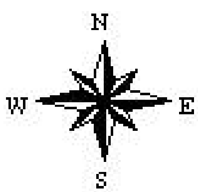
Chapter 1

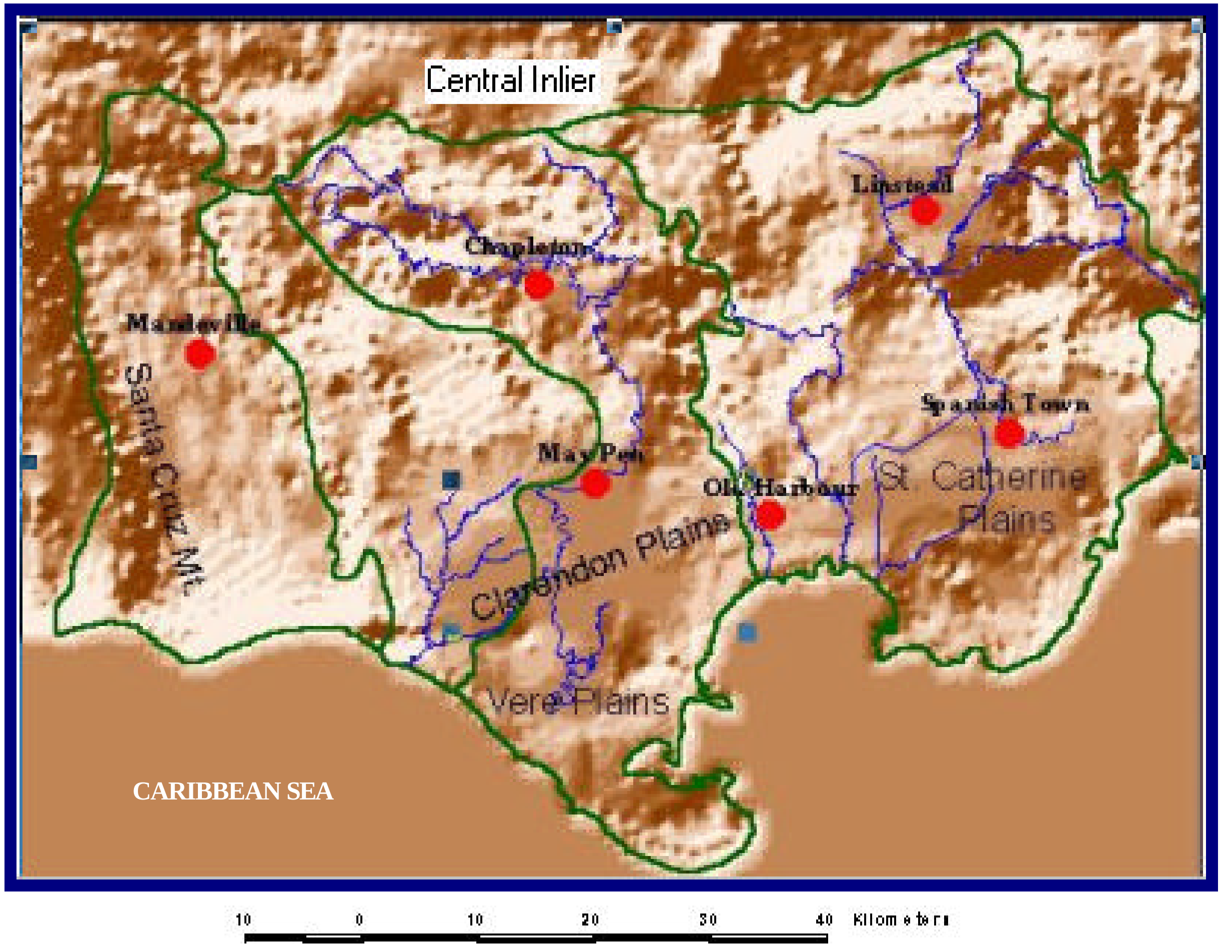
INTRODUCTION

Background

Agriculture is important to the Jamaican economy, accounting for 36% of the country’s labor force (Water Resources Authority of Jamaica, 1990) and also for the generation of foreign exchange. The Jamaican government considers the agricultural industry a high priority sector if the nation is to achieve self-sufficiency in food resources. The seasonal nature and spatial variation of rainfall distribution on the Caribbean Island of Jamaica makes irrigation necessary for the extensive cultivation of crops. The shortage of irrigation water from surface runoff has led to local over exploitation of the White Limestone and alluvial aquifers underlying the Rio Cobre and Rio Minho-Milk river basins (White, 1980). The proximity of many irrigation wells to the coast has led to saltwater intrusion into the aquifers. Flow from the Rio Cobre, Rio Minho, and Milk River is southward to the sea from their source in the Central Inlier. The Central Inlier is the island's main watershed located east-west above the northern boundary of the basins (Figures 1.1a-b).

The (WRAJ), in its effort to alleviate the increasing demand for water and agricultural acreage in the region, proposed two developmental strategies: 1) a scientific approach to water resources management and 2) crop diversification. The scientific approach involves the use of ground-water simulation models to quantitatively determine the spatial and temporal trends of hydraulic parameters and derive a hydrologic budget to





STUDY AREA

Base from United Nations Development Program/OAS- Government of Jamaica, Underground Water Authority Map of Watershed Management Units. Digitized by the author from 1:250,000 scale, using Lambert Conical Orthomorphic Projection. UTM Zone 18.

