with regard to runoff and recharge. Considering that only the lower reaches of the Hope River have alluvial material similar to the Liguanea aquifer, it seems unlikely that identical recharge coefficients can be postulated on that basis. It is possible that both areas possess similar recharge coefficients, but these values should be derived independently via water balance calculations.

In summary, the earlier works focused on the feasibility of transporting the large quantities of water from the Blue Mountains into the Kingston Metropolitan Area. The water yield potential of the Liguanea aquifer was largely ignored. The studies which gave

estimates of potential water yield from the aquifer used "synthetic data" and long-term trend analysis techniques to generate average values, which in reality fluctuate dramatically on a seasonal and areal basis. The later works by the Water Resource Division recognized this problem and incorporated small-scale subdivisions and close examination of the varieties of physical processes into their research.

Major drawbacks remain, however, to all the research which has been done for this area. The tendency to use average rainfall, runoff, recharge, and outflow is still dominant and cannot be totally eliminated. The physical processes are under-investigated, and therefore little attempt is made to incorporate variations in temperature or soil moisture change into the derivation of precipitation surplus.

The most important previous omission has been the almost complete disregard for monthly, seasonal, and annual variation in total rainfall. The application of one overall coefficient for, say, recharge will yield highly inaccurate values for dry and wet years.

Finally, the timing of available surplus is an important consideration largely ignored by previous workers. The possibility of artificial recharge is keyed to knowledge of location and timing of surplus as well as timing of water need.

CHAPTER II

HYDROLOGICAL ASPECTS OF THE LIGUANEA BASIN ENVIRONMENT

Introduction

The portion of total precipitation which becomes recharge for the Liguanea aquifer depends to a large extent on the physical and man-made environment of the study area. This chapter identifies those aspects of the environment which directly influence the hydrology of the Liguanea basin, and particularly groundwater recharge.

The quality of available data is very important in this work. The absence of complete data sets has been a primary obstacle of previous attempts to estimate the recharge to the Liguanea aquifer. The quality of the major data sets assembled for this research, therefore, is assessed in this chapter.

The Physical Environment

The Study Area

The study area, located on the south coast of Jamaica, covers an area of 72 square miles with four marked lithologic and relief subdivisions (Figure 2-1). Each subdivision exhibits a degree of homogeneity which merits separate hydrologic analysis, and each of the four areas has sufficiently distinctive characteristics to suspect that groundwater recharge differs from one to the other. The subdivisions are: (1) the Liguanea aquifer is a gently sloping

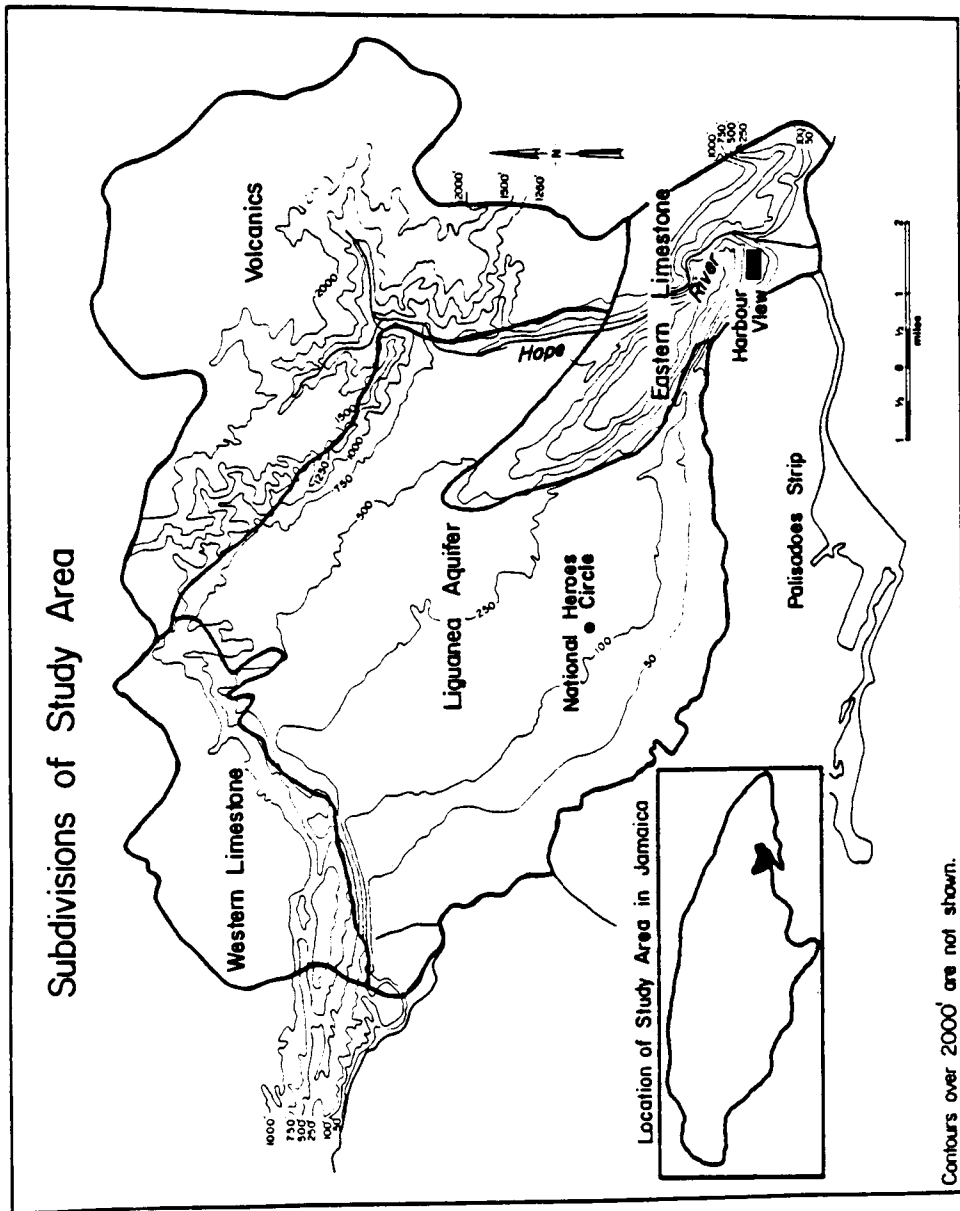


Figure 2-1. Subdivisions of the Study Area.

alluvial fan which slopes in a southwesterly direction and rises from sea level in the south to 750 ft in the north. Its area of 34.8 square miles is 48.4% of the total study area. Analysis of groundwater storage and recovery focuses on this area (Figure 2-1).

2. The Western Limestone Hills located north and west of the alluvial plain are at an elevation of over 1000 ft. They cover 9.73 square miles or 12.5% of the area. These hills are devoid of surface drainage, and their subsurface drainage patterns are uncertain.

3. The Eastern Limestone Hills are east of the Liguanea alluvial fan and oriented in a southeasterly direction with an elevation of over 1000 ft. They cover 7.66 square miles or 10.6% of the total area.

4. The Volcanic Foothills located to the northeast of the Liguanea alluvial fan, contain the extensive drainage system of the Hope River. These hills are the lowest south-facing sections of the Blue Mountains. They cover 19.82 square miles or 27.5% of the total area.

Climate

The climate of Jamaica is determined in the main by the island's location in a tropical area with northeasterly trade winds combined with localized orographic effects. Accordingly, the northern slopes of the Blue Mountains are covered in part by rain forests, while the southern sides of the mountains, including the

Kingston area, have a semi-dry to dry climate. Annual variations in temperature, sunshine hours, and relative humidity are small compared to daily variations.

Precipitation

Jamaica is located within the wet-and-dry tropics. It has two rainy seasons May-June and October-November, which account for about 80% of the total annual rainfall. Occasionally the rainy seasons fail to materialize resulting in drought conditions. Rainfall can be categorized into three types:

1. Year-round orographic rainfall associated with mountain ranges and north-facing slopes, accounting for 15-20% of the total precipitation.
2. Winter rains associated with periodic incursions of cool polar air from the North American continent account for 5-10% of total precipitation.
3. High-intensity rainfall associated with waves in the easterlies (May-June) or hurricanes (October-November) accounts for 70-80% of total precipitation.

During the period of May to November, the subtropical high pressure over the North Atlantic is comparatively weak and has a northerly position. The trade wind inversion over Jamaica is then located at a high altitude or is non-existent, and rainfall is produced by the trades in association with land and sea breezes. In May through later summer, rains may also be caused by weak wave

disturbances and by more well-developed tropical storms also called hurricanes. The hurricane season is from July to October, with a peak intensity in September.

From December to March the trade winds are weaker, and the trade wind inversion is normally located at much lower altitudes, which means that the trades are often incapable of ascending the highest terrain in the Blue Mountains. This is the dry season in Jamaica. During this period rains may be caused occasionally by cold fronts traveling equatorward from the North American mainland.

The height and orientation of the Blue Mountains is the most dominant physical influence on the hydrology of the region. The Liguanea basin, located as it is on the leeward (south) side of the Blue Mountains, receives significantly less annual rainfall (approximately 130 inches per annum) than the regions further north. Within the basin there are also marked differences in rainfall totals between the foothills of the Blue Mountains to the north and the alluvial plain to the south.

Winter rains usually occur over the entire island and, though sporadic, their occurrence may significantly affect the recharge of the aquifer.

The most significant rainfall for aquifer recharge, however, is the high intensity rainfall associated with easterly waves and hurricanes. Their occurrence is seasonal and unpredictable. Several researchers have recognized the importance of these

rains to the hydrology of Jamaica.¹ Nevertheless, all water resource studies to date have used average annual rainfall instead of seasonal values as the unit of analysis. In this research, the marked seasonality as well as the intensity of the rainfall as it affects groundwater recharge is central to the analysis.

Temperature

Temperature is rather high all year in Jamaica, although some important variations in temperature are associated with seasons and elevations. During the winter months, the temperature in the study area varies between 70°F and 82°F, with the highest temperatures on the low-lying alluvium and the cooler ones in the foothills of the Blue Mountains. During the summer the average temperature is higher, 84°F on the plains.

Geology

The most comprehensive geologic survey of the Liguanea basin was done in 1974 and is published as an annotated map by the Geologic Survey Department of the Ministry of Mines and Natural Resources.² The following description of the hydrogeology of the study area is

¹(a) Barry Floyd, "Climate of Jamaica," Caribbean Quarterly, Vol. 12, No. 3, 1966; (b) Howard Humphries and Sons, "Kingston Regional Groundwater Investigations," 1971; (c) Tippet-Abbott-McCarthy-Stratton, "Comparative Study of Water Supply Projects for Kingston and Surrounding Area," 1977.

²Geology of Kingston (Map), published by the Survey Department, 1974.

based mainly on this source and on additional work done by the National Water Commission in 1983.¹

Five geologic periods significantly affected the study area. Cretaceous history consisted of many distinct episodes that resulted in the emplacement of a wide variety of rocks including clastics, pyro clastics and igneous rocks. These lithologies are separated from overlying Tertiary rocks by a marked angular unconformity. Cretaceous sedimentary and igneous activity were terminated by the Laramide orogeny, which heralded a period of intensive tectonics in the Wagwater belt (Figure 2-1). Central to the sequence of events was movement along the Wagwater fault system. The upthrow of Cretaceous materials provided the source of sediments, while a graben trough between faults provided a proximal and accessible repository for those sediments.² Sediment accumulation was rapid as evidenced by the characteristics of both the Wagwater and Richmond formations, which are thick sequences of continental and marine sediments respectively. Between tectonic events lenticular bands of impure limestone were laid in the sequence. The resulting white limestone is characterized by massive crystalline structure with abundant micro- and macro-fossils, indicating deposition in shallow water. During the middle Miocene and Pliocene period, the island was subjected to massive uplift resulting, in its present gross form. In

¹ National Water Commission, Flow West Project, 1983.

² Ibid.

the study area, detritus from both carbonate and non-carbonate rocks were deposited along the coasts. These deposits, together with coral reefs, formed the August Town formation of the lower coastal group. In the later periods, Pleistocene and Holocene, the Hope River probably flowed across the Liguanea plains along the channel presently occupied by the Sandy Gully,¹ depositing alternating lenses of gravels, sand, and clays, leading to a thick heterogeneous formation. The growth of this delta was terminated by capture of the headwaters of the Hope River by streams flowing to the coast at Harbour View (Figure 2-1, p. 15). Sediments similar to those comprising the Liguanea formation are found at Harbour View, and longshore marine currents probably account for the shape of the Palisadoes Strip (Figure 2-1).

The geologic history of the study area helps to identify the areas of potential water flow below surface. For example, knowledge of previous water channels above surface may indicate present subsurface water flows. Thus the role of the Hope River in the formation of the Liguanea aquifer is important, because present day surface flows follow the old river basin, and it would be a logical starting point to assume that subsurface flow also follows the same route. More importantly, in-depth knowledge of the geological characteristics of the three different lithologies present in the study area forms the basis for the allocation of surplus water between runoff and recharge.

¹Ibid.

The Aquifer

Significant to the water storage of the study area is the relict alluvial fan of the old course of the Hope River, consisting of redeposited igneous-derived clastics which slope gently seaward from the limestone fold fringing the Cretaceous inlier. It has been suggested¹ that the alluvial basin be subdivided into north and south blocks based on evidence from boreholes showing a bedrock rise. This subsurface geologic high, if present, would affect the rate of flow and the storage capacity by creating an additional hydraulic head and an effective barrier to cross-basin underflow. The depth of the aquifer is not known, but from borehole logs the alluvium is known to be at least 850 ft. thick at National Heroes Circle (Figure 2-1, page 15). The alluvial fill consists of irregular deposits of coarse materials interspersed among fine silts and clays. Using well log information from five wells, Kings House, Shortwood, National Stadium, Liguanea Club and Elleston Flats, the following description of the layered material of the aquifer is derived and presented:

<u>Depth</u>	<u>Characteristics</u>
0-80 ft.	Medium to coarse sand predominates with up to 15% clay in some areas.

¹Tippets-Abbott-McCarthy-Stratton and Mattis-Demain-Beckford and Associates. "Comparative Study of Water Supply Projects for Kingston and Surrounding Area," Vols. 1 and 2. New York, USA and Kingston, Jamaica, July 1977.

- 80-120 ft. Medium to very coarse sand occurs with less than 5% clay.
- 120-200 ft. Very coarse sand, fine gravels and up to 35% clay with some silt.
- 200-240 ft. Coarse sands, clay, and water at the National Stadium and Liguanea Club, i.e., the lower sections of the basin. Even at Elleston Flats, the material gets progressively finer with depth, and the clay portion increases here and elsewhere.
- 240-280 ft. Fine sand and tight clays are very closely intermingled.

Finally, it should be noted that the heterogeneity of the alluvium is consistent with that of the present Hope River Flood plain. This characterization of the layered material of the aquifer is an important aid in the process of allocating surplus water to recharge or runoff. The higher the percentage of sand and the closer to the surface that it occurs, the greater will be the ability of the aquifer to receive and retain water. In the case of the Liguanea aquifer, medium to very coarse sand predominated in the top 200 ft. of the aquifer, which suggests that with available water, the aquifer could be a viable storage facility.

Drainage

The study area is drained on the east by the Hope River, which is supplied by springs and mountain tributaries at the highest points of the volcanic foothills (Figure 2-2). This is the

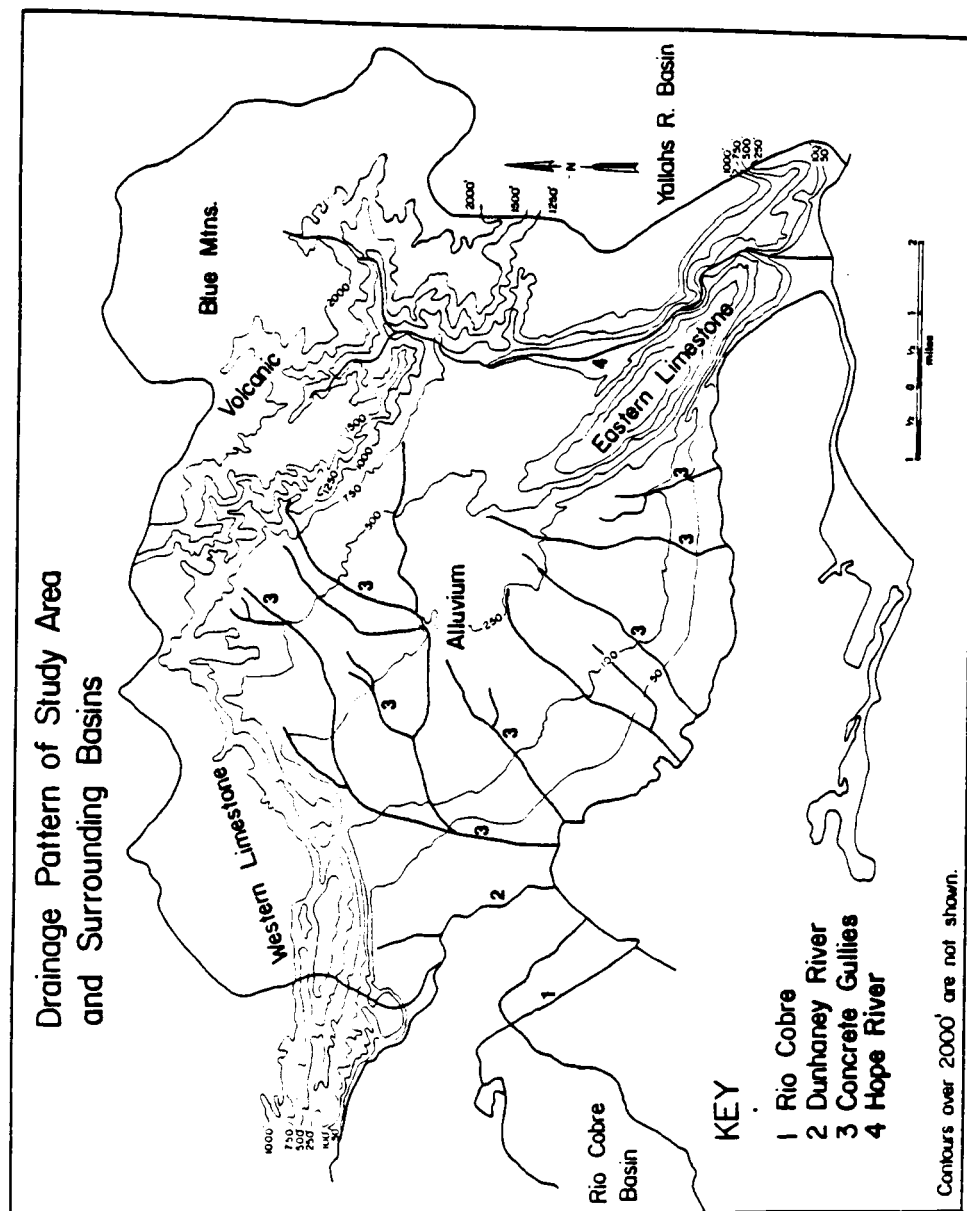


Figure 2-2. Drainage Pattern of Study Area and Surrounding Basins.

only perennial stream in the study area, and for much of its lower course the valley is dry and its water diverted into the Mona reservoir. It is difficult to determine how much water flows into the aquifer from the Hope River. Some researchers¹ have argued that the flow is away from the aquifer, while others believe that there is extensive subsurface interbasin flow into the aquifer. Water balance calculations might help decide the issue.

The limestone hills have no surface drainage. Instead, water seeps through cracks and fissures and reappears as springs at the interface at the base of the limestone hills and the upper boundary of the alluvium or takes one or both of the following two paths. The subsurface flow of the western limestone could seep directly into the alluvium below surface or it could flow along the interface westward to the Duhaney River (Figure 2-2). The eastern limestone drains westward toward the aquifer, and at its base groundwater could flow into the aquifer or southward to the sea. Knowledge of the direction of subsurface water flow out of both limestone areas is important, because these areas could logically generate large quantities of recharge to the aquifer. The lack of surface drainage on the limestone means that there are no streamflow data from which to estimate base flow which could be used as a guide in estimating recharge. The significant fact here is that the absence of surface flow means that a very high percentage of surplus water goes underground.

¹(a) Personal communication with Lloyd Donaldson and Michael White, 1985; (b) Water Resources Division, "Further Development of the Aquifer of the Liguanea (Hope River) Basin," 1980.

Man-Made Environment

Urban Form

The surface of the Liguanea aquifer is the site of Kingston, a metropolis of three quarters of a million people. The density of built-up areas varies greatly¹ (Figure 2-3). The alluvial area contains two urban sub-areas: (a) the waterfront, area with the highest percentage of pavement: closely-packed streets, high density zinc roofs and paved or tightly compacted clay yards. In this waterfront area are also located some of the most water-intensive industrial plants and port facilities in Kingston. In this region natural recharge is likely to be relatively low since the high percentage of impermeable surfaces would facilitate rapid surface runoff directly into the ocean. (b) North of the waterfront area, but still on the alluvium, the pattern of land use is suburban with considerable expanse of grass-covered yard space and fruit trees. At the upper rim of the alluvial plain the houses are widely spaced and many open areas are present. The presence of large tracts of open spaces causes less interference for water infiltrating into underground storage in the upper alluvium than in the region closer to the waterfront. Consequently, recharge in the upper alluvium should be higher than runoff when rainfall intensity is low or average. During hurricanes and other high-intensity rainfall episodes, however, runoff even from this area will be large, generally exceeding recharge. This means

¹This section is based on fieldwork and analysis using 1:50,000 air photos obtainable at the Survey Department, Kingston Jamaica.

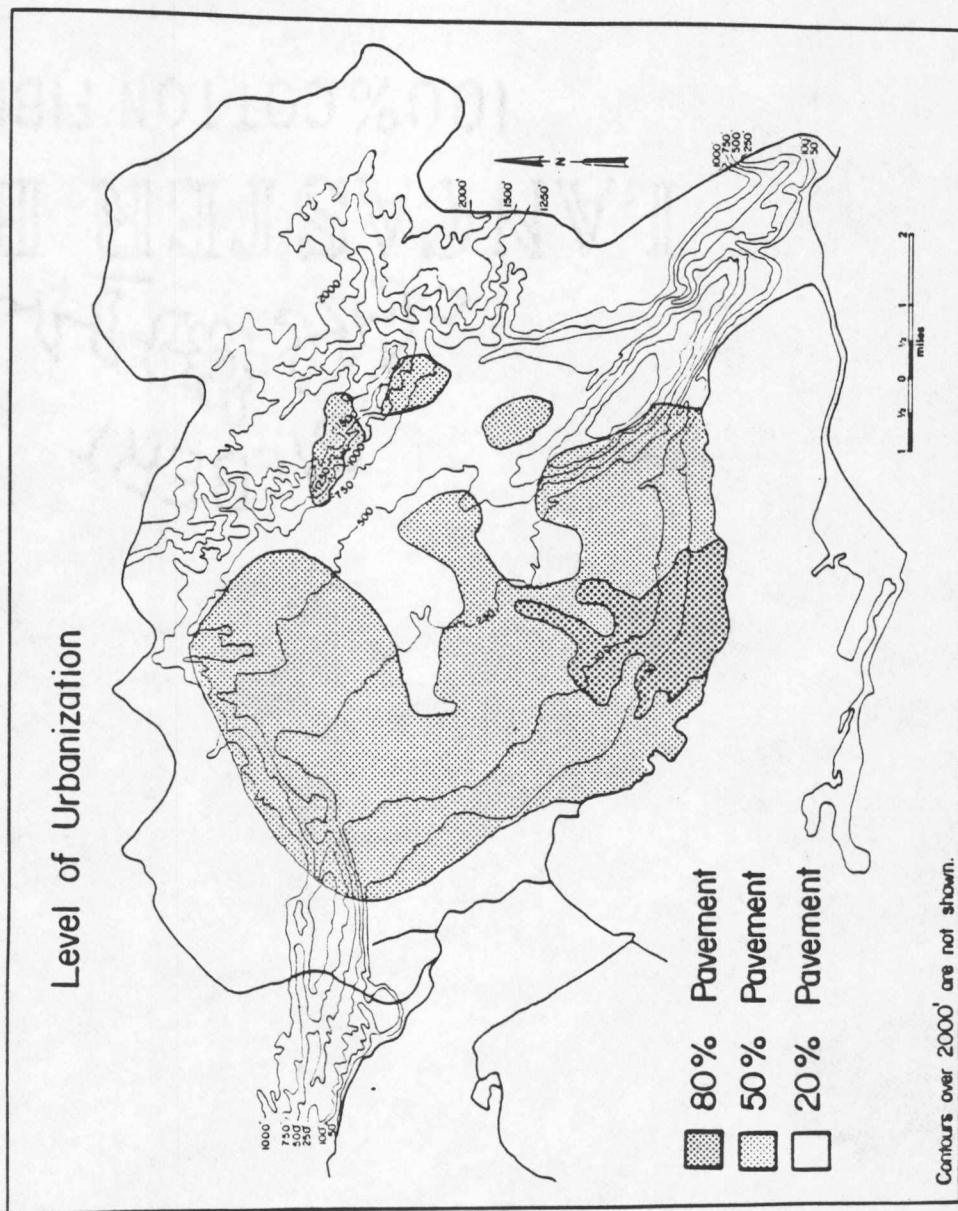


Figure 2-3. Level of Urbanization.

that the porportion of surplus water which can be allocated to aquifer recharge must vary significantly from wet to dry years. The alluvium with a high percentage of impermeable surfaces should have a higher percentage of runoff than the volcanics or limestones, in all years.

