3. HYDROGEOLOGY

3.1 Geology

3.1.1 General Geology

The Study Area is underlain by a variety of pyroclastic and sedimentary rocks formed from Miocene to the Quaternary. For the basic geological condition, a geological maps prepared by MRD and available reports, such as the " Outline of the Geology of Viti Levu (1967)", interpretation SLAR imagery of the mains island of Fiji, 1987", and "Geology of Fiji, 1989". The compiled geological map of the Study Area is shown in Fig. 3.1.1. The stratigraphy of the Study Area is summarized below.

Age	Lithology	Formation
Quaternary	Clay, silt, sand and gravel	Alluvial deposits
	Mainly silty clay and silty sand, partly gravel layers	Terrace deposits
Pliocene	Hornblende andesite lava	Vatia series
	Biotite and augite andesite Tuff, mudstone, and grits	Tavua series
	Bedded basaltic flows and breccia (Nacilau volcano) Basalt and basaltic breccia Basaltic flows (pillow lava and columnar basalt) Tuffaceous sandstone, mudstone, and tuff Basic tuff with agglomerate Chloritized trachy basaltic volcanics Augite and hornblende andesite (Karavi volcanics)	Ba series
Mio-Pliocene	Andesitic breccia and flows Intercalation of andesitic breccia and sandstone	Koroimavua series
	Sandstone and conglomerate	Suva series
Miocene	Sandstone, argillites, and conglomerate	Sigatoka series
Pliocene ?	Intrusive rocks	

The oldest rock formation of the Study Area belongs to Sigatoka series of the Miocene crops out at a small limited area in the western part of Navala in the upper reaches of the Ba river. The Sigatoka series consists of sandstone, argillites, and a conglomerate, occurring in the shape of an anticline.

In ascending order of the stratigraphic sequence, the Suva series and the Koroimavua series were formed in the Mio-Pliocene age. The Suva series consists of conglomerate and the alternation of sandstone and shale which from 10 to 20 cm thick beds. The grayish to light greenish sandstone is very hard in the fresh parts, but weathering has generally progressed. The conglomerate was only partially observed, but tuffaceous breccias were predominantly observed accompanying the alternation of sandstone and shale instead of the conglomerate. The series is surrounded by the overlying Koroimavua series.

The Koroimavua series is formed of hornblende andesite and breccia locally intercalated with sandstone, occupying in the southwestern part of the Study Area. The sandstone layers seem to be affected by volcanic action and the bedding planes are frequently disconnected and folded by faults and foldings.

In the Pliocene, volcanic activities produced a huge amount of pyroclastic rocks of basalt, basaltic breccia, andesite. Tuffaceous sandstone, mudstone and tuff were also accompanied. These products are classified into the Ba series, the Tavua series and the Vatia series in ascending order, covering the most part of the Study Area.

The basalt and basaltic breccia are the most common types of rock occupying more than half of the Study Area from low hills to mountains.

The middle reaches of the Ba river, the southernmost part of the Study Area, and the uppermost reaches of the Ba river, are predominantly underlain by tuffaceous sandstone, mudstone and tuff. The bedding planes of the rocks dip gently at around 10°, in various directions. Cracks have developed in the sandstone and they appear to be rectangular in shape and about 50 cm in size.

The chloritized trachy basaltic rocks of the Ba series underlie the area of Rakiraki, surrounding a steep small mountain composed of intrusive rocks, about 5 km east of Rakiraki. The rock texture is similar to the andesitic rocks and very hard in the fresh part. The eastern peninsula of Rakiraki includes basic tuff with an agglomerate of the Ba series. Weathering of the tuffaceous rocks is developed in this part and the topography is gentle in general.

Typical pillow lavas of the Ba series are evident in the upstream reaches of the Yaqara river. Joints in a radial direction were frequently observed in the pillow lavas, but they are very hard in general.

Very hard augite and hornblende andesites of the Ba series underlie the moderately steep mountains in the northwestern part of Ba. The andesite is very hard in the fresh part but it is cracky in general. Generally, residual soil has developed thickly in this part.

The bedded basaltic flows and breccia of the Ba series are distributed at the west coast of the Study Area.

As for the Tavua series, the rocks of biotite and augite andesite form a circle of about 7 km in diameter in the eastern part of Vatukoula. This large circle is assumed to be a caldera. A sequence of tuff, mudstone, and grits of surround the above biotite and augite andesite, in the form of a circle band of about 0.5 km in width. These rocks form the outer wall of the caldera.

Thick hornblende andestic lavas of the Vatia series were observed on the Vatia peninsula in the western part of Tavua. The fresh andesite is grayish and very hard but joints have developed and vertical outcrops are evident on the steep slopes.

Other than the effective rocks, intrusive diorite rock crops about 5 km west of Rakiraki and about 3.5 km east of Vatukoula.

The flat plains several meters above the present riverbeds are composed of terrace deposits of silty materials with a thin intercalation of sandy materials formed in the Quaternary. Predominant terrace deposits were observed along the Ba river, Nasivi river, and Yaquara river. In the middle reaches of the Ba river the terrace deposits consists of mainly silty materials with rounded small gravel layers and thin shell layers, forming flat plains 5 m to 7 m above the present riverbed.

Alluvial deposits were predominantly observed along the Ba river, Nasivi river, Yaqara river, and Penang river. The soft sediments in the low and flat zone of old river channels in the downstream reaches of the Ba river, are included in the river deposits.

3.1.2 Geological Structure

According to the "Outline of the Geology of Viti Levu, P.Rodda (1967)", during the upper Miocene, sediments were deposited in several large basins, and in an elongated basin north-east of Sigatoka, which was apparently fault-controlled. Many of these rocks are now folded, but some of the synclinal features are probably caused by initial dip, compaction effects, and penecontemporaneous movement of faults. A broad anticline south-south-east of Ba shows progressively steeper dips in rocks of the Ba and Koroimavua series, suggesting intermittent rising of the core of the anticline over an extended period.

Several north-southerly faults, up to 10 km in length, which occurred in the lower Pliocene to Miocene dominate structurally in the south part of Study Area. The longest fault (Namau Fault), separates the sandstone and conglomerate of the Suva series and the intercalation of andesitic breccia and sandstone of the Koroimavua series at the south of Navala village.

The Tavua series in Vatukoula formed a typical caldera structure, caused by several volcanisms accompanied by subsidence and / or collapse of the volcanic mass.

According to results interpreted from aerial photographs in the Study Area, generally the lineaments directions are NW-SE and NE-SW. Most of the lineaments directions are NWW-SEE in the middle reaches of the Ba river, E-W, NW-SE and NE-SW in the upper reaches of the Ba river, E-W and N-S in the mountain between Ba and Tavua, NE-SW and NW-SE in the southern part of Tavua, NWW-SEE in the area of Vatukoula, NWW-SEE and NE-SW in the mountain between the Yaqara river and Rakiraki, and NWW-SEE, NE-SW and NE-SW in the Rakiraki area.

Lineaments interpreted by SLAR imagery (D.I.J.Mallick and F.Habgood, 1987) were also included in the geological map. Their remarkable directions are E-W and NE-SW in the middle reaches of the Ba river, NW-SE and NE-SW in the upper reaches of the Ba river, NW-SE and NWW-SEE in the western part of Ba, E-W, NE-SW, NWW-SEE, and NEE-SWW in the area of Vatukoula, and NWW-SEE, NEE-SWW, and NW-SE in the area of Rakiraki.

3.1.3 Geophysical Prospecting

Geophysical prospectings were carried out for confirmation of the fractured zones and water bearing beds by electromagnetic sounding and electric sounding in the first and second field investigations (See the details in APPENDIX-B).

According to results of the electromagnetic sounding, most of the apparent resistivity values are less than 100 ohm-m, and more than half of them are less than 30 ohm-m. This indicates that the surface is composed of highly weathered material. The phase angle values mostly vary between 15° and 60°. Many low resistivity anomalies may be found, but most of them are likely to be due to weathering of the surface because of their phase angles of less than 45° indicating that the lower part is more resistive than the surface.

Water within the faults and fractures in the volcanics will produce distinctive low resistivity anomalies against the solid rock.

Some promising areas with faults and fractured zones can be found where distinct low resistivity anomalies and phase angles of more than 45° exist, indicating that the lower layer is more conductive than the surface. Their locations are shown in Fig. 3.1.2. Fairly significant anomalies are found in line 2, 12, 31, 32, 35, 41, and 42.

According to the interpretation of the electric sounding and compared with the existing MRD well data, the main aquifer is probably in the low resistivity zone beneath or between the high resistivity layers. A resistivity boundary of 30 ohm-m can be roughly divided into low and high resistivity zones, which may be subdivided into two zones by boundaries of 10 ohm-m and 100 ohm-m, respectively.

The low resistivity zone will correspond to the weathered volcanic and sedimentary material or fractured zone, and the high resistivity zone will reflect fresh volcanic rocks. The very low resistivities of less than 10 ohm-m possibly point to a higher clay content or a higher groundwater salinity. Consequently, the aquifer zone in this area is likely to be characterized by resistivities of less than about 30 ohm-m beneath or between the high resistivity zones. The areas with the above mentioned resistivity structures are shown in Fig. 3.1.2.

The test well sites were finally determined by considering the geophysical prospecting results which indicated low resistivity anomalies. The detailed drilling results are shown in APPENDIX-C.