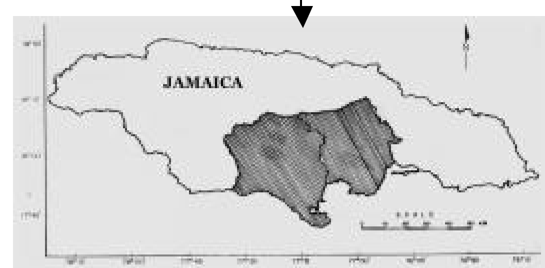
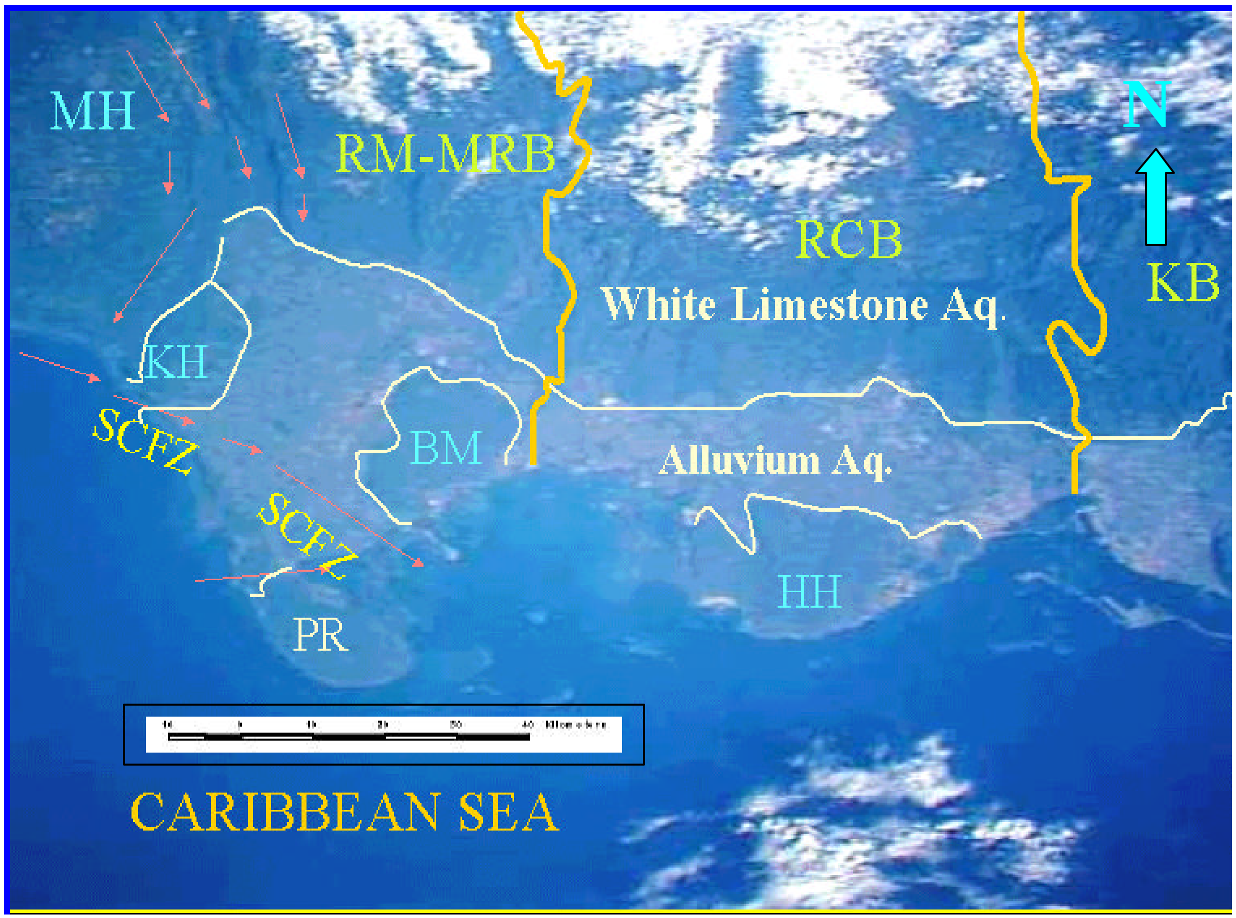


Figure1.1a Location, extent, and topography of study and model areas.



EXPLANATION

BASINS

RCB - Rio Cobre Basin
RM-MRB - Rio Minho-Milk River Basin
KB - Kingston basin

LIMESTONE HILLS

MH - Manchester Highlands (Ls)
KH - Kemps Hill (Ls).
BM - Brazilletto Mt. (ls)
PR - Portland Ridge (ls)
HH - Hellshire Hills (ls.)

STRUCTURAL FEATURES

SCFZ - South Coast Fault Zone
- Faults

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BOUNDARIES

- White Limestone/ alluvium contact

- Basin Boundary

Figure 1.1b Digital image and aerial view of the Rio Cobre and Rio Minho-Milk river basins on the south coast of Jamaica West Indies.

assist in the water resources management of the region. Crop diversification allows the replacement of sugarcane, the dominant crop in both basins, with more profitable crops to improve irrigation efficiency from 50% to 90%. This would include the construction of daily or weekly storage reservoirs that would: 1) save water, 2) reduce unmet demand, and 3) provide additional revenue for financing the development of new water sources for the expansion of irrigation.

The distribution of water demand is based on the location of irrigated lands, population concentrations, and water-consuming industries. There are more extensive irrigable lands in the southern section of the island where rainfall is low than in the north where rainfall is high and there are less cultivable lands. This results in a higher water demand in the south compared to the north. The three most important extensively cultivated areas with existing irrigation systems or potential irrigation are: 1) St. Catherine Plains in the Rio Cobre basin and 2) Clarendon Plains and the Vere Plains in the Rio Minho-Milk River basin (Figure 1.1). As of 1998, approximately 11,500 ha (28,417 acres) are irrigated in the St. Catherine Plains, out of a potential area of 17,000 ha (42,007 acres). In the Clarendon Plains, about 18,200 ha (44,972 acres) are irrigated out of a potential of 27,100 ha (66,964 acres). Most of the water-consuming industries, bauxite-alumina and sugarcane processing, are located in the south. The concentration of agriculture and industry in the south has created a growing demand for services and labor, leading to higher population densities and subsequent increased demand for water resources.

A number of new wells were drilled in 1990 under the Water Resources Expansion Program to supplement the supply of water to irrigated areas. Currently, there are 352 active pumping wells extracting 271,925,000 m^3/yr from the aquifer systems. Highly localized well spacing and excessive pumpage has resulted in deterioration of the region's water quality. The WRAJ representing the major developer of ground-water, encourages a scientific approach to siting well locations and determining optimal pumping rates. The WRAJ is actively pursuing several alternatives to the problem of diminished water quality and quantity with the aim of increasing the water resources of the region. It plans to meet the projected demand of 529 to 632 MCM/yr (million cubic meters per year) for various sectors of industry during the years 2000 – 2015 (Tables 1 - 2.). An accurate hydrologic model is essential for water managers to make informed decisions with regard to future conditions based on projected pumping rates.

Purpose and Scope

The purpose of this thesis is to investigate ground-water flow in the White Limestone aquifer of the Rio Cobre and Rio Minho-Milk river Basins and calculate a hydrologic budget for the region. This thesis provides: 1) a technical discussion of geologic and hydrologic characteristics of the alluvial and White Limestone aquifers, 2) development and application of a three-dimensional finite-difference ground-water flow model, and 3) rate of recharge from precipitation to the water table. The ground-water flow model utilizes data collected by the WRAJ (1998) and United Nations Development Program (UNDP, 1975). This thesis is intended for the scientifically informed public

Table 1. Water demand in the Rio Minho-Milk River basin (MCM/year, excluding export).