Man-Made Drainage

On the alluvial plain most natural courses have been channelized to protect the built-up area from flooding (Figure 2-2). These concrete-lined gullies carry water from two sources: the wastewater of sewage plants and runoff from prolonged and intense rainfall. They quickly remove surplus water from the area which decreases the percentage of surplus water available for groundwater recharge.

Data Quality

The quality of available data is the chief practical obstacle to water resource analysis of the Liguanea aquifer and was a major factor influencing the design and execution of this research. Previously, with the exception of precipitation records, much of the data had been collected and recorded for specific projects, and collection was discontinued at the end of the project. This strategy resulted in extensive area coverage of the major climatic parameters, but for discontinuous periods of time. Because of the lack of continuity, the data often prove inadequate as the basis for solving hydrologic problems in the study area.

Precipitation Data

The most complete records are those of monthly precipitation. Sixteen stations are dispersed over the basin (Figure 2-4) and provide fairly good continuous data. The data used were previously analyzed by the Water Resources Division, with all missing data being estimated by using the mean of the three nearest stations.¹ Spot checking of several of the values revealed fairly consistent estimates, and matching the complete document to the original records at the Meteorological Office confirmed their accuracy. Daily precipitation records were available for four stations (Figure 2-4) and were copied directly from the original records at the Meteorological Office.

Well Data

The well records are more complicated. For accurate measurements of water table fluctuations, it is necessary to measure the elevations of water in (1) wells that are designed for pumping but are not presently being pumped or in (2) observations wells designed specifically to furnish water table elevations. The Water Resources Division appears to combine the two functions for several wells by pumping during high demand periods then reverting to observation function at times of either low yield or low water demand. Therefore, the records of water table elevations must be

¹Water Resources Division. "Further Development of the Aquifer of the Liguanea (Hope River) Basin," 1980.

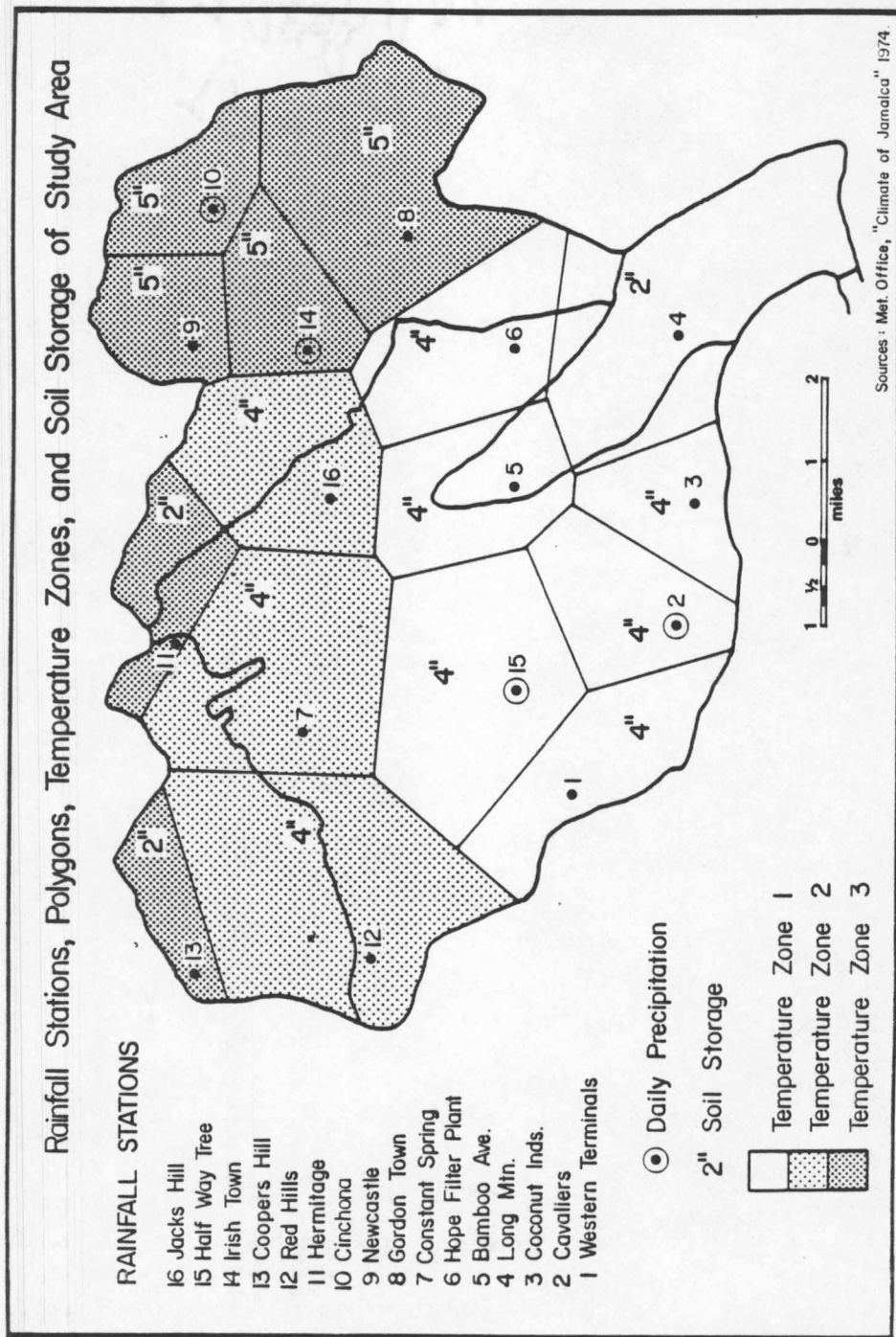


Figure 2-4. Rainfall Stations, Polygons, Temperature Zones, and Soil Storage of Study Area.

extrapolated from the complete records of well levels for both pumping and non-pumping observations. The records are very specific about pumping and non-pumping data and give an indication of observation readings done next to wells which were being pumped. These nearby pumping wells could create cones of depression which might influence the height of the water table, so their identification was a further refining of the data set.

The point of reference for well readings also created some problems for validation of the observation readings. For some projects, the reference base was sea level and for others the elevation of the land was used as the reference. Using topographic sheets, adjustments were made converting all readings to sea level, with the readings below sea level having negative values.

Streamflow

Prior to 1954, no organized program existed for the systematic collection of streamflow data in Jamaica; in 1980, however, the Water Resources Division published "Monthly Streamflow Data for Jamaica" containing records for the streams of the study area. These records are also plagued by missing data, many times for several years, and because of the discrete geology and hydrology of the basin, it is deemed unwise to estimate from neighboring basins. For this reason streamflow data were excluded from the basic quantitative analysis of the study and are used only as a means of comparison and calibration of the results.

Pumpage

The National Water Commission, which has the responsibility of supplying municipal water to the Kingston Metropolitan Area, maintains the pumpage records of non-commercial wells. These records are available only since 1977, when it became a matter of policy to record the amount of water pumped from all sources. These are reliable data of the amount of water being removed from the aquifer by pumping of government-controlled wells.

The commercial users of water pump directly from the aquifer for cooling and other industrial purposes and are required by the National Water Commission to report the volume of water withdrawn for each month.

Overall Assessment of Data Availability and Quality

The best available data are the records of monthly and daily precipitation. These values are crucial to the water budget analysis which is used in this work. The records of water pumped out of the aquifer since 1977 are also considered accurate and are used here with confidence.

The years of missing data for both streamflow and well data prevented long-term testing of the recharge or runoff generated by the water budget analysis. Streamflow was available to test for runoff for the Hope River only for 1971; and well data were available to test recharge on the alluvium only for 1977 and 1979. Thus the lack of complete data restricts the analysis to 1971, 1977, and 1979.

This restriction did not adversely affect the study, since 1971, 1977, and 1979 are good examples of a normal, dry, and wet year, respectively.

CHAPTER III

METHOD OF SIMULATING AND TESTING RECHARGE AND RUNOFF IN THE LIGUANEA BASIN

Introduction

Measurements of the amount of water stored underground are difficult to make in most environments, and in the Liguanea Basin the scarcity of well records and other measurable parameters further complicates the problem. Gustafsson (1968)¹ refers to the difficulties of analyzing groundwater under natural conditions and states: "Questions relating to groundwater geography have been apparently far too complicated and variable to be understood theoretically and analytically." However, there are ways to estimate recharge to underground storage via a systematic water balance approach using inputs of precipitation and calculated outputs such as evapotranspiration, combined with good observations and reasoning concerning the physical processes regulating the system. The simulation of recharge is best undertaken within a conceptual framework that synthesizes the hydrologic system. For the Liguanea Basin, the model is adjusted to reflect the systematic functioning of each lithologic and relief-based subdivision of the basin. Validation of model outputs

¹Yngve Gustafsson. "Groundwater Problems." Proceedings of the Int. Symposium held in Stockholm, October 1966. Ed. by E. Ericksson, Y. Gustafsson, and K. Nilsson. Oxford, New York: Pergamon Press, 1968.

involves comparison of the simulated recharge with change in storage estimated from well height observations.

Hydrologic System Analysis

One way to view the complex of climatic and edaphic variables which determine how rainfall will be allocated among physical processes is to conceptualize the area as a surface-soil-earth system, each with distinct but interacting subsystems. Chorley and Kennedy (1971)¹ refer to these as cascading systems and define them thus: "Structures within which the output from the subsystem forms the input for the next subsystem and within which a regulator may operate either to divert a part of the impact of mass or energy into store or to create a throughput, producing the systems output" (p. 77).

In Figure 3-1, we represent the Liguanea Basin Hydrologic Cascade by a structure of inputs, outputs and regulators. Rainfall (P) reaching the surface is allocated by infiltration capacity (F^*). Rainfall intensity in excess of (F^*) goes directly to surface runoff (q_0) via streams and concrete gullies. The rest infiltrates to soil and groundwater (F). Soil moisture storage capacity (M^*) takes first call on all infiltrating water, hence the amount of water not in excess of M^* becomes soil moisture storage (M), and the remainder flows downward as recharge to the groundwater (G) or is evaporated

¹R. J. Chorley and B. Kennedy. "Physical Geography, A Systems Approach." London: Prentice-Hall, Inc., 1971.

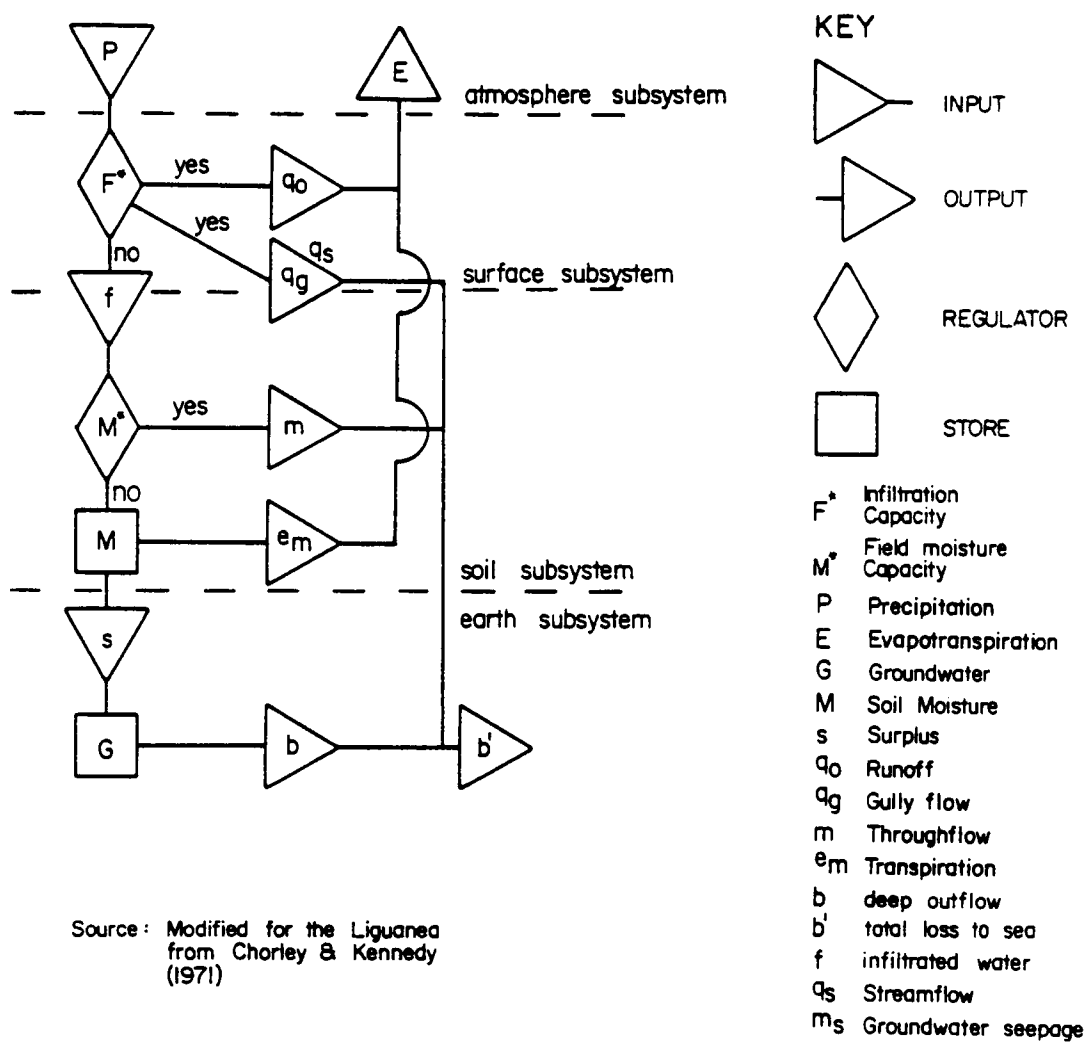


Figure 3-1. Liguanea Basin Hydrologic System.

to the atmosphere (e_m) as well as flowing downslope sub-parallel to the surface as throughflow (m). Water flows out to sea (b) from the gullies (q_g), the streams (q_s), via throughflow (m) and as ground-water seepage (m_s).

Regional Differences of Water Allocations

Significant differences in allocations and outputs exist between the alluvial plain, the limestones, and the volcanics as a result of variations in the values of infiltration rates, soil moisture storage, and dissimilar drainage patterns. In the volcanic subdivision, the Hope River controls the pattern and timing of drainage. Initially, runoff enters the upper streams rapidly because of the steep upper slopes. This is followed by slower flowing throughflow and fissureflow which enters the Hope River after varying periods below the surface. The lag time between rainfall episode and peak flow in this subdivision has been referred to by the National Water Commission (1983)¹ as being surprisingly long, and this aspect of drainage has to be incorporated into any model of moisture flux for the volcanic subdivision. The extensive forest and shrub cover help to slow down the runoff process and, in combination with the deeply incised valleys, prevent excessive flooding in an area which has a high percentage of prolonged and intense rainfall episodes. Compared to the adjacent alluvial subdivision, where flooding is often

¹National Water Commission, Flow West Project, 1983.

a problem, the Hope River is an efficient drainage mechanism. Thus the significant features of moisture flux on the volcanics are low infiltration capacity (F^*) and high soil moisture capacity (M^*), with the system functioning basically as a surface supply system with high values of runoff and throughflow and small values of recharge.

The two limestone subsystems, which are characterized by extensive joints and fissures, exhibit high infiltration capacity, a virtual absence of overland flow, and very low soil moisture storage capacity because of thin or non-existent soils. Thus the percentage of total recharge is correspondingly high.

The alluvium has a high natural potential for recharge, but the extensive use of concrete has significantly altered the functioning of both its infiltration capacity (F^*) and its soil storage capacity (M^*). Extensive areas of concrete diminish the areal occurrence of soil at the surface and so reduce the potential for infiltration and soil moisture storage. The effect of urbanization on the timing and quantity of runoff is well documented.¹ In the Liguanea basin, urban development is concentrated in the region next to the waterfront which also has the lowest rainfall totals.

¹(a) Y. S. Yu and J. S. McNown. "Runoff from Impervious Surfaces," *Journal of Hydraulic Research*, Vol. 2, No. 1, 1964;
(b) Robert A. Muller. "Some Effects of Urbanization on Runoff as Evaluated by Thornthwaite Water Balance Models," in *Proceedings of the Third Annual American Water Resources Conference*, Urbana, Illinois, 1967.

This leads to moderate runoff. Single family homes in the northern wetter reaches of the alluvial plain have less effect on infiltration, yielding moderate values of F^* and M^* (Figure 2-3, p. 27). The way the Hope River drains the volcanics is not duplicated by the concrete gullies in the alluvial plain, i.e., no water is lost or gained from the sides of the concrete gullies, and they act as a quick-flow system for runoff, with all water reaching them being discharged to the ocean.

Subsystem Model Interactions and the Water Balance

The subsystems for which the most reliable data are available are the surface and soil root zone subsystems. Several models are available for estimating the temporal characteristics of water allocations at the surface/soil interface. The Thornthwaite Water Balance Method¹ uses relatively simple data inputs of rainfall and temperature. Using the Thornthwaite Method for allocating water during dry soil conditions, it is possible to establish a systematic framework for partitioning rainfall in the surface/soil zone according to reasoned responses to energy demands, the moisture regime and the condition of capillary storage. The water budgeting procedure is carried out with the built-in assumptions of temperature and soil moisture storage as shown on Figure 2-4, p. 30.

¹C. W. Thornthwaite and J. R. Mather. "The Water Balance," Publications in Climatology, Vol. VIII, No. 1, Centerton, NJ, 1955.

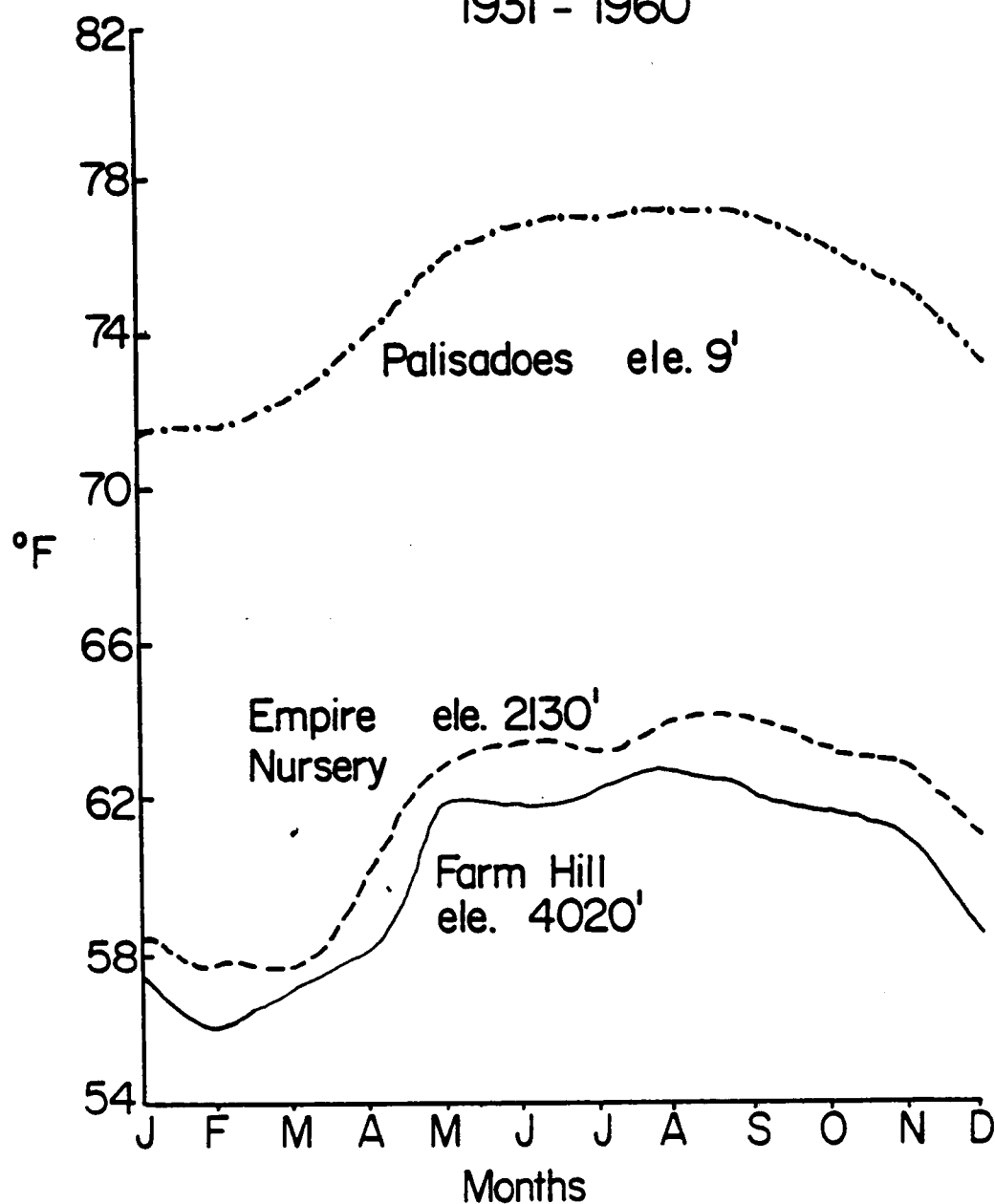
Rainfall regions are based on point data. The regions are derived using the Thiessen polygon method, which performs well where the distribution of gauges is not uniform and where precipitation gradients are strong.¹ For the basin as a whole, data for sixteen rainfall stations were available, and for each of the sixteen polygons (regions) separate water balance calculations were made.

Temperature acts as a surrogate measure of the energy available to power the latent heat exchanges and determines the allocation of moisture to evaporation. Within the basin, three distinct, relief-related temperature zones are discernible. Figure 3-2 shows the 30-year mean for three stations at representative locations used in the water budget analysis. Potential evapotranspiration was calculated by the Thornthwaite method using these temperature zones.

The moisture input to the soil root zone subsystem is precipitation minus evaporation at the surface. Thus, the assumption is made that moisture not evaporated at the surface enters the soil root zone, where soil moisture storage capacity is the main regulator (Figure 3-1). The allocation of moisture to soil moisture storage depends on the antecedent moisture condition of the soil. For the Liguanea basin, the soil moisture storage which has been assigned for each region is given in Figure 2-4, page 30, and is based

¹Ven Te Chow. "Handbook of Applied Hydrology, a Compendium of Water Resources Technology." New York: McGraw-Hill, 1964.

Mean Daily Minimum Temperature at Selected Stations for 30 Year Period 1931 - 1960



Source: "Climate of Jamaica" Met. Office 1974

Figure 3-2. Mean Daily Minimum Temperature at Selected Stations for 30 Year Period, 1931-1960.

on general guidelines from "Publications in Climatology" (Table 10, page 244),¹ which is summarized in Table 2.

TABLE 2
ASSIGNED SOIL MOISTURE STORAGE CAPACITY IN INCHES

Storage	Lithology	Explanation
2	Limestone	Thin soils
4	Alluvium	Deep unsorted sand, silts and clays
5	Volcanics	Deep soils of fine texture

The average rainfall in the study area from 1971-1979 is 46"; during the wettest year of 1979 the area received 71"; and in the driest year of 1976 it received 22". The marked variations in annual totals suggest that water balance analysis would also show marked variations between wet, average, and dry years. In Table 1, p. 5. the frequency of dry, average, and wet years over the period is shown, and from extensive work with precipitation data

¹C. W. Thornthwaite and J. R. Mather. "The Water Balance." Publications in Climatology, Vol. VIII, No. 1, Centerton, NJ, 1955.

for Kingston it is suggested that this pattern for the 1970s is a repetition of the pattern for the past 30 years. The choice of one representative year from years of the same type was based on the availability of matching stream and well data. The monthly water budget for each region incorporates the seasonal variations in potential evapotranspiration and precipitation:

$$P - (\text{Evap} + \text{St. } \Delta) = \text{Surplus.}$$

The output of the water balance analysis of importance here is the surplus for regions. Surplus represents water left over after amounts have been subtracted for evapotranspiration and soil moisture storage from monthly precipitation. It is assumed that surplus will comprise different percentages of total rainfall for wet, average, and dry years. These surplus values are then re-grouped as subtotals for the limestone, volcanics, and alluvium. The regions and subdivisions are shown on Figure 3-3, and their area and percentage representation is given in Tables 3 and 4.

