Chapter 3

HYDROGEOLOGY

Areal Extent of Aquifers and Confining Unit

The conceptual hydrogeologic framework for the study area consists of two aquifers separated by a confining unit. It is defined on the basis of the lithologic and hydrogeologic properties of the Cretaceous volcanics, Late Tertiary Yellow Limestone and mid-Tertiary White Limestone, and Quaternary alluvial sediments. A map of the hydrostratigraphic units of Jamaica is provided in Figure 3.1. The Cretaceous volcanics and volcaniclastics, and the dolomitized and recrystallized Yellow Limestone Group form an impermeable basement complex unit. This unit is present in the Rio Cobre and Rio Minho-Milk river basins and occupies 25 percent of the island's area (Appendix I, Table 7) outcropping along the ESE - WNW central spine of the island in exposed inliers and in western Jamaica (Figure 2.9b – 2.10). The mid to late Tertiary White Limestone Group outcrops mainly in the highlands, forming the principal aquifer of the Rio Cobre and Rio Minho-Milk river basins, and overlying the basement rocks. The White Limestone aquifer is separated from the overlying alluvial aquifer by a thin red marine clay that acts as a confining unit to separate the aquifers into independent hydraulic systems (White, 1980). The Quaternary alluvium covers the Coastal Plains in the southern half of the Rio Cobre and Rio Minho-Milk river basins, but ends abruptly along the Milk River. Subsurface stratigraphic relationships between these hydrogeologic units are illustrated in a N-S cross-section across the center of the island from Philadelphia, St. Ann (A) to where the Rio Minho drains to the sea at The Alley (A') (Figures 3.1 – 3.2).

Table 4 summarizes the relations between the hydrogeologic units, geologic formations, ages, and corresponding hydrogeologic names used in previous investigations.

White Limestone Aquifer

The White Limestone is the principal aquifer in the Rio Cobre and Rio Minho-Milk river basins and supplies 96 % of the island's ground-water. It is the represented by a thick confined aquifer and rests unconformably on the volcanic basement unit. Although the White Limestone Group has been differentiated into ten formations, mainly on the basis of bio-stratigraphic criteria, it forms one hydrogeologic unit (Wedderburn, 1971). In the Rio Cobre and Rio Minho-Milk river basins, the White Limestone aquifer is represented by the Newport, Troy, and Waldeston Formations (Table 3 and 4) and occupies almost 66 percent of the island's area (Appendix I, Table 7).

The White Limestone unit thickens southward from the northern boundary to the coast where it reaches a thickness of about 700 m. White Limestones crops out over two-thirds of the island's surface or around inliers of older rocks and dips beneath plateaus attaining a maximum thickness of 1219 m. The thickness of the White Limestone unit considered for this study extends from 400 m above sea level to 250 m below sea level. Lithological logs from over 400 wells drilled in the White Limestone and alluvial aquifers were used to derive the thickness of each hydrogeologic unit.

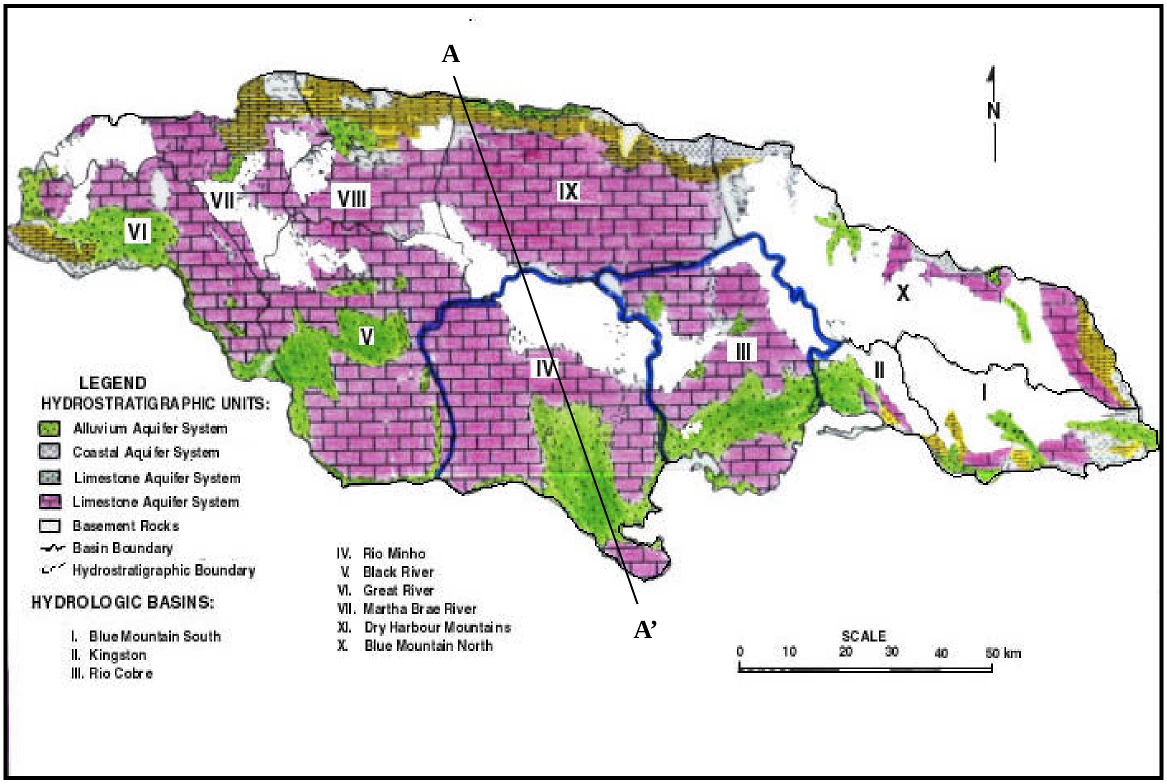

Figure 3.1 Hydrostratigraphic map of Jamaica (WRAJ, 1990).