3.2 Test Well Drilling and Pumping Test

3.2.1 Drilling Operation

Test well drilling works were executed with an average depth of 70 m in order to understand the aquifer at the eleven sites selected as indicated in Fig. 3.2.1 and Table 3.2.1. The target depth of the test wells was determined by the depth of the existing wells, and from the hydrogeological and geological information of The Study Area. The drilling work commenced on January 21, 1994 using MRD's rotary type drilling rig (Model Top-200) which had been repaired with the assistance of JICA. Three test wells, TW004, TW005, and TW010 were completed in the initial period, before the end of March 1994.

The drilling work resumed on May 23, 1994 using two drilling rigs, one of which, Top-300, was provided for the Study by JICA. The drilling work was carried out smoothly on eleven sites using the direct rotary method and completed by the end of August 1994 as shown in Fig. 3.2.2. The details of the drilling records and the tests of each well are described in APPENDIX-C.

The proposed site TW007 was relocated to TW012 because no agreement could be reached regarding land acquisition. During the drilling of the TW006 test well, it was observed that after drilling was completed to a depth of 70 meters, the water coming from the deeper aquifer possessed an objectionable odor, while the water from the shallower aquifer seemed to be of good quality. Therefore, an additional shallow borehole (TW006A) was drilled to a depth of 21.3 meters adjacent to TW006. Then, the drilled borehole of the original TW006 was filled with sandy material and covered with cement to a depth of 18 meters, leaving the upper aquifer uncovered.

3.2.2 Casings and Screens

Steel pipes six inches in nominal diameter were used as casing pipes. Stainless wedge wire wound type screens, six inches in nominal diameter, were employed. Before the installation of the string of casings and screens, geophysical logging was carried out on each drilled hole in order to justify the location of the water bearing section in relation to the geological records. Geophysical logging was carried out using the GEO-LOGGER 3030 MARK2 to inspect normal resistivity, SP, temperature, and gamma rays. Screens were assembled to fit with the location of the water bearing fissure zone of the consolidated rock or the gravely bed. Steel pipes eleven inches and nine inches in nominal diameter were also used for temporary surface work.

3.2.3 Gravel Enveloping

Sieved natural gravel ranging from 3 to 10 mm in diameter was employed to envelope the string of casings and screens of each test well, except the stable drilled holes in consolidated rock masses. The gravel was placed into the annular space between the wall of the drilled hole and the string of casings and screens from the ground surface using a bucket and, then, the top portion of the annular space was sealed with cement mortar up to the ground surface.

3.2.4 Development

Initially the development of the test wells was carried out using the high velocity jetting method to remove drilling fluid and clogging materials from screens, gravel envelops and , the surrounding walls of rocks. This operation was continually carried out until the water become almost clean with only small quantities of sand present.

The air lift method was then applied in the second stage of development, using an air pipe which was lowered to the bottom of the drilled hole. Final development was executed using the over pumping method by utilizing the test pump. Pumping was continually carried out until the water became free of sand. In the case of TW002 drilled in an unconsolidated bed under the Ba river, the overpumping method was conducted for 130 hours in order to remove bentonite.

3.2.5 Pumping Tests

Pumping tests were carried out on eleven test wells from June to August 1994, using a step drawdown test, a continuous pumping test for 48 hours, and recovery observations. The results of the pumping tests are shown in Table 3.2.2.

The step drawdown test was performed using four steps of pumping rates in each test well to evaluate the productivity of yield and well loss at each test well. The constant pumping rate for each step was maintained for 3 hours. The step drawdown test was carried out on only seven of the eleven test wells, because of the poor yield of some test wells.

Continuous pumping test were executed on eleven test wells for 48 hours, pumping at a constant rate, to confirm the hydrogeologic constants. However, it was impossible in four of the eleven test wells to maintain a constant pumping rate for 48 hours because of the poor yield. Instead, pumping tests were additionally applied to two of MRD's existing boreholes to confirm the existence of water bearing rock and their hydrogeologic constants.

3.3 Aquifer

3.3.1 Groundwater Recharge Conditions

The Study Area is located in the northern coastal area of Viti Levu. The Ba, Nasiebi, Yaqara, and Penang rivers drain this area and flow from the southern mountainous region to the northern flat coastal plain through low undulating hills. The mountainous regions and low undulating hills are underlain by consolidated pyroclastic rocks and lava formed in the Miocene-Pliocene, which are partly intercalated with sedimentary rocks. Some alluvial deposits exist on the riverbeds and in the coastal area covering the above-mentioned volcanic materials.

According to the meteorological and hydrological study, the recharging amount of rainfall is estimated to be between 485 and 843 mm / year, which is equivalent to 25 to 38 per cent of the basin mean rainfall. The runoff ratio is affected by topography and geology, as well as by land use. In the mountainous slope forest is not predominant but grass grows widely. Low undulating hills are utilized for sugar cane fields. About 80 per cent of annual rainfall occurs during the rainy season. Therefore, it is inferred that a large amount of rainfall immediately flows out as surface runoff, and a major part of the recharge flowing into the subsurface weathered zone will return to streams which flow on impervious hard rock.

The shallow aquifer can receive a certain amount of recharge from rainfall. However, percolation from the shallow aquifer to the deep aquifer is less effective because of the permeability of the consolidated rock masses.

3.3.2 Water Bearing Bed

In North Viti Levu, as shown on the Geological Map in Fig. 3.1.1, the main lithological units are Quaternary deposits, Pliocene basaltic rock, Mio-Pliocene andesitic brecccia, sedimentary rock, Miocene sandstone, and conglomerates. The water bearing bed of the Study Area has been classified into three types of aquifer based on the geological information and test well drilling results.

(1) Quaternary aquifers

Alluvial deposit aquifers are the most common exploitable groundwater sources in many regions. However, boreholes are generally not drilled in these deposits in the Study Area, because the groundwater potential is relatively low and drilling is difficult.

The Quaternary deposits are composed of alluvial deposits and terrace deposits, which are located in limited narrow areas along the Ba, Nasivi, Yaqara, and Penang rivers. These deposits consist of clay, sand, and gravely materials which sometimes form low permeable shallow aquifers.

According to the data of TW002 in the yard of the PWD depot in Ba, gravel and coarse sand layers continue for about 30 m in depth near the Ba river. These gravel and sand layers seem to be a middle potential aquifer. According to the electrical prospecting, the middle reaches of the Ba river and the lower reaches of the Nasivi river show fine impervious deposits.

River terraces elevated several meters above the present riverbed have formed along the river channel of the Yaqara river. The terrace deposits consist of rounded gravel of an average 20 ~ 30 cm in diameter. The terrace deposits seem to bear groundwater and are considered to be potential aquifers. Results of the electrical prospecting and data of abandoned boreholes show imperious sediments and sea water intrusion in the Penang river alluvial flat plain. The groundwater from TW002 does not satisfy the criteria for a potable water supply, due to high Iron (Fe) and Manganese (Mn) levels. This tendency is the same as the other alluvial aquifers in Viti Levu.

(2) Tertiary sedimentary rock aquifer

In contrast to the Quaternary sediments, Tertiary sediment sequences usually exhibit a rather insistent stratigraphy. The primary porosity of a layer of Tertiary sediments is often strongly reduced by compaction and cementation. Water bearing beds with secondary porosity are usually aligned along the bedding plane's fractures and joints.

This type of aquifer is mainly distributed in the low hill area along the Ba river in the south of Ba. Tertiary sediment rocks consist of tuffaceous sandstone and mudstone. Tuffaceous sandstone of the Ba series was confirmed at the left bank of the Ba river near Moto by TW003 (77 m). According to the geological log, this formation is compacted and solid without a fractured zone. Therefore, groundwater development is not expected from the tuffaceous sandstone.

Tuffaceous mudstone of the Ba series was deposited at the right bank of the Ba river in the Koronubu area. TW006 was drilled up to 76 m to confirm the permeability of the tuffaceous mudstone. According to the geological log and driller's information, tuffaceous mudstone has several fractured zones. These are confined aquifers with self-flowing heads and moderate to high permeabilities. However, very high electrical conductivities, 1,400 micro-simens /cm, show at the fractures below 31.7 m. The existence of high electrical conductivities and bad odor, indicate stagnant aquifer conditions. Therefore, the development potential of the fractured aquifer in the tuffaceous mudstone is expected at only the most shallow rechargeable fractured water bearing bed (10 to 20 m in depth). According to the existing well data and electrical prospectings, the distribution of water bearing fractured mudstone beds is located in a limited area of Koronubu.

Older Tertiary sediments in the higher elevation areas which belong to the Suva series, Sigatoka series, and the lower part of the Ba series are not expected to develop groundwater, due to their steep topographic condition with stronger compaction and cementation.

(3) Volcanic rock aquifers

Volcanic rocks have various hydrogeological properties including excellent aquifers and impervious layers. Excellent aquifers usually occur in porous lavas and loose pyroclastic flows of recent age (Quaternary period). However, older volcanics (Tertiary) are generally poorer aquifers than Quaternary volcanics, due to the sedimentation of secondary minerals into fissures and weathering.

There are no Quaternary volcanic rocks found in the Study Area. Consequently, fractured volcanics are the most common type of volcanic aquifer in the Study Area. These types of aquifers generally consist of weathered porous fractured zones or sheared zones of the Ba volcanic series. Other volcanic rocks belong to the Vatia series, Tavua series, and Koroimavua series, and Intrusive rocks seem to be generally impermeable except the open fractures and joints.

Bedded basaltic flows and breccia (Nacilau volcanics) is distributed in the most western area of the Study Area. They are characterized by a generally low permeability, due to having less fractures.