Allocation of Surplus to Recharge and Runoff

The allocation of water by the surface/soil subsystem determines the input to the surface/earth subsystem through infiltration capacity, F^* , and rainfall intensity. High rainfall intensity is significant mainly during tropical disturbances (see Table of Occurrence of Tropical Disturbances, Appendix 1). During 1979, a wet year, a tropical depression in June and two hurricanes in September brought high-intensity rainfall to the basin. The two incidences

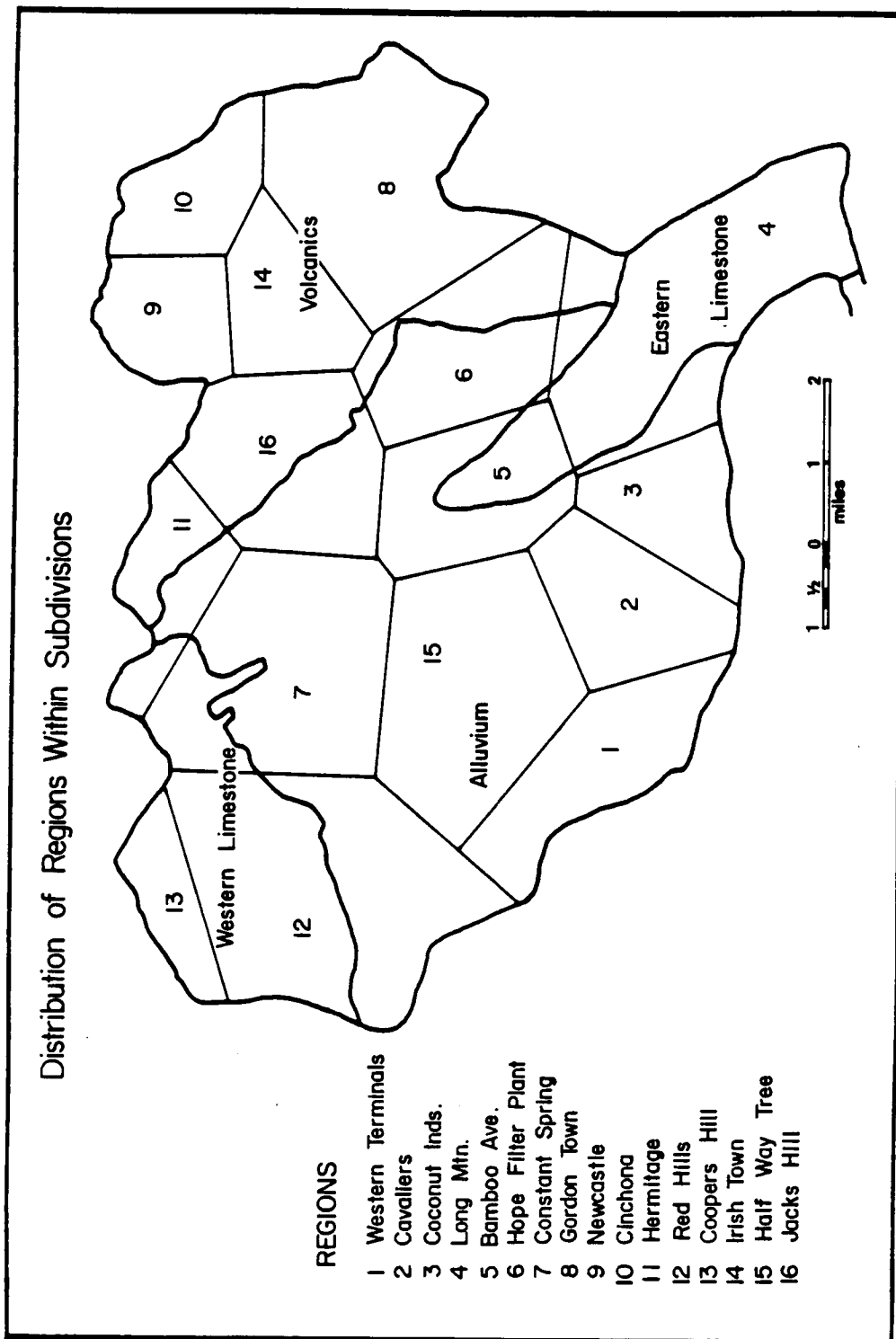


Figure 3-3. Distribution of Regions Within Subdivisions.

TABLE 3
AREA OF RAINFALL POLYGONS (REGIONS)

Rainfall Station	#	Acres	Area in Sq. Miles	% of Total Area
Cinchona	10	1615	2.53	3.50
Gordon Town	8	3479	5.45	7.54
Hope	6	1988	3.11	4.31
Irish Town	14	1863	2.92	4.04
Newcastle	9	1242	1.94	2.69
Long Mountain	4	5467	8.55	11.85
Bamboo Avenue	5	2609	4.08	5.60
Coconut Inds.	3	1615	2.53	3.50
Jacks Hill	16	2982	4.66	6.46
Cavaliers	2	2857	4.44	6.19
Western Terminals	1	2609	4.04	5.65
Half Way Tree	15	4100	6.41	8.89
Constant Spring	7	4348	6.80	9.43
Hermitage	11	1739	2.71	3.77
Red Hills	12	6461	10.09	14.01
Coppers Hill	13	1118	1.75	2.42
Total Area		46092	72.01	100.00

TABLE 4
PERCENTAGE OF REGIONS PER SUBDIVISION

Rainfall Station	% in Subdivision	Rainfall Station	% in Subdivision
<u>Volcanics</u>		<u>Alluvium</u>	
#9	100	#3	100
#10	100	#2	100
#14	100	#1	100
#8	100	#15	100
#6	50	#5	67
#11	50	#7	86
#16	66	#11	29
#4	12	#16	34
		#6	50
		#4	9
		#12	36
<u>West Limestone</u>		<u>East Limestone</u>	
#13		#4	79
#12	100	#5	33
#11	64		
#7	21		
	14		

of high-intensity rainfall episodes within days of each other created excessively moist antecedent conditions and very high runoff percentages as expected. During 1971, an average year, normal May and October rainfalls occurred, and, in 1977, a dry year, all stations showed below-average rainfall.

Infiltration capacity works in conjunction with rainfall intensity. When precipitation falls at a faster rate than water can be absorbed by the soil, a larger percentage of water must run off. On the alluvium, the presence of extensive concrete surfaces in the south near the waterfront nullifies the normally high infiltration capacity. On the volcanics the nearly impermeable nature of the underlying lithology and the steepness of the valley sides should produce high runoff once the soil is saturated. On the limestone thin soils and massive cracks permit rapid infiltration and minimal runoff as evidenced by the absence of streams in the area.

Estimated allocations of surplus to recharge and runoff based on the expected effects of rainfall intensity and infiltration rates for regions of the basin are derived for each of the three years. The water-balance analysis, based on the Thornthwaite model, provides a simulated surplus but does not determine the division of the surplus between water which goes to local runoff and that which goes to groundwater recharge. In basins where there are long records of streamflow data, the baseflow as a percentage of total precipitation can be used as a reasonable measure of recharge, and the remainder

of surplus is considered runoff. Shelton (1981)¹ uses this method in partitioning runoff and recharge in the Deschutes Basin. In the case of the Liguanea basin, the baseflow of the Hope River, which covers less than one-third of the total area and is largely on volcanic lithologies, was measured for 1974 and 1975 by the Water Resources Division. It was found that measured baseflow for 1974 was 52% of total rainfall for that year, and baseflow for 1975 was 54%. These percentages, however, were adjusted downward by the Water Resources Division to 40% of total rainfall for both years, for reasons that are not entirely clear.

For this work, however, the focus is on partitioning surplus, not precipitation. Surplus is considered a better indicator of the available moisture, because "We cannot tell whether a climate is moist or dry by knowing the precipitation alone. We must know whether precipitation is greater or less than the water needed for evaporation and transpiration (and soil moisture storage)."² Furthermore, three distinctively different surface conditions for infiltration are represented in the study area, and it is unrealistic to expect the conditions on the volcanics of the Hope River basin, where there are measured values, to be applicable to the other subdivisions of the Liguanea basin, each of which has different lithologies, temperatures, and levels of urbanization.

¹M. L. Shelton. "Runoff and Land Use in the Deschutes Basin." *Annals of the Association of American Geographers*, Vol. 71, No. 1, March 1981.

²C. W. Thornthwaite. "An Approach Toward a Rational Classification of Climate." *Geographical Review*.

In consultation with Lloyd Donaldson of the Water Resources Division, and after careful perusal of the monthly surplus generated by the water balance procedure and the estimates proposed in a recent work,¹ a baseflow of 35% of surplus for the recharge on the volcanics has been adopted here as reasonable. For the volcanics area, then, 65% of surplus goes to runoff and 35% to recharge. The alluvium, which is a more permeable material, should have a greater proportion of water go to recharge and less to runoff. Some parts of the alluvium, however, are densely built-up, with a high proportion of impervious surfaces which should considerably decrease the permeability. It was not necessary to consider adjusting for high permeability on the lower alluvium areas, since in all cases there were no surplus to be allocated. For the alluvium, the allocations adopted are 65% recharge and 35% runoff. On the two limestone subdivisions the lack of surface streams and the many fissures and cracks of the limestone meant that recharge would have to be estimated as much greater than runoff. The allocations adopted are 85% recharge and 15% runoff.

The allocation of surplus at the subdivision level were estimated without knowledge of the observed pattern of streamflow or well fluctuations in the basin. They evolved from detailed discussions with hydrologists Donaldson and White, from an assessment of

¹ Lloyd Donaldson is on assignment with the Jamaican government to develop a National Water Plan and was in the process of developing and testing estimates of recharge to the Liguanea aquifer.

the comparative geology of each subdivision as outlined on pages 19-21, and from casual observation of the flow of runoff in response to individual rainfall episodes. Given the limited information on which these estimates were derived, it is reasonable to assume errors of $\pm 10\%$ in each case.

These initial estimates for each subdivision were used at the regional level with further adjustments for rainfall intensity in the wet year of 1979. It is estimated that as much as a 10% increase in runoff occurred on the volcanics, a 15% increase in runoff occurred on the alluvium, and a 20% increase occurred on the limestones. These numerical differences are based on the idea that the greater the initial value of runoff, the less will be the percentage increase during storms. For regions with no surplus a value of zero is given.

Table 5 incorporates all these adjustments by regions and for representative years. In using this table one must keep in mind that the allocations represent estimates based on very limited measured data and depends heavily on subjective judgements drawn from extensive experience, from field observations, from principles of hydrology, and from consideration of lithologic and soil differences over the area. In order to have confidence in these allocations, they need to be compared with observed values for either or both recharge and runoff.

TABLE 5

ALLOCATION OF SURPLUS WATER TO RECHARGE AND RUNOFF

Rainfall Station	Year	% Allocation	Estimated % Error	Reasons
Western Terminals	1971	No surplus		
	1977	No surplus		
	1979	50% recharge 50% runoff	10%	Alluvium, wet year Alluvium, wet year
Cavaliers	1971	No surplus		
	1977	No surplus		
	1979	50% recharge 50% runoff	10%	Alluvium, wet year
Coconut Inds.	1971	No surplus		
	1977	No surplus		
	1979	50% recharge 50% runoff	10%	Alluvium, wet year
Long Mountain	1971	35% runoff 65% recharge		Limestone
	1977	No surplus		
	1979	50% recharge 50% runoff	10%	Wet year
Hope Filter Plant	1971	No surplus		
	1977	No surplus		
	1979	50% recharge 50% runoff	10%	Alluvium, wet year

TABLE 5 (CONTINUED)

Rainfall Station	Year	% Allocation	Estimated % Error	Reasons
Bamboo Avenue	1971	No surplus		
	1977	No surplus		
	1979	50% recharge	10%	Alluvium, wet year
		50% runoff		
Gordon Town	1971	65% runoff		Volcanics
		35% recharge		
	1977	65% runoff		
		35% recharge	10%	Volcanics
	1979	75% runoff		Volcanics, wet year
Irish Town		25% recharge		
	1971	65% runoff		Volcanics
		35% recharge		
	1977	65% runoff	10%	Volcanics
		35% recharge		
	1979	75% runoff		Volcanics, wet year
Newcastle		25% recharge		
	1971	65% runoff		Volcanics
		35% recharge		
	1977	65% runoff	10%	Volcanics
		35% recharge		
	1979	75% runoff		Volcanics, wet year
		25% recharge		

TABLE 5 (CONTINUED)

Rainfall Station	Year	% Allocation	Estimated % Error	Reasons
Hermitage	1971	65% runoff		Volcanics
		35% recharge		
	1977	65% runoff		Volcanics
		35% recharge	10%	
	1979	75% runoff		Volcanics, wet year
		-25% recharge		
Constant Spring	1971	35% runoff		Limestone
		65% recharge		
	1977	35% runoff		Limestone
		65% recharge	10%	
	1979	50% recharge		Limestone, wet year
Jacks Hill		50% runoff		
	1971	15% runoff		Volcanic/limestone
		85% recharge		Interface, faulted
	1977	15% runoff		Volcanic/limestone
		85% recharge	10%	Interface/faulted
Half Way Tree	1979	35% runoff		wet year
		65% recharge		
	1971	No surplus		
	1977	No surplus		
	1979	50% runoff	10%	Alluvium, wet year
		50% recharge		

TABLE 5 (CONTINUED)

Rainfall Station	Year	% Allocation	Estimated % Error	Reasons
Red Hills	1971	15% runoff		Upper limestone
		85% recharge		
	1977	15% runoff	10%	Upper limestone
		85% recharge		
Coppers Hill	1979	35% runoff		Upper limestone, wet year
		65% recharge		
	1971	15% runoff		Upper limestone
		85% recharge		
	1977	15% runoff	10%	Upper limestone
Cinchona		85% recharge		
	1979	35% runoff		Upper limestone, wet year
		65% recharge		
	1971	65% runoff		Volcanics
		35% recharge		
	1977	65% runoff		Volcanics
		35% recharge	10%	
	1979	75% runoff		
		25% recharge		Volcanics, wet year

Validation Tests of Systems Outputs

The runoff and recharge volumes are derived from the simulated surplus, with adjustments for local differences in infiltration rates and soil and bedrock storages. The validity of the outputs of a water budget analysis can be checked by comparing actual runoff (observed) with a simulated runoff. It must be noted that unavailability of runoff data, except for one region, restricted the completeness of the validation tests. Gordon Town, located in the middle of the volcanics, has streamflow data for 1971. On the alluvium, well data are available from 1973 to 1979. From the data available it is possible to compare simulated runoff with streamflow on the volcanics during 1971, and change in storage with simulated recharge on the alluvium for the dry year of 1977 and the wet year of 1979.

Simulated Runoff vs. Streamflow

In the model, simulated runoff is equivalent quantitatively to streamflow. The annual flow of the Hope River should therefore match the total annual simulated runoff of the volcanic subdivision.

Simulated Recharge vs. Change in Storage

The study area is basically a closed hydrologic system. If all inputs and outputs are measurable, the change in storage of the

aquifer should be equal to recharge minus deep outflow. It is possible to calculate the change in storage for 1977 and 1979 using available well data and the following procedure.

Method for Calculating Change in Observed Storage

Monthly values of the height of the water table for each water year (February-January) were recorded for wells which were not being pumped that month. Stations which show lowest water levels prior to the onset of the May rains and highest water levels at the end of the October rains are used to determine the change in storage for each of the six years. Monthly or seasonal fluctuations between the lowest and highest values are ignored, and wells with insufficient data to judge the possible range are omitted. The spread of available well data for stations with values for at least two seasons of the 1977 and 1979 water years are shown in Tables 6 and 7.

For each year all the negative (fall) and positive (rise) water table movements for each well are added separately and the mean storage calculated and recorded. If 50% of the stations showed a +5 ft. and the other showed a -5 ft. change in water table elevation, it was assumed that there was no net storage change for that year. Volume calculations were made for each year using the following formula:

$$\text{Area (Based on Number of Wells)} \times \text{Storage Change} \times \\ \text{Specific Yield} = \text{Volume} .$$

The specific yield of an aquifer is based on the local texture and thickness of its materials. The Water Resources Division

TABLE 6
SPREAD OF AVAILABLE WELL DATA IN FT., 1977

Well	J	M	J	J	A	D	F	Change
Chancery Hall								
Forest Hills								
Havendale 1			56.42			23.10		-33.32
Montgomery								
Kings House 1			27.52				29.81	2.29
Kings House 2		31.92					30.88	-1.04
Oakland				15.62			15.50	-.12
Ashenheim Rd.					11.85		11.42	-.43
Sp. Town Rd. 2	4.11						4.74	-.63
Sp. Town Rd. 1								
Cockburn Pen			4.44				4.36	-.08
Hope Gardens								
Liguanea Club								
Hope Vet.								
Havendale 2								
Dunrobin	33.66						29.83	-3.83
Tarrants								
Lyndhurst	178.84						181.50	-2.66
Hunts Bay 8								
Hunts Bay 9		18.28					17.10	-1.18
Buttercup								

TABLE 7
SPREAD OF AVAILABLE WELL DATA IN FT., 1979

Well	F	M	J	O	N	Change
Chancery Hall			19.49		25.06	5.57
Forest Hills						
Havendale 1	58.90				73.89	14.99
Montgomery						
Kings House 1	28.41				35.28	6.87
Kings House 2	28.76				37.96	8.80
Oakland	16.45				19.57	3.12
Ashenheim Rd.						
Sp. Town Rd. 2						
Sp. Town Rd. 1						
Cockburn Pen		4.20			8.10	3.90
Hope Gardens						
Liguanea Club	17.58			21.08		3.50
Hope Vet.	408.82			16.21		7.39
Havendale 2						
Dunrobin		30.00			34.25	4.25
Tarrants	8.22				13.67	5.45
Lyndhurst						
Hunts Bay 8						.64
Hunts Bay 9						
Buttercup	96.75				95.92	.83

recommends a value of .14 for the specific yield of the Liguanea aquifer.¹ To use this value in the present work an assessment of the composition of the aquifer was made using the well log data summarized on pages 22-23. The Liguanea basin consists mainly of a combination of silt and sand with lenses of clays, which, according to the theoretical guidelines of Dunne and Leopold (page 206),² suggest that .14 is a suitable value of specific yield for this aquifer.

Total Alluvium Water Allocations

In this final step of the analytical procedure, all the parameters of the annual hydrologic system of the aquifer are presented for verification in the following equation:

$$[(P - RO - E - \Delta st) + Sew] - [Pu + GWD] = \Delta S$$

$$\text{Inflow} - \text{Outflow} = \text{Storage change}$$

P = Precipitation

RO = Surface Runoff

E = Evapotranspiration

Δst = Change in soil storage

Sew = Inflow from sewerage

Pu = Pumpage from groundwater

GWD = Groundwater outflow to ocean

¹In 1980 WRD calculated storage coefficients of 0.14 on the Portmore area of the Lower Rio Cobre basin which has similar lithology, grain size distribution and alluvium thickness.

²T. Dunne and L. Leopold. "Water in Environmental Planning." San Francisco: W. H. Freeman, 1978.

ΔS = Change in groundwater storage.

In the context of the foregoing framework, the above equation can be simplified to:

$$(\text{Simulated Recharge} + \text{Sewerage Recharge}) - (\text{Pumpage} + \text{Groundwater Outflow}) = \text{Storage Change} .$$

The values for sewerage recharge are the estimates of the Water Resources Division (1980).¹ They are fairly constant and are deemed reliable enough to be used here. Pumpage figures are tabulated from records of the Water Commission, and groundwater outflow data are those calculated by the National Water Commission.²

This equation is in effect a first approximation of the water fluxes of the aquifer, since so many of the variables are estimated or extrapolated. If both sides of the equation are quantitatively equal or very close in value, the methods used here can be considered a useful tool for determining groundwater recharge. Major differences between the two sides of the equation, however, would point to differences between the water allocations used and the water allocations that actually occur.

¹The Water Resources Division in 1980 extrapolated for the entire metropolitan area from per capita waste water from the Harbour View Treatment Plant which handles 100% of waste water for a known population.

²National Water Commission, Flow West Project, 1983.

CHAPTER IV
LOCATION AND TIMING OF RECHARGE AND RUNOFF IN
THE LIGUANEA BASIN

Introduction

This chapter presents the outputs of the water balance calculations, referred to as surplus.¹ Surplus here represents the total amount of water available for allocation to runoff and recharge, and the monthly point value is volumetrically related to the area of each polygon. What follows is detailed data on runoff and recharge as well as maps and diagrams to illustrate areal and temporal distribution of these flows in the study area for the three selected years.

The analysis is based on the application of Thornthwaite's water balance model. Temperature and precipitation data are generated for each polygon region, and the water balance gives values for surplus which are allocated to runoff and recharge. By using the water balance analysis within this small mesh of distinct regions, much greater accuracy should be achieved in quantifying the runoff and recharge because of the particular mix of climatic and physical parameters which exists in each sector. However, it is also critical that the runoff and recharge be totalled by subdivisions, since the aquifer represents one subdivision.

¹ Highlights of the water budget analysis are attached as Appendix 1. Also included for information are values of the climatic parameters used in generating the surplus for each sector.

The Liguanea aquifer represents one of the four subdivisions, but recharge to it may not be limited to the area it covers. The isolation of the hydrological boundaries of the aquifer thus involves knowing the values of recharge and runoff for each contributing region that comprises the overall discharge area of the aquifer and its surroundings.

The most significant output of the water balance analysis for this study is the monthly surplus for each region. Monthly surplus is divided into runoff and recharge, based on the allocation coefficients presented and discussed in the previous chapter (Table 5, p. 49). Recharge and runoff volumes can be validated for each year and each area through comparison with measured values of streamflow and changes in well heights. Tables 8, 9, and 10 give volume of simulated annual surplus by subdivision for each of the three years in millions of U. S. gallons.

Runoff

The volumes of simulated annual runoff by subdivisions for each of the three years representing dry, average, and wet years are also given in Tables 8, 9, and 10. Figure 4-1 shows the areal distribution of calculated runoff for all three years by sectors. As expected, total runoff for the wet year is almost twice that of the average years and over ten times that of the dry year, yet important variations exist between the subdivisions during the three years. Runoff is consistently higher in the volcanics than

TABLE 8
DISTRIBUTION OF WATER (MILLIONS OF GALLONS), 1971 (AVERAGE)

Subdivision	Precipitation	Simulated		
		Surplus	Runoff	Recharge
Volcanics	29609	15937	9414	6523
East Limestone	4539	349	18	331
West Limestone	15657	6070	1199	4871
Alluvium	28102	8580	1792	6788
Total	77907	30936	12423	18513

TABLE 9
DISTRIBUTION OF WATER (MILLIONS OF GALLONS), 1977 (DRY)

Subdivision	Precipitation	Simulated		
		Surplus	Runoff	Recharge
Volcanics	16197	2736	1570	1166
East Limestone	3836	0	0	0
West Limestone	8861	476	148	328
Alluvium	17079	638	222	416
Total	45973	3850	1940	1910

TABLE 10
DISTRIBUTION OF WATER (MILLIONS OF GALLONS), 1979 (WET)

Subdivision	Precipitation	Simulated		
		Surplus	Runoff	Recharge
Volcanics	32487	20908	12022	8886
East Limestone	10139	1810	1496	314
West Limestone	16538	7616	2022	5594
Alluvium	45903	15883	6598	9285
Total	105067	46217	22138	24079

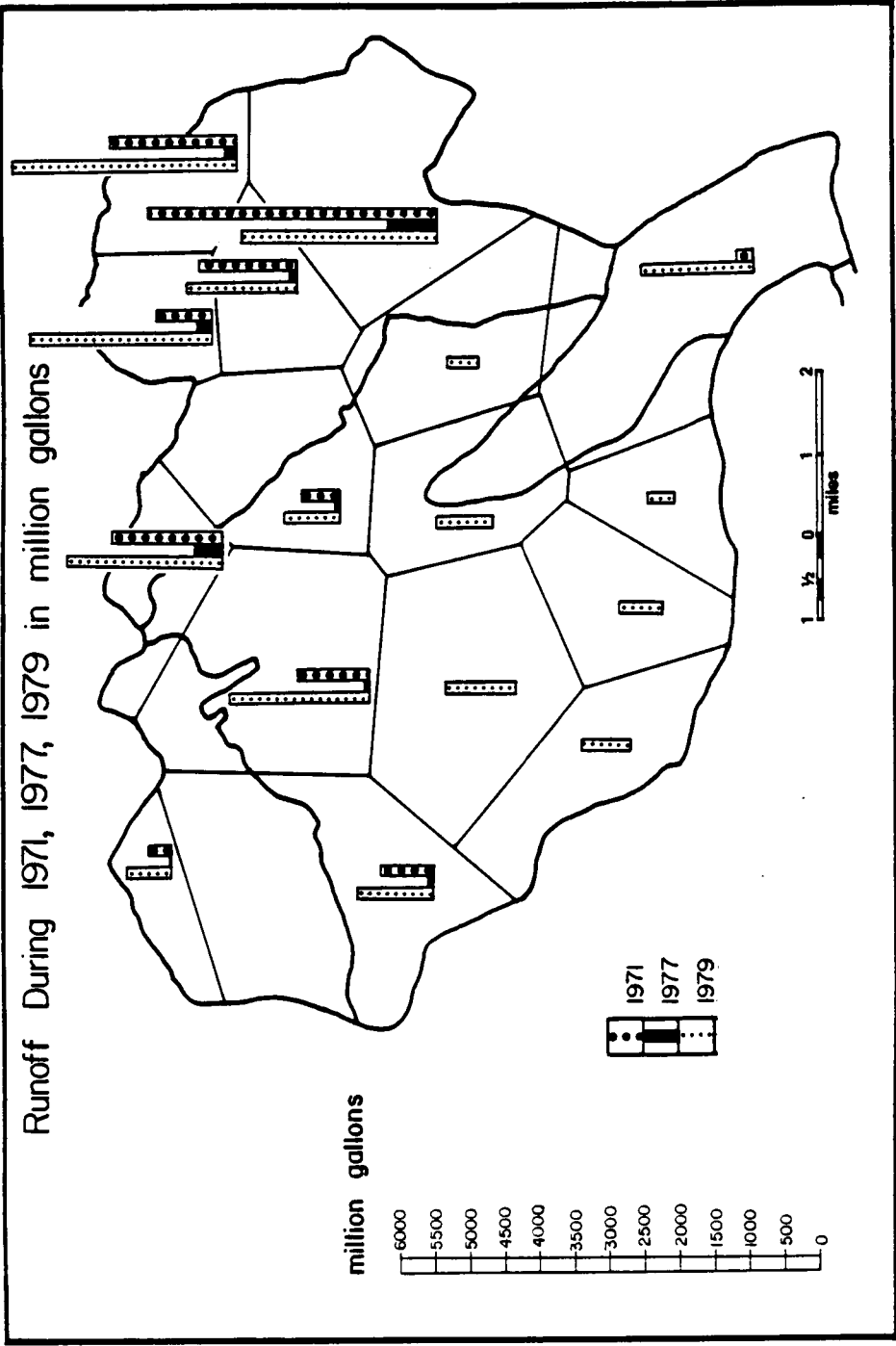


Figure 4-1. Runoff During 1971, 1977, and 1979 in Million Gallons.

in all the other subdivisions combined. Runoff during the wet year is over six times that in the dry year, yet only about 30% greater than the average year. The East Limestone has no runoff during the dry year because of a lack of surplus in all its contributing regions. A higher percentage of total rainfall drained as runoff from the alluvium during the wet year of 1979 than during the other two years.