Demand Sector	1990	2000	2015 (projected)
Domestic (including tourism)	20.2	24.3	31.1
Industrial	19	19	19
Agricultural	389	486	582
Total Demand	428.2	529.3	632

Table 2. Summary of Water Supply Needs by Consumer Sector and Basins

PRESENT AND FUTURE WATER SUPPLY (MCM/year)

	Basins	
	Rio Cobre	**Rio Minho-Milk River**
Present Supply:		
Domestic Urban	29.0	12.50
Domestic Rural	1.90	7.65
Tourism	0.00	0.07
Total Domestic	30.90	20.22
Industry	259.80	329
Agriculture	14.0	19.0
Total Basin	304.7	362.88
Demand 2015:		
Domestic Urban	33.42	16.49
Domestic Rural	8.60	14.42
Tourism	2.60	0.16
Total Domestic	44.62	31.07
Industry	391	582.0
Agriculture	14.0	19.0
Total Basin	449.62	632.07
Future Supply With Present Systems:	**29.0**	**12.50**
Domestic Urban	1.90	7.65
Domestic Rural	0.00	0.07
Tourism	30.90	20.22
Total Domestic	259.80	375.0
Industry	14.0	19.0
Agriculture	304.7	414.22
Total Basin		
Developmental Needs: *		
Domestic Urban	4.42	3.99
Domestic Rural	6.70	6.77
Tourism	2.60	0.09
Total Domestic	13.72	10.85
Industry	131.20	207.0
Agriculture	0.00	0.00
Total Basin	144.92	217.85

*Developmental needs are defined as the difference between the demand in the year 2015 and the future supply with present systems.

and, specifically for the Water Resources Authority and hydrologic consultants who may use the results to formulate water resources management decisions.

This modeling study includes: 1) conceptualization of the ground-water system of the Rio Cobre and Rio Minho-Milk river basins, 2) calibrating the model to derive optimal parameters, and 3) simulating the ground-water flow to determine the ground-water basin and hydrologic budget. Conceptualization of the ground-water-flow regime is based on previous studies and hydrologic data that include: lithologic information obtained from field observations and well cores, hydraulic heads measured in wells, stream discharge measured at stream gauges, and hydraulic properties determined from specific-capacity tests. The U. S. Geological Survey modular three-dimensional finite-difference program MODFLOW (McDonald and Harbaugh, 1988) is used to simulate ground-water flow in the White Limestone and alluvial aquifers. The ground-water budget is calculated using ZONEBUDGET (Harbaugh, 1990), which calculates sub-regional water budgets using results from steady state or transient MODFLOW simulations.

Previous Investigations

As of 1999, no previous ground-water investigation or hydrologic modeling study had integrated the combined areal extent of both the Rio Cobre and Rio Minho-Milk river basins. However, previous ground-water investigations were conducted in several sections of the study area, including the Upper and Lower Rio Cobre basin and the lower Rio Minho basin (Clarendon Plains), to assist with the management and allocation of water resources of the region.

Versey (1963) first described the characteristics of the alluvial aquifer of the Lower Rio Cobre basin. A hydrologic investigation conducted by the Food and Agricultural Organization (FAO) on behalf of the United Nations Development Program (1970-1972) concentrated primarily on the development and management of water resources in the Lower Rio Cobre basin. Smart and Smith (1976) used dye tracers to determine the sinks and sources of karst ground-water flow in the Upper Rio Cobre basin. White (1980) assessed the implications of the landward advance of the saline front and upconing from pumpage on the future management of the White Limestone aquifer in the St. Catherine Plains of the lower Rio Cobre basin. Botbol (1982) simulated the impact of saline intrusion on the ground-water flow and water quality in the White Limestone aquifer of the Lower Rio Cobre basin under transient conditions. Walters (1984) used the Nash parametric model (1958) to predict fluctuations in ground-water levels as aquifer response to actual or synthesized rainfall series by the White Limestone aquifer of the Upper Rio Cobre basin, and compared it to the Instantaneous Unit Hydrograph (IUH) normally used for granular-media aquifers. This approach assisted in the management of the aquifer by treating it as a linear time-invariant model with a response function representing the rise in water levels in response to rainfall. Basayanake (1988) evaluated the extent and productivity of the alluvial aquifer in the Rio Cobre basin to assist in national water management and its allocation to the region.

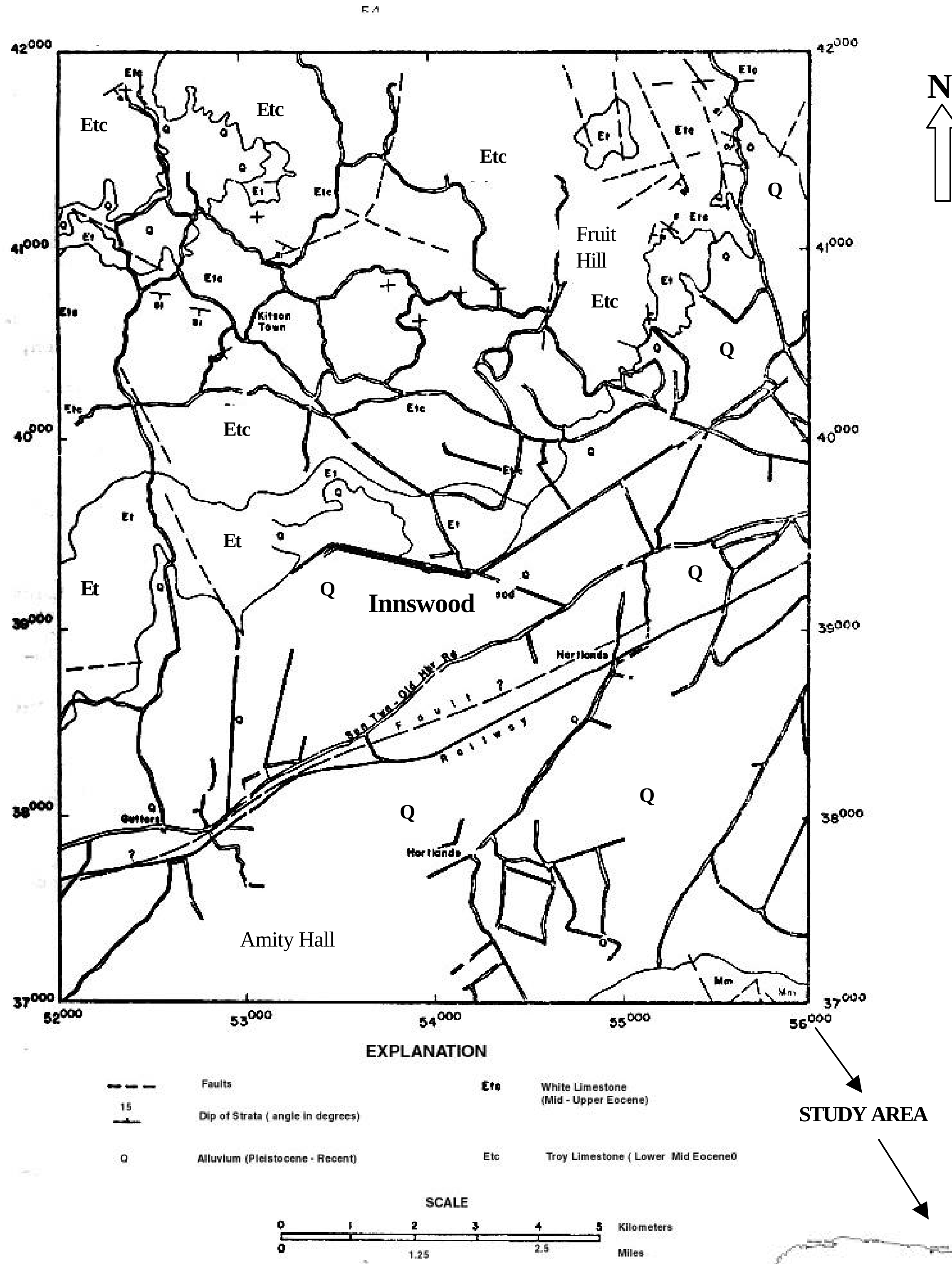
Taylor and Chubb (1956) were the first to conduct ground-water investigations within the Rio Minho-Milk River Basin. They determined that drilling of pumping wells in the White Limestone aquifer beneath the Clarendon Plains improved the irrigation water supply and allowed increased agricultural acreage in the region. The hydrogeologic framework of the White Limestone aquifer in the Clarendon Plains and other basins was described by Versey (1960). Hill and Ellington (1961) used statistical methods to show the existence of three principal zones of hydrochemical facies in the ground-water flowing through Clarendon Plains. These facies correlate with: 1) northern limestone outcrops, 2) the central interior valleys, and 3) the coastal plains. White (1985) discussed the impact of the transmissivity and specific yield distributions on ground-water flow and storage in the White Limestone aquifer. He concluded that ground-water flow through these aquifers is controlled by conduit flow in the karst regions, whereas specific yield is a function of diffuse flow. Howard et al. (1993) and Mullings (1993) used environmental isotopes to trace the migration of saline ions from the sea into Clarendon Plains in the lower Rio Minho-Milk River basin. The results indicate that migration of seawater occurs into the Rio Minho-Milk River basin across permeable sections of the South Coast fault as previously stated by (Royall and Banhan, 1981; and Horsefield; 1974).