The most intensively developed aquifer in the Study Area is the very hard dark grayish augite and hornblende andesite (Karavi volcanics) underlying the moderately steep mountains in the Karavi and Raviravi areas in the northwestern part of Ba. The andesite is very hard in the fresh part but in some places it is cracked and permeable therefore forming a good aquifer. However, the ratio of unsuccessful boreholes is relatively high due to the unexpected distribution of open joints and fractures. The aquifer is generally 20 to 40 m below the surface.

Many boreholes are drilled in basalt and basaltic breccia of the low hill areas, because it is widespread along the northern coast except the Tavarau-Raviravi area, Vatia penisula, Vatukoula caldera, and the Rakiraki area. The potential for groundwater in the rock formation is either low or high depending on the intensity of the fracturing.

Generally, the low hill areas between the Ba river and the Nasivi river have medium potential aquifer conditions. However, the low hill areas between the Nasivi river and the Yaqaqra river are poor, except the basalt and agglomerate rock aquifer of the Yaqara river. The high fracturing volcanic rock aquifer at GW254 in Yaqara possesses the highest specific capacity (19.64 l/s/m) of the Study Area. The specific capacity usually ranges from 0.01 to 0.59 l/s/m. The main aquifer is generally situated from 10 to 50 m below the surface. However, TW001 and TW008 show a deeper depth of aquifer, because these well are located at a higher elevation. For example, Screens in the TW001 were installed 43.1 to 69.35 m below surface.

Typically very hard pillow lavas are evident in the steep mountain area of the upstream reaches of the Yaqara river, forming an impermeable layer. The chloritized trachy basaltic rocks underlie the Rakiraki area and surround the small steep mountainous area composed of intrusive rocks, about 5 km east of Rakiraki. According to the geological log of TW011, these rocks are non water bearing beds, because very hard compacted rocks and thick volcanic ash were found underlain by strong weathered clayey rocks.

3.3.3 Hydraulic Constants

(1) Well loss of JICA test wells

The step drawdown test is used to determine the efficiency of the pumping well. It is reasonably understood that the drawdown of the water level by pumping includes two components, namely the drawdown of an aquifer loss in accordance with the aquifer characteristics, and the drawdown of a well loss caused by turbulent head loss in and around the well screen. The well loss is associated with turbulent flow and is expressed as,

$$Sw = BQ + CQ^2 \quad \text{or} \quad Sw/Q = B + CQ$$

where:	Sw	:	Total drawdown
	Q	:	Discharge rate
	B	:	Aquifer loss coefficient
	BQ	:	Aquifer loss
	C	:	Well loss coefficient
	CQ^2	:	Well loss

Therefore, the total drawdown Sw consists of the aquifer loss BQ and the well loss of CQ^2. Evaluation of the well efficiency is expressed in Table 3.3.1. Generally, test wells were showing a large ratio of well loss (54 % to 84%) that is probably caused by the small drilling diameter and the limited opening of fractured rock. Because, the larger diameter wells (TW002 and TW006) show a rather small ratio (24 % to 35%) compared with the smaller wells. Another point of view, is the range of specific capacity is showing from 0.1 to 0.6 l/s/m which means the drawdown is very large compared with the pumping ratio.

(2) Transmissivity of the Study Area

Transmissivity is calculated by applying Jacob's modification of the non-equilibrium formula . The analyzed results of the pumping tests are shown in Table 3.3.2. The values of transmissivity obtained can be classified into three groups.

The first group, has a large transmissivity of more than 200 m^2/day, expecting high groundwater development potential in the Study Area. However, more attention will be paid to the evaluation. In the case of GW254 in Yaqara, based on the initial drawdown data collected during the pumping tests, a large transmissivity

(2,676 m^2/day) was obtained by the gradual decline of the water level. However, the decline became steeper 5 hours after pumping started. As a result of the steeper decline, a smaller transmissivity of 829 m^2/day occurred. It is observed that the distribution of a better aquifer is limited around the test wells and that the surrounding rock mass possesses a much smaller transmissivity.

The second group has medium transmissivity (200 - 20 m^2/day) in medium fractured rock masses and alluvial formations. The test wells belonging to the second group can produce groundwater in 5 to 1 l/sec.

The third group has poor transmissivity of less than 20 m^2/day in the limited fractures of the consolidated volcanic rock masses where the test well yield is less than 1 l/sec of water with great drawdown.

According to the distribution of transmissivity in the Study Area, the low hill areas between the Ba river and the Nasivi river generally show better transmissivity compared with other areas, except for the Yaqara area.

3.4 Meteorology and Hydrology

3.4.1 General

The Study Area covers an area of 1,567 km^2 in the northern part of Viti Levu. As indicated in Fig. 3.4.1, annual rainfall varies from 1,800 mm along the coast to 3,800 mm in the mountains around Nadarivatu. The Study Area can be divided into the following nine drainage basins. Division into different basin is shown in Fig. 3.4.2.

Basin No.	River	Catchment Area (km^2)
1	(small creeks)	38
2	Ba	957
3	(small creeks)	55
4	Nasivi	191
5	Waisai, etc.	32
6	Yaqara	112
7	Korolulu,Wailoa, etc.	49
8	Nakauvadra / Penang	102
9	(small creeks)	27
Total		1,567

In general, the mountains in the upstream basin of the rivers possess very steep slopes and are not densely forested. The middle and lower reaches are cultivated for growing sugar canes. It seems that runoff concentration happens within a short period due to less retardation effect of the upstream basin. It is reported that the lower reaches of the major river basins are sometimes inundated when heavy rainstorms occur. Drought occasionally occurs in the dry season owing to the significant difference in rainfall between wet and dry seasons as well as the above mentioned basin characteristics. In the small catchment basins, in the dry season the amount of water in streams becomes very low, or almost no flow occurs. The rate of loss by evaporation might be relatively high, especially in the lower reaches which are mostly covered with sugar cane farmland. The following presents a preliminary estimation of average runoff and the recorded lowest flow at the principal stream gauges:

River	Stream Gauge	Catchment Area (km^2)	Average Runoff (m^3/sec)	Lowest Recorded (m^3/sec)
Ba	Toge	578.7	22.3	2.34
Ba	Navala	322.0	15.7	1.79
Nasivi	Vatukoula	96.0	2.3	0.17
Nakauvadra	Vatusekiyasawa	38.4	0.8	0.06

3.4.2 Rainfall Study

(1) Available records

The rainfall records were provided by PWD's Western Division and FMS on a daily basis from 32 rain gauge stations. The stations possess records which were collected over a different length of time. The records collected over the longest periods of time were obtained at Rarawai Mill (from 1925), Penang Mill (from 1930), and Nadarivatu (from 1936). However, the collection of records was interrupted around the 1960s or 1970s. Several of PWD's stations were installed with automatic recorders in the early 1980s.

(2) Review of the records

Before estimating the basin mean rainfall, the daily rainfall records for the 32 stations were reviewed by the following process:

1) Check of missing records
2) Examination by double mass curve
3) Examination by correlation
4) Interpolation of missing records based on correlation

After the process of review, the rainfall records used for the estimation of the basin mean rainfall were selected taking into consideration the recorded period and the location of the rain gauge stations. The 23 stations selected are shown below.

No.	Station	Period of Records	No.	Station	Period of Records
V7748C	Tavua Filter House	1970-1992	V77765	Vaturu Met	1982-1992
V77482	Tagitagi	1956-1992	V7775D	Nadrugu	1983-1992
V77491	Yaqara	1965-1992	V7777A	Bukuya Depot	1981-1992
V77554	Lololo Pine	1979-1992	V7778A	Nanoko	1983-1992
V77563	Varoka	1981-1992	V77794	Nadrau Met	1977-1992
V7756D	Ba Filter House	1960-1992	V78311	Penang Mill	1930-1992
V77571	Veisaru	1956-1992	V7831B	Vaileka Depot	1970-1992
V77581	Vatukoula	1965-1992	V78401	Drauniivi Pine	1979-1992
V77591	Nadarivatu	1936-1992	V7840B	Vatukacevaceva	1983-1992
V7765A	Navilawa	1972-1992	V7841A	Narara	1971-1992
V7768A	Navala	1981-1992	V7850A	Naseyani	1971-1992
V77691	Taunabe	1982-1992			

(3) Basin mean rainfall

For the low flow study discussed in the succeeding section, the basin mean rainfall is generally required for a period of at least 20 years. However, at almost half of the stations the recorded periods were less than 20 years. The following methods were therefore applied in order to estimate the basin mean rainfall for longer periods.

1) Basin mean rainfall for the last 10 years : Case 1

The Thissen Polygon was formulated using the 23 rain gauge stations mentioned above, as shown in Fig. 3.4.3. The basin average rainfall was estimated for the period from 1983 to 1992.

2) Basin mean rainfall for a long period : Case 2

The Thissen Polygon was formulated using the 12 rain gauge stations where the records were collected over the longest period of time, as shown in Fig. 3.4.4. The period was determined to be 22 years, from 1971 to 1992, according to the availability of records.