Recharge

The volumes of recharge in millions of U. S. gallons calculated by region are grouped into the four subdivisions for the three representative years in Table 10.

Figure 4-2 shows the calculated recharge by regions and suggests the flow of recharge to the Liguanea aquifer.

Total recharge during the wet year of 1979 was greater than that of any other year. It is over ten times that of the dry year of 1977, but only about 25% more than the total recharge for the average year of 1971. During both 1979 and 1971, the alluvium subdivision generated slightly more recharge than the volcanics, but in the dry year of 1977, the pattern is reversed and the volcanics have had more than twice as much recharge as the alluvium. Recharge during the average year was unexpectedly high relative to the recharge for the wet year.

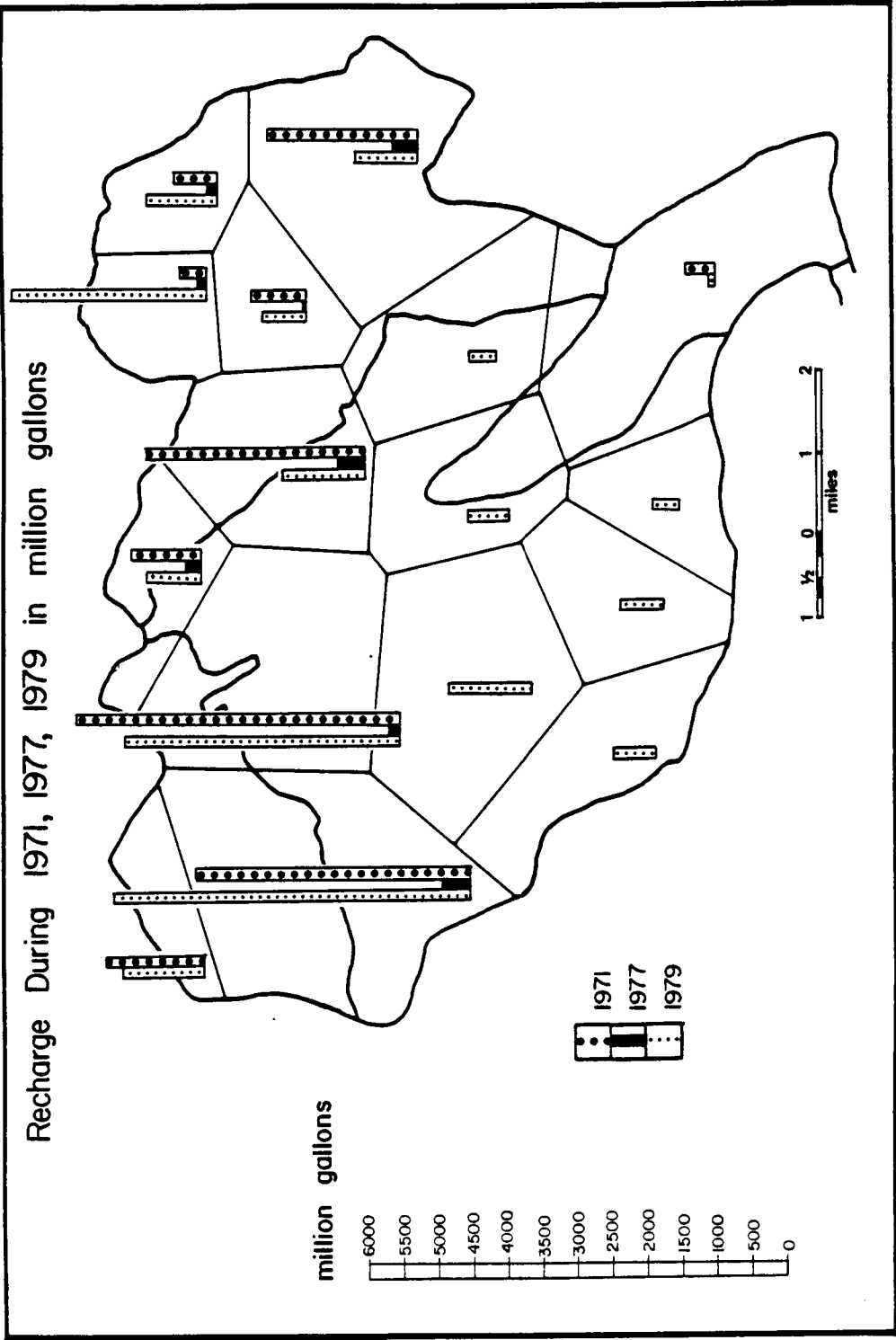


Figure 4-2. Recharge During 1971, 1977, and 1979 in Million Gallons.

Validation of Recharge/Runoff Volumes

Simulated runoff/recharge volumes, even those derived with the most detailed attention to lithology and physical characteristics, need to be validated with measured or calculated values to justify confidence for further use. Earlier, the data limitations for such tests were discussed (page 32) but working with the best available data of measured streamflow and well levels, it is possible to test the simulated runoff and recharge as generated by the model. The results of these validation tests are presented below.

Validation Test Using Streamflow

The Hope River Basin is a well-defined drainage sub-basin within the study area, with records of measured streamflow at Gordon Town for 1971. The Water Resources Division (1980) used the baseflow of the Hope River to predict the recharge to the Liguanea aquifer,¹ but for purposes of this study the measured streamflow of the Hope River is compared only to the calculated runoff of the regions measured. A strong positive correlation between predicted runoff from a water budget analysis and measured streamflow on the volcanics can be taken as an indication that

¹ WRD calculated the percentage of average rainfall which flowed as baseflow in the Hope River 52% in 1974 and 54% in 1975, then subtracted 12% and 15% respectively for "rainfall anomalies" and determine that recharge is therefore 40% of total rainfall for the neighboring Liguanea aquifer.

runoff values simulated from a water budget analysis are valid estimates of actual runoff. The flow of the Hope River is measured at Gordon Town and the drainage area includes Newcastle, Cinchona, Irish Town, and the Gordon Town region.

The monthly values for simulated runoff and measured stream-flow are given in Table 11. As expected, the comparison of measured to simulated on a monthly basis is not good, because the simulated values are calculated assuming immediate runoff from the precipitation when, in fact, a lag should be expected. This lag time is particularly evident in the May-June-July period. When computed on an annual basis, however, the lag time is masked, and simulated runoff is only about 4% less than measured. Such close agreement gives credibility to a water budget approach to estimating total runoff.

Validation Test Using Well Levels

The use of well data to test aquifer recharge involves the estimation of the change in storage of the groundwater for the entire alluvial subdivision. The procedure is designed to match simulated recharge with change in water table height as measured by well levels for 1977 and 1979. The values for calculated change in storage have been estimated using water level data for wells in the basin. These values are compared to the change in storage using recharge based on precipitation and infiltration.

TABLE 11

COMPARISON OF MEASURED AND SIMULATED RUNOFF AT GORDON TOWN IN CUBIC FEET PER SECOND

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Measured Streamflow (Gordon Town)	20.1	15.8	13.1	13.9	14.2	14.1	8.9	12.4	16.5	25.7	60.9	18.7	234.3
Simulated Runoff (Upper Volcanic)	2.6	6.8	1.9	4.5	35.3			39	15	27.7	91	1.3	<u>225.1</u>
	Annual Difference												9.2
	(= 3.9%)												

Below is a step-by-step account of the storage changes over the two years using well data, quantification of the water balance equation giving simulated storage change, and finally a comparison of the two sets of storage change values. The changes in well heights for 1977 and 1979 are given in Table 12, and the wells used are plotted on Figure 4-3 to illustrate the areal coverage of the analysis. The average movements in water table level from which the volumes are calculated are represented in Table 13.

To convert average well fluctuations to volumes of stored water, simply multiply the area-weighted net change in water level by the specific yield.¹ For example, in the dry year of 1977, 90% of the alluvium recorded an average change in water table height of -4.43 ft., and the remaining 10% recorded a change of +2.29 ft. The total area of the alluvium is 34.8 square miles, so the net storage change is:

$$(34.8 \text{ mi}^2)(640 \text{ ac/mi}^2) [(-4.43)(.9) + (2.29)(.1)] (.14) = \\ -1.172 \times 10^4 \text{ acre ft.}$$

This volumetric unit may be converted to any other desired unit with standard conversion factor

¹National Water Commission (1983) calculated a range of 0.02 to 0.33 and uses the 0.14 value as an acceptable conservative average.

TABLE 12
WELL FLUCTUATIONS, RAW DATA (FT.)

Well	1977	1979
Chancery Hall		5.57
Forest Hills		
Havendale 1	-33.32	14.99
Montgomery Cnr.		
Kings House 1	2.29	6.87
Kings House 2	-1.04	8.80
Oakland	-.12	3.12
Ashenheim	-.43	
Spn. Twn. Rd. 2	-.63	
Spn. Twn. Rd. 1	-.08	
Cockburn Pen		3.90
Hope Gardens		
Liguanea Club		3.50
Hope Vet.		7.39
Havendale 2		
Dunrobin	-3.83	4.25
Tarrants		5.45
Lyndhurst	-2.66	
Hunts Bay 8		.64
Hunts Bay 9	-1.18	.83
Buttercup Pk.		

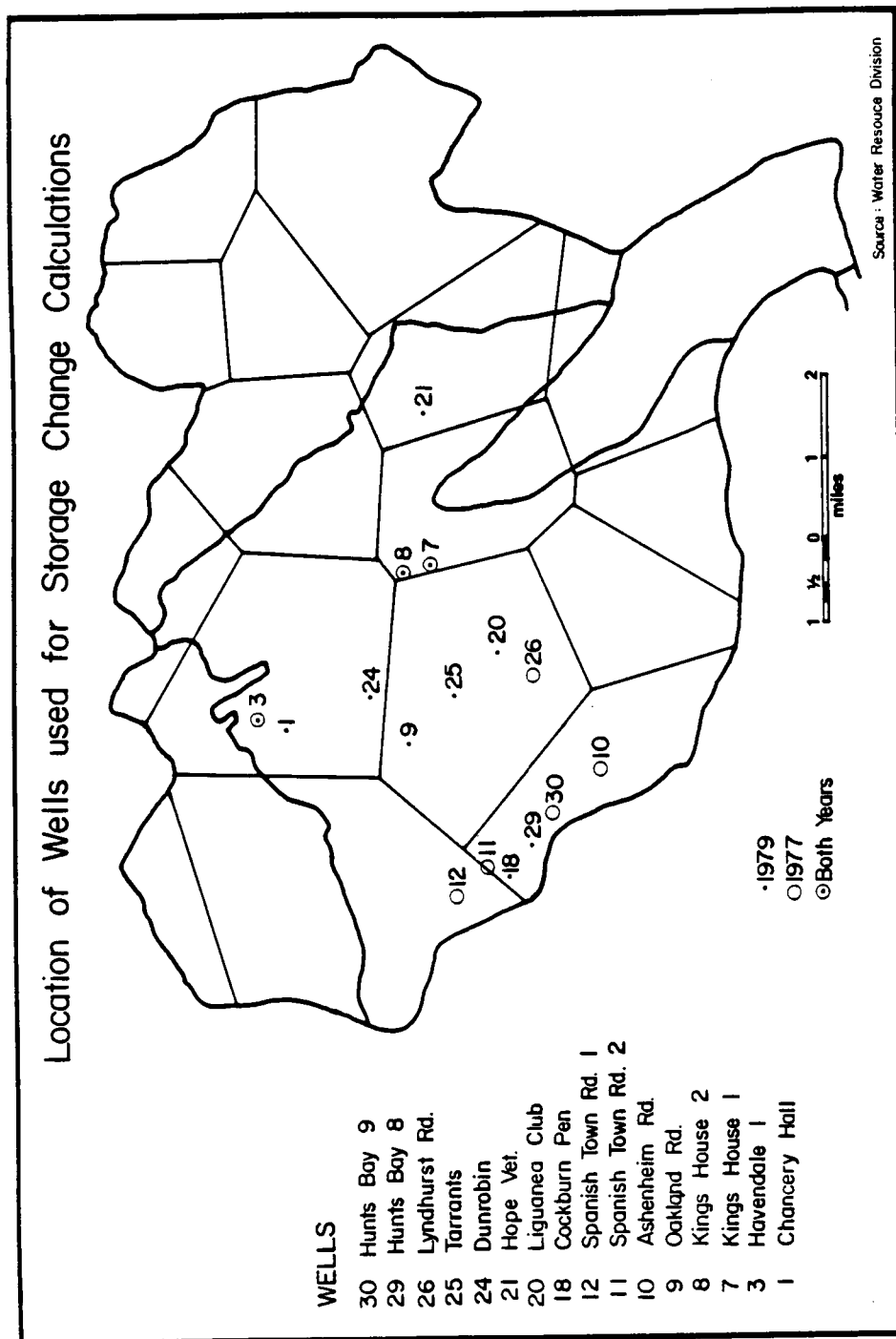


Figure 4-3. Location of Wells Used for Storage Change Calculations.

TABLE 13
OBSERVED WATER TABLE MOVEMENT IN FEET

Year	Well Fluctuations (ft.)	% of Area
1977	-4.43	90%
	+2.29	10%
1979	+5.44	100%

$$\begin{aligned}
 (-1.172 \times 10^4 \text{ ac. ft.})(43,560 \text{ ft}^2/\text{ac}) &= -5.105 \times 10^8 \text{ ft}^3 \\
 -5.105 \times 10^8 \text{ ft}^3 \times 7.48 \text{ gal/ft}^3 &= 3.818 \times 10^9 \text{ gal.} \\
 &\text{or 3818 million gallons.}
 \end{aligned}$$

For the wet year of 1979, average change in water table over the entire basin was +5.44 ft., which converts to:

$$(34.9)(640)(+5.44)(.14) = +1.696 \times 10^4 \text{ ac/ft.}$$

or

$$\frac{(1.696 \times 10^4)(43,560)(7.480)}{10^6} = 5526 \text{ million gallons.}$$

In Table 14 are the calculated changes in storage using well levels:

TABLE 14
VOLUMES OF STORED WATER IN MILLION GALLONS

<u>Year</u>	
1977	-3818
1979	+5526

Simulated Storage Change

Simulated storage change, the focal analysis of this work, is the storage change in the Liguanea aquifer which would result if the recharge estimated by the water balance and allocation analyses is accurate. It is derived by adding the recharge allocated from the water balance/allocation analysis to the water which is generated by sewerage recharge and subtracting from that total the sum of all water pumped from the aquifer and groundwater outflow. The following equation represents the above:

$$(\text{Simulated Recharge} + \text{Sewerage Recharge}) - (\text{Pumpage} + \text{Groundwater Outflow}) = \text{Storage Change} .$$

Each element of the equation is explained and its determined values for 1977 and 1979 are given below.

Simulated Recharge

Simulated recharge for 1977 is 416 million gallons and for 1979 it is 9285 million gallons. Both values are reported in Table 10 (see page 64 under alluvium).

Sewerage Recharge

The sewerage recharge calculations of 5840 million gallons per year are used as a constant for all years, because all reported estimates of sewerage recharge indicate only minor variations among years.¹

Pumpage

Total pumpage from the aquifer is the sum of withdrawal from all municipal wells plus the amount pumped by all industrial owners of private wells. The total industrial pumpage is also considered a constant and is reported by the National Water Commission to be 1439 million gallons per annum.

From National Water Commission's records for 1977 it is estimated that 3407 million gallons were pumped (see Table 15).

Adding the total municipal pumpage of 3407 million gallons to the industrial pumpage of 1439 million gallons give a total pumpage for 1977 of 4846 million gallons.

For 1979, 3302 million gallons were pumped (see Table 16).

Adding the municipal pumpage of 3302 million gallons to the industrial pumpage of 1439 million gallons gives a total pumpage of 4741 million gallons in 1979 (see Table 17).

¹Water Resources Division. "Further Development of the Aquifer of the Liguanea (Hope River) Basin," 1980.

TABLE 15
MUNICIPAL PUMPAGE, MILLIONS OF GALLONS, 1977

Well	J	F	M	A	M	J	J	A	S	O	N	D	Yr.
Cavaliers	28	28	34	33	18	14	23	34	32	32	18	21	315
Montgomery Cnr.	28	23	17	16	9	21	28	28	27	28	7	-	323
Long Mountain	27	-	-	-	3	1	5	-	-	-	-	-	36
Rennock Lodge	88	78	88	83	83	86	80	89	85	86	85	89	1021
Trench Town	19	24	27	26	27	25	5	-	-	-	-	-	153
Forest Hills	-	10	42	42	42	48	56	54	52	27	26	27	426
Chancery Hall	40	32	36	35	40	37	45	45	43	41	40	36	470
Havendale 1	5	-	-	-	-	-	-	-	-	-	7	12	24
Havendale 2	22	20	20	15	16	14	25	26	18	16	3	2	197
Hampstead	19	16	21	18	11	12	23	21	18	17	10	13	199
Beverly Hills	39	35	33	-	-	-	5	16	20	14	14	22	198
Devon House	11	12	12	8	6	10	13	13	13	13	12	13	136
Total													3407

Source: National Water Commission.

TABLE 16

MUNICIPAL PUMPAGE, MILLIONS OF GALLONS, 1979

Well	J	F	M	A	M	J	J	A	S	O	N	D	Yr.
Cavaliers		6	17	13	13			3	1				53
Montgomery	24	25	24	12	19			22	4	13	19	16	178
Rennock Lodge	18	36	41	63	70	85	90	83	84	87	86	19	762
Trench Town	17	17	22	21	7			15	14	21	215	13	362
Tulloch Springs	161	137	146	82	18	21	52	22	61	142	216		1058
Forest Hills	37	42	21	24	26						4		154
Chanchery Hall	24	37	26	34	41	24	3	21	18	10	9	16	263
Havendale 1	13	4	10										27
Havendale 2	17	16	17	20	22	14		14	18	4			142
Hamstead		8	10	10	11	11	16	17	17	79	19	19	217
Beverley Hills	15	14	15	13	15	14							86
Total													3302

Source: National Water Commission.

TABLE 17
TOTAL PUMPAGE OF WELLS ON ALLUVIUM IN MILLION GALLONS

Year	Municipal	Industrial	Total
1977	3407	1439	4846
1979	3302	1439	4741

Outflow

Humphries (1971)¹ calculated the deep outflow to the sea from the Liguanea aquifer as equivalent to 12 inches of rainfall over the entire basin, and although it is possible that deep outflow varies with water table elevation, in the absence of more reliable information the converted volume of 5110 million gallons per annum is used.

Total Water Balance Calculations

It is now possible to calculate the simulated storage change for 1977 and 1979 using the values previously determined for each element of the following equation:

$$(\text{Simulated Recharge} + \text{Sewerage Recharge}) - (\text{Pumpage} + \text{Groundwater Outflow}) = \text{Storage Change.}$$

¹Humphries and Sons. "Kingston Regional Groundwater Investigations." Westminster, United Kingdom, 1971.

1977

Simulated Recharge to Alluvium = 416 Million Gallons (see
Table 10, page 64)

Sewerage Recharge = 5840 Million Gallons

Pumpage = 4846 Million Gallons

Groundwater Outflow = 5110 Million Gallons

$(416 + 584) - (4846 + 5110) = -3700$ Million Gallons

1979

Simulated Recharge to Alluvium = 9285 Million Gallons (see
Table 10, page 64)

Sewerage Recharge = 5480 Million Gallons

Pumpage = 4741 Million Gallons

Groundwater Outflow = 5110 Million Gallons

$(9285 + 5840) - (4741 + 5110) = 5274$ Million Gallons.

Matching Simulated and Observed Values of Storage Change

The storage change values of -3700 million gallons in 1977 and +5274 million gallons in 1979 can now be referred to as simulated storage change and values of storage change based on well data can now be referred to as observed storage change. A comparison of both sets of storage change values for each year constitutes the validation tests using well data.

1977

Simulated Storage Change = -3700 Million Gallons

Observed Storage Change = -3818 Million Gallons

Difference of 118 Million Gallons or 3.19%.

Results indicate that in 1977 the analytical procedure underestimates the storage change in the Liguanea aquifer by 3.19%.

1979

Simulated Storage Change = 5274 Million Gallons

Observed Storage Change = 5527 Million Gallons

Difference of 253 Million Gallons or 4.6%.

Results indicate that in 1979, the analytical procedure underestimates the storage change in the Liguanea aquifer by 4.6%. It might be significant that in both the dry year of 1977 and the wet year of 1979, the simulated storage change is a consistent underestimate.

Summary

The validation tests of simulated recharge and runoff used measured streamflow in the volcanics for 1971 and fluctuations in well heights in the alluvium in 1977 and 1979. As can be seen in Table 18 below, the difference between simulated recharge and runoff and observed runoff (1971) and measured well data (1977, 1979) was less than 5% in each case.

This justifies confidence in the analytical procedure in two important ways. First, the total surplus generated by the water balance analysis is a close approximation of the excess water available for runoff or recharge in the basin; and second, the recharge/runoff allocations used in this work (refer to Table 5, pages 49-52) are good predictors of aggregate water fluxes in the study area.

TABLE 18
RESULTS OF VALIDATION TESTS

Year	Test	% Deviance
1971	Streamflow	3.0
1977	Well	3.19
1979	Well	4.60

CHAPTER V

THE OCCURRENCE AND FLOW OF WATER IN THE LIGUANEA BASIN

Introduction

The results of the validation tests showed a positive agreement of over 95%. This leads to the conclusion that both the water balance analysis and the allocations used to decide between runoff and recharge are good predictors of the water flows in the study area. This means, in effect, that the relationship between runoff and recharge and the amount of total precipitation in any of the regions of the study area can be estimated for wet, dry or average years by using the combination of water balance and allocation analyses proposed here. Further, if it is possible to establish a good predictable relationship between runoff/recharge and total precipitation then, in cases where quick estimates are needed, such results or coefficients could be used instead of the lengthy water balance analysis.

Coefficients Based on Water Budget Simulation

The available climatic data for the study area are from the stations recording precipitation. Previous recharge estimates for the Liguanea aquifer use a uniform percentage of total precipitation as a recharge coefficient. Logic suggests that applying a single recharge coefficient for the entire basin and for all years both wet and dry, is unrealistic. By using a water budget model adjusted

by region to account for different lithologies and physical characteristics, more realistic values of runoff and recharge can be generated that recognize the different allocation of precipitation in dry and wet years. Runoff and recharge coefficients by type of year can be generalized for each region, and these could be used for rapidly estimating recharge when only total precipitation is known. The following data illustrate the relationship between surplus, runoff, recharge, and total precipitation on an annual basis for each region.

Surplus Coefficient

Surplus as a percentage of total rainfall for each region for the three years is given in Table 19. The patterns of these surplus coefficients for 1971, 1977, and 1979 are shown on Figures 5-1, 5-2, and 5-3 respectively.