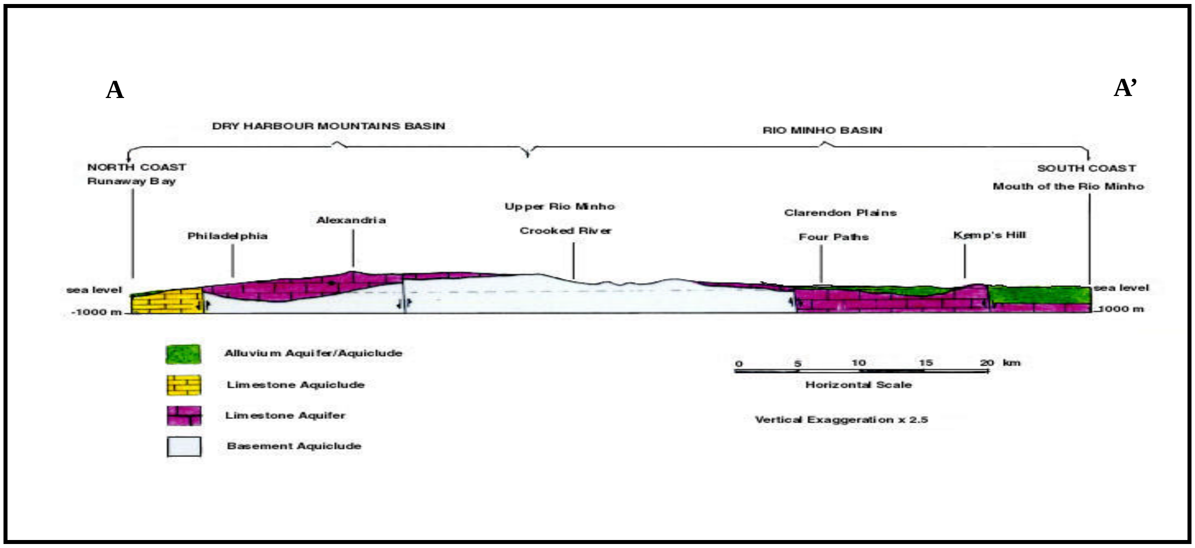

Figure 3.2. Geologic section through Central Jamaica showing the subsurface relationships between the hydrostratigraphic units, (WRAJ, 1990).

Table 4. Age, lithology, and general hydrologic properties of principal geologic units, Rio Cobre and Rio Minho-Milk river basins, Jamaica, West Indies.

HYDROGEOLOGIC COLUMN SHOWING AQUIFERS AND CONFINING UNITS IN MODEL AREA

Age	Group	Formation	Geologic Unit	Lithology	Thickness (m)	Hydrologic Properties
Recent	Alluvium	Liguanea Formation	Younger Alluvium Fluvio - alluvial sediments	Unconfined fluvio-alluvial clays,volcanics and volcaniclastic debris and marine sediments.	to 243	**AQUIFER** Well developed surficial aquifer, heterogeneous and anisotropic.
Pleistocene	Alluvium	Liguanea Formation	Older Alluvium Red Marine and interior valley clays.	Variable thickness, limited in lateral extent. Grades laterally to the August Town Formation in some areas. Unconformably overlies the main aquifer laterally. Referred to in the literature as 'Red Marine Clay'.	to 46	**AQUITARD** Confining unit separates the alluvial and the limestone aquifer.
Upper Eocene	Coastal Group	August Town Formation	Soft marls, muddy carbonates, calcareous sands, and gravels.	Limited in lateral extent. Part of recharge area for Cockpit springs to the east. Chalky marls and lenses of clay and sand overlying rubbly limestone. This formation becomes more extensive beyond the eastern end of the study area.	< 30	Subsurface barrier to limestone aquifer. Low permeability.

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HYDROGEOLOGIC COLUMN SHOWING AQUIFERS AND CONFINING UNITS IN MODEL AREA

Age	Group	Formation	Geologic Unit	Lithology	Thickness (m)	Hydrologic Properties
Mid- Miocene to Mid -Eocene	White Limestone Group	Newport/ Browns Town. Formations	Crystalline biosparites	Corals limestone with coralline algae, molluscs and forams.	to 1219	**AQUIFER** Exhibits mature karstic features such as very high infiltration capacity, highly developed secondary permeability, predominant subsurface drainage and highly compartmentalized sub-surface conduit flow. Contains four water-bearing levels that correlate with Pleistocene base flows.
		Walderston/ Somerset/ Swansick Formations	Loose rubbly limesones.	Massive to pink soft sparite, rich white limestone, microsparite.	to 243	
		Troy/ Claremont Formations	Very Compact dolomites. Shallow - water shelf facies	Well bedded, recrystallized and partially dolomitized members of the White Limestone Group except the Montpelier Formation.	122 to 243	
Lower to Mid Eocene	Yellow Limestone Group	Chapleton Formation/	Marginal-marine facies	Well bedded, yellow, medium grained calcarenite. High clay content. Forms the base of karstification of Tertiary limestone.	21 to 152	**BASAL AQUITARD** Locally yields water to wells but is not an important aquifer.
		Guy's Hill Formation			30 to 61	
Cretaceous (Barremian to Maastrictian)	Basement	Guy's Hill Formation	Volcanic complex, andesitic tuffs, tuffaceous conglomerates and sandstones	Lowest stratigraphic unit. Mainly volcanics and volcaniclastics. Basaltic and andesitic flows, and laharic breccias.	-	Contains no active production wells, but supports low yield seasonal streams. Contains some water in fractures.

Complete coverage of the area was obtained by kriging to interpolate and extrapolate thicknesses from known points. Well logs used in the hydrogeologic framework analysis are listed in Appendix 1, and Tables 8 and 9. Figure 3.3 shows the well locations used in the hydrogeologic framework analysis. Note that most of the wells are located in the southern part of the study area. Kriged thicknesses in the northern part of the study area are only approximate and based on simulation results. Figures 3.4 illustrates the general depth and thicknesses of the hydrogeologic units from the highland area (Central Inlier) through the south coastal plain. Figures 3.5 through 3.6 shows the elevation of the top of the White Limestone aquifer relative to sea level, thickness, and also areal extent.

Limestones in Jamaica are categorized by their hydrologic control on occurrence of ground-water flow. (Versey, 1960; Sweeting 1972). Two limestone groups are recognised:

(a) Massive and compact limestones in which water moves along fissures and conduits with little or no primary permeability. Secondary porosity and permeabilty can be high where fissures predominate in these limestones (Cardy, 1971).