3) Conversion

The basin mean rainfall was obtained using the following equations:

$R_b = R_1$ (1983-1992)

$R_b = R_2 \times CF$ (1971-1982)

$CF = R_{1ave} / R_{2ave}$

Where, R_b : Basin mean rainfall

R_1 : Basin mean rainfall calculated by "Case 1"

R_2 : Basin mean rainfall calculated by "Case 2"

CF : Conversion factor

R_{1ave} : Average annual rainfall of "Case 1" (1983-1992)

R_{2ave} : Average annual rainfall of "Case 2" (1983-1992)

The basin mean rainfall was estimated for the upstream basins of the stream gauges such as Toge, Vatukoula, and Vatusekiyasawa. The basin mean rainfall was also estimated for the nine catchment basins in the Study Area. The average annual rainfall of each basin is presented below:

Upstream Basins of the Stream Gauges :

River	Stream Gauge	Catchment Area (km^2)	Basin Mean Rainfall (mm)
Ba	Toge	578.7	2,700
Nasivi	Vatukoula	96.0	2,666
Nakauvadra	Vatusekiyasawa	38.4	2,389

9 Catchment Basins

Basin No.	River	Catchment Area (km^2)	Basin Mean Rainfall (mm)
1	-	38	2,118
2	Ba	957	2,517
3	-	55	1,839
4	Nasivi	191	2,311
5	Waisali	32	1,807
6	Yaqara	112	2,193
7	Korolou/Wailoa	49	2,203
8	Penang	102	2,360
9	-	27	1,990

3.4.3 Runoff Study

(1) Available records

The river stage records were collected from four stream gauging stations: the Toge and Navala stations on the Ba river, the Vatukoula station on the Nasivi river, and the Vatusekiyasawa station on the Nakauvadra river. Since the stages were recorded on an hourly basis, an arrangement was made to compare the hourly river stage to the daily mean runoff using the stage-discharge rating equations for the respective gauging stations. However, the rating equations did not cover the whole periods for which the river stage records were available. The availability of the river stage data and the stage-discharge rating equations are listed below:

Station	Period of River Stage Record	Period of Rating Equation
Toge	1979 - 1992	1979 - 1986
Navala	1982 - 1992	1982 - 1985
Vatukoula	1977 - 1992	1977 - 1985
Vatusekiyasawa	1980 - 1992	1980 - 1984

(2) Review of records

For the low flow study discussed in this section, continuous runoff records for at least 20 years were generally required. However, the period of collection of the available runoff records was less than 10 years, and it was found that a significant number of records were missing. A runoff simulation model was therefore applied in order to provide long-term runoff records for the low flow study.

The simulation model requires runoff records and the mean rainfall of the basin upstream of an objective stream gauge. The runoff records to be used for the simulation model were selected from the available records in the period where the number of missing records is small.

River	Stream Gauge	Period of Runoff Records
Ba	Toge	1982 - 1986
Nasivi	Vatukoula	1982 - 1985
Nakauvadra	Vatusekiyasawa	1981 - 1984

The selected runoff records were examined using the double mass curve with the mean rainfall of the upstream basin. The results of this examination were judged as acceptable.

(3) Outline of the runoff simulation model

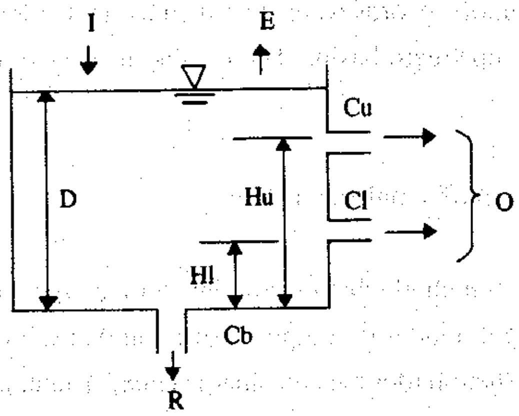
The tank model method which is a serial storage type model was applied for the runoff study. The tank model is composed of a number of containers which indicate the catchment basin (hereinafter the container is called a 'tank').

The tanks have several holes on their sides and bottoms. Rain enters the top tank first then passes into the lower tank through holes on the bottom of the upper tank. Water also passes through holes on the sides of the respective tanks. Water moving through the bottom holes indicates infiltration, while runoff moving through the side holes of all the tanks indicates river discharge.

Normally, low flow can be analyzed by the serial tank model using four containers. Each tank represents the runoff mechanism on the ground surface or layer, and is a component of the runoff hydrograph, which are generally considered as follows:

Tank	Ground Surface/Layer	Runoff Component
Top	Surface	Surface Runoff
2nd	Surface Layer	Intermediate Runoff
3rd	Lower Layer	Groundwater Runoff (Baseflow)
4th		

At some time step runoff and infiltration of a tank are calculated using the following diagram and equations:



(1) $D' = D + I - E$

(2) $O = (D' - Hu) \times Cu + (D' - Hl) \times Cl$ $\quad (D' > Hu)$

$O = (D' - Hl) \times Cl$ $\quad (Hl < D' < Hu)$

$O = 0$ $\quad (D' < Hl)$

(3) $R = D' \times Cb$

(4) $D'' = D' - O - R$

Where,

I	:	Rainfall or infiltration from the upper tank
O	:	Runoff
R	:	Infiltration to the lower tank
E	:	Evapotranspiration
Cu	:	Coefficient of the upper hole on the side
Cl	:	Coefficient of the lower hole on the side
Cb	:	Coefficient of the bottom hole
Hu	:	Height of the upper hole from the bottom
Hl	:	Height of the lower hole from the bottom
D	:	Depth of water (storage of tank)
D'	:	Depth of water after calculation process (1) above
D"	:	Depth of water after calculation process (4) above

Note : All variables are in mm.

Calculations are made for all tanks from the upper to the lower tanks. The sum of runoff from the side holes of all the tanks indicates river runoff. The reaming depth of each tank constitutes the initial depth for the next step, and the calculations are repeated using the same process.

The tank model can express the following complicated runoff phenomena:

- Initial loss depending on previous rainfall
- Non-linearity
- Runoff rate depending on the runoff magnitude
- Components of runoff, such as surface runoff, intermediate runoff, and groundwater runoff
- Lag time

The tank model is convenient in that runoff can be estimated using simple arithmetic.

The disadvantage of the tank model is that the constants, such as coefficients and the height of the tank holes, have to be determined by trial and error. It may take a lot of time for the calculations before the constants are fixed.

(4) Preparation of the runoff simulation model

The tank models were prepared for the upstream basins of the Ba river at Toge, the Nasivi river at Vatukoula, and the Nakauvadra river at Vatusekiyasawa. The inputs for the preparation of the tank models are listed below:

1) Catchment area of the objective basins
2) Runoff records observed at the stream gauges
3) Mean rainfall of the upstream basins for the period corresponding to that of the observed runoff records
4) Evapotranspiration estimated using the evaporation records
5) Constants of the tank model

Runoff could be computed once the tank parameters were set. The constants were analyzed by comparing the computed runoff with the observed runoff using the runoff hydrograph and flow duration curve. Model calibration was carried out by trial and error for setting the constants until the computed hydrograph and flow duration curve fit those of the observed. The constants, hydrographs, and flow duration curves obtained for the respective stream gauges are shown in Fig. 3.4.5 to 3.4.9.

(5) Low flow analysis

Using the tank model discussed above, long-term runoff was simulated on a daily basis for the respective stream gauges. The runoff was simulated for 22 years from 1971 to 1992 using the basin mean rainfall for the corresponding period. A flow duration curve was also prepared as shown in Fig. 3.4.10. The following results were obtained from the long-term runoff estimations:

Average Runoff and Loss(1971-1992)

Stream Gauge	Catchment Area (km^2)	Average Runoff (m^3/sec)	Runoff Depth (mm)	Basin Mean Rainfall (mm)	Loss (mm)
Toge	578.7	27.57	1,502	2,700	1,198
Vatukoula	96.0	2.73	897	2,663	1,766
Vatusekiyasawa	38.4	1.03	846	2,389	1,543

Low Flow

Stream Gauge	Catchment Area (km^2)	Period	Runoff (m^3/sec)		
			Average	95 %	Min.
Toge	578.7	1971-1992	27.57	3.06	2.44
Vatukoula	96.0	1971-1992	2.73	0.26	0.19
Vatusekiyasawa	38.4	1971-1992	1.03	0.10	0.06

3.4.4 Groundwater Recharge

The tank model discussed in this section aims mainly at evaluating river runoff, namely surface water. In addition, the tank model assesses the conditions of infiltration and storage in the ground layer, as well as the surface water. Accordingly, groundwater recharge can be estimated approximately by assessing infiltration and storage in the tank model. The following presents a preliminary estimation of groundwater recharge using the results of the tank model simulation.

Firstly, runoff from the respective tanks was assessed in order to clarify the components of the runoff hydrograph. Outflow from the side holes in the 3rd and 4th tanks could be considered as baseflow, which is the groundwater runoff. On the other hand, variations in the sum depth of the 3rd and 4th tanks were compared with those in the groundwater level continuously recorded. The variation patterns of both values were found to be quite similar. These results indicate that water moving through the holes in the bottom of the 2nd tank and 3rd tanks of the model can be assumed as groundwater recharge.

According to this assumption, groundwater recharge was estimated for each basin where the tank model simulation was carried out. Estimations were carried out for an average year and a drought standard year with a return period of 10 years. The values presented below were obtained through simulation conducted over 22 years (1971-1992):

Average Year

River	Basin	Catch-ment Area (km^2)	Average Year	Basin Mean Rainfall (mm)	/1 Direct Runoff (mm)	/2 Ground-water Runoff (mm)	/3 Recharge (mm)	/4 Evapotrans-piration (mm)
Ba	Upstream Toge G/S	578.7	1972	2,644	985	552	704	955
Nasivi	Upstream Vatukoula G/S	96.0	1981	2,532	568	226	843	1,121
Nakauvadra	Upstream Vatusekiyasawa G/S	38.4	1990	2,328	541	227	582	1,205

Drought Standard Year

River	Basin	Catch-ment Area (km^2)	Drought Standard Year	Basin Mean Rainfall (mm)	Direct Runoff (mm)	Ground-water Runoff (mm)	Recharge (mm)	Evaptrans-piration (mm)
Ba	Upstream Toge G/S	578.7	1983	2,100	808	209	495	797
Nasivi	Upstream Vatukoula G/S	96.0	1992	1,857	308	103	492	1,057
Nakauvadra	Upstream Vatusekiyasawa G/S	38.4	1980	1,589	243	112	319	1,027

Note :/1 Direct Runoff (DR)
The sum of runoff from the side holes of the top and 2nd tanks.