In the dry year of 1977 there is no surplus on the lower sections of the alluvium or on the western limestone hills. The highest percentage of surplus occurs in the volcanics and upper limestone regions during the wet year of 1979. The regions straddling the eastern limestone hills and the volcanic and alluvium subdivisions are an intermediate zone with consistently more surplus than the area to its south and less surplus than the area to its north.

Runoff Coefficient

Runoff as a percentage of total rainfall for each region for the three years is given in Table 20. The patterns of these runoffs

TABLE 19
SURPLUS AS PERCENT OF TOTAL RAINFALL

Station	1971 (Average)	1977 (Dry)	1979 (Wet)
Western Terminals			29
Cavaliers			25
Coconut Inds.			27
Long Mountain	16		36
Bamboo Avenue			28
Hope Filter			25
Constant Spring	31	3	45
Gordon Town	61	20	49
Newcastle	50	25	69
Hermitage	58	28	61
Red Hills	29	5	41
Half Way Tree			30
Coopers Hill	57		57
Irish Town	53	10	56
Cinchona	47	22	67
Jacks Hill	43	7	36

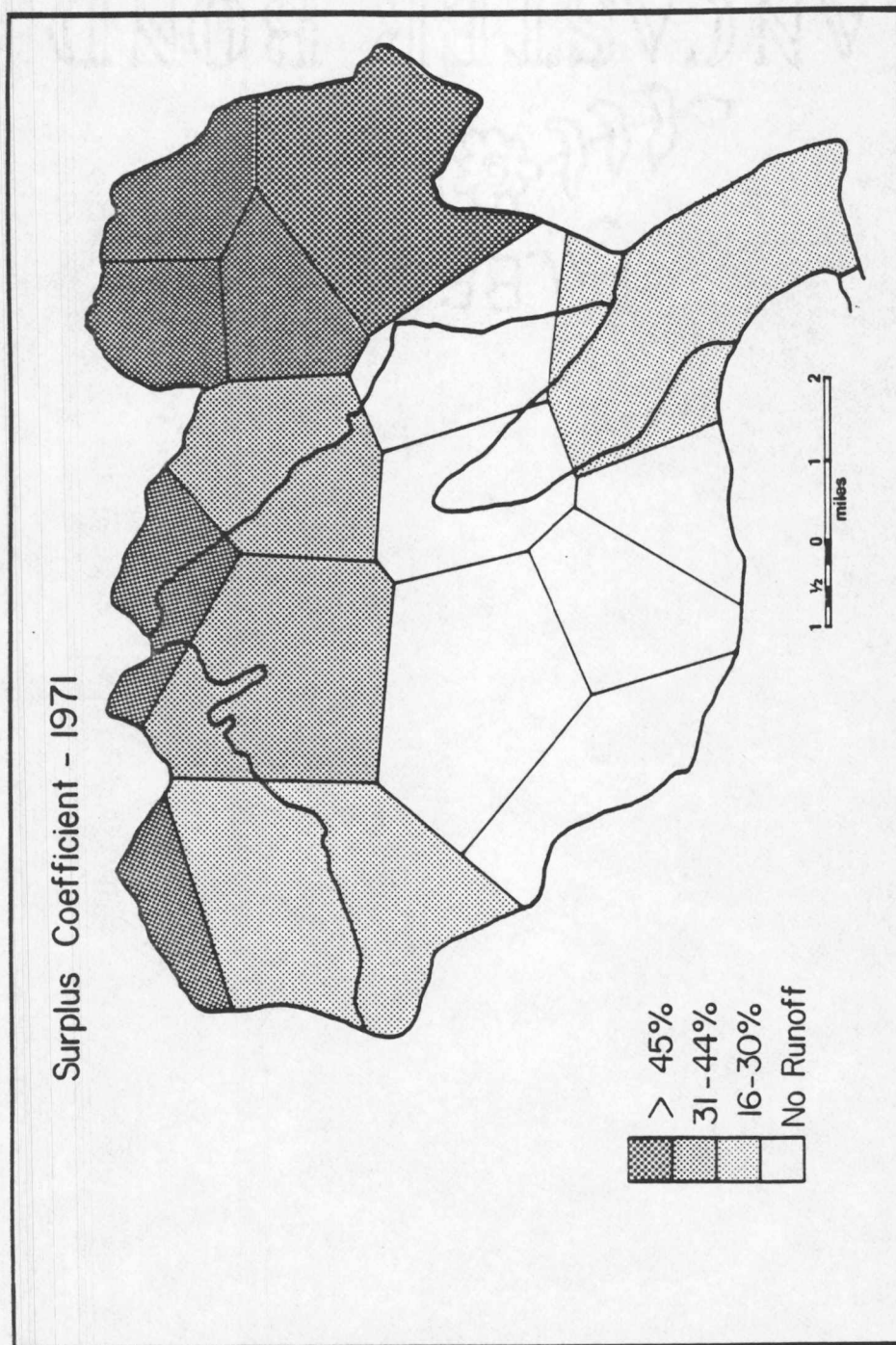


Figure 5-1. Surplus Coefficient, 1971 (Average).

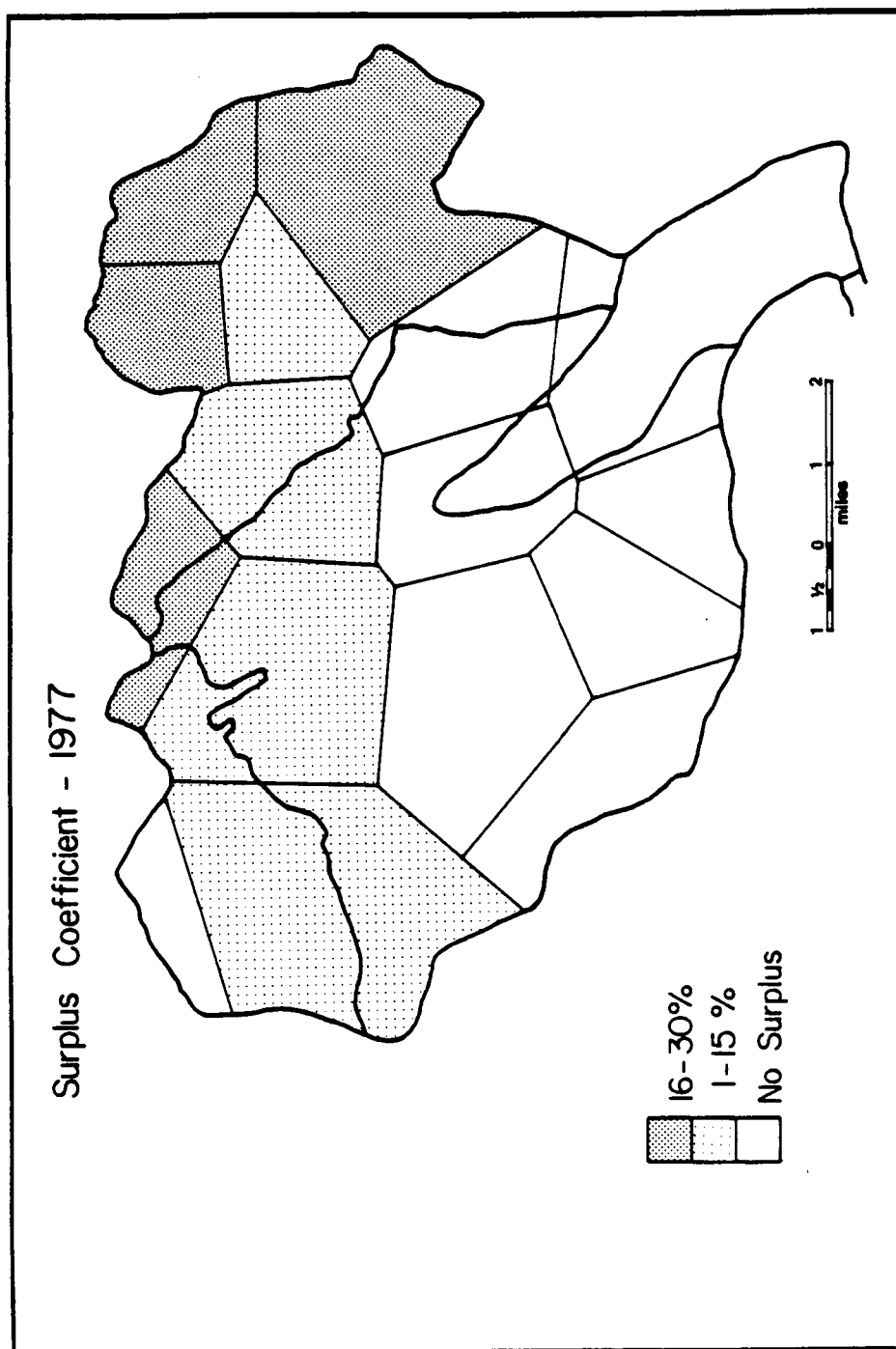


Figure 5-2. Surplus Coefficient, 1977 (Dry).

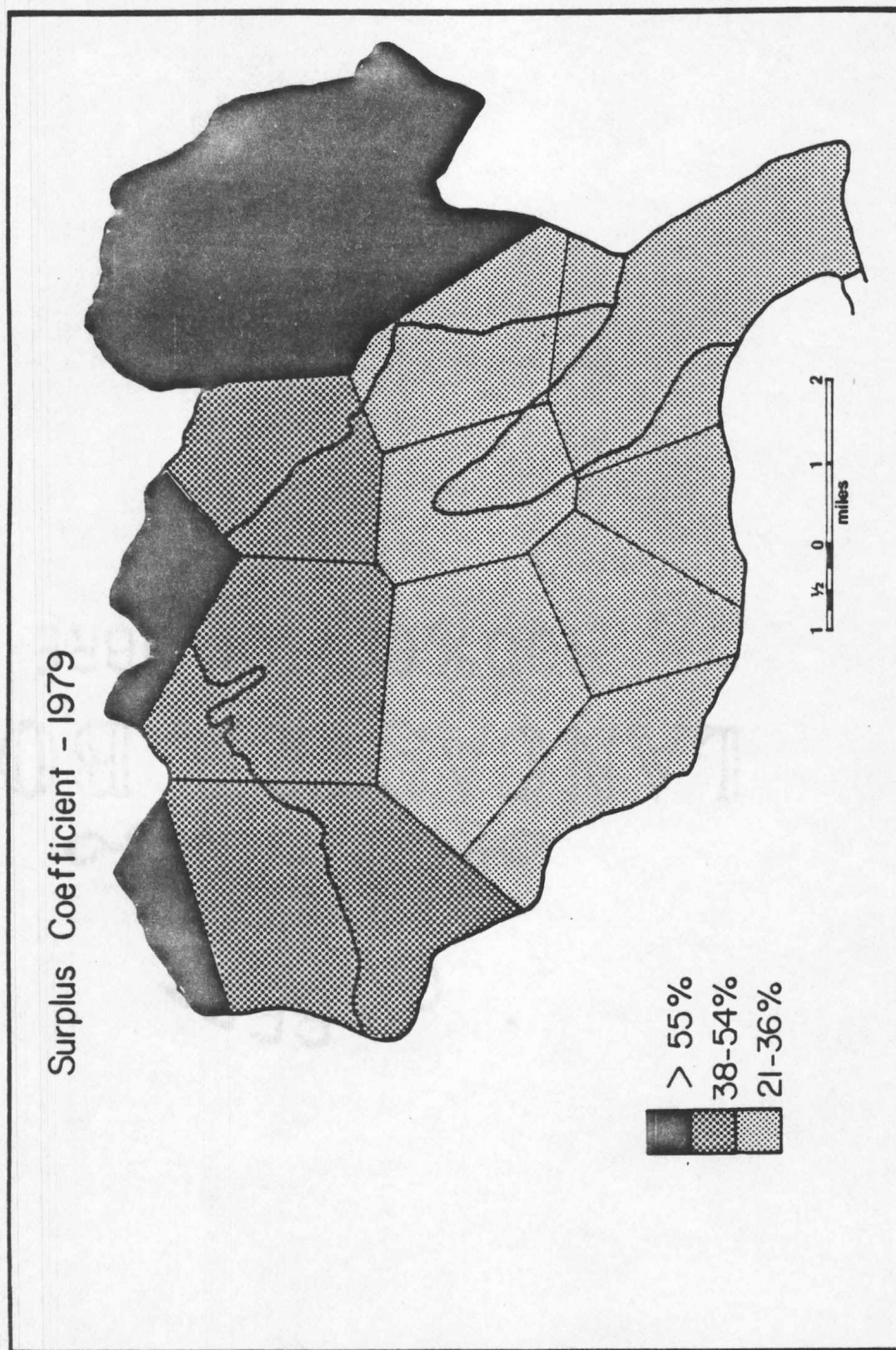


Figure 5-3. Surplus Coefficient, 1979 (Wet).

TABLE 20
RUNOFF AS PERCENT OF TOTAL RAINFALL

Station	1971 (Average)	1977 (Dry)	1979 (Wet)
Western Terminals			15
Cavaliers			13
Coconut Inds.			13
Long Mountain	5		15
Bamboo Avenue			15
Hope Filter			13
Constant Spring	11	1	15
Gordon Town	39	15	37
Newcastle	32	16	52
Hermitage	38	18	46
Red Hills	4	1	16
Half Way Tree			15
Coopers Hill	8		20
Irish Town	38	6	42
Cinchona	26	7	51
Jacks Hill	6	1	13

coefficients for 1971, 1977, and 1979 are shown on Figures 5-4, 5-5, and 5-6 respectively.

Runoff occurs on the regions of the volcanics and on the upper limestone during any kind of year and on the regions of the lower limestone and alluvium only during a very wet year. The runoff coefficients for the wet year of 1979 ranged from 13% in the southern regions to 52% at Newcastle in the northern volcanics. During the dry year of 1977, 50% of the regions experienced no runoff, and values ranged from 1% at Constant Spring to 18% at Hermitage.

Recharge Coefficients

Recharge as a percentage of total rainfall for each region for the three years is given in Table 21. The patterns of these recharge coefficients for 1971, 1977, and 1979 are shown on Figures 5-7, 5-8, and 5-9 respectively.

During the wet year of 1979 all stations showed significant values of recharge, with a range of 13% to 35%, but the recharge coefficients for the average year of 1971 are even higher in some regions. For example, Coopers Hill in the upper limestone has a recharge coefficient of 49% in 1971, which is 12% higher than its 1979 value. The alluvium areas have predictably low values for all years.

Volume of Recharge to the Liguanea Aquifer

Recharge of the Liguanea aquifer is largely accomplished during exceptionally wet years and by the excessive rainfalls accompanying major tropical disturbances. In 1979, three tropical

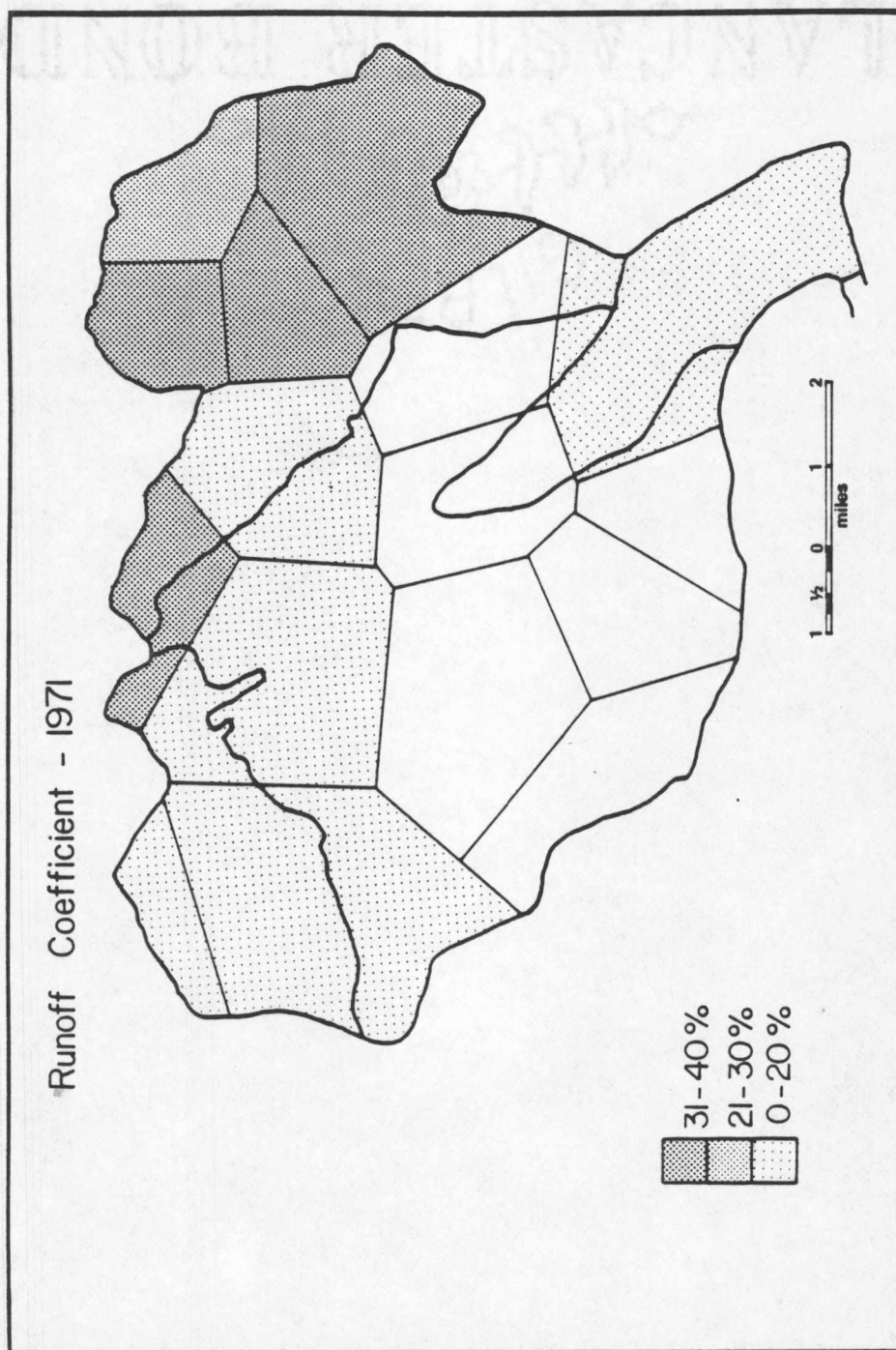


Figure 5-4. Runoff Coefficient, 1971 (Average).

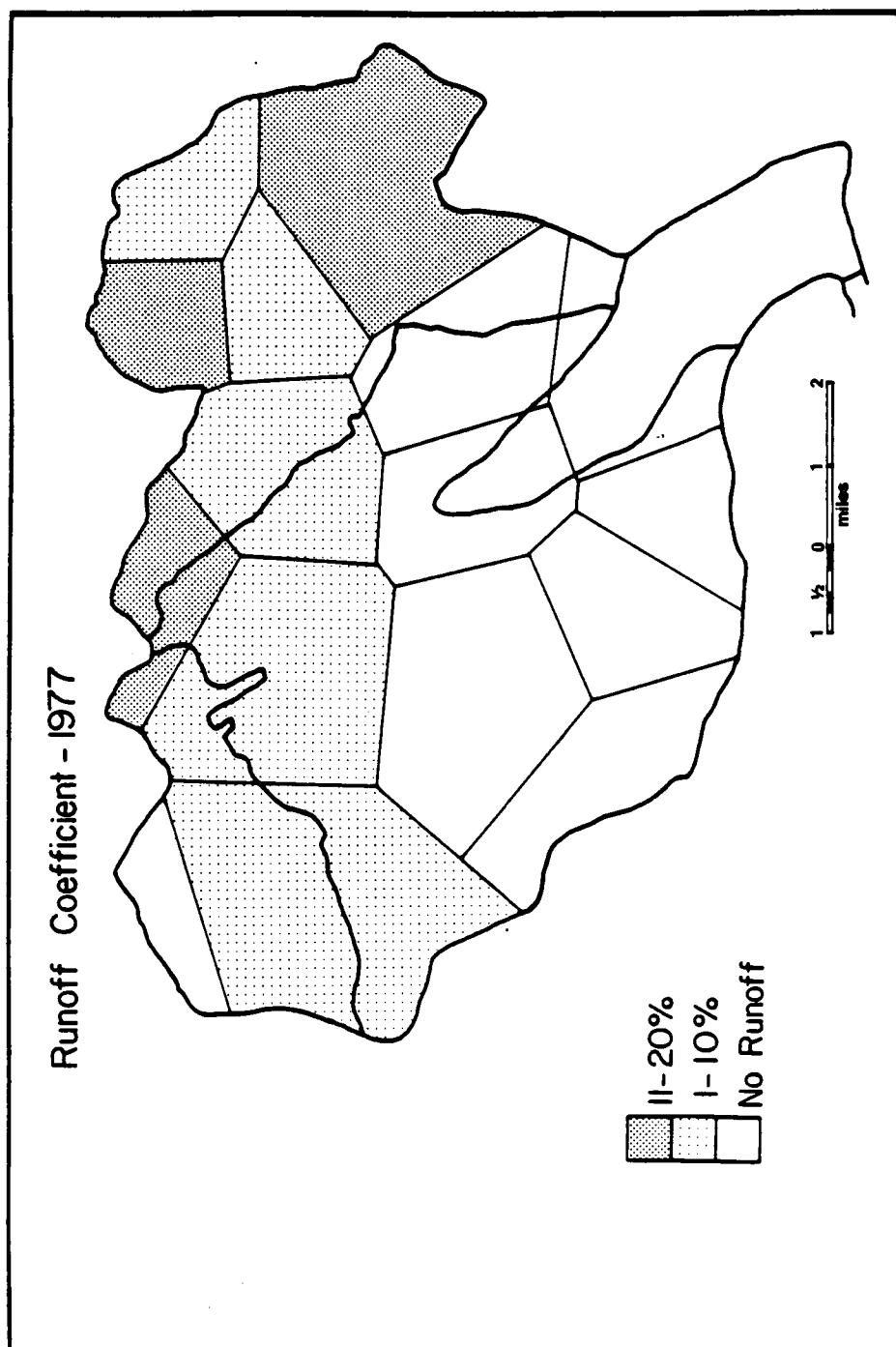


Figure 5-5. Runoff Coefficient, 1977 (Dry).

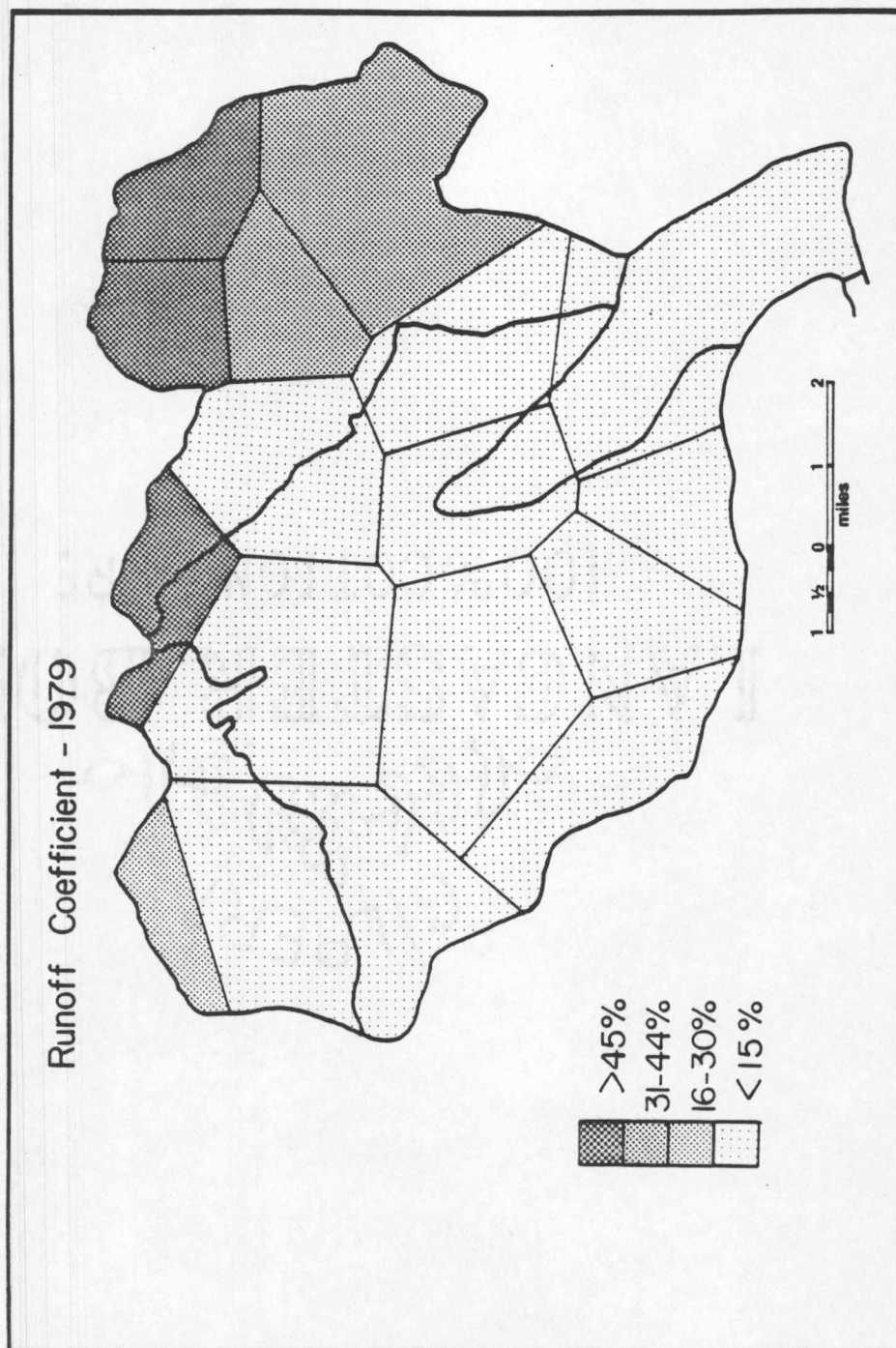


Figure 5-6. Runoff Coefficient, 1979 (Wet).