(b) Chalks, soft marly limestones, and rubbly, nodular limestones all with a characteristic low primary permeability. Fine-grained chalk occurs as a very thin, coastal band. This coastal band effectively impedes the vertical movement of flow resulting in the creation of individual ground-water reservoirs or sub-basins

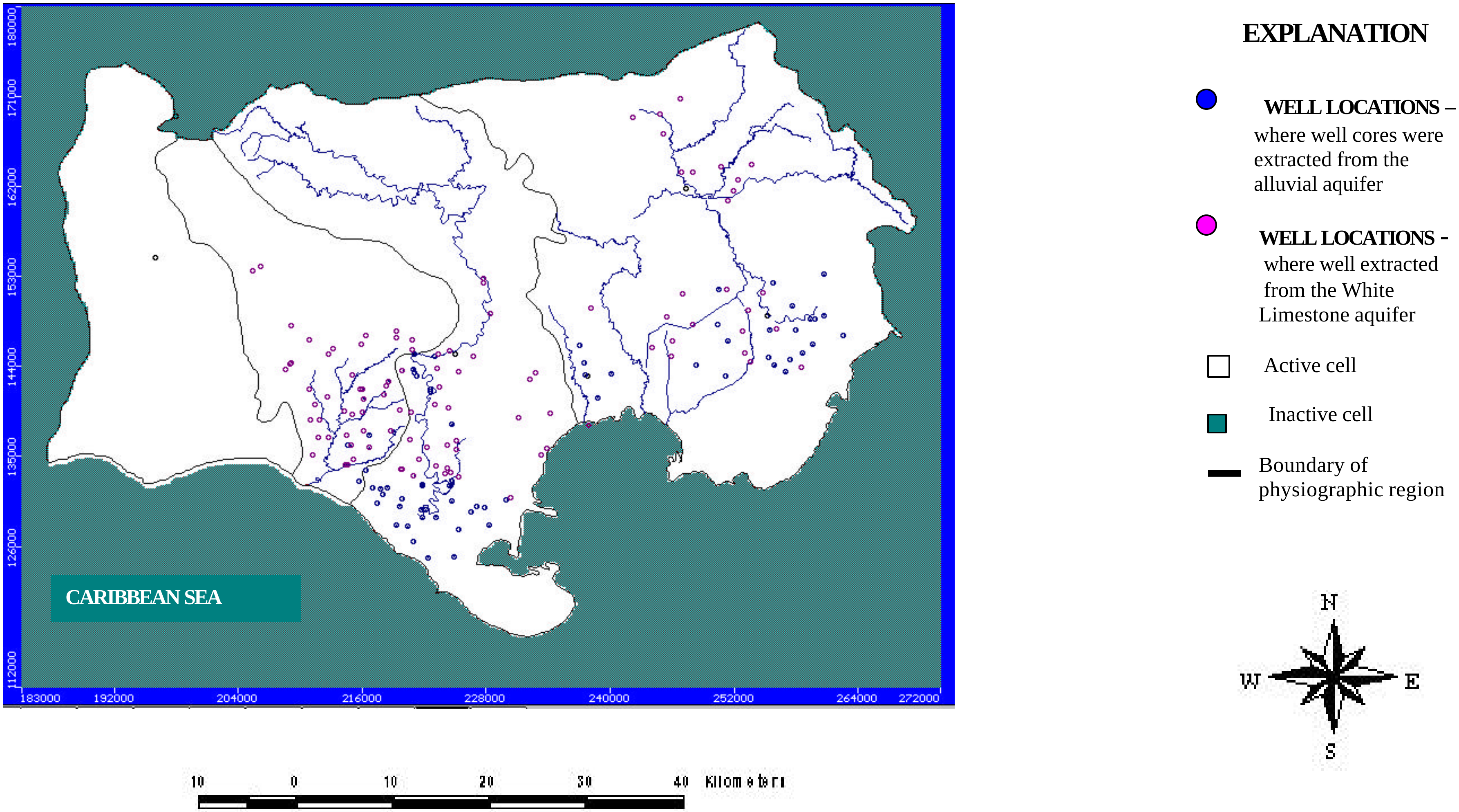
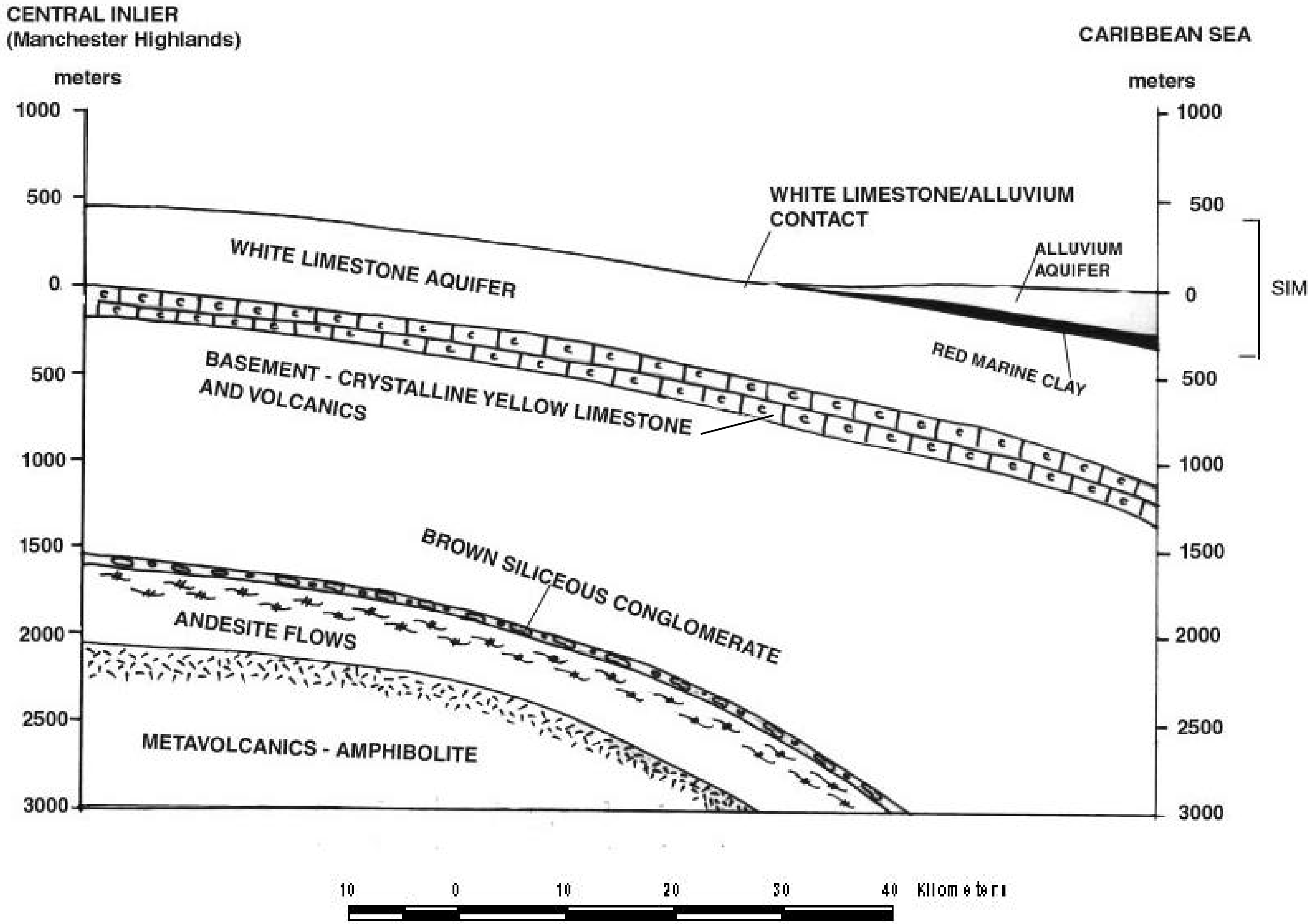
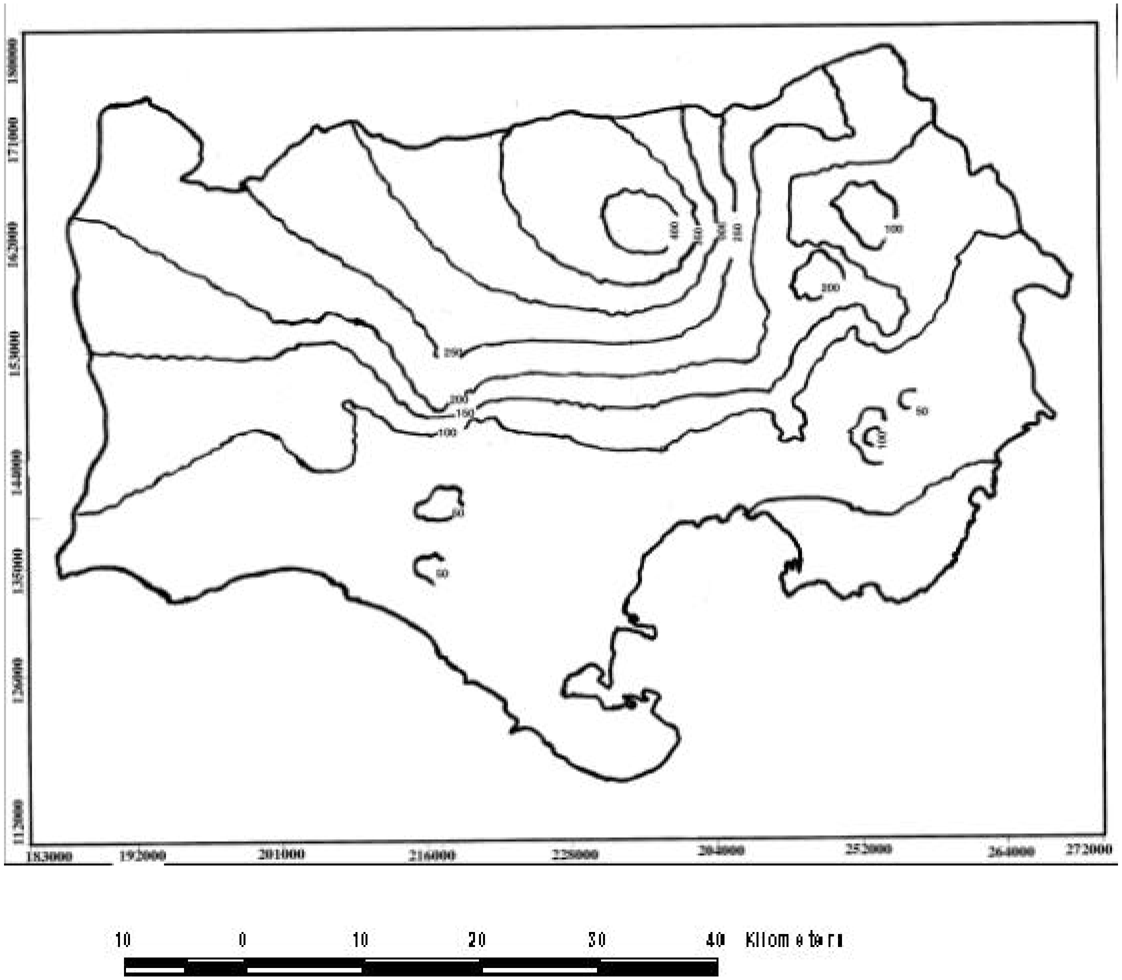