In previous studies, geophysical investigations have been used in conjunction with lithologic descriptions to assist in the interpretation of subsurface geologic features: this was in anticipation of how the structure would influence ground-water flow throughout sections in the study area. The National Aeronautic and Space Administration (NASA) with the assistance of the U.S. Geological Survey (1971) conducted geophysical investigations on surface and subsurface geology of the White Limestone aquifer in the Rio Minho-Milk River basin. The technology involved the use of thermal infrared scanning to detect the temperature of submarine discharge off coastal areas of the Rio Minho-Milk River basin. The Netherlands Institute of Applied Geoscience, National Geological Survey TNO (The Netherlands Organization) in association with WRAJ (formerly the Water Resources Division) used electrical resistivity methods to determine the geologic and hydrologic conditions in the Innswood area of the Lower Rio Cobre basin (Fernandez, 1979) (Figure 1.2). An east-west trending buried fault with a 250 m uplift of White Limestone on its northern block was interpreted from the seismic profile. Wadge et al. (1983) used the results of a gravity survey in conjunction with well cores to construct gravity models to explain the negative gravity anomaly associated with the Quaternary Alluvium fill: his proposing the presence of an underlying graben in the South Coast Fault Zone (SCFZ) of the lower Vere Plains and Rio Minho-Milk River basin. Gravity and magnetic surveys were also conducted in the Rio Minho-Milk River basin by the Canadian International Development Agency (CIDA; 1991) under the guidance of the University of the West Indies Seismic Research Unit (UWI-SRU) at Mona, Jamaica.

DESCRIPTION OF STUDY AREA

Physiography

The study area shown in Figures 1.1a-b covers approximately 2,550 km^2 of south coastal plains, extending to mostly rugged highland regions of the north and including two contiguous basins in central Jamaica, the Rio Cobre and Rio Minho-Milk River basins. The Rio Cobre basin is contained in the parish of St. Catherine and the Rio Minho-Milk River basin extends over the parishes of Clarendon and Manchester (Figure 1.3). These basins contain Jamaica's largest extensively cultivated and irrigated



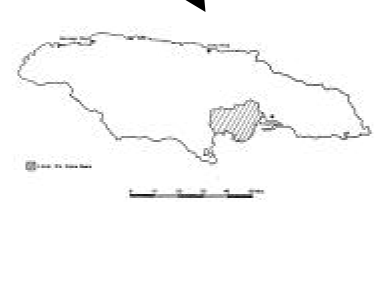


Figure 1.2. Map of geology of the Innswood Area.

Figure 1.3 Map of the Jamaica and location of the Rio Cobre and Rio Minho-Milk river basins, Jamaica West Indies.

farmlands. The Rio Cobre and Rio Minho both flow to the south coast from the island's main watershed, the Central Inlier. The main orientation of the drainage net coincides with the primary fault trend, which is north-northwest to south-southeast. Land elevation varies throughout the study area from 0 – 150 m above mean sea level (amsl) in the coastal plains, 150 – 600 m in the interior highlands, and 600 – 1200 m in the western and northern boundaries of the study area. The vegetation cover in the highlands consists of evergreen and broad-leaved tree species, with a sparse occurrence of more valuable species such as conifers. Sugarcane and banana cultivation is confined mainly to the interior valleys and coastal plains.

CLIMATE

Rainfall and Temperature

Temperature and rainfall patterns vary according to location, altitude and the time of year. Jamaica's climate is tropical marine, modified by land and sea breezes, such as the northeast trade winds. There are micro- and macro spatial variations in the seasonal distribution of rainfall. Long-term, mean annual rainfall over the island is approximately 1,958 mm (78 ins) (Evans, 1973; Chin, 1977; MacFarlane, 1979). The highest precipitation occurs in the eastern section of the island along the Blue Mountains, where rates range from 3,000 to 5,000 mm/yr. In the south coastal plains of the parishes of St. Catherine and Clarendon, precipitation rates are less than 1,500 mm/yr (Figure 1.4). Island-wide long-term mean annual rainfall is mainly bimodal, exhibiting a characteristic