/2 Groundwater Runoff (GR)

The sum of runoff from the side holes of the 3rd and 4th tanks.

Total Runoff = (DR) + (GR)

/3 Recharge (G)

Runoff from the bottom holes of the 2nd and 3rd tanks.

/4 Evapotranspiration (E)

Evapotranspiration (E) can be calculated using the following equation.:

Basin Mean Rainfall (R) = (DR) + (G) + (E)

With reference to the above results, groundwater recharge for each catchment basin in the Study Area was estimated using the following equation.

$$G = Gg \times \frac{R}{Rg}$$

Where,

G	:	Groundwater recharge
Gg	:	Groundwater recharge for the gauged basin
R	:	Basin mean rainfall
Rg	:	Basin mean rainfall for the gauged basin

The estimated groundwater recharge in each catchment basin is shown in Table 3.4.1. The detailed assessment of groundwater recharge and development potential is discussed in Chapter 4.

3.4.5 Surface Water Potential

Surface water potential was evaluated under the following conditions:

1) Assumed development points:
   - Ba river at Toge G/S
   - Nasivi river at Vatukoula G/S
   - Nakauvadra river at Vatusekiyasawa G/S.
2) Return period of the drought standard year is set at 10 years.
3) The simulated minimum daily discharge year is assumed as the river maintenance flow.
4) No storage scheme is considered.
5) Possible development yield is derived from the daily discharge exceeding the river maintenance flow. Dependability of the yield is set at 95%, which means that a deficit occurs for 18 days during the drought standard year.

The daily discharge simulated by the tank model was used for the evaluations. The following results were obtained:

Ba River at Toge G/S

- Catchment Area	:	578.7 km^2
- Drought Standard Year	:	1983
- Min. Discharge	:	2.443 m^3/sec
- 95% Discharge in 1983	:	2.836 m^3/sec
- Possible Development Yield	:	0.393 m^3/sec (12.394 MCM/year)

Nasivi River at Vatukoula G/S

- Catchment Area	:	96.0 km^2
- Drought Standard Year	:	1992
- Min. Discharge	:	0.188 m^3/sec
- 95% Discharge in 1992	:	0.238 m^3/sec
- Possible Development Yield	:	0.050 m^3/sec (1.577 MCM/year)

Nakauvadra River at Vatusekiyasawa G/S

- Catchment Area	:	38.4 km^2
- Drought Standard Year	:	1980
- Min. Discharge	:	0.058 m^3/sec
- 95% Discharge in 1980	:	0.073 m^3/sec
- Possible Development Yield	:	0.015 m^3/sec (0.473 MCM/year)

The above results were referred to for the estimation of surface water potential in the whole Study Area. The following equation was applied for the estimation:

$$Y = Yg \times \frac{R}{Rg} \times \frac{A}{Ag}$$

Where,

Y	:	Possible development yield (MCM/year)
Yg	:	Possible development yield for the gauged basin (MCM/year)
R	:	Basin mean rainfall (mm/year)
Rg	:	Basin mean rainfall for the gauged basin (mm/year)
A	:	Catchment area (km^2)
Ag	:	Catchment area of the gauged basin (km^2)

Table 3.4.2 shows the results of the above calculation.

The possible development yield of each basin in the Study Area is estimated below:

No.	River	Catchment Area (km^2)	Possible Development Yield (MCM/year)	(m^3/year/km^2)
1.	-	38	0.638	16,800
2.	Ba	957	19.107	19,965
3.	-	55	0.624	11,344
4.	Nasivi	191	2.723	14,256
5.	Waisali	32	0.357	11,147
6.	Yagara	112	1.515	13,528
7.	Korlou/Wailoa	49	0.557	11,359
8.	Penang	102	1.241	12,168
9.	-	27	0.277	10,260

3.5 Groundwater Flow

3.5.1 Groundwater Flow

The groundwater level contours of the shallow aquifer in the dry and rainy season are shown in Fig. 3.5.1, based on the simultaneous water level observations of the dug wells. The groundwater in the shallow aquifer generally flows down from north to south and east to west. The general hydraulic gradient of the main area is as follows.

Season	Hydraulic gradient		
	Ba Uplands	Tavua Basin	Penang Basin
Dry	1:60 - 1:110	1:40 - 1:50	1:60 - 1:90
Rainy	1:50 - 1:100	1:50 - 1:60	1:50 - 1:80

The hydraulic gradient at the lower elevation exists almost in parallel to the surface gradients, but the hydraulic gradient of the high elevation area is more gentle than the surface profile due to the thick pervious residual soil.

The difference in the water level of each well ranges from 0.19 to 4.89 meters between the dry and rainy season.

3.5.2 Groundwater Level Fluctuation

Seven automatic water level recorders were installed at the existing MRD boreholes in October 1993, and 3 were fitted at the test wells drilled initially by the JICA Study Team, in order to observe the fluctuations of the water level of the wells. These recorders were installed in a shelter. However, 2 of the recorders at the existing MRD boreholes GW044 and GW042 were damaged by some people in May and August 1994, respectively. The location of these observation wells is plotted in Fig. 2.3.1.

The hydrographs of the observation wells recorded between October 1993 and August 1994 are shown in Fig. 2.3.2. Water levels in the boreholes are within 9 meters below the ground surface. The hydrograph shows two different types of fluctuation. One type of fluctuation indicates that the water level rises gradually, a little after the beginning of the rainy season, then it remains at an almost constant level until the beginning of the dry season, and then declines towards the end of the dry season. Water level fluctuations in the existing boreholes GW042, GW030, and GW035 belong to this type.

Another type of fluctuation shows that the water level rises rapidly, corresponding to the precipitation at the beginning of the rainy season and then declines gradually towards the end of the dry season. Annual fluctuations of the water level are greater in the latter than in the former. Annual water level fluctuations in these boreholes reach a maximum of 2.5 meters.

The hydrographs of the test wells are shown in Fig. 3.5.4. These indicate the same type of fluctuations as those of the former type of MRD boreholes. A disturbance on the TW010 hydrograph occurred during the pumping test. These different types of water level fluctuations could be caused by low permeable closed water bearing beds.

Tidal fluctuations of the water level ranging from 2 to 4 cm are observed at the existing boreholes GW013, GW014 and GW042. These boreholes are located 0.3 to 2.5 km from the coast.

Daily water level fluctuations have been measured at two selected dug wells. The hydrographs of these dug wells, which correspond to the daily rainfall at Ba town are shown in Fig. 3.5.5. Water levels rise immediately after heavy rain and decline immediately after the rain has stopped at both dug wells GW003 and GW028 with a range of 0.5 - 1.2 meters. The water level fluctuates more sharply in concordance to the amount of rainfall compared to that of the boreholes. The difference in the annual water level between the rainy season and the dry season at the dug wells is 2.2 meters.

Simultaneous observations of the well water levels were carried out to understand the groundwater flow conditions of 12 existing boreholes and 28 dug wells listed in Fig. 3.5.2, in both the dry and rainy seasons. Water levels range from 0.25 to 13.17 meters below the ground surface according to the measurement carried out in September 1993 in the dry season (See Table 3.5.1). The water level of the same wells was measured in the rainy season in March 1994. The difference in water levels of each well ranges from 0.19 to 4.89 meters between the dry and rainy seasons. In general, greater fluctuations occurred in dug wells than in boreholes.

3.5.3 Thermal Spring

Thermal springs are common in volcanic and tectonic activity areas. Thermal water usually originates from surface water or shallow groundwater. However, thermal water circulation covers a greater distance and takes a longer time compared with normal groundwater circulation. Because, water from the surface must move downward through faults or fractured zones to the deeper heating source. Water rises up toward the surface when its temperature rises above boiling point after reaching a heating source through other vertical fractured zones.

According to the existing hydrogeological map of Viti Levu (MRD 1991), several thermal springs exist in the Study Area. Four thermal springs and two springs were confirmed by the JICA-MRD Study Team. The thermal springs, which rise in volcanic rocks, are located in the sea and near the coast between Tavua and Rakiraki. The thermal spring of Waikatakata at Rabulu Road has a temperature of 44.9°C, which is the highest water temperature in the Study Area. The discharge rate of this spring is constantly about 5 l/s. However, the biggest thermal hot spring in the Garampani area on the northern side of Vatukola has disappeared due to a subsurface shaft constructed for Emperor gold mining. It is indicated that the hydrogeological conditions of thermal water are that it is rare and unstable

The biggest discharge rate for a spring is 50 l/s. The spring is located on the slope of a mountain in Wai Matalevu in the upper reaches of the Yaqara river. It rises in volcanic rock, and the water temperature is 25.6°C with low conductivity. Therefore, the recharged water of Wai Matalevu does not reach its heated source and is probably discharged through tubular channels or fractures in the shallow part of the volcanic terrain.