TABLE 21
RECHARGE AS PERCENT OF TOTAL RAINFALL

Station	1971 (Average)	1977 (Dry)	1979 (Wet)
Western Terminals			13
Cavaliers			13
Coconut Inds.			13
Long Mountain	9		15
Bamboo Avenue			15
Hope Filter			13
Constant Spring	20	2	29
Gordon Town	21	7	12
Newcastle	18	9	17
Hermitage	20	10	15
Red Hills	25	4	35
Half Way Tree			15
Coopers Hill	49		37
Irish Town	18	3	14
Cinchona	21	8	17
Jacks Hill	37	7	24

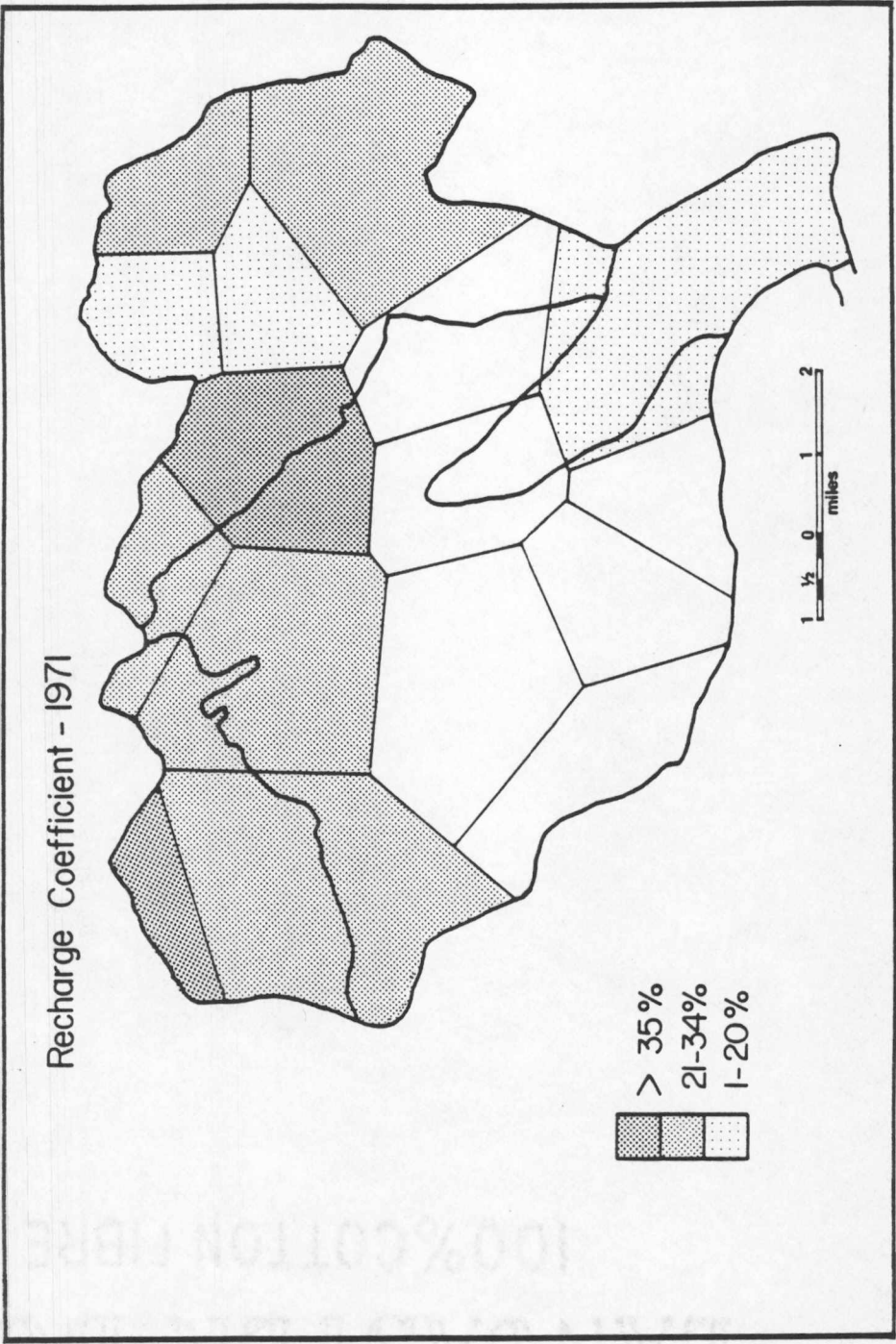


Figure 5-7. Recharge Coefficient, 1971 (Average).

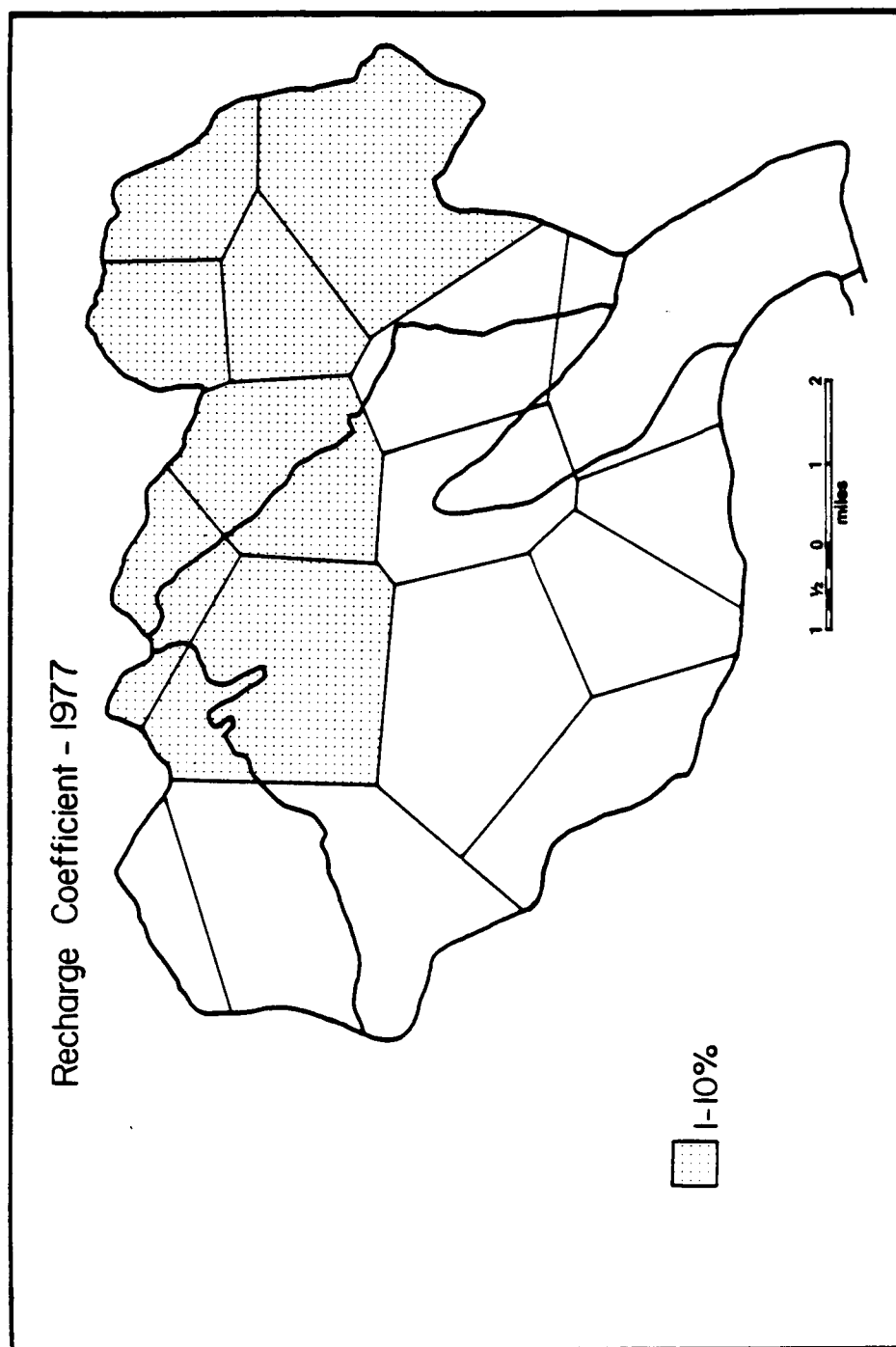


Figure 5-8. Recharge Coefficient, 1977 (Dry).

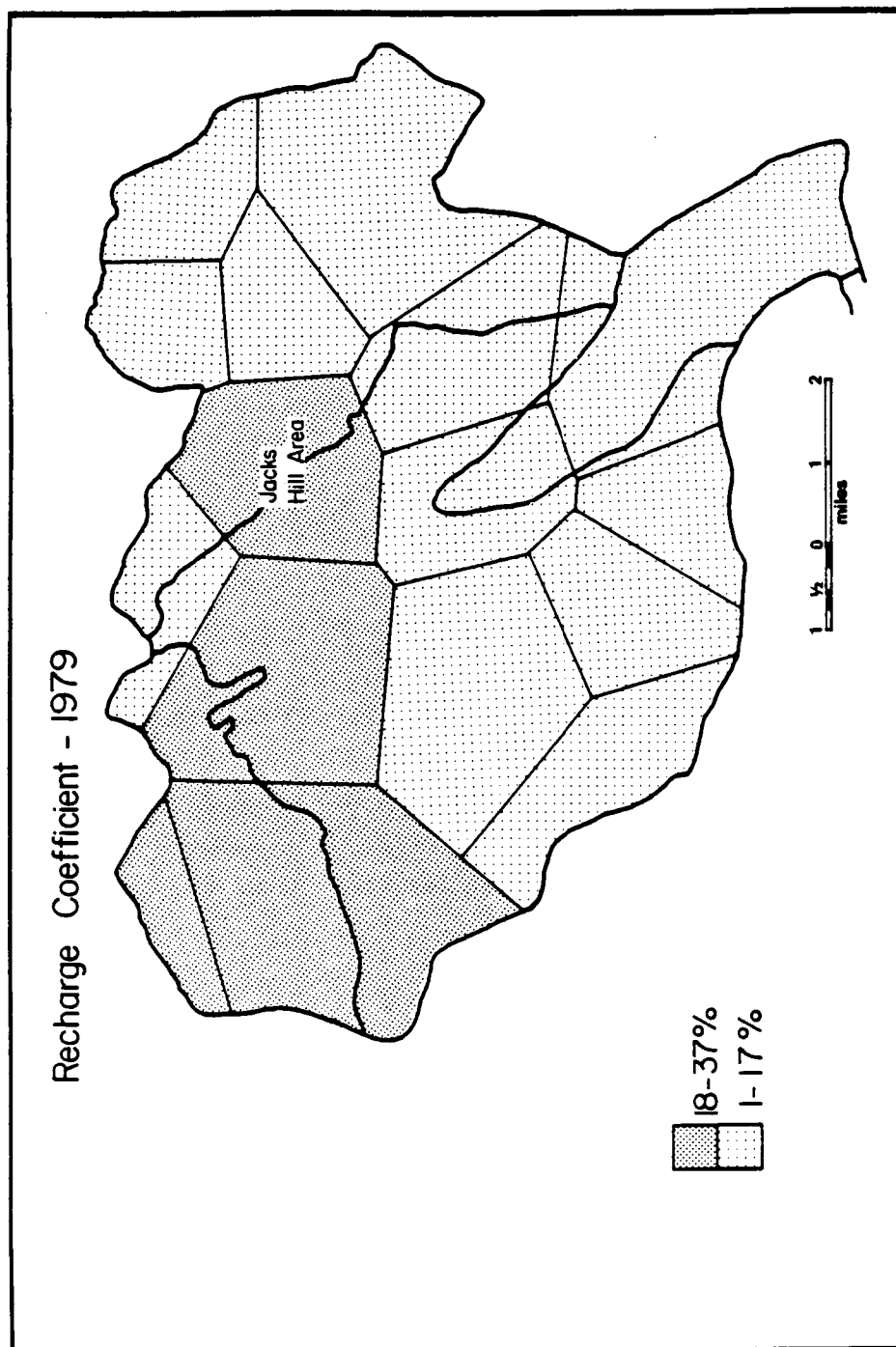


Figure 5-9. Recharge Coefficient, 1979 (Wet).

weather systems passed close to the island. On June 12, a tropical depression passed 85 miles offshore, and during September 2 and 11-13 hurricanes David and Frederick passed 173 and 172 miles offshore, respectively. Precipitation from these three weather systems resulted in the water table of the aquifer rising by an average of 5.44 ft., representing an increase of more than 5000 million gallons of groundwater. From the water balance analysis it is clear that the month of September, 1979, was a time of substantial recharge over the entire basin (see the high surplus values in Appendix 2). From the recharge map on page 67, an apparent feature is the abundance of recharge at the limestone/upper alluvial interface and the abrupt declines both north and south. Size of the various regions is the main factor accounting for the large volumes, but even in regions of similar size, there is a distinct difference between, say, the Constant Spring and the Long Mountain regions. During 1979, the upper sectors played a dominant role in providing the input to the groundwater system and, on average, the unit area recharge from this area is greatest in terms of both the absolute quantity and proportion of precipitation (see Table 21, p. 94). In the wet year of 1979, however, even the regions of the lower alluvium showed gains averaging 300-1000 million gallons per sector.

In the volcanics, the volume of recharge is less than runoff. This is reflected by the recharge patterns shown on Figure 4-2, p. 67, where recharge is noticeably less in the volcanics than in adjacent areas with less total precipitation. The limestone areas,

though smaller in size, registered recharge volumes of over 100 million gallons during 1979.

It is evident that recharge over the entire study area is closely related to the occurrence of one or more tropical weather systems in 1979; yet recharge for 1971, a non-hurricane year, exceeded that of 1979 in 40% of the study area. This is one of the most significant findings of this work, for it highlights the role of high natural and artificial runoff during high-intensity rainfall episodes. These episodes do not prevent recharge; they just do not yield as high a proportion of recharge in relation to total precipitation.

During 1971, the lower reaches of the aquifer experienced no recharge because of low volumes of precipitation, all of which was taken up by evapotranspiration and soil moisture storage. The increase in precipitation northward and a better distribution of surplus throughout the year (7-8 months of surplus) permitted a higher percentage of the available moisture to go underground in these northerly areas.

In 1971, the highest per-unit recharge occurred in the limestone area of Coopers Hill and the limestone/alluvial interface area of Jacks Hill. Here up to 39% of total rainfall, or an average of 1500 million gallons, went to groundwater.

In the dry year of 1977, 50% of the regions had no surplus and hence no recharge. These sectors were located throughout the lower reaches of the aquifer and in the upper limestone areas of

Coopers Hill, where extremely low total precipitation limited moisture allocations to soil moisture storage and evapotranspiration. Nevertheless, several stations had one or more wet months which generated recharge; for example, 500 million gallons of recharge on the Gordon Town sector.

Even in a dry year, the upper alluvial and volcanic areas receive enough rainfall to generate a surplus in some months, but the high overall water need far exceeds the recharge allocated from this surplus. With annual pumpage responding only to annual demand and wells juggled to keep apace, the water table fell an average of 3.75 ft., a decrease in storage of almost 400 million gallons.

Hydrological Boundaries

Defining the hydrological boundaries of the Liguanea aquifer is a difficult procedure, made somewhat easier by the results of the water balance analysis and the close correlation achieved by the tests using streamflow and changes in well heights.

These tests indicate that there are at best insignificant inflows to the alluvial aquifer from any of the other lithologic subdivisions in the study area. The simulated change in storage of the alluvium using well data consistently yields estimates of recharge within 5% of the observed storage change. Figure 5-10 gives the hypothetical picture of subsurface water flows in the study area on

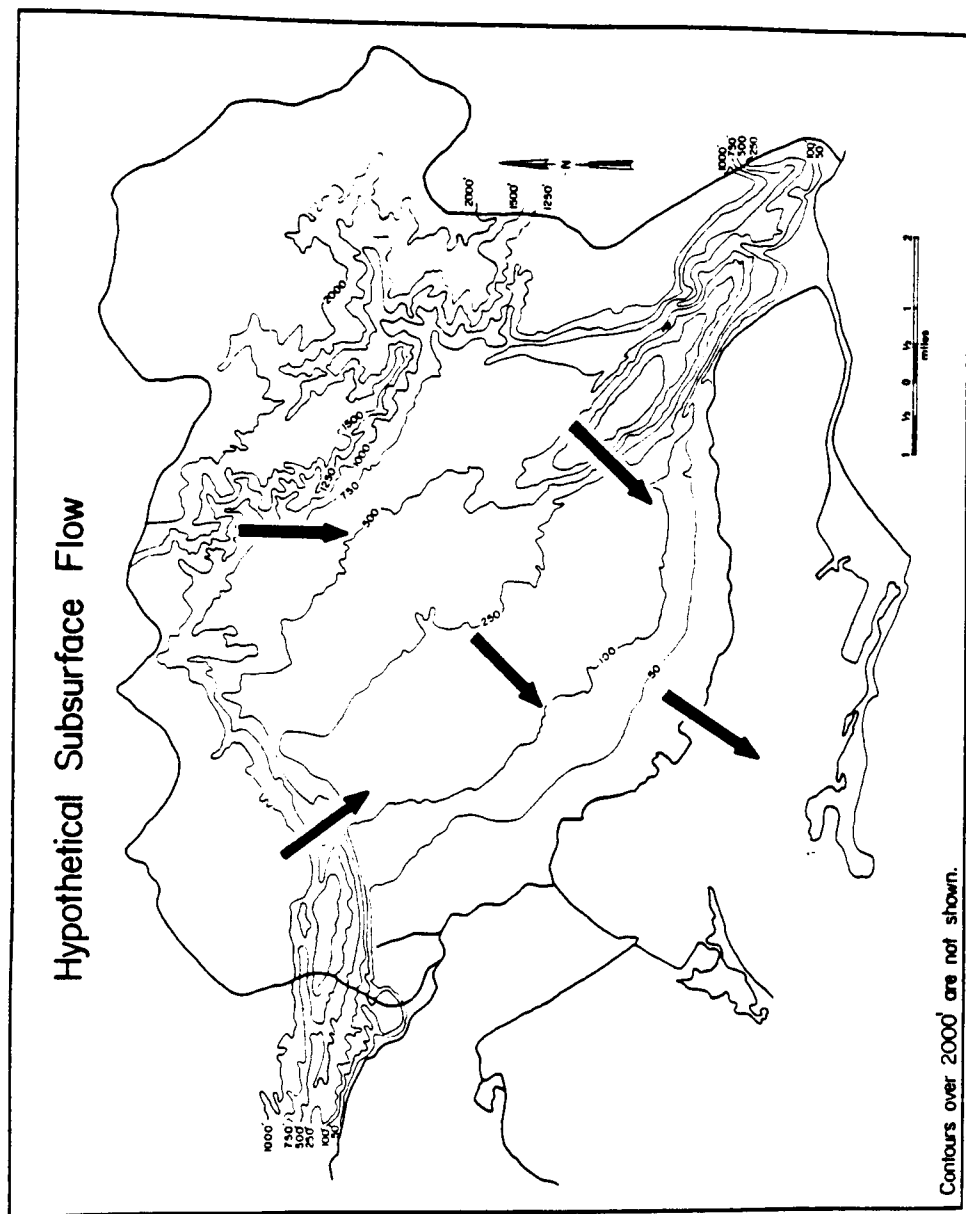


Figure 5-10. Hypothetical Subsurface Flow of Water to the Liguanea Aquifer.

which the initial assumptions were formulated.¹ Figure 5-11 shows the quantified subsurface flow directions for each of the three years studied (Table 10, page 64) and suggests that subsurface flow follows approximately the pattern of surface flow as represented by the orientation of the concrete gullies and the Hope River on Figure 2-2, page 24.

The possibility of minor inter-subdivision flow exists in the Jacks Hill sector, where the alluvial aquifer interfaces with the narrow band of limestone in the vicinity of the upper section of the Wagwater fault line (see Figure 2-1, p. 15). This could account for the consistent, small underestimations of the simulated recharge of the alluvium by the water balance procedure. This Jacks Hill region has been shown to be a high-recharge source area (Figure 4-2, p. 65), and inter-subdivision leakage could affect average groundwater table elevation by as much as the 5% difference registered by the analytical procedure.

Feasibility of Artificial Recharge

Untapped runoff represents the moisture endowment potentially available for artificial recharge in the Hope River system. At present the runoff from five sectors, the four volcanic sectors and Hermitage, is utilized for municipal supply. The volcanics are drained by the Hope River, and streamflow is tapped below Gordon

¹Initial examination of the topography suggested facile subsurface flow from the surrounding areas of higher elevation into the Liguanea aquifer.

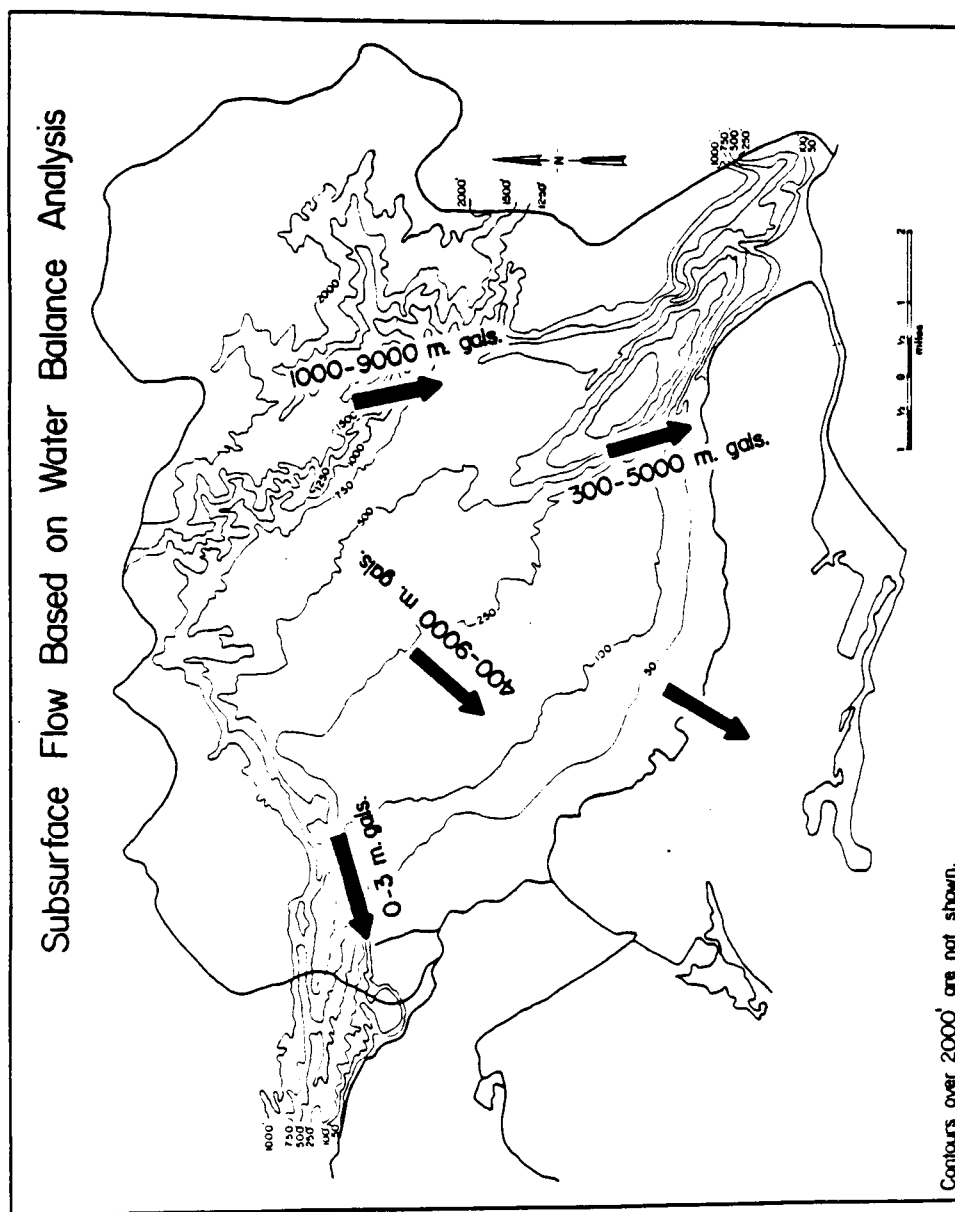


Figure 5-11. Subsurface Flow Based on Water Balance Analysis.