Figure 3.3 Location of wells where data was used to determine surface elevation of the study area.



DATUM IS MEAN SEA LEVEL

Figure 3.4 General depth of aquifers, the confining unit, and basement from the Central Inlier through the south coastal plain.



EXPLANATION

— 50 —**ALTITUDE OF THE WHITE LIMESTONE AQUIFER.** Contour Interval is 50 meters. datum is mean sea level

— Boundary of physiographic region

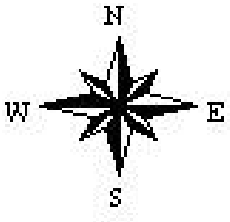
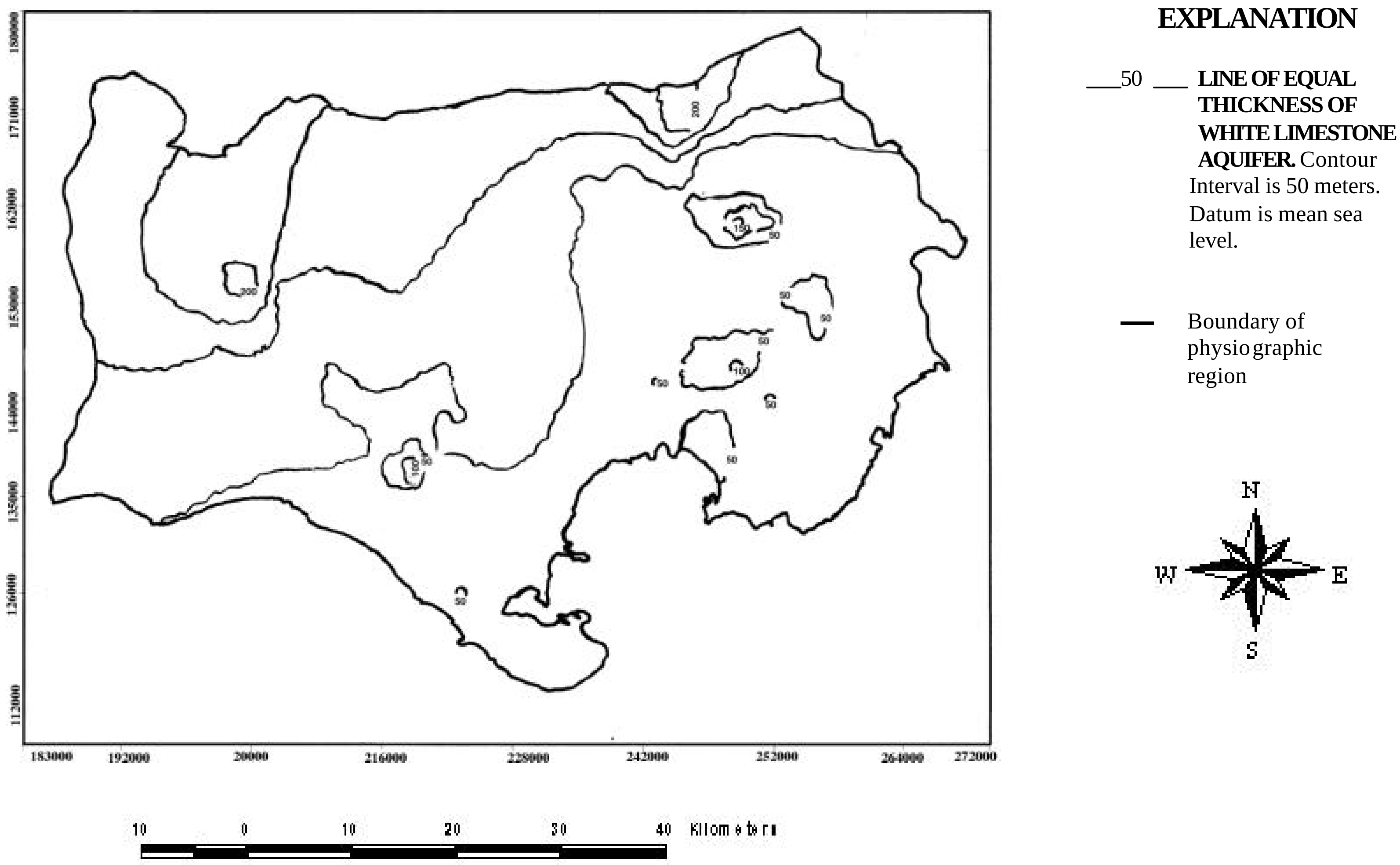