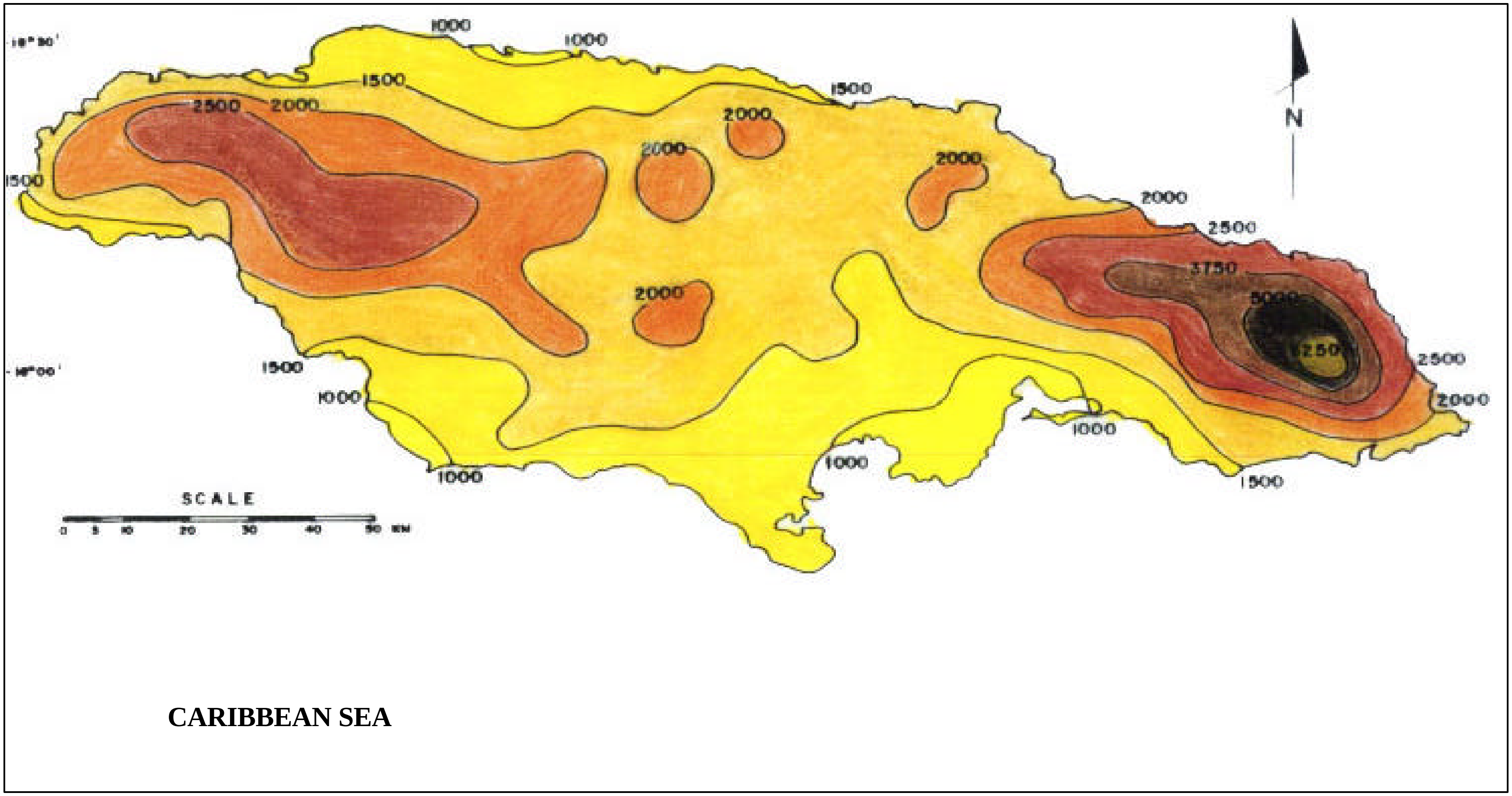


Figure 1.4. Annual rainfall distribution expressed in millimeters over Jamaica (Source: Evans (1973), Jamaica Meteoriological Division.

pattern with the primary maxima in May and October and minima in March and June (Chin, 1977; Vickers, 1977; and Nkendiram, 1979). The average number of rainy days per year varies from 60 to 200. Whereas places with lower numbers of rainy days receive low annual rainfall, high rainy day regions are not necessarily the wettest areas. For example, 180 rainy days per year produce more than 5000 mm annually near the Blue Mountain Peak in eastern Jamaica, but only 1750 mm on the north coast. The main dry season lasts from December to April with a somewhat less significant dry period in July. A month is described as dry if rainfall is below the monthly average of 155 mm or wet if

it is average or above. The island is affected by torrential rainfall and tropical depressions from July to November, and is characterized by periodic flood-producing rainfall of high intensity and magnitude. Drought is more severe in the south compared to the north. The characteristic islandwide bimodal pattern in rainfall distribution, where the the primary maxima occur in May and October, coincides with the typical mean monthly rainfall observed for the Rio Cobre and Rio Minho- Milk river basins shown in Figure 1.5.

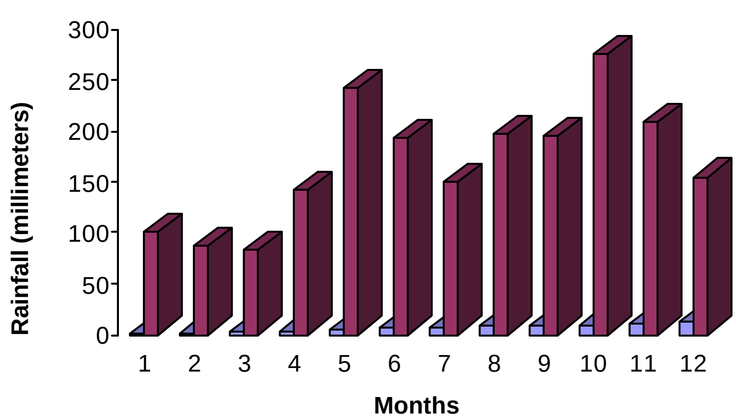
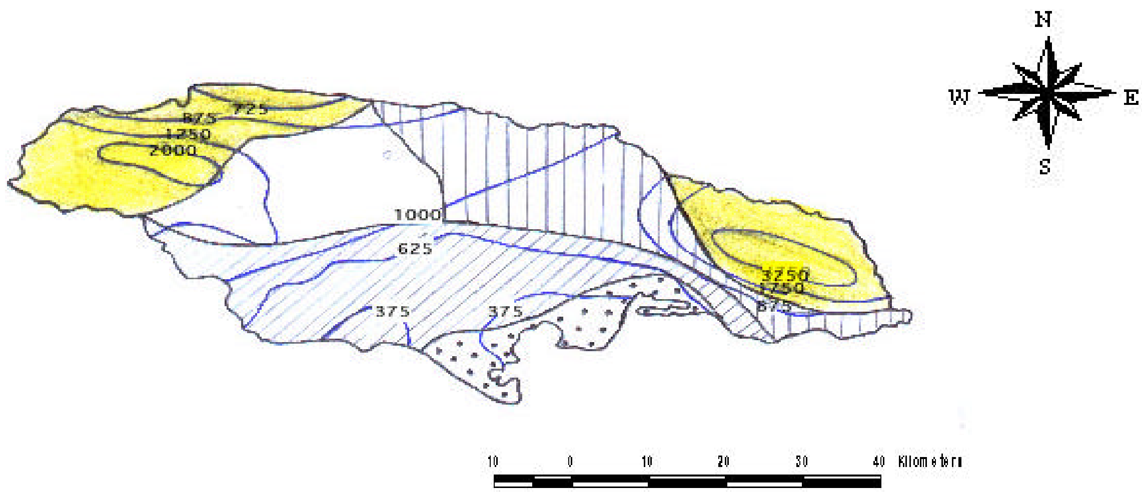