Town (see Figure 2-1, p. 15) and conducted via an aqueduct to the Mona reservoir. During periods of tropical storms, the water in excess of the reservoir capacity is allowed to flow via the normally dry lower river valley to the sea. The wet season flows of the Wagwater River are directed to the Hermitage reservoir. Runoff from all other regions represents overland surface flow and gully-flow, which in periods of tropical storms, presents a flood hazard to the heavily built-up alluvial plain.

At present, therefore, the runoff during major rainfall events is channelled out of the drainage system and into the ocean to prevent loss of life and property during hurricanes and tropical storms. At the limestone/alluvial interface this represented between 700 to 2000 million gallons in 1979, and even in the dry year of 1977 it amounted to between 100-200 million gallons. Again it is seen that large quantities of runoff are generated on the alluvium whenever rainfall occurs in short, intense episodes, regardless of the overall antecedent moisture of the basin. High runoff totals occurred in 1979, even on the lower alluvium, where Half Way Tree had 1036 million gallons of runoff. This was the result of the combination of high-intensity rainfall episodes and saturated soils (see Appendix 1). The less intense rainfall of 1971 resulted in annual runoff in ten of the sixteen regions, concentrated in the volcanics, limestone and limestone/alluvial interface areas, Figure 4-1, p. 63.

The temporal distribution of moisture surplus available as runoff is an important consideration when planning for artificial recharge. During 1979, runoff of the lower alluvium was limited to two

peak months, April and September. From daily rainfall records, it is estimated that a total of 16-19 days of runoff occurred in the Half Way Tree region, a figure which is considered representative of the rest of the alluvial basin. For the six lower alluvial regions, this represents an estimated total of just under 4000 million gallons which flowed to the sea in 16 days of 1979, yet it is doubtful whether any of this water could have been saved.

The temporal distribution of runoff in the upper alluvium and at the limestone/alluvial interface is most pertinent to the question of artificial recharge to the Liguanea aquifer, for this region is the source of the highest volumes of runoff generated on the alluvium. Even in the dry year of 1977, some runoff occurred in this upper portion of the basin during the months of May and October (see Appendix 1)¹ for the wet and average years. Runoff occurred on a regular basis during several months of the year and for 1979 was 2670 million gallons spread over 50-55 days.

The water balance procedure indicates that sufficient moisture exists during wet years in the lower alluvium and in all years in the upper alluvium. This moisture can generate runoff for an average of 55 days each year and as much as 6500 million gallons in the wettest years. Artificial recharge of this quantity of water would supply Kingston with adequate water supply to meet present demand, were it possible to retain all runoff. The portion of the runoff from the

¹Appendix 1, "Water Budget Analysis of Sixteen Rainfall Stations in the Liguanea/Hope River Basin."

limestone/alluvial interface that might be diverted to artificial recharge is not known, but realistically it could make a significant contribution to the groundwater reserves.

The most suitable areas for artificial recharge should have high runoff, open unused land and be on the alluvium. Extensive fieldwork reveals the existence of large tracts of open land in the Jacks Hill/Upper Norbrook region (see Figure 5-12). This is the southern end of the upper alluvium/limestone interface. Although no extensive on-site analysis has been done to determine the suitability of this region for artificial recharge, the region appears to meet all of the above criteria.

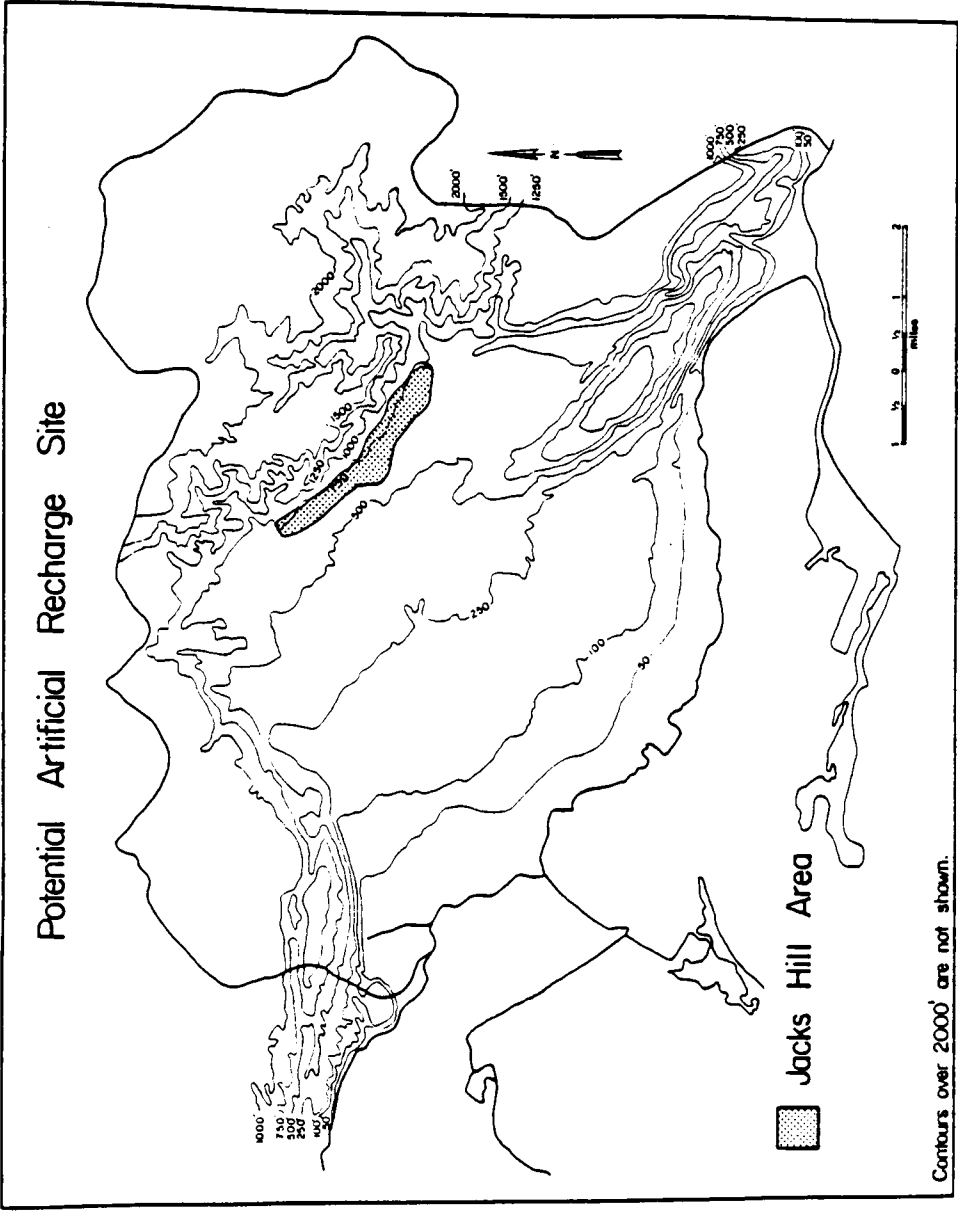


Figure 5-12. Potential Artificial Recharge Site.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The results of this study indicate that the water balance model is a valid analytical tool for estimating aggregate recharge and runoff at the subdivision level in the Liguanea basin. However, the analysis was done with such limited observed data that caution should be exercised in interpreting the simulated results at the regional level. The following discussion of the timing and quantities of water fluxes in the area is based on areal and temporal distribution of the annual recharge and runoff values generated by the model.

The Localized Strategy

The significant difference between the analysis of this work and that of the earlier studies, reviewed in Chapter I, is the emphasis on a more localized strategy rather than an extensive approach to water assessment. Nowhere is the difference between the two strategies more noticeable than in the various coefficients developed to indicate the percentage of total precipitation which is allocated to recharge and runoff in different parts of the Liguanea basin.

The two most recent previous studies on the Liguanea aquifer estimate recharge to the entire alluvium to be 40% (WRD 1980)¹ and

¹Water Resources Division. "Further Development of the Aquifer of the Liguanea (Hope River) Basin," 1980.

69% (NWC 1983)¹ of total rainfall. Recharge coefficients derived from the analytical procedure of this work are given in Table 10, p. 64). It can be seen that recharge coefficients vary considerably over the basin and between wet, average, and dry years. During the 1977 dry year, recharge coefficients were no more than 10% in any region and, for half of the regions, no portion of the total rainfall could be allocated to recharge (see Figure 4-2, p. 65). Recharge coefficients of up to 49% were derived for the upper limestone at Coopers Hill in 1971, and in 1979 recharge coefficients above 35% were rather uniformly distributed over the basin.

Based on the results from this limited study, recharge values for those areas of the basin with high recharge agree closely with Water Resources Division 1980 estimates for the average and wet years, but for all other years and during all dry months, recharge allocations using the 40% Water Resources Division coefficients would grossly overestimate recharge to the aquifer for about 90% of the time. Recognition of the pattern of variability of recharge coefficients between regions and from year to year is the major contribution of the localized strategy toward estimating long-term recharge to the Liguanea aquifer.

The close agreement between simulated runoff and streamflow in the Hope River as found by this study is another argument in favor of the localized strategy as an effective tool for hydrological

¹National Water Commission. "Flow West Project," 1983.

calculations. Sweco (1980)¹ and NWC (1983)² both found unsatisfactory correlations between streamflow and rainfall in the Hope River basin when overall coefficients were applied to average rainfall and streamflow volumes. By using small subareas and more detailed modeling of the physical processes, it has proved possible to achieve greater predictive agreement with streamflow at Gordon Town.

The Limestone/Alluvial Interface

The major source of recharge water to the Liguanea aquifer is the set of regions straddling the limestone/alluvial boundary, which stretches across the upper portions of Red Hills, Constant Spring and Jacks Hill. These regions correspond closely to the area identified by previous researchers³ as a subsurface upper basin, separated from the lower basin by an impermeable barrier. Although it is not possible to confirm the presence of such a barrier, it is clear from the recharge pattern that these northern alluvial regions fill first, then discharge slowly through the various layers of silt, sand, and clay to the sea. The generally slow movement of water, even through quite porous material and across gentle gradients, would suggest some backing up is possible, and if, in addition, there exists a natural

¹Sweco, Government of Jamaica Ministry of Mining and Natural Resources. Hydrology and Water Management in Blue Mountains Multi-purpose Project Pre-Investment Study, February 1980.

²National Water Commission. "Flow West Project," 1983.

³(a) Government of Jamaica, Blue Mountain Multi-purpose purpose Project, Sweco, December 1980; (b) National Water Commission, "Flow West Project," 1983.

division interrupting the already slow flow, there could be tremendous potential for water storage and utilization in this upper basin area. This subregion should be targeted for careful hydrological monitoring. Control of urbanization and restrictions on the clearing of vegetation and quarrying might be necessary so as not to affect adversely the recharge coefficient of the area.

Tropical Water Systems

The major climatic process governing total moisture endowment to the Liguanea aquifer is the occurrence of hurricanes and other tropical weather systems, with recharge totals closely reflecting their pattern of occurrence. From 1971-1979, there were five years in which these systems came close enough to the island to affect rainfall totals significantly. During the same nine years, a total of nine storms affected the study area, three of which were in June and September 1979. This regular pattern of occurrence is representative of the last 100 years of records,¹ which indicates that the four year span from 1919-1922 was the longest hurricane-free period, followed by the three years from 1976-1978 as the second longest. In fact, the groundwater systems of Jamaica are generally topped to overflowing at least once every 2-3 years, with minor recharge periods interspersed between those years.

¹See Appendix 2, Ministry of Public Utilities and Transport, Meteorological Division. "Tropical Weather Systems Which Passed Within 175 Statute Miles of Jamaica Since the Beginning of 20th Century."

In addition, the excessive runoff generated by these weather systems represents potential water for recharge to the groundwater system via artificial methods. The planned entrapment of a portion of the runoff, especially in the high-recharge source areas, would compensate for the constant and high volumes of water loss to deep outflow and would be one method of maximizing the benefits of the moisture endowment provided by the tropical weather systems.

Inter-Subdivision Flow at Jacks Hill

The analytical procedure established that only minor inter-subdivision flow occurs from the surrounding lithologic subdivisions into the alluvium, yet in the region of greatest potential sub-surface flow, topographical evidence suggests that large quantities of surface runoff flow into the alluvial plain from the adjacent limestone. The Jacks Hill region, which is at the base of the limestone hills, is severely eroded, with an extensive system of deep ravines. This region is at an elevation of about 750 ft. above sea level. The high potential recharge in the Jacks Hill area suggests the need for preservation and monitoring of that region. Strict control of housing development and of vegetation clearing is necessary. Already, the washing away of roads and the rapid spread of ravines by water rushing down from the top of the divide has halted plans for further suburban development. More active interception of localized natural flows could significantly improve recharge to the alluvium while stabilizing the physical environment.

This region should be more closely investigated by water planners, since it offers the best opportunity for artificial recharge to the aquifer.

Recommendations

The results of this study emphasize that quantified models of physico-hydrologic processes can anticipate moisture flows into and within the Liguanea/Hope Basin on a detailed localized scale. It provides alternatives to the generally ad hoc approach to water planning, which has been based on incomplete knowledge of the system. The present dominant role of groundwater as a supply for the city is viewed as permanent and desirable, and suggestions to improve the efficiency of the underground storage process is a focus of this work. The concepts and methods employed in the analysis of the Liguanea/ Hope River basin are generally applicable to similar watersheds throughout Jamaica and indeed throughout the Caribbean. The following suggestions are made to take the job of water planning for the city of Kingston beyond this initial first step.

Continuous Computerized Water Budget Analysis

Further refinement of the guidelines for allocating water on the basis of physico-hydrologic processes of the region requires continuously monitoring inputs and outputs of the natural water system. This monitoring process could be calibrated on a regular basis by measured water elevation in observation wells and records of stream-flow in the Hope River. By using smaller subareas, such as the ones

utilized in this work, it would be possible to anticipate water volumes from various wells and to adjust pumpage to closely reflect the expected flows. This would help to eliminate the present pattern of pumping depressions in the lower basin and would provide for better long-term planning of water delivery to residential and commercial users.

Increased knowledge of the subsurface moisture fluxes would improve chances of conjunctive use of both surface and subsurface water storage. At present water planning is almost totally dependent on information of the storage levels in the Hermitage and Mona reservoirs. Whenever the water in these two storage facilities falls below established danger points, a frantic water policy goes into operation which is a combination of: (a) extensive rotated lock-off of water supply to parts of the city during several hours each day; (b) public appeal for conservation, especially with respect to swimming pools and lawn watering; (c) increased pumpage from groundwater supplies; and (d) importation of water from the drainage basins to the east and west of the city. Once the dry season or drought year is passed and the reservoirs are once again being supplied by surface runoff, the pattern of water use returns to normal until the next emergency. A continuous record of all the moisture fluxes pertinent to the supply of water to the city could anticipate periods of drought, and by more efficient, long-term underground storage of the moisture surplus identified by this work, the more disruptive crises of this wet-and-dry tropical climatic regime could probably be avoided.

Artificial Recharge

Probably the most important concept of the localized strategy is the emphasis on conservation and efficient utilization of all available water. It has been demonstrated that large volumes of surplus water are lost to the system, which suggests that serious investigation of the feasibility of artificial recharge should be done. The likely source areas fall within the limestone/alluvial interface regions.

Artificial recharge has been successfully used in urban areas throughout the world, especially where recent severing has led to dramatic decrease in groundwater levels.¹ The planned sewerage of residences throughout Kingston would remove up to 5840 million gallons of contaminated water per annum from the aquifer and provide storage space for at least that much fresh water. Already in the adjacent St. Catherine plains, pilot studies of specially constructed artificial recharge ponds have been conducted with some favorable results. Furthermore, other potential conduits for artificially recharging the aquifer exist within the city, if the extensive network of concrete gullies were redesigned to allow seepage to the strata below at selected sites.

¹(a) R. Maknoon and S. J. Burgess. "Conjunctive Use of Groundwater and Surface Water," *Journal of the American Water Works Association*, 70, 419-24, 1978; (b) H. I. Nightingale and W. C. Bianchi. "Groundwater Recharge for Urban Use, Leaky Acres Project," *Groundwater*, 11, 36-43, 1973.

Finally, the concluding view of the Liguanea aquifer is that of a vital, natural self-replenishing system which, with careful monitoring and management techniques, could provide adequate water to the growing metropolitan area of Kingston for the near future.

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APPENDICES

APPENDIX 1

WATER BUDGET ANALYSIS OF SIXTEEN RAINFALL STATIONS IN THE LIGUANEA/HOPE RIVER BASIN

1971

Western Terminals

	J	F	M	A	M	J	J	A	S	O	N	D
TOF*	77.6	77.4	73.2	78.6	80.9	81.9	84.5	84.4	81.9	80.9	79.1	78.6
PE	4.60	4.32	3.39	5.35	5.38	6.27	6.78	6.60	5.81	5.70	4.79	4.84
P	1.26	.57	.20	.64	.39	0.0	0.19	5.16	3.03	4.65	3.89	.25
ST	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.75	1.35	1.03	.83	.26
D	3.08	3.75	3.19	4.71	5.99	6.27	6.08	0.0	1.38	.73	.88	4.02
S												

Cavaliers

	J	F	M	A	M	J	J	A	S	O	N	D
TOF*	77.6	77.4	73.2	78.6	80.9	81.9	84.5	84.4	81.9	80.9	79.1	78.6
PE	4.60	4.32	3.39	5.35	6.38	6.27	6.78	6.60	5.81	5.70	4.79	4.84
P	1.11	.63	.34	.96	.57	.13	.29	6.30	2.80	4.11	4.43	.27
ST	.20	0.0	0.0	0.0	0.0	0.0	0.0	3.70	1.83	1.22	1.11	.35
D	3.34	3.49	3.05	4.39	5.81	6.14	6.49	0.0	.21	.98	.25	3.81
S												

Coconut Inds.

	J	F	M	A	M	J	J	A	S	O	N	D
TOF*	77.6	77.4	73.2	78.6	80.9	81.9	84.5	84.4	81.9	80.9	79.1	78.6
PE	4.60	4.32	3.39	5.35	6.38	6.27	6.78	6.60	5.81	5.70	4.79	4.84
P	1.28	.77	.16	.77	.55	.02	.43	8.04	3.48	4.60	2.97	.21
ST	.10	0.0	0.0	0.0	0.0	0.0	0.0	1.44	2.19	1.65	1.04	.32
D	3.10	3.45	3.23	4.58	5.83	6.25	6.35	0.0	1.58	.56	1.21	3.91
S												

Hope Filter

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.6	77.4	73.2	78.6	80.9	81.9	94.5	94.4	81.9	80.9	79.1	78.6
PE	4.60	4.32	3.39	5.35	6.38	6.27	6.78	6.60	5.81	5.70	4.79	4.84
P	1.26	.93	1.31	3.18	4.86	.92	.72	7.74	3.80	5.97	5.22	.67
ST	.58	.25	.10	0.0	0.0	0.0	0.0	1.14	0.0	.27	.43	1.37
D	2.53	3.06	1.93	2.07	1.52	5.35	6.06	0.0	.10	0.0	0.0	3.23
S												

Constant Spring

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.7	77.5	78.4	79.4	80.6	81.7	91.0	81.1	81.7	80.7	84.7	78.7
PE	4.60	4.32	5.25	5.35	6.04	6.27	6.44	6.27	5.81	5.70	5.92	4.84
P	1.64	2.18	2.05	2.26	10.53	2.87	2.66	15.68	16.78	6.44	10.04	.75
ST	.65	.37	.20	.10	4.0	2.51	1.16	4.0	4.0	4.0	4.0	0.0
D	2.23	1.86	3.03	2.99	0.0	1.91	2.43	0.0	0.0	0.0	0.0	1.47
S	0.0	0.0	0.0	0.0	.59	0.0	0.0	6.57	10.97	.74	4.12	0.0

Gordon Town

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	68.3	68.6	70.1	70.9	72.4	72.0	72.7	73.4	73.2	72.8	72.0	68.6
PE	2.59	2.43	3.09	3.46	4.03	3.96	4.06	4.29	3.67	3.60	3.38	2.56
P	4.35	1.45	2.46	3.55	20.25	1.40	.53	26.50	5.75	10.83	30.80	1.75
ST	1.76	4.10	3.60	.09	5.0	2.97	1.44	5.0	5.0	5.0	5.0	4.24
D	0.0	0.0	.13	0.0	0.0	.53	2.0	0.0	0.0	0.0	0.0	0.5
S	0.0	0.0	0.0	0.0	11.31	0.0	0.0	18.65	2.08	7.25	27.42	0.0

Long Mountain

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	68.3	68.6	70.1	70.9	72.4	72.0	72.7	73.4	73.2	72.8	72.0	68.6
PE	2.59	2.43	3.09	3.46	4.03	3.96	4.06	4.29	3.67	3.60	3.38	2.56
P	3.89	5.64	3.73	6.70	9.14	.45	1.33	8.89	3.35	10.59	16.81	3.55
ST	5.0	5.0	5.0	5.0	5.0	2.44	1.40	5.0	4.68	5.0	5.0	5.0
D	0.0	0.0	0.0	0.0	0.0	.95	1.69	0.0	0.0	0.0	0.0	0.0
S	1.3	3.21	.64	3.24	5.11	0.0	0.0	3.0	0.0	6.67	13.43	.99

Bamboo Ave.