Figure 3.5 Altitude of top and areal extent of White Limestone aquifer.



EXPLANATION

___50 ___ **LINE OF EQUAL THICKNESS OF WHITE LIMESTONE AQUIFER.** Contour Interval is 50 meters. Datum is mean sea level.

— Boundary of physiographic region

Figure 3.6 Thickness and areal extent of the White Limestone aquifer.

within the White Limestone aquifer system. This accounts for high streamflows in the dry season and is typical of rivers like the Rio Cobre draining areas of White Limestone aquifer outcrops. The most productive areas of the aquifer are associated with nodular bedding in the White Limestone with well yields as much as 20,000 m^3/d.

Hydrodynamically -Controlled Diagenesis

Carbonate islands respond to karst formation in relation to their depositional nature. Jamaica is described as a carbonate-rimmed island with non-carbonate as well as carbonate rock exposed on the surface (Mylorie and Carew, 1997). Primary porosity in the White Limestone Group associated with carbonate deposition ranges from 25 – 40 %. Lithification, pressure solution, recrystallization, and the growth of neomorphic spar reduce the porosity of the White Limestone aquifer. Subsequent cementation and compaction reduce or obliterate the intergranular space during diagenesis. Post-depositional alteration by chemical diagenetic processes like dolomitization and subsequent fracturing by tectonic movements in the White Limestone results in secondary porosity. Many ancient carbonate platforms like the White Limestone aquifer exhibit a significant reduction in porosity when vertical and horizontal fractures later become filled with marine cements and internal sediments (e.g. Flugel, 1982; Playford, 1984; and Kerans, 1985).

The flow of meteoric water through fissures or the storage of water causes the rocks of the White Limestone aquifer to undergo chemical diagenesis, changes in rock fabric, porosity, and chemical dissolution. The porosity is enhanced further by karst solution along penetrable fissures resulting from circulating ground-waters (Ford and Williams, 1989). The possibility must exist for: (1) chemically aggressive ground-water to recharge the system, (2) the rock unit to transmit water through the fractures, and (3) ground-water to drain from the system (Stringfield and LeGrand, 1966).

Karst

The hydrology of karst features within the White Limestone aquifer differs from that found in aquifers with fractured crystalline basement rock (e.g. granite). The permeability of karst aquifers changes with time as a result of solubility of the limestone (Cvijic, 1918). Variable recharge conditions and subsurface heterogeneity enhances the hydrologic complexity of the White Limestone aquifer as water enters it by infiltration through soils, pores, fractures in exposed rock outcrops, solution enlarged fractures (conduits) and collapsed zones. Water travels through interconnected networks of pores, fractures, and solution conduits.

Karst is evident near the water table of the unconfined White Limestone aquifer but is confined beneath the alluvium. Karst development is marked by the abundance of sinkholes and conical hills (kegel karst) in the White Limestone Group. Since the end of the Mid-Miocene, karstification has been continuously active in the exposed White Limestone hydrogeologic unit. After the Pleistocene, karstification in the White Limestone occurred mainly along an east-west trend in the faulted, coastal areas of Jamaica. Karst features and conduits, leading to highly permeable, anisotropic rock masses, are favored if: 1) topography and drainage, bedding features, or jointing promote flow localization that focuses the solvent action of circulating ground-water; and 2) well connected pathways or high ground-water velocity pathways are maintained between recharge and discharge areas (Maidment, 1989). Karstic regions of the White Limestone contain solution-generated cavities permitting rapid transport of ground-water, often by means of turbulent flow, and can carry large sediment loads particularly after storm events (Delleur, 1999).

The conduits in the karstic areas of the White Limestone aquifer have been studied in resistivity and other surveys in Jamaica (Sweeting, 1972). The results of preliminary resistivity surveys of the White Limestone unit in the Pedro Plains area of south-west Jamaica indicate that three zones of resistivity may exist in some parts of the unit: 1) a high resistivity zone of aeration, 2) the low resistivity saturated rock, and 3) the high resistivity compact limestone (Sweeting, 1972). A list of the various hydrographic zones associated with karst regions are presented in Appendix I, Table 10.

In the White Limestone aquifer, a portion of the ground-water flow discharges as large springs (Fig. 3.8). A dense network of underground streams drains the White Limestone aquifer mainly beneath the Rio Minho-Milk River basin. Transported sediment in this aquifer sometimes clogs conduits, obstructing the free flow of water under gravity. This may lead to the mounding of ground-water and consequently, great seasonal fluctuations of the water level. When ground-water becomes ponded behind geologic barriers within the White Limestone aquifer, significant fresh water storage occurs.