3.6 Water Quality

3.6.1 General

(1) Purpose of the Water Quality Analysis

The objectives of the Study were to evaluate the groundwater resources potential and formulate a groundwater development plan for providing North Viti Levu with an adequate and safe water supply. The main industries in the Study Area are sugar production and gold mining. A huge amount of agrochemicals and fertilizers are consumed for the cultivation of sugar cane, and these components infiltrate into the soil. Wastewater containing heavy metals is probably discharged into rivers and dust containing noxious materials falls onto the ground surface. In addition, the constituents of the groundwater change when the groundwater dissolves subsurface substances. For these reasons, a water quality analysis of the surface and subsurface water is very effective for studying the hydrologic circulation.

Therefore, the purpose of the water quality analysis was as follows:

1) to determine the suitability of groundwater as a potable water supply,
2) to analyze the circulation of groundwater based on its geochemical characteristics

The water quality analysis was scheduled to be carried out in both the dry season and rainy season, because the groundwater environment changes remarkably due to surface groundwater recharge. The water samples from the test wells were collected during execution of the pumping tests to avoid the influence of mud water from drilling and stored well water.

(2) Sampling Points and Date

The location of the water sampling points are shown in Fig. 3.6.1 and Fig. 3.6.2. The JICA-MRD Study Team examined the sampling points in regard to the existing wells' location, their hydrological environment, and other factors. 61 water samples were collected in the dry season and 64 in the rainy season, to analyze the potability of the water supply and geochemical investigations. In addition, 10 samples were collected in both seasons for an agrochemical analysis. The details of the locations are shown in Table 3.6.1.

The sampling dates are as follows:

	Dry Season	Rainy Season	Test Wells
Heavy Metals	: 11-12 Aug., 1993	1- 2 Feb., 1994	during the pumping tests
Agrochemicals	: 20 Aug., 1993	31 Jan., 1994	-
Physical and Geochemical Items	: 7- 9 Sep., 1993	1- 2 Feb., 1994	during the pumping tests

(3) Items and Methods of the Water Quality Analysis

The purpose of the water quality analysis was to determine the suitability of the groundwater as a potable water supply and to investigate the circulation of the groundwater. The JICA-MRD Study Team decided that the following 32 items should be studied as part of the water quality analysis:

1. Temperature	2. pH
3. Electric Conductivity (EC)	4. Color
5. Turbidity	6. Total hardness
7. Sodium (Na)	8. Potassium (K)
9. Calcium (Ca)	10. Magnesium (Mg)
11. Iron (Fe)	12. Manganese (Mn)
13. Ammonium (NH4)	14. Bicarbonate (HCO3)
15. Carbonate (CO3)	16. Chloride (Cl)
17. Sulfate (SO4)	18. Nitrite (NO2)
19. Nitrate (NO3)	20. Fluoride (F)
21. Copper (Cu)	22. Lead (Pb)
23. Zinc (Zn)	24. Chromium (Cr)
25. Cadmium (Cd)	26. Mercury (Hg)
27. Arsenic (As)	28. Cyanide (CN)
29. Aluminum (Al)	30. Silica (SiO2)
31. Total Dissolved Solids (TDS)	32. Agrochemicals (See Section 3.5.3)

The tests were conducted at the National Water Quality Laboratory of PWD. The water quality samples were examined according to the "Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WEF, 1992, 18th edition)".

The water samples for the agrochemical analysis were brought to Japan and examined using the gas chromatography-mass spectrometry method (GC-MS).

3.6.2 Suitability of the Groundwater as a Potable Water Supply

(1) Criteria of Water Quality for a Potable Water Supply

PWD possesses a water supply service where the guidelines of the World Health Organization (WHO) are applied in order to control the quality of the water supply. The essential constituents are as follows :

pH		6.5 - 8.5	
Color	less than	15	TCU
Turbidity	less than	5	NTU
Total hardness	less than	500	mg/l
Total dissolved solids (TDS)	less than	1,000	mg/l
Iron (Fe)	less than	0.3	mg/l
Manganese (Mn)	less than	0.1	mg/l
Aluminum (Al)	less than	0.2	mg/l
Chloride (Cl)	less than	250	mg/l
Sulfate (SO4)	less than	400	mg/l
Nitrate (NO3)	less than	10	mg/l
Fluoride (F)	less than	1.5	mg/l
Cyanide (CN)	less than	0.1	mg/l
Sodium (Na)	less than	200	mg/l
Copper (Cu)	less than	1.0	mg/l
Lead (Pb)	less than	0.005	mg/l
Zinc (Zn)	less than	5.0	mg/l
Chromium (Cr)	less than	0.005	mg/l
Cadmium (Cd)	less than	0.005	mg/l
Mercury (Hg)	less than	0.001	mg/l
Arsenic (As)	less than	0.05	mg/l

WHO reexamined and amended the criteria to more strict limits in 1993.

(2) Results of the Water Quality Analysis

The results of the water quality analysis are shown in DATA BOOK-C. The items which exceeded the WHO standards are shown in Fig. 3.6.3 and Fig. 3.6.4. The ratio of water quality exceeding the standards for potable water is shown in Table

3.6.2. The constituents' concentration level is compared with the standards for potable water. The regional characteristics of water quality are as follows:

1) The Eastern Area

This area is contained within the Penang river basin, the Wailevu-Narewa Coastal Plain, and the Yaqara River Basin. The results of the water quality analysis are different for the dry season and the rainy season. In the Penang River Basin during the dry season, the concentration level of Cadmium (Cd) in the water of the dug wells and the river is higher than the standards set. The concentration level of Sodium (Na) and Chloride (Cl) in the dry season, is about four times the amount stipulated by WHO due to saline water intrusion. Heavy metal contamination and saline water intrusion disappear in the rainy season. In the Penang River Basin and the Wailevu-Narewa Coastal Plain, the concentration level of Iron (Fe), Manganese (Mn), and Aluminum (Al) in natural water in the dry season is lower than the WHO standards. However, in the rainy season these concentrations are higher. Since these constituents are contained within the upper soil or aquifer, they are washed out during heavy rains in the rainy season. In the Yaqara River Basin, the concentration level of Iron (Fe), and Aluminum (Al) in the boreholes is higher than the WHO standards. This well is not in use, therefore, the presence of higher concentrations of the above are probably due to corrosion of pipes or the accumulation of groundwater.

2) The Central Area

This area is divided into the Rabulu Coastal Plain, the Tavua Basin, the Matalevu Uplands, and the Vatia-Lousa Coastal Plain. In the Rabulu Coastal Plain, the water quality is good in the dry season, but the concentration levels of Aluminum (Al) in the dug wells and/or hot springs is higher than WHO standards during the rainy season. In Tavua Basin, the concentrations of heavy metals such as Chromium (Cr), Lead (Pb), and Arsenic (As) in the branches of the Nasivi river exceed the standards for potable water because these branches receive wastewater from the gold mines. The concentration levels of Sodium (Na) and Chloride (Cl) in the lower reaches of the Nasivi river in the dry season are higher than the standards set by WHO because of saline water intrusion. Cadmium (Cd) in several dug wells exceeds the WHO standards in the dry season. In the Matalevu Uplands and Vatia-Lousa Coastal Plain, the concentration level of Iron (Fe) and Manganese (Mn) in the groundwater is sometimes higher than the standards set by WHO.

3) The Western Area

This area includes the Mountainous Area, the Koronubu Uplands, the Moto Uplands, the Ba Uplands, the Ba River Lower Plain, and the Tavarau-Raviravi Coastal Plain. The water quality in the upper reaches of the Ba river is very good in the dry season, but because of soil erosion in the rainy season, concentrations of iron (Fe) and aluminum (Al) exceed the WHO standards. In this area, the pH value and turbidity of the water of some dug wells are higher than the standards set, but the quality of water in the boreholes in the dry season corresponds to the criteria for a potable water supply. The concentration level of iron (Fe), manganese (Mn), and aluminum (Al) in the groundwater during the rainy season is sometimes higher than the WHO standards.

4) The Test Wells

The items exceeding the water quality standards for potable water were as follows:

Color	TW003, TW005, TW009, TW011
Turbidity	TW003, TW005, TW009
Iron (Fe)	TW002, TW003, TW005, TW009
Manganese (Mn)	TW002, TW003, TW005, TW009
Aluminum (Al)	TW003, TW005, TW009

The water quality of five test wells (TW001, TW004, TW008, TW010, and TW012) was very good and did not exceed the standards. Iron (Fe), manganese (Mn), and aluminum (Al) are generally contained within soil or strata, and are dissolved in the groundwater. Iron or manganese ions cause coloring or turbidity to exceed the standards.

3.6.3 Influence of Agrochemicals and Fertilizers

(1) Use of Agrochemicals and Fertilizers and Their Criteria

The main industry in the Study Area is sugar production. Therefore, the land in this area is used mostly for sugar cane fields. Many agrochemicals and fertilizers are consumed in sugar cane planting. The different kinds of agrochemicals which are now used are shown below :

	Commercial Name	Technical Name	Application
For Sugar Cane	Butoxone	dicamba + 2,4-D	pre-planting
	Cane Spray 333	dicamba + 2,4-D	pre-planting
	Diuron 90	diuron	pre-planting
	Gramoxone	paraquat	pre-planting
	Roundup	glyphosate	
	Velpar	hexazinone + diuron	post-planting
For Other Crops	Fusilade	fluazifop-butyl	post-planting
	Ronstar FLO	oxadiazon	post-planting
	Saturn EC50	benthiocarb 5-[4-chlorobenzyl] N, N-diethylthio-carbonate	
	Starn F34	propanil	

The criteria of agrochemical use in regard to potable water supplies were decided by WHO and the Environmental Protection Agency (EPA). The criteria of agrochemicals now being used in Fiji are as follows :

	WHO	EPA
2,4-D	< 0.03 mg/l	< 0.1 mg/l
glyphosate	-	< 0.07 mg/l
propanil	< 0.02 mg/l	-

The fertilizers being used in sugar cane planting are Ammonium Sulfate, Di-Ammonium Phosphate, and Triple Superphosphate.