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	68.3	68.6	70.1	70.9	72.4	72.0	72.7	73.4	73.2	72.8	72.0	68.6
PE	2.59	2.43	3.09	3.46	4.03	3.96	4.06	4.29	3.67	3.60	3.38	2.56
P	3.89	5.64	3.73	6.70	9.14	.45	1.33	8.89	3.35	10.59	16.81	3.55
ST	5.0	5.0	5.0	5.0	5.0	2.44	.81	5.0	4.68	5.0	5.0	5.0
D	0.0	0.0	0.0	0.0	0.0	.95	1.10	0.0	.24	0.0	0.0	0.0
S	1.3	3.21	.64	3.24	5.11	0.0	0.0	.41	0.0	6.67	13.43	.99

Red Hills

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.7	77.5	78.4	79.4	80.6	81.7	81.0	81.1	81.7	80.7	84.7	78.7
PE	4.60	4.32	5.25	5.35	6.04	6.27	6.44	6.27	5.81	5.70	5.92	4.84
P	5.47	4.41	5.87	4.40	12.06	3.75	2.70	8.28	16.22	9.38	20.04	2.54
ST	.87	.09	.62	2.16	4.0	1.26	.35	2.36	4.0	4.0	4.0	1.36
D	0.0	0.0	0.0	0.0	0.0	.78	3.74	0.0	0.0	0.0	0.0	.66
S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.77	2.68	13.12	0.0

Hope Filter

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.6	77.4	73.2	78.6	80.9	81.9	84.5	84.4	81.9	80.9	79.1	78.6
PE	4.60	4.32	3.39	5.35	6.38	6.27	6.78	6.60	5.81	5.70	4.79	4.84
P	.90	.77	.17	.98	3.24	.12	1.74	4.45	2.26	5.85	1.98	3.08
ST	.48	.20	.10	0.0	0.0	0.0	0.0	0.0	0.0	.15	1.95	1.24
D	2.94	3.27	3.12	4.27	3.14	6.15	5.04	2.15	3.55	0.0	1.01	1.05
S												

Constant Spring

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.7	77.5	78.4	79.4	80.6	81.7	81.0	81.1	81.7	80.7	84.7	78.7
PE	4.60	4.32	5.25	5.35	6.04	6.27	6.44	6.27	5.81	5.70	5.92	4.84
P	.89	.88	.33	4.30	3.70	.50	2.95	6.48	5.81	10.98	3.05	7.17
ST	1.54	.64	.15	.10	.05	0.0	0.0	.21	0.0	4.0	1.92	2.33
D	2.92	2.54	4.43	1.0	2.29	5.72	3.49	0.0	0.0	0.0	.79	0.0
S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.28	0.0	0.0

Gordon Town

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	68.3	68.6	70.1	70.9	72.4	72.0	72.7	73.4	73.2	72.8	72.0	68.6
PE	2.59	2.43	3.09	3.46	4.03	3.96	4.06	4.29	3.67	3.60	3.38	2.56
P	1.72	2.10	.76	3.75	5.77	.98	4.24	8.21	8.01	8.93	2.21	5.57
ST	4.13	3.91	2.43	2.14	.40	0.0	.18	4.1	5.0	5.0	3.83	5.0
D	0.0	.05	.85	0.0	0.0	2.98	0.0	0.0	0.0	0.0	0.0	0.0
S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.3	5.33	0.0	1.84

Newcastle

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	68.3	68.6	70.1	70.9	72.4	72.0	72.7	73.4	73.2	72.8	72.0	68.6
PE	2.59	2.43	3.09	3.46	4.03	3.96	4.06	4.29	3.67	3.60	3.38	2.56
P	2.64	2.65	.88	6.46	8.06	2.59	.27	4.22	3.97	6.64	5.76	6.41
ST	5.0	5.0	3.79	5.0	5.0	3.78	1.75	1.72	2.02	5.0	5.0	5.0
D	0.0	0.0	0.0	0.0	0.0	1.12	1.76	.04	0.0	0.0	0.0	0.0
S	0.5	.22	0.0	1.79	4.03	0.0	0.0	0.0	0.0	.32	2.38	3.85

Cinchona

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	68.3	68.6	70.1	70.9	72.4	72.0	72.7	73.4	73.2	72.8	72.0	68.6
PE	2.59	2.43	3.09	3.46	4.03	3.96	4.06	4.29	3.67	3.60	3.38	2.56
P	2.64	2.65	.88	6.46	8.06	2.59	.27	4.22	3.97	6.64	5.76	6.41
ST	5.0	5.0	2.97	5.0	5.0	3.63	1.75	1.72	2.02	5.0	5.0	5.0
D	0.0	0.0	0.0	0.0	0.0	0.0	1.76	.04	0.0	0.0	0.0	0.0
S	.05	.22	0.0	.79	4.03	0.0	0.0	0.0	0.0	.06	2.38	3.85

Hermitage

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	68.3	68.6	70.1	70.9	72.4	72.0	72.7	73.4	73.2	72.8	72.0	68.6
PE	2.59	2.43	3.09	3.46	4.03	3.96	4.06	4.29	3.67	3.60	3.38	2.56
P	1.24	1.66	.18	3.50	5.74	1.02	4.04	8.45	8.22	9.25	1.79	5.52
ST	.96	.64	.14	.18	1.89	.41	.41	2.0	2.0	2.0	.85	2.0
D	.31	.45	2.41	0.0	0.0	1.64	.02	0.0	0.0	0.0	.54	0.0
S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.57	4.55	5.65	0.0	1.81

Red Hills

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.7	77.5	78.4	79.4	80.6	81.7	81.0	81.1	81.7	80.7	84.7	78.7
PE	4.60	4.32	5.25	5.35	6.04	6.27	6.44	6.27	5.81	5.70	5.92	4.84
P	2.39	2.93	2.27	6.36	7.86	2.27	2.35	6.71	5.32	8.94	5.45	6.03
ST	1.40	.87	.31	1.01	1.82	.75	.18	.44	2.53	3.24	2.55	1.21
D	1.02	.86	2.42	0.0	0.0	2.93	3.52	0.0	0.0	0.0	.02	0.0
S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.77	0.0	0.0

Coopers Hill

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	68.3	68.6	70.1	70.9	72.4	72.0	72.7	73.4	73.2	72.8	72.0	68.6
PE	2.59	2.43	3.09	3.46	4.03	3.96	4.06	4.29	3.67	3.60	3.38	2.56
P	2.39	2.93	2.27	3.26	0.71	2.27	3.35	4.74	2.56	2.81	2.30	3.52
ST	1.80	.50	1.29	1.15	.21	.08	.05	.45	1.10	.72	.40	.96
D	0.0	0.0	.03	.06	2.38	1.56	.68	0.0	.46	.41	.76	0.0
S												

Irish Town

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	68.3	68.6	70.1	70.9	72.4	72.0	72.7	73.4	73.2	72.8	72.0	68.6
PE	2.59	2.43	3.09	3.46	4.03	3.96	4.06	4.29	3.67	3.60	3.38	2.56
P	0.15	.80	0.0	4.98	5.81	0.0	0.10	5.41	3.17	8.12	3.87	4.58
ST	3.04	2.18	1.16	2.68	4.46	2.24	1.0	2.12	1.62	5.0	5.0	5.0
D	1.42	.77	2.07	0.0	0.0	3.52	2.74	0.0	0.0	0.0	0.0	0.0
S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.14	.49	2.02

Half-Way Tree

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.6	77.4	73.2	78.6	80.9	81.9	84.5	84.4	81.9	80.9	79.1	78.6
PE	4.60	4.32	3.39	5.35	6.38	6.27	6.78	6.60	5.81	5.70	4.79	4.84
P	.53	.64	.25	1.24	2.19	0.0	1.95	2.87	1.18	5.33	1.14	0.0
ST	.20	.10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.63	1.42	.42
D	3.85	3.58	3.04	4.11	4.19	6.27	4.83	3.73	4.63	0.0	1.44	3.84
S												

Jacks Hill

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.7	77.5	78.4	79.4	80.6	81.7	81.0	81.1	81.7	80.7	84.7	78.7
PE	4.60	4.32	5.25	5.35	6.04	6.27	6.44	6.27	5.81	5.70	5.92	4.84
P	1.72	2.41	1.56	6.85	8.79	1.56	1.67	7.31	5.50	10.18	5.67	6.42
ST	1.91	1.17	.46	1.96	4.0	1.20	.36	1.40	3.69	4.0	3.75	1.58
D	2.55	1.17	2.98	0.0	0.0	3.16	3.93	0.0	0.0	0.0	0.0	0.0
S	0.0	0.0	0.0	0.0	.71	0.0	0.0	0.0	0.0	4.17	0.0	0.0

1979

Long Mountain

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.6	77.4	73.2	78.6	80.9	81.9	84.5	84.4	81.9	80.9	79.1	78.6
PE	4.60	4.32	3.39	5.35	6.38	6.27	6.78	6.60	5.81	5.70	4.79	4.84
P	.57	.96	.25	12.16	3.93	11.08	5.32	1.17	22.24	2.68	2.83	.90
ST	.10	.02	.01	4.0	2.13	4.0	2.74	.68	4.0	1.84	1.12	.41
D	3.93	3.28	3.15	0.0	.32	0.0	0.0	4.75	0.0	1.03	.84	3.53
S	0.0	0.0	0.0	2.82	0.0	2.94	0.0	0.0	13.11	0.0	0.0	0.0

Bamboo Avenue

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.6	77.4	73.2	78.6	80.9	81.9	84.5	84.4	81.9	80.9	79.1	78.6
PE	4.60	4.32	3.39	5.35	6.38	6.27	6.78	6.60	5.81	5.70	4.79	4.84
P	.51	1.25	.67	9.36	2.52	10.00	4.39	.44	25.36	3.13	3.62	.69
ST	.10	0.0	0.0	4.0	.14	3.87	1.67	.45	4.0	2.07	1.53	.54
D	3.65	2.97	2.72	0.0	3.72	0.0	.33	4.94	0.0	.64	.63	3.16
S	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	16.00	0.0	0.0	0.0

Hope Filter

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.6	77.4	73.2	78.6	80.9	81.9	84.5	84.4	81.9	80.9	79.1	78.6
PE	4.60	4.32	3.39	5.35	6.38	6.27	6.78	6.60	5.81	5.70	4.79	4.84
P	.24	1.01	.41	9.49	2.34	10.16	4.29	.17	26.21	2.98	3.49	.43
ST	.20	.10	0	4.0	1.41	3.89	2.11	.41	4.0	1.99	1.42	.47
D	4.09	3.21	2.88	0.0	1.45	0.0	.71	4.73	0.0	.80	.73	3.46
S	0.0	0.0	0.0	0.0	.14	0.0	0.0	0.0	16.81	0.0	0.0	0.0

Western Terminals

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.6	77.4	73.2	78.6	80.9	81.9	84.5	84.4	81.9	80.9	79.1	78.6
PE	4.60	4.32	3.39	5.35	6.38	6.27	6.78	6.60	5.81	5.70	4.79	4.84
P	.56	1.90	.80	4.72	3.54	13.70	6.25	1.81	29.12	5.33	4.21	.70
ST	.02	.01	0.0	0.0	0.0	2.0	1.50	.11	2.0	1.64	1.20	.13
D	3.93	2.41	2.58	.63	2.84	0.0	.03	3.40	0.0	0.1	.14	3.07
S	0.0	0.0	0.0	0.0	0.0	5.43	0.0	0.0	21.42	0.0	0.0	0.0

Cavaliers

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.6	77.4	73.2	78.6	80.9	81.9	84.5	84.4	81.9	80.9	79.1	78.6
PE	4.60	4.32	3.39	5.35	6.38	6.27	6.78	6.60	5.81	5.70	4.79	4.84
P	.52	1.98	1.35	4.23	5.94	10.26	4.22	3.71	30.01	4.60	3.38	.97
ST	.28	.12	0.0	0.0	0.0	3.99	2.07	.99	4.0	3.02	2.10	.78
D	3.58	2.18	1.92	1.12	.44	0.0	.64	1.81	0.0	.12	.49	2.55
S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.19	0.0	0.0	0.0

St. Georges

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.6	77.4	73.2	78.6	80.9	81.9	84.5	84.4	81.9	80.9	79.1	78.6
PE	4.60	4.32	3.39	5.35	6.38	6.27	6.78	6.60	5.81	5.70	4.79	4.84
P	.63	2.04	.80	7.22	3.82	6.55	4.76	3.89	25.48	5.37	2.90	.98
ST	.30	.20	.10	1.87	2.07	1.13	1.15	.57	4.0	3.67	2.26	.83
D	3.44	2.18	2.49	0.0	2.36	0.0	1.24	2.13	0.0	0.0	.48	2.43
S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	16.24	0.0	0.0	0.0

Constant Spring

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.7	77.5	78.4	79.4	80.6	81.7	81.0	81.1	81.7	80.7	84.7	78.7
PE	4.60	4.32	5.25	5.35	6.04	6.27	6.44	6.27	5.81	5.70	5.92	4.84
P	.74	4.75	3.57	13.78	8.84	9.91	12.40	6.99	31.31	8.02	8.16	2.99
ST	.72	.43	2.60	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	2.48
D	2.10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.61
S	0.0	0.0	0.0	7.03	2.80	3.64	5.96	.72	25.5	2.32	2.24	0.0

Gordon Town

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	68.3	68.6	70.1	70.9	72.4	72.0	72.7	73.4	73.2	72.8	72.0	68.6
PE	2.59	2.43	3.09	3.46	4.03	3.96	4.06	4.29	3.67	3.60	3.38	2.56
P	1.17	5.54	1.46	10.59	5.59	8.79	5.92	2.89	26.65	4.29	5.10	.95
ST	.35	5.0	3.59	5.0	5.0	5.0	5.0	3.6	5.0	5.0	5.0	3.39
D	0.0	0.0	1.15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
S	0.0	.80	0.0	5.72	1.56	4.83	1.86	0.0	21.74	.69	1.72	0.0

Newcastle

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	68.3	68.6	70.1	70.9	72.4	72.0	72.7	73.4	73.2	72.8	72.0	68.6
PE	2.59	2.43	3.09	3.46	4.03	3.96	4.06	4.29	3.67	3.60	3.38	2.56
P	4.70	10.77	8.31	30.20	9.81	11.73	5.52	2.48	34.98	7.67	12.37	4.99
ST	5.0	5.0	5.0	5.0	5.0	5.0	5.0	3.45	5.0	5.0	5.0	5.0
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
S	2.11	5.45	5.22	26.74	5.78	7.77	1.46	0.0	29.50	4.07	8.99	2.43

Cinchona

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	68.3	68.6	70.1	70.9	72.4	72.0	72.7	73.4	73.2	72.8	72.0	68.6
PE	2.59	2.43	3.09	3.46	4.03	3.96	4.06	4.29	3.67	3.60	3.38	2.56
P	4.70	10.77	8.31	30.20	9.81	11.73	5.52	2.48	34.98	7.67	12.37	4.99
ST	5.0	5.0	5.0	5.0	5.0	5.0	3.19	5.0	5.0	5.0	5.0	5.0
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
S	2.11	8.34	5.22	26.74	5.78	2.77	1.46	0.0	29.50	4.07	8.99	2.43

Hermitage

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	68.3	68.6	70.1	70.9	72.4	72.0	72.7	73.4	73.2	72.8	72.0	68.6
PE	2.59	2.43	3.09	3.46	4.03	3.96	4.06	4.29	3.67	3.60	3.38	2.56
P	1.67	6.63	5.08	17.88	12.40	9.76	6.42	1.05	22.94	8.89	6.74	2.17
ST	.98	2.0	2.0	2.0	2.0	2.0	2.0	.35	2.0	2.0	2.0	1.62
D	.28	0.0	0.0	0.0	0.0	0.0	0.0	1.59	0.0	0.0	0.0	0.01
S	0.0	3.18	1.99	14.42	8.37	5.8	2.36	0.0	17.62	5.29	3.36	0.0

Red Hills

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.7	77.5	78.4	79.4	80.6	81.7	81.0	81.1	81.7	80.7	84.7	78.7
PE	4.60	4.32	5.25	5.35	6.04	6.27	6.44	6.27	5.81	5.70	5.92	4.84
P	1.33	5.48	5.01	16.00	10.26	10.15	4.97	6.43	24.05	9.45	4.95	2.28
ST	.29	1.16	2.76	4.0	4.0	4.0	1.81	1.97	4.0	4.0	2.14	.89
D	2.67	0.0	0.0	0.0	0.0	0.0	.28	0.0	0.0	0.0	.11	1.31
S												

Coopers Hill

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	68.3	68.6	70.1	70.9	72.4	72.0	72.7	73.4	73.2	72.8	72.0	68.6
PE	2.59	2.43	3.09	3.46	4.03	3.96	4.06	4.29	3.67	3.60	3.38	2.56
P	1.33	5.48	5.01	10.00	10.26	10.15	4.97	6.43	24.05	9.45	4.95	2.28
ST	.87	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	1.72
D	.41	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
S	0.0	1.92	1.92	12.54	6.23	6.19	.91	.14	20.35	5.85	1.57	0.0

Irish Town

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	68.3	68.6	70.1	70.9	72.4	72.0	72.7	73.4	73.2	72.8	72.0	68.6
PE	2.59	2.43	3.09	3.46	4.03	3.96	4.06	4.29	3.67	3.60	3.38	2.56
P	1.60	6.52	4.92	12.08	10.63	8.72	5.03	1.01	28.63	8.74	5.07	5.21
ST	4.09	5.0	5.0	5.0	5.0	5.0	5.0	1.72	5.0	5.0	5.0	5.0
D	0.0	0.0	0.0	0.0	0.0	0.0	1.69	0.0	0.0	0.0	0.0	0.0
S	0.0	3.18	1.83	8.62	6.60	4.76	.97	0.0	21.68	5.14	1.69	.65

Half-Way Tree

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.6	77.4	73.2	78.6	80.9	81.9	84.5	84.4	81.9	80.9	79.1	78.6
PE	4.60	4.32	3.39	5.35	6.38	6.27	6.78	6.60	5.81	5.70	4.79	4.84
P	.18	.74	.66	12.32	3.80	8.11	4.03	3.17	26.37	3.48	2.82	.28
ST	.13	.03	0.0	4.0	2.06	1.28	.64	.31	4.0	2.26	1.36	.43
D	4.22	3.48	2.70	0.0	.64	0.0	2.11	3.1	0.0	.48	.87	3.63
S	0.0	0.0	0.0	2.07	0.0	0.0	0.0	0.0	16.87	0.0	0.0	0.0

Jacks Hill

	J	F	M	A	M	J	J	A	S	O	N	D
T ⁰ F*	77.7	77.5	78.4	79.4	80.6	81.7	81.0	81.1	81.7	80.7	84.7	78.7
PE	4.60	4.32	5.25	5.35	6.04	6.27	6.44	6.27	5.81	5.70	5.92	4.84
P	.38	1.26	0.96	4.82	3.53	8.99	3.33	2.57	33.66	3.39	2.93	.67
ST	.06	0.0	0.0	0.0	0.0	2.72	1.80	.70	4.0	2.21	1.02	.36
D	3.9	3.0	4.29	.53	2.51	0.0	2.19	2.60	0.0	.62	1.80	3.51
S	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.55	0.0	0.0	0.0

*T⁰F = Temperature in degrees Fahrenheit.

PE = Potential evapotranspiration.

P = Precipitation.

ST = Soil moisture storage.

D = Deficit.

S = Surplus.

APPENDIX 2

TROPICAL WEATHER SYSTEMS WHICH PASSED WITHIN 125 STATUTE MILES OF JAMAICA SINCE THE BEGINNING OF THE 20TH CENTURY

Year	Dates of passage over or when closest to island	Type of weather System	Name	Section of island most affected	Nearest distance to island
1900	August 3	Hurricane	-	St. Mary, Portland, St. Thomas and St. Ann	115 miles
1901	July 5-6	Tropical Storm	-	South Coast	173 miles
"	September 13-14	Tropical Storm	-	North Coast	115 miles
1903	August 10-11	Hurricane	-	Manchester, Clarendon, St. Elizabeth & Westmoreland	Hit south-west
1904	June 12-13	Tropical Storm	-	Westmoreland and Hanover	Hit west
"	October 13-14	Tropical Storm	-	Western Jamaica	86 miles
1905	October 4-5	Hurricane	-	Eastern Jamaica	23 miles
1906	October 14	Hurricane	-	South Coast	115 miles
"	November 6-7	Tropical Storm	-	Western Jamaica	58 miles
1907	June 24-25	Tropical Storm	-	South Coast	138 miles
1908	September 29	Tropical Storm	-	Portland, St. Thomas and St. Mary	173 miles
1909	July 16-17	Tropical Storm	-	South Coast	29 miles
"	August 6	Tropical Storm	-	South Coast	86 miles
"	August 23-24	Hurricane	-	Portland, St. Thomas, St. Mary and St. Ann	46 miles
"	September 15-16	Tropical Storm	-	Westmoreland and St. Elizabeth	115 miles
"	October 8	Hurricane	-	Westmoreland and St. Elizabeth	115 miles
"	November 11-12	Tropical Storm	-	St. Thomas and St. Andrew	144 miles
1910	August 24-25	Tropical Storm	-	Manchester, St. Elizabeth and Clarendon	Hit south
"	September 8-9	Hurricane	-	Portland, St. Mary, St. Ann, and Trelawny	29 miles
1911	October 24	Tropical Storm	-	Portland and St. Mary	58 miles
1912	October 11	Tropical Storm	-	Hanover and Westmoreland	144 miles

Year	Date of passage over or when closest to island	Type of weather system	Name	Section of island most affected	Nearest distance to island
1912	November 18	Hurricane	-	Hanover and Westmoreland	Hit west
1915	August 12-13	Hurricane	-	St. Ann	Hit north
"	September 1	Hurricane	-	Westmoreland	86 miles
"	September 25	Hurricane	-	St. Elizabeth and Clarendon	115 miles
1916	August 15-16	Hurricane	-	Clarendon, St. Elizabeth, Manchester and Hanover	Hit south-west
"	August 30-31	Hurricane	-	South Coast	69 miles
"	October 13	Hurricane	-	South Coast	144 miles
1917	September 23	Hurricane	-	St. Mary	29 miles
1918	August 3-4	Tropical Storm	-	South Coast	58 miles
1923	October 18	Tropical Storm	-	Western Jamaica	144 miles
1924	November 7-8	Tropical Storm	-	Clarendon and St. Ann	Hit south-north
1927	October 18	Tropical Storm	-	Hanover	86 miles
1928	August 10-11	Hurricane	-	Portland, St. Mary and St. Thomas	115 miles
"	September 2-3	Tropical Storm	-	St. Catherine, Clarendon and Manchester	Hit E-W along south
1930	September 4-5	Tropical Storm	-	North east Coast	173 miles
1931	August 13-14	Tropical Storm	-	South Coast	173 miles
"	September 8-9	Tropical Storm	-	South Coast	58 miles
"	September 12-13	Tropical Storm	-	St. Thomas, St. Catherine, Manchester, Clarendon and St. Elizabeth	Hit east-west
1932	September 28-29	Tropical Storm	-	St. Thomas, St. Catherine, Manchester & Clarendon	Hit east-west

Year	Dates of passage over or when closest to island	Type of weather system	Name	Section of island most affected	Nearest distance to island
1932	November 8-9	Hurricane	-	Hanover and Westmoreland	150 miles
1933	July 1-2	Hurricane	-	South western coast	173 miles
"	July 16-17	Tropical Storm	-	St. Mary and St. Ann	Hit north
"	August 16	Tropical Storm	-	St. Elizabeth and Westmoreland	58 miles
"	September 19-20	Hurricane	-	South Coast	81 miles
"	October 29-30	Hurricane	-	Westmoreland, Hanover and St. James	Hit SW-N
1934	October 20-21	Tropical Storm	-	St. Catherine, St. Ann and Trelawny	Hit SE - NW
1935	September 24	Hurricane	-	Hanover and Westmoreland	58 miles
"	October 21-23	Hurricane	-	East-north-west Coast	58 miles
1938	August 11-12	Hurricane	-	South Coast	58 miles
"	August 23-24	Hurricane	-	South Coast	144 miles
1939	November 1-2	Hurricane	-	North-west Coast	58 miles
1942	August 24-25	Hurricane	-	North Coast	144 miles
"	September 16-19	Tropical Storm	-	South Coast	29 miles
1944	July 26-27	Tropical Storm	-	St. Thomas Negril	115 miles
"	August 20-21	Hurricane	-	West Coast	Hit east-west
"	October 13-14	Hurricane	-	West Coast	144 miles
1945	October 11	Hurricane	-	South-west Coast	144 miles
1947	August 11	Tropical Storm	-	St. James and Hanover	173 miles
1947	September 20	Tropical Storm	-		Hit north west

Year	Dates of passage over or when closest to island	Type of weather system	Name	Section of island most affected	Nearest distance to island
1948	September 18	Tropical Storm	-	Hanover	Hit west
1949	October 12-13	Tropical Storm	-	Westmoreland, Hanover and St. James	Hit SW-NW
1950	October 15-16	Hurricane	King	Westmoreland and Hanover	58 miles
1951	August 17-18	Hurricane	Charlie	St. Andrew, St. Catherine, Manchester and Clarendon	Hit SE-SW
"	September 4-5	Tropical Storm	Dog	South Coast	144 miles
1953	September 23-24	Tropical Storm	Florence	South Coast	46 miles
"	October 3-4	Tropical Storm	-	North-west Coast	58 miles
1954	October 11-12	Hurricane	Hazel	Eastern Coast	115 miles
1955	August 23	Tropical Depression	-	South-western Coast	115 miles
"	September 14	Tropical Storm	Hilda	North Coast	127 miles
"	September 26-27	Hurricane	Janet	South Coast	144 miles
1956	October 30-31	Tropical Depression	Greta	East Coast	58 miles
1958	September 1-2	Hurricane	Ella	North-east Coast	115 miles
1958	September 15	Tropical Storm	Gerda	North Coast	58 miles
1961	October 15-16	Tropical Depression	Gerda	Kingston, St. Andrew, St. Catherine & St. Ann	Direct Hit S W
1963	October 4-6	Hurricane	Flora	Eastern half	173 miles
1964	August 24-25	Hurricane	Cleo	St. Ann, St. Mary & Portland	58 miles
1966	September 29-30	Hurricane	Inez	St. Mary, Portland	144 Miles
1967	September 12-13	Tropical Storm	Beulah	St. Thomas	52 miles
1969	August 31	Tropical Storm	France-lia	South Coast	144 miles
1970	May 20-22	Tropical Storm	Alma	Hanover, Westmoreland	121 miles

Year	Dates of passage over or when closest to island	Type of weather system	Name	Section of island most affected	Nearest distance to island
1973	October 17	Tropical Storm	Gilda	Hanover, Westmoreland, St. James	121 miles
1974	August 31	Hurricane	Carmen	South Coast	46 miles
"	September 15	Tropical Storm	Rifi	South Coast	52 miles
1975	August 25	Tropical Depression	Caroline	North Coast	150 miles
"	September 18	Tropical Storm	Eloise	North Coast	115 miles
1979	June 12	Tropical Depression	-	St. James, Hanover St. Elizabeth & Westmoreland	86 miles
"	September 2	Hurricane	David	Eastern half	173 miles
"	September 11-13	Hurricane	Frederic	South-eastern Section	127 miles
1980	August 5-6	Hurricane	Allen	East and North Coasts	35 miles

VITA

Jacqueline Pryce-Harvey was born in Spanish Town, Jamaica, on September 24, 1952. She attended primary schools in Spanish Town and St. Ann and received a government scholarship to St. Andrew High School in 1962. She graduated from the University of the West Indies in 1977 with an upper second class honors degree in Geography. She was awarded a Government of Jamaica post-graduate scholarship and spent the 1977-78 academic year at the University of Aston, Birmingham, England pursuing graduate work in Remote Sensing.

In October 1978 she returned to Jamaica to continue a Ph.D. program while teaching high school geography and later in 1980-81 lectured in Physical Geography at the University of the West Indies.

In 1981 Mrs. Pryce-Harvey accepted a teaching assistantship at The University of Tennessee, Knoxville. She received the Doctor of Philosophy degree with a major in Geography in August 1985.

Mrs. Pryce-Harvey is married with one child. She is presently teaching at the University of Kentucky in Lexington.