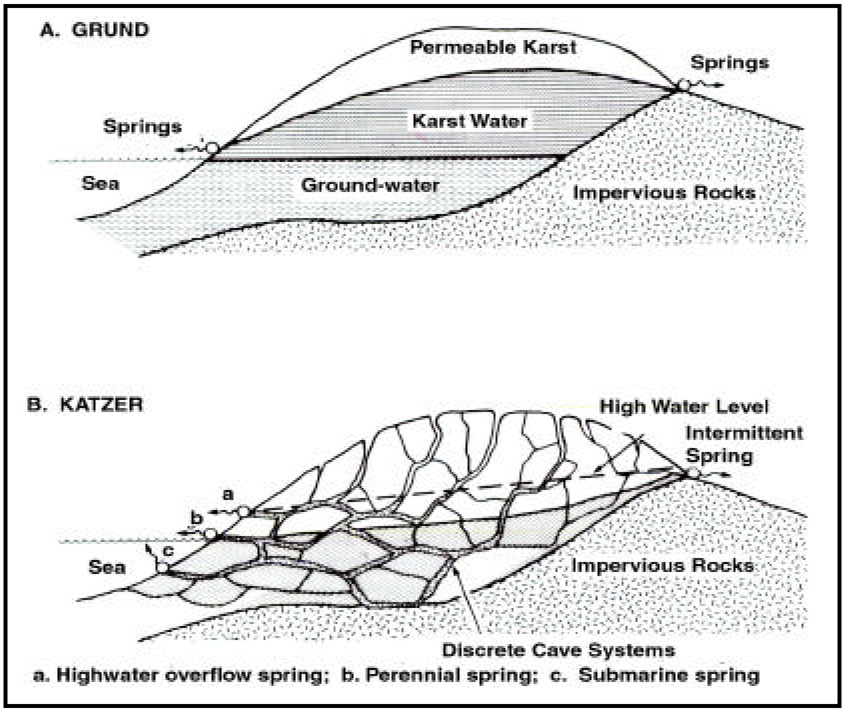


Figure 3.7 A. Essential features of karst groundwater system according to Grund (1903) who envisaged a fully integrated circulation with stagnant water below sea level. B. The karst water system according to Katzer (1909), who stressed the existence of an essentially independent subterranean river network. (Source: Ford, 1989)

Numerous researchers working in karst and carbonate terrains have accredited different secondary processes to the development of extensive subsurface hydraulic systems characteristic of the drainage patterns in Jamaica's White Limestone aquifer. Versey (1960) elaborated on the secondary processes that contributed to the development of the karstic White Limestone. He claimed the height of the water table impacted the force of ground-water flow through the aquifer. The height of the water table combined with the abrasive action of the sediment load increases the development of conduit permeability in the White Limestone aquifer. Contrary to Versey's opinion, Sweeting (1955,1958) felt the dissolution of the limestone was due to infiltration from aerial precipitation regardless of the level of the water table in these aquifers.

Structural features like folds, joints, faults, non-carbonate layers (chert and shale), grain size, and magnesium carbonate content are commonly cited as factors contributing to enhanced conduit permeability in karst aquifers (Dreiss, 1984). It is apparent that a combination of joints, fractures, chemical dissolution and transport all work concomitantly in karst aquifer systems to enhance subsurface porosity and permeability hydrologic systems. Conduits acting as passageways for hydraulically-transported sediments and subsequent clogging may contribute to excessive mounding of ground-water in storage and may explain the subsequent flooding of riverbanks that occurs occasionally along both the Rio Minho and Rio Cobre rivers.

Conduit Flow

Two types of ground-water flow are recognized in the White Limestone aquifer of Jamaica: (a) diffuse flow and (b) conduit flow (White, 1985; Atkinson, 1977). These flow types are summarized in Table 5. Laminar-diffuse flow occurs within the primary porosity and minor secondary porosity of the rock. These flow types are also characteristic of carbonate aquifers in regions of low to moderate relief, e.g. the White Limestone aquifer.

Table 5. Types of carbonate aquifer systems in regions of low to moderate relief of Jamaica (modified from White, 1969 and 1977) with modifications from LeGrand and Stringfield (1971) and Legrand, Stringfield and LaMoreaux (1976).

FLOW TYPE	HYDROLOGIC CONTROL	ASSOCIATED CAVE TYPE
I. DIFFUSE FLOW (fine-textured permeability)	Shaley limestone; crystalline dolomites. High primary porosity or uniformly distributed fractures.	Caves rare, small, have irregular patterns.
II. CONDUIT FLOW (coarse-textured permeability)	Thick, massive soluble rocks Conduits develop along bedding, joints, fractures, or fold axes.	Integrated conduit cave systems.
A. Perched	Karst system extends to considerable depth below base level.	Cave streams perched – often have free air surface.
1. Open	Soluble rocks extend upward to land surface.	Sinkhole inputs; heavy sediment load; short channel morphology caves.
2. Capped	Aquifer overlain by impervious rock.	Vertical shaft inputs; lateral flow Under capping beds; long integrated caves.
B. Deep	Karst system extends to considerable depth below base level.	Flow is through submerged conduits.
1. Open	Soluble rocks extend to land surface.	Short tubular abandoned caves likely to be sediment-choked.
2. Capped	Aquifer overlain by impervious rock.	Long, integrated conduits under caprock. Active level of system inundated.
III. CONFINED FLOW	Diffuse flow or free flow systems stratigraphically and structurally bound between beds of low permeability.	
A. Artesian	Impervious beds which force flows below regional base level.	Rare, small irregular caves (free flow). Inclined 3-D network caves.
B. Sandwich	Thin beds of soluble rock.	Rare, small irregular caves (diffuse flow). Horizon 2-D network caves.

Conduit flow is related to submerged karst features formed during glacial lowstands. Conduit flow is believed to be responsible for the precipitation of marine cements in limestones during *in situ* chemical and biological processes (Land and Goreau, 1970). A corresponding drop in pressure allows slow channelized flow to accelerate to higher velocities through conduits as required by the conservation of mass.

Ground-water movement in the White Limestone aquifer on Jamaica is controlled primarily by conduit flow (Versey, 1956; Walters, 1984; White, 1985; Mullings *et al*., 1993), and the general direction of flow is from exposed outcrops near the highlands (Central Inlier) toward the sea on the island's south side. Figure 3.8 shows a schematic diagram of the general direction of flow from the Central Inlier to the Caribbean Sea. Recharge areas are dominated by exposures of White Limestones and characterized by highly compartmentalized permeability. Surface exposures of White Limestone are characterized by the notable absence of surface streams due to its near-surface high permeability and well-developed subsurface drainage systems. Jamaica's surface runoff predominates on the outcrops of basement rocks in the Central Inlier. This surface runoff rapidly infiltrates as recharge when the runoff water flows to areas of exposed White Limestone. The surface water resources are characterized by a marked seasonal variability in flow.