The constituents dissolved from the fertilizers are mainly Nitrogen, Phosphorus, and Sulfur. Therefore, the criteria of these components are referred to in Section 3.6.2 (1).

2) Results of the Water Quality Analysis

The results of the agrochemical analysis in natural water are shown in DATA BOOK-C. The concentration levels of all agrochemicals are less than the limit of detection set by WHO and EPA for potable water. Therefore, contamination by agrochemicals does not take place in the Study Area in the dry season or the rainy season.

The concentration levels of the main fertilizers such as Nitrate (NO3) and Sulfate (SO4) are shown in Tables 3.6.2 to 3.6.4. The concentration levels of these fertilizers are less than the standards for potable water in all the water samples except for one sample. Therefore, contamination by fertilizers does not take place in this area.

3.6.4 Geochemical Characteristics of the Surface and Subsurface Water

The results of the geochemical analysis are shown in DATA BOOK-C. The tri-linear diagram and hexa-diagram of the mainly dissolved constituents are shown in Fig. 3.6.5 to 3.6.10.

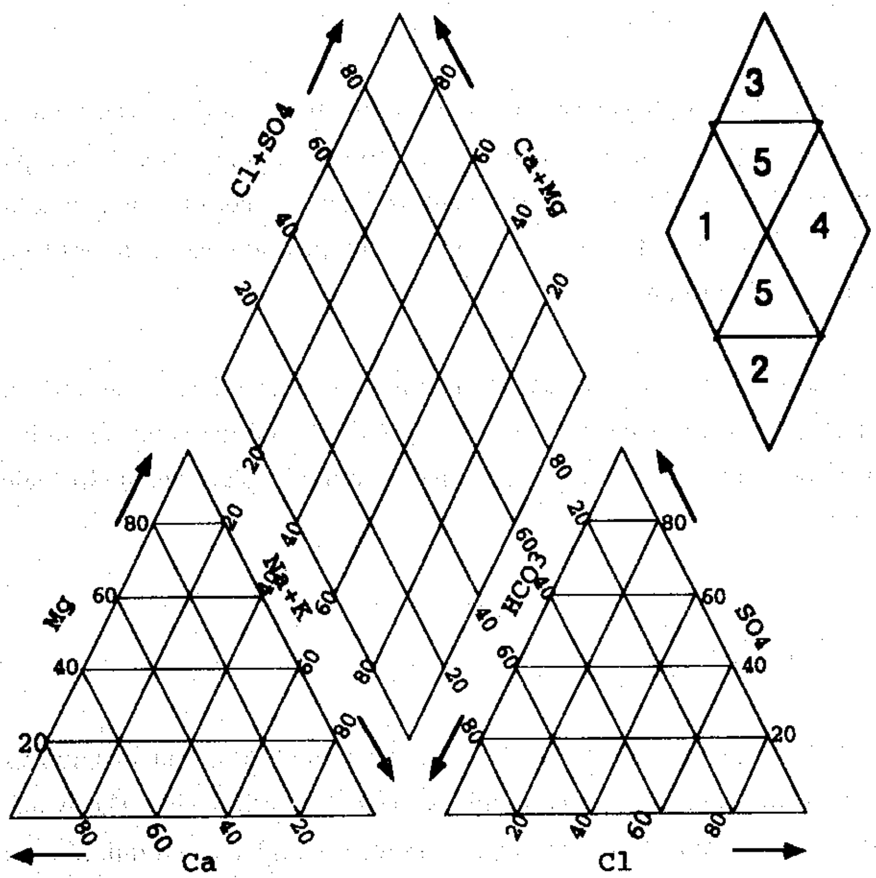
The principally dissolved components in the surface and subsurface water are the following seven ions :

Cations : Sodium (Na), Potassium (K), Calcium (Ca), Magnesium(Mg)
Anions : Chloride (Cl), Bicarbonate (HCO3), Sulfate (SO4)

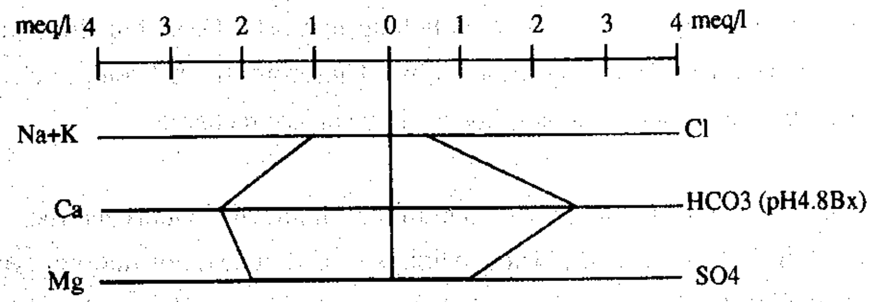
Water is classified into 5 types in the tri-linear diagram, as shown in the figure below. The amount of ions contained within the water is indicated in equivalent concentrations such as meq/l. The amount of each cation and anion in the water, expressed as a percentage of the total amount of cations respectively, was plotted in the tri-linear diagram shown below. The water is generally classified into 5 types according to the plotting position in the tri-linear diagram, as listed below :

Type - 1 Alkaline Earth Bicarbonate [Ca(HCO3)2 type]
2 Alkaline Bicarbonate [NaHCO3 type]
3 Alkaline Earth Non-bicarbonate [CaSO4 or CaCl2 type]
4 Alkaline Non-bicarbonate [Na2SO4 or NaCl type]
5 Internal Type (often combined with type-2 or 3)

Usually, types 1, 2 and 5 are normally fresh water, type 3 is volcanic or mine water, and type 4 typically sea water.



The hexa-diagram, as shown in the figure below, has three parallel coordinate axes, upon which the determined values of the six major ions were plotted. By connecting the six points, a concave or convex hexagonal shape is obtained, the shape and size of which vary according to the concentration of the constituents. The trilinear and hexa-diagrams were prepared on the basis of the circulation of groundwater in the Study Area.



The regional geochemical characteristics are summarized below :

(1) The Eastern Area

In the Penang River Basin, the constituents of the river water and groundwater are $Ca(HCO_3)_2$, or natural fresh water. But the composition of sample No. R011 belongs to NaCl in the dry season because of saline water intrusion. The water sample SP001 was obtained at a hot spring and its composition was different from that of the groundwater in this area.

The Wailevu-Narewa Coastal Plain is located near the sea, but the constituents of the surface and subsurface water are $Ca(HCO_3)_2$, and the concentration of dissolved ions is low. Thus, saline water intrusion does not take place and hydrologic circulation is rapid.

(2) The Central Area

In the Rabulu Coastal Plain, the water sample SP002 contains more sodium than any other ions, but the sample point is located on a hillside. The water belongs to $CaSO_4$ or $CaCl_2$ type however, the reason for the high concentration of sodium fossil water seepage. The composition of the other sample points are $Ca(HCO_3)_2$ or internal type, which is representative of normal groundwater.

In Tavua basin, the water is classified as $Ca(HCO_3)_2$ or internal type, except for sample No. R014 and GW020. The concentration level of sodium and chloride in R014 is very high because of saline water intrusion both in the dry and rainy seasons. The mainstream of the Nasivi river contains a meager supply of ions, but the samples from the branches, such as sample No. R017 or R016, have a very high concentration of ions probably due to discharge from the gold reduction plants. The constituents in the water of the dug wells in this area belong to $Ca(HCO_3)_2$, but the concentration levels are very different among these wells. Therefore, the hydrologic circulation of groundwater is rather local and is influenced by surface recharge.

The constituents in the groundwater of the Matalevu Uplands and the Vitia-Lousa Coastal Plain indicate that the water belongs to $Ca(HCO_3)_2$ or internal type, but the amount of dissolved ions is different between the dug wells and boreholes. Near Tavua, the concentration levels of the dug wells are higher than those of the boreholes. Near the Ba area, the phenomena are reversed. Therefore, it is suspected that the groundwater circulates in a local and limited area. The concentration levels of the constituents in the river water samples are very low, indicating rainfall is quickly discharged into the river.

(3) The Western Area

In this area, the composition of irons in the surface and groundwater are generally Ca(HCO3)2 or internal type. The concentration levels of the constituents in water at midstream or dug wells on the upper side of the plain are very low. Therefore, it is inferred that rainfall quickly infiltrates into the soil and is recharged into the groundwater. On the lower side of the plain, there is a tendency for more ions to occur, and the concentration level of magnesium ions is higher in boreholes than in dug wells.

In the Tavarau-Raviravi Coastal Plain, the composition of the groundwater resembles type-1. The concentration of sodium in the dug wells is higher than in the boreholes, and the concentration of magnesium in the tube wells is higher than in the dug wells because of the hydro-geological and groundwater recharge conditions.

In conclusion, groundwater is almost always alkaline earth bicarbonate type, or typical natural water, but correlation among the groundwater quality in the wells rarely appears. Therefore, hydrologic circulation in the Study Area is inferred to be regional. Rainfall quickly infiltrates and is recharged into the groundwater, and the groundwater flow pass is short, and discharges into the river.

4. GROUNDWATER RESOURCES EVALUATION

4.1 General

Based on the hydrogeological characteristics and the potential for groundwater development, the Study Area is divided into 13 groundwater regions as shown in the Fig. 4.1.1. The characteristics of these groundwater regions are described in Table 4.1.1. The potential for groundwater development in each region is presented in this chapter.