Figure 1.5. Monthly mean rainfall in the Rio Cobre and Rio Minho-Milk River basins, Jamaica, WI (1 refers to January and 12 to December, WRA, 1990)

Temperatures in the coastal lowlands are fairly uniform. Mean daily temperatures range from a seasonal low of 26°C (75 °F) in January and February to a high of 28°C (82 °F) in July and August. Daily sunshine hours are fairly constant throughout the year, averaging about 8.2 hours in the Southern Plains (Evans, 1973). Humidity varies with elevation and is generally above 60 percent with the highest percentages occurring in the morning hours (85%) and falling off by mid afternoon (62%). Temperatures and total average annual potential evapotranspiration (PE) in the Rio Minho-Milk River basin are lower than in the Rio Cobre basin (Appendix I, Tables 1 and 2). Mean monthly relative humidity on the south coast is nearly constant throughout the year and averages 74% (Evans, 1973). Total annual evapotranspiration rates distributed in the ten hydrologic basins range between 1,362 -2,457 mm. Average monthly evapotranspiration rates for the Rio Cobre and Rio Minho-Milk river basins are 156 mm and 138 mm respectively, or 70 % of average annual precipitation.

Rainfall and Runoff

Runoff is strongly correlated with rainfall in drainage basins outside zones of karst development. High runoff is partially the result of steepness of slopes and intensity of rainfall. Rainfall-runoff correlation coefficients are slightly higher in basins of heavy rainfall than compared with basins of low rainfall. The rainfall-runoff coefficient may be defined as the percentage of mean annual rainfall that runs off overland after a rainfall event. Mean annual runoff in Jamaica is approximately 1265.50 mm or 65% of the mean annual rainfall, yielding a rainfall-runoff coefficient of 0.65 (Figure 1.6). The distribution of rainfall is reflected in the runoff pattern in Jamaica. Nkemdirim (1979) analyzed rainfall and runoff relationships of seven major rivers in Jamaica, including the Rio Cobre and Rio Minho-Milk River basins. He observed a strong correlation between annual rainfall and runoff in these rivers (Figure 1.6). Because rainfall in the southern coastal region is relatively low, basin yield in the Rio Cobre and Rio Minho-Milk river basins is low with runoff averages of less than 375 mm/yr or rainfall-runoff coefficients of 0.30 to 0.40.



EXPLANATION

RAINFALL-RUNOFF COEFFICIENTS

0.7 - 0.8
0.6 - 0.7
0.4 - 0.6
0.3 - 0.4
Less than 0.3
— 375 — Rainfall in millimeters

Figure 1.6 Mean annual rainfall and runoff coefficient: Source compiled by Nkemdirim, 1979.

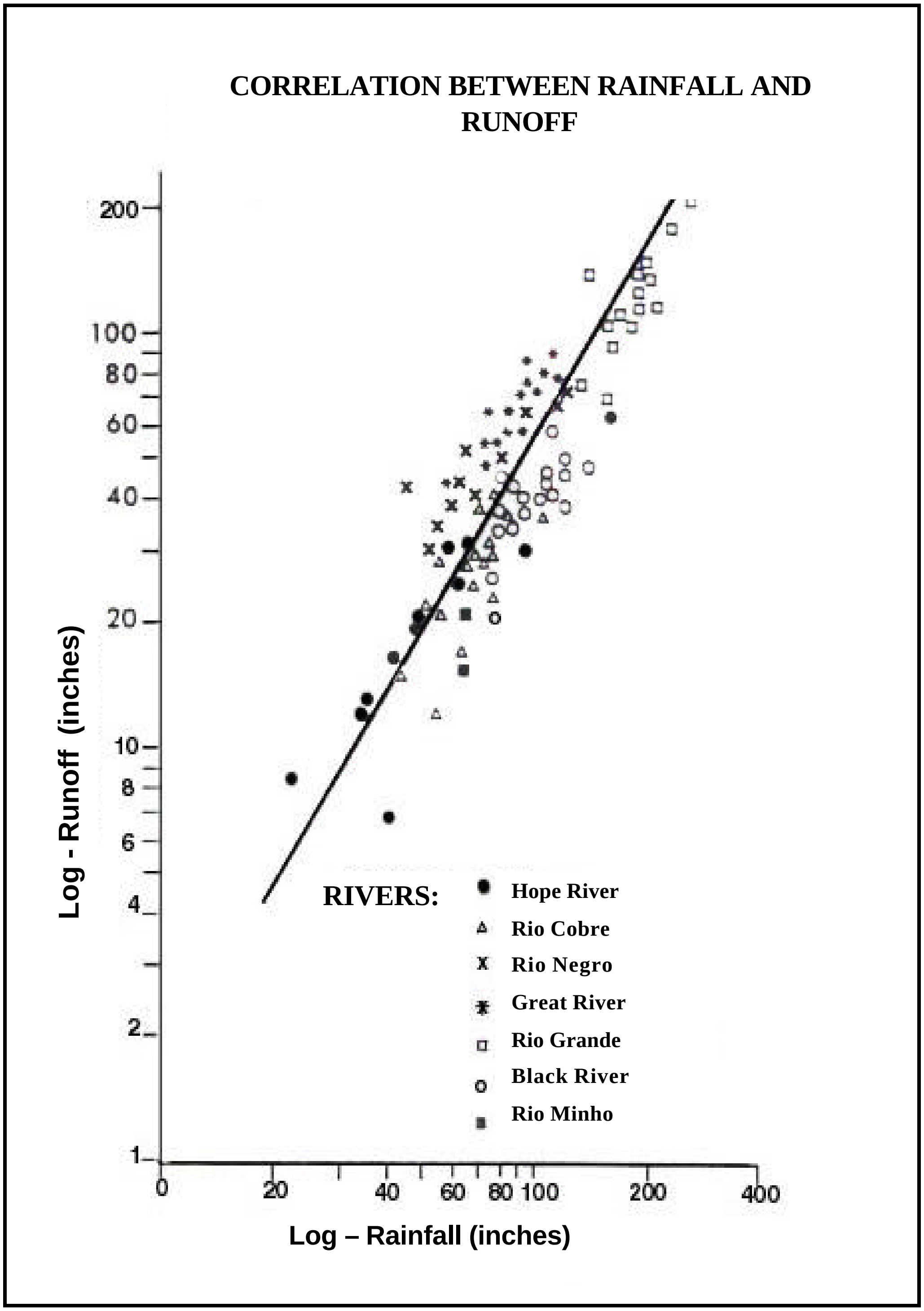


Figure 1.7 The correlation between rainfall and runoff of the seven largest rivers in Jamaica, West Indies (Nkemdrim, 1979).