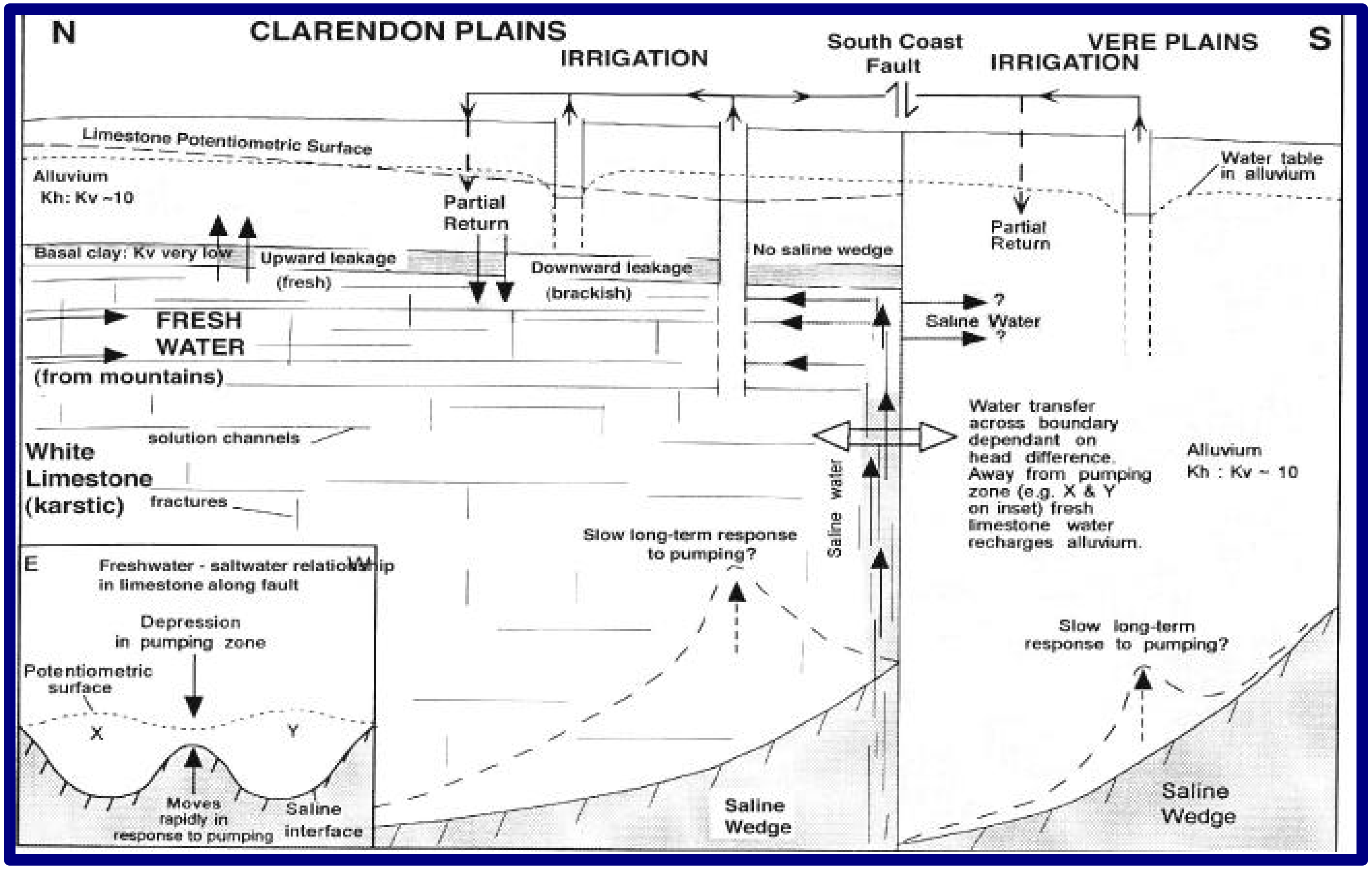


Figure 3.8 Schematic diagram of ground-water flow regime of the White Limestone Aquifer of the Rio Minho-Milk River basin (Source: Mullings et al., 1993)

Confining Unit (Red Marine Clay)

The red marine clay (interior valley clays) represents the confining unit that separates the confined White Limestone aquifer from the unconfined alluvial aquifer. The clay is discontinuously developed around both contiguous basins. This fine-grained thin layer ranges from less than 2 m to 24 m thick, is limited in extent and also has a low hydraulic conductivity value [1 x 10 10^{-6}m/d]. The confining unit allows the underlying White Limestone to become pressurized above atmospheric and therefore has a higher hydraulic head than the values than the overlying alluvial aquifer. However its effect cannot be ignored because of the differing head values of the overlying and underlying aquifers.

Alluvial Aquifer

The alluvial aquifer is predominantly a clayey unit, but within the upper 20 to 30 m of coastal alluviums, formation of sufficiently thick layers of intercalated sand and gravel are developed and functions as an aquifer in the Kingston, Rio Cobre, Rio Minho, and Blue Mountain Basins (Figure 1.8). The alluvial aquifer provides 4 % of the island's ground-water. Figures 3.9 and 3.10 show the top elevations of the alluvial aquifer relative to sea level within the study area, the thickness, and aerial extent. The aquifer represents an important source of irrigation water in the Rio Cobre and Rio Minho-Milk river basins and is a source of recharge to the confined sections of the White Limestone aquifer. The alluvial aquifer functions as a barrier to horizontal ground-water flow in some areas where clayey units predominate. Contact springs emerge from the White

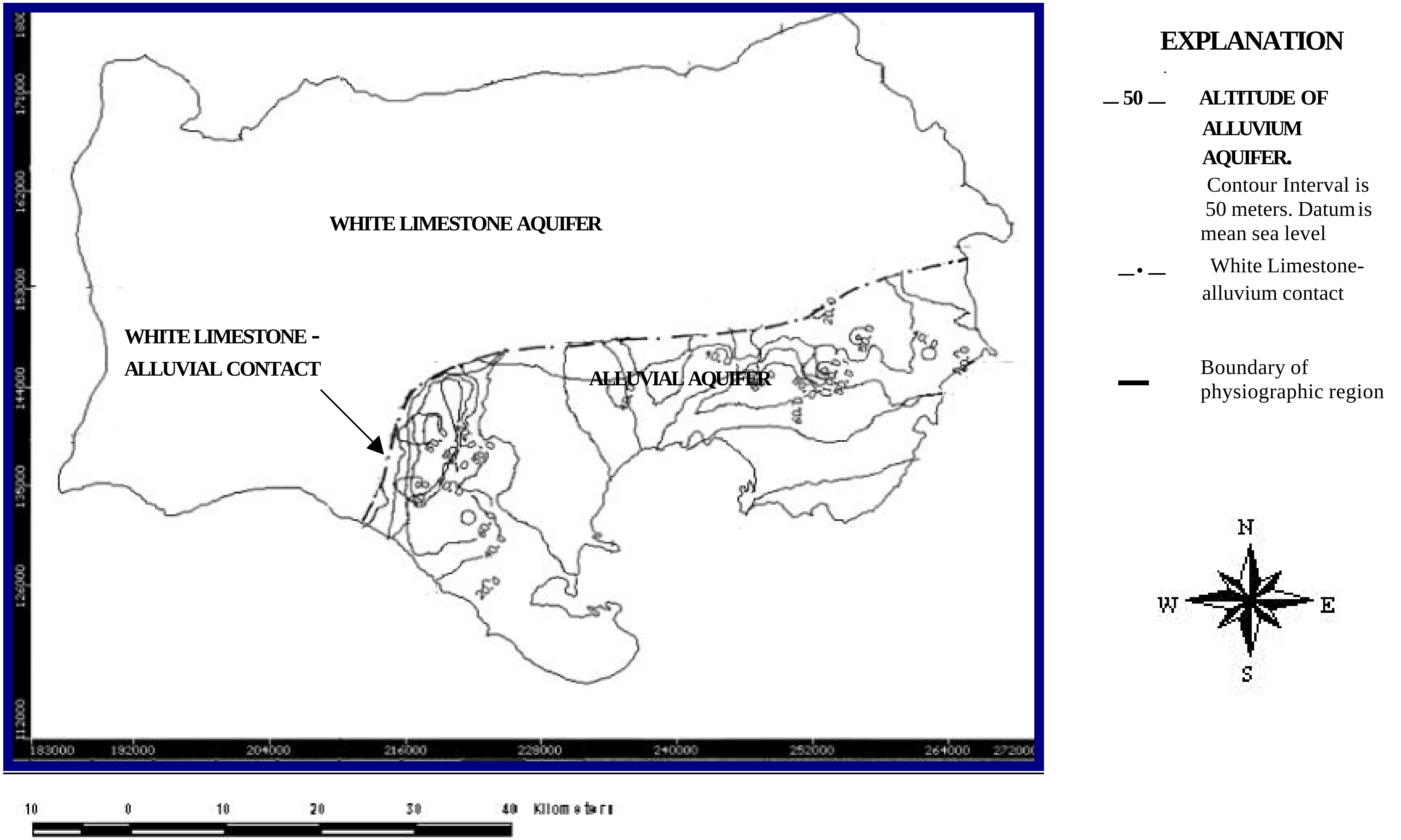


Figure 3.9 Altitude of top and areal extent of the Alluvium aquifer

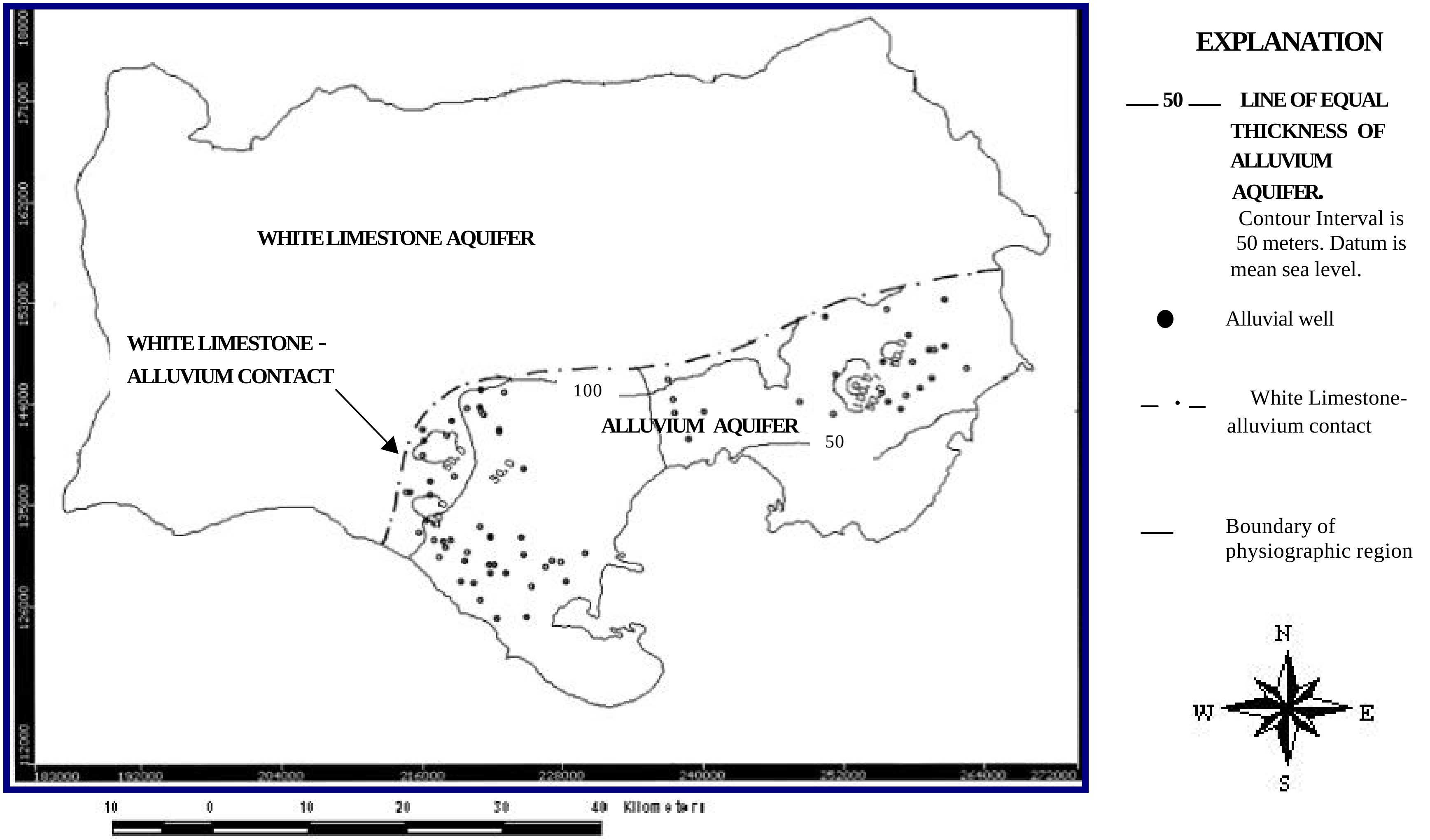


Figure 3.10 Thickness and areal extent of the Alluvium aquifer.