Surface Water

Surface water dominates the hydrology of the study area. The three major rivers are the Rio Cobre, the Rio Minho, and Milk River. Several tributaries including Pindars River, Rock River, and a few springs also drain the area. Surface runoff leaving the highlands of the study area: 1) drains into the Rio Cobre and Rio Minho or their tributaries; 2) recharges the ground-water system; and 3) evaportranspires from the basins. Since the principal mountains span from west to east along the island's central axis, the direction of flow is from north to south. The springs are the Cockpit and Salt River springs. The rivers receive flow from the dense network of underground tributaries in the White Limestone outcrops of the highland regions. Rivers draining the White Limestone aquifer maintain a higher sustained yield than rivers draining the Cretaceous regions that are characterized by recrystallized Yellow Limestone with low storage potential (Chin, 1977). The Rio Cobre basin accounts for 6% (Appendix 1, Table 3) of the surface and ground-water supply of the island. The Rio Cobre flows through St. Catherine, and provides water for domestic and irrigation purposes in the region. Some water is diverted from the Rio Cobre by gravity flow to the fields irrigated by the Rio Cobre irrigation network. Additional sources of water for irrigation (and aquaculture) include some of the smaller streams, ground-water from wells pumping from the White Limestone and alluvial aquifers, and surface water imported from the Rio Minho-Milk River basin. The mean annual stream flow of the Rio Cobre measured at the Bog Walk gauging station is 934,839 m^3/d (Appendix 1, Table 4-5). In addition, several manufacturing plants in the area also pump ground-water from the White Limestone and alluvial aquifers.

In the Rio Minho-Milk River basin, the Rio Minho and Milk Rivers account for 8.4% of the surface and ground-water supply of the island (Appendix 1, Table 3). The Rio Minho is ephemeral in its uppermost reaches and becomes perennial downstream of Alley (Figure 1.8), mainly as a direct result of the return flow of unused irrigation water. The mean annual flow of the Rio Minho measured at the Danks (Rock River) gauging station is 368,483 m^3/d (Appendix 1, Tables 4 and 6). Flow in the Milk River is ephemeral between Porus and Scott's Pass because of the high infiltration rates in the highly permeable underlying White Limestone aquifer (Figure 1.8). Springs at Scott's Pass help to maintain a perennial flow in the Milk River down to Spring Plains where flow becomes intermittent. Downstream from the town of Rest, the river once again becomes perennial to its discharge point into the sea. This perennial flow is sustained mainly from runoff irrigation water in the coastal plains. In the lower plains, the Milk River becomes large enough that it is navigable for three kilometers inland of the sea and supplies a system of canals for irrigation of the Vere Plains.

Hydrologic Basins

The watersheds of Jamaica are divided into ten hydrologic basins (Figure 1.9). Basin boundaries are demarcated in some cases by: 1) perceived no-flow boundaries between basins, 2) the presence of surface water divides, and 3) physical features (topographic highs or lows). These basins may be further divided into sub-basins that are represented as discrete hydrologic sub-units of a basin where discharge may take place between sub-basins within the larger basin. For example, the Upper Rio Cobre basin acts as a closed inland ground-water sub-basin with no underflow leaving or entering the

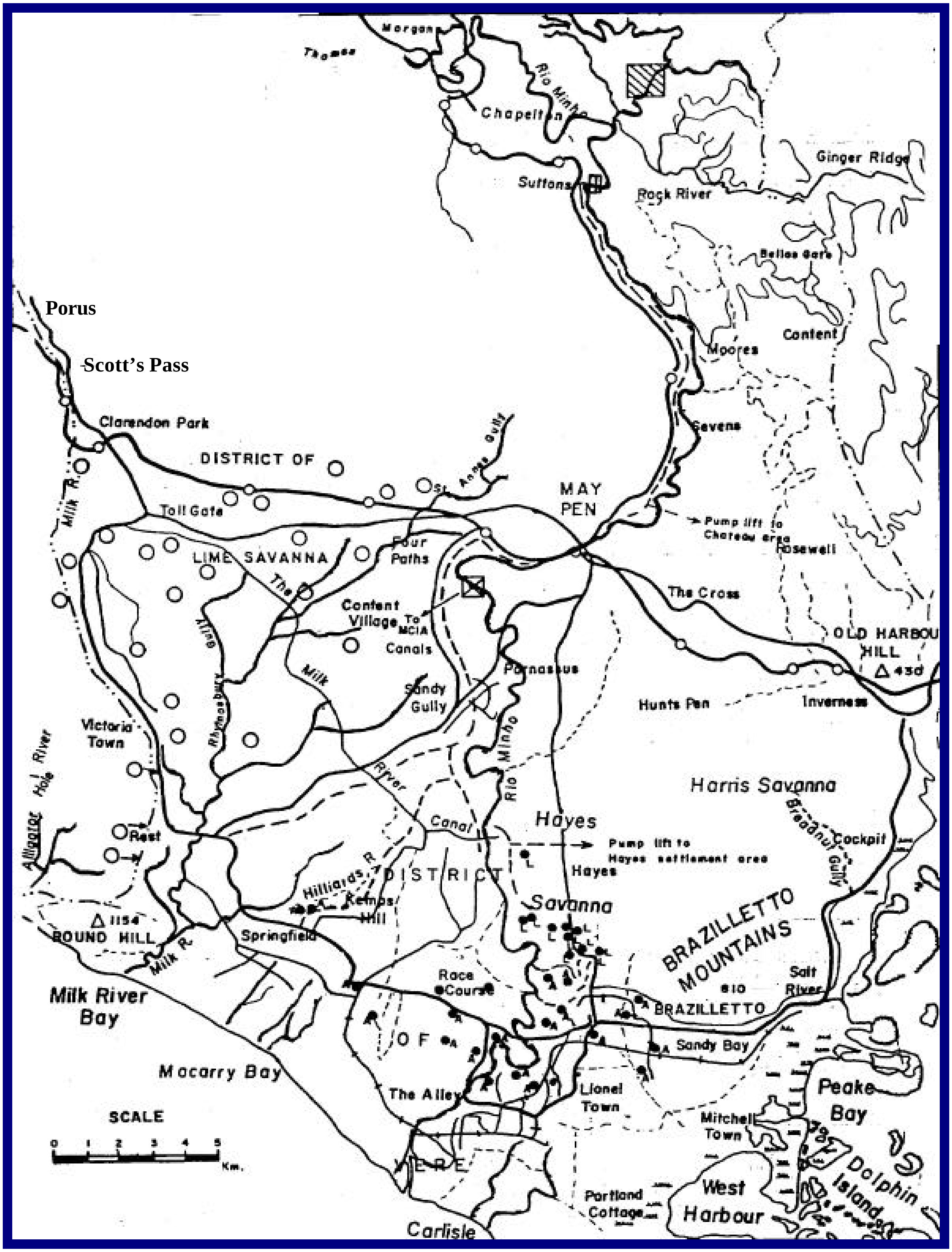
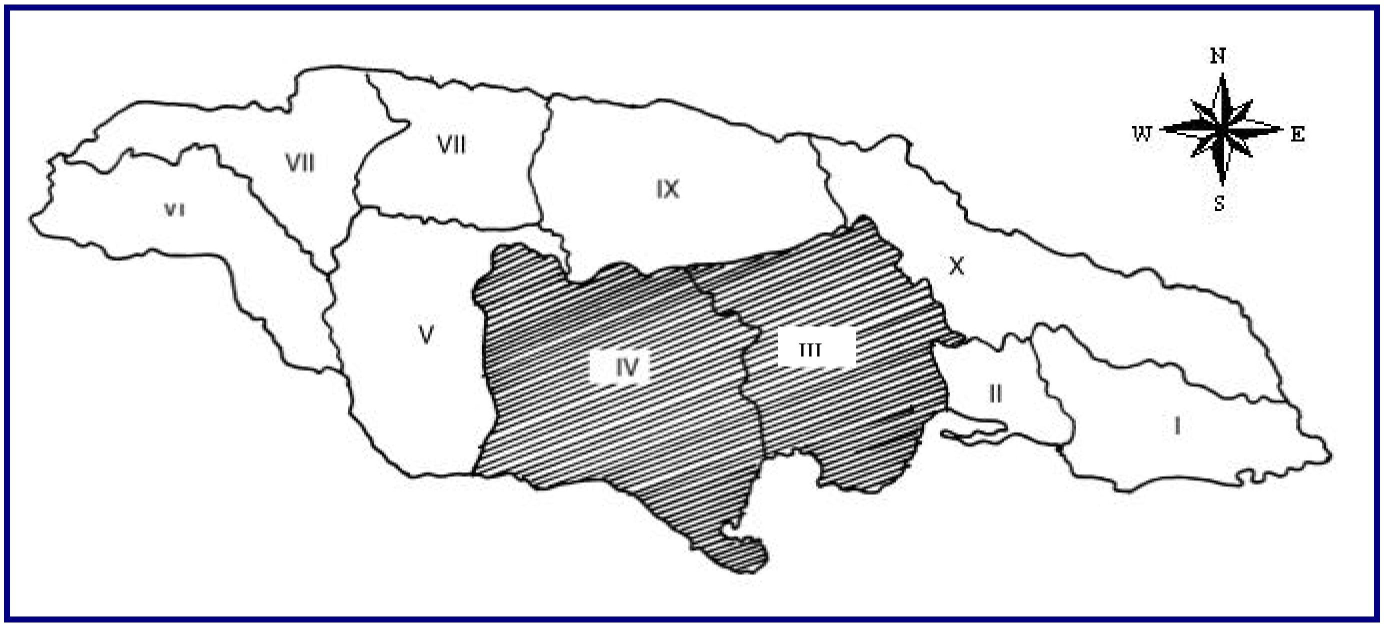


Figure 1.8 A map of the Milk River located in the Rio Minho-Milk River basin (Source: WRAJ, 1990).



I - Blue Mountain South
II - Kingston
III - Rio Cobre
IV - Rio Minho
V - Black River
VI - Cabarita River
VII - Martha Brae
VIII - Dry Harbor Mountains
IX - Great River
X - Blue Mountain North

Figure 1.8 Map of hydrologic basins of Jamaica (shaded area represents the extent of this investigation).

White Limestone aquifer of the sub basin only surface flow and evapotranspiration (White, 1980 and Chin, 1977).

Ground-water Use

Ground-water resources are essential to supplement current shortages caused by irrigation of crops during dry periods. Ground-water is pumped from wells to supplement the current surface water shortages and the increased demand from the industrial and domestic sectors. Flow of water for irrigation on sugar estates is diverted to dams via canals from the Rio Cobre. Improper well spacing has led to abandonment of wells pumping salt water and also the necessity of replacement. Wells are sited within major flow paths or along faults aligned in the direction of ground-water flow. Efforts to establish wells in the recharge areas of these basins have resulted in moderate success (average yield of 89.42 m^3/d) to outright failure. Wells developed in karst regions of the White Limestone aquifer obtain most of their flow from water bearing fissures and conduits that intersect the well bore.

Agricultural Use and History

The origin of Jamaican agriculture was based on crops produced on plantations for the international market and financed by external capital and a slave labor system. Agriculture provided food for export while the economy in turn relied on foreign exchange from the export of crops to import staple foods for its local population. The structural dichotomy of Jamaican agriculture has existed since the establishment of the slave labor system. Its two main sectors of agriculture are 1) estate production of major crops and livestock, and 2) small-holdings (less than 4 hectares) producing staple food crops, select export crops, and some livestock for domestic consumption. The main crops are sugarcane, bananas, citrus, pimiento, coffee, cocoa, coconuts, ginger, and tobacco. In addition, a variety of tropical and subtropical fruits are grown. These include pineapple, ackee, grape, strawberry, and jackfruit. Livestock production includes pigs, cattle, and poultry. In addition, aquaculture is practiced in inland microdams.

Approximately 80% of Jamaica’s land surface is mountainous with more than 50% having slopes of greater than 20°. This makes these regions particularly susceptible to watershed erosion. Small-scale cultivation occurs upland of the central plains and the mountainous areas of remaining parishes (Figure 1.3). Large-scale cultivation of export crops occupies the most resource-rich lands, that is, the coastal and interior valleys that have relatively fertile soils.

Soils

There are four main groups of soils on Jamaica: (a) the soils of the upland plateau (covering approximately 64% of the island); (b) alluvial soils which are found on the relatively flat land (14%); (c) highland soils found in the east and central region (11%); and other soils (11%). Upland plateau soils are of two types: terra rossa (red limestone) and rendizina (black marl). The rendizinas are clay soils, which overlie the yellow limestone and marls. Alluvial soils consist of loam, sand, and gravel. Highland soils are derived from mainly shale, conglomerate, and volcanic. The other soils are formed from calcareous shale, or are weathered from igneous and metamorphic rocks, limestone, and shale.