The potential for groundwater development is generally determined by the capacity to sustain the production of groundwater by balancing the recharge, without any environmental problems. It is practically difficult to evaluate regionally the groundwater balance in the whole Study Area because of the poor transmissivity of the aquifer and the complicated topographic feature. The groundwater balance was studied by the simulation method in the limited area of the right bank of lower reaches of the Ba river where the water demand is high. However, it is considered that the capacity of yield of a typical borehole is one of the factors of groundwater development.

Therefore, the potential for groundwater development is essentially justified by the yield capacity of common boreholes such as test wells. Transmissivity is also considered in each region. The potential grade of each region is presented under the following criteria:

Pumping yield (l/sec)	Transmissivity (m^2/day)	Grade
> 5	> 200	Excellent
1 - 5	20 - 200	Medium
<1	<20	Poor

Water quality is taken into consideration in this evaluation. Sea water intrusion makes further development impossible, however, this water quality can be acceptable for groundwater development if treatment can improve the quality to slightly exceeds the criteria.

4.2 Groundwater Resources Potential

4.2.1 Mountainous Area

The region of the Mountainous Area, forming a steep topography above the 200 meters contour line, occupies about 70 per cent of the Study Area. Much of the Mountainous Area is covered with Ba volcanic series and in the upper reaches of the Ba river, it is underlain with Tertiary sedimentary rocks. Both rocks are well consolidated. It is inferred that water bearing rocks only occur in the fissures of the consolidated rock series.

A few inhabitants live in this area, in small isolated villages. Groundwater use is comparatively low as the people fetch household water every day from streams or small springs.

The test well TW001 was placed at an elevation of 62 meter on the periphery of the mountainous area, 4 km west of the Ba river. The static water level in the well was observed at 23 meters below ground level, a level which is deeper than other test wells. This test well produces water at a rate of 3 l/sec.

The Mountainous Area may have a recharge capacity because of its vast area and enormous volume of rainfall. However, runoff occurs quickly. The water level will be fixed depending on the balance between subsurface recharge and discharge. However, in general, the higher the elevation the deeper the groundwater level. Groundwater development will be practically impossible in the higher areas of this region, except the areas in the lower periphery.

Therefore, in this region, groundwater will be abstracted locally from the fissure zones of the consolidated rocks in a limited area of the lower periphery of the mountains.

4.2.2 Tavarau-Raviravi Coastal Plain

This region is located in the most western part of the Study Area and forms a low coastal plain extending 10 km in an east-west direction, bounded by a steep mountain in the south and by a mangrove coast in the north. The land in much of the region has been used to produce sugar cane, especially in the lower parts. The region is underlain by augite and hornblend andesite and possesses thick weathered residual soil.

125 boreholes are used by villagers in this region. The amount of groundwater abstracted is estimated at 199 m^3/day. Therefore, in the Study Area, this region utilizes the most groundwater. It is noted that sea water intrusion may occur due to the high electrical conductivities observed in water samples taken in the boreholes along the coast .

Consequently, groundwater development is unable to develop further in this region, Thus, potential in this area is considered to be poor except for some fracture concentration zones in the mountain side.

4.2.3 Ba River Lower Plain

This region is located on the flat plain along the lower reaches of the Ba river, where river terrace deposits exist. The deposits are not very consolidated indicating the presence of a permeable bed is under the riverbed. The results of the examination of test well TW002 indicate that the sediments contain impervious clayey materials. The transmissivity obtained is as low as 21 m^2/day, and , in addition, iron and manganese ions slightly exceed the WHO standards for potable water. This suggests that the potential for groundwater development is low even though the yields of the test well show that the region is a potential medium grade.

4.2.4 Moto Uplands

The Moto Uplands region is located between Moto and Toge on the left bank of the Ba river, where sugar cane fields are wide spread. The region is underlain by a fine grained tuffaceous sandstone of the Ba series from the Tertiary period, which is well consolidated. Observations carried out on widely exposed outcrops indicate that the fissures which occur in these rock masses are very poor. The TW003 test well could not locate a good fissure section in the borehole. It is inferred that this is common in the rock masses of this region, thus, groundwater development potential in this region is poor.

4.2.5 Koronubu Uplands

This region is located at the right bank of the middle reaches of the Ba river and comprises low undulating hills where sugar cane fields are wide spread. Consolidated tuffaceous mudstone masses of the Tertiary period are widely distributed. In the southern part of the region boreholes are not present due to the difficulty of drilling through fissures in the fresh sedimentary rock masses. In the northern area, on the contrary, several existing boreholes have been used to supply water.

The TW006 test well, drilled in the northern part of this region, encountered several fissure zones in the sedimentary rock masses at a depth of 70 meters. The quality of water in the shallow fissure zones is good,. However, water in the deeper fissure zones which extend 31.7 to 37.0 meters in depth, possess an objectionable odor and a high electrical conductivity of 1,400 MS/ cm. Thus, the deeper section of the test well up to 18.8 meters below the ground surface was filled with sand and mud and covered with mortar, leaving the upper section of the fissure zones free of materials. An additional test well (TW006A) was drilled near the original test well at a depth of 21.35 meters to obtain water from the shallow fissure zones. Both test wells yield water at a rate of around 2 l/sec, and the quality of their water is acceptable, though turbidity slightly exceeds the WHO standard.

This suggests that groundwater may be recharged with precipitation and only circulate in the shallow fissure zones, and that water in the deeper sections is occurred stagnant fossil water. Therefore, the potential for groundwater development is gradedmedium in the limited shallow fissure zones. The water quality of the deeper fissure zones will be carefully inspected when drilling is carried out.

4.2.6 Ba Uplands

The region of the Ba Uplands is located on the right bank of the lower reaches of the Ba river and includes the town of Ba. The region chiefly comprises low undulating hills with vast sugar cane fields outside the residential areas of the town. Basalt and basaltic breccia of the Ba series of the Tertiary period are common in this area.

The PWD water supply system covers about 70 % of the region, however, a number of private boreholes have been used in and outside the system. The main source for the water supply system is surface water. However, groundwater is added to this system by four boreholes which act as supplementary water sources, of which three are located in the Ba Uplands region and one in the Koronubu region. The yields of these boreholes, which act as supplementary water sources, range from 1.5 to 2.7 l/sec, or a maximum 320 m^3/ day.

Two test wells, TW004 and TW005, were built in this region. Pumping tests were executed on these test wells and also on an existing MRD borehole, GW035. These wells produced water at a rate ranging from 2.2 to 4.8 l/sec and transmissivity from 20 to 138 m^2/day. The groundwater level was measured at a depth of 8 to 9 meters.

The essential aquifer is the fissure zones of the volcanic rock masses, which are distributed irregularly in the rock masses. It is noted that several unsuccessful boreholes still remain in this region and that these constitute 20 to 30 % of the total number of existing boreholes.

In general the water quality is good except for some samples where the concentration levels of iron, manganese, and aluminum and turbidity were slightly over the WHO standards. This was probably due to the addition of decomposed ions from the weathered rocks.

The potential for groundwater development is considered medium in this region. The demand for water is considerable in this region because it contains the biggest town in the Study Area and many rural communities. A careful Study is needed to be carried out to further develop groundwater without any problems or interference, and sea water intrusion. For this reason, this region was selected for the Study on groundwater balance, which will use the groundwater model simulation method.

4.2.7 Vatia-Lousa Coastal Plain

The Vatia-Lousa Coastal Plain is situated between the Natunuku peninsula and the west coast of the Vatia peninsula and is formed chiefly of basaltic or andesitic rocks of the Tertiary period. There are several boreholes abstracting water at an estimated rate of 109 m^3/day.

Tidal fluctuations were observed in the water level monitoring records of the existing borehole GW042. High electrical conductivity, up to 920 MS/cm, was observed in the water from several existing boreholes along the coastal area. Thus, it is feared that further groundwater development may cause sea water intrusion to progress. The potential for groundwater development seems to be poor in this region.

4.2.8 Matalevu Uplands

This region is located along the coast and extends in a rectangular shape between the Tavua Basin and the Mountainous Area of the Vatia peninsula, and comprises undulating hills. The region is composed of fresh and hard basaltic lavas and their weathered soil. The land is commonly used for sugar cane fields.

Test well TW008 was drilled in the southern part of the region and when pumping produces water at a rate of 1.3 l/sec. In addition, there are 27 production boreholes and three existing MRD boreholes. Their water levels are a short distance below the ground surface. Several of these boreholes are self-flowing.

Water quality is good throughout this region. It is presumed that groundwater is sufficiently recharged not only through the surface weathered zone but also through the mountainous area in the south. Therefore, the potential for groundwater development in this region is medium.

4.2.9 Tavua Basin

Tavua Basin lies in the central part of the Study Area along the Nasivi river. The region comprises undulating hill masses dissected by the Nasivi river and its tributaries. Along the lower reaches of the Nasivi river, is an alluvial plain which extends to the coast. The region is formed by basaltic rocks. In the upper reaches a gold mine has been opened in a caldera at Vatukoula.

PWD's water supply system supplies about 50 % of the inhabitants of the region including the town of Tavua. The 61 production boreholes confirmed in this region, abstract water at an estimated rate of 99 m^3/day. A majority of these boreholes are distributed throughout this region, especially in the southern and eastern areas where no water supply system exists. On the other hand, it was observed that a number of boreholes were abandoned because they did not produce water.

The rate of these abandoned boreholes is about 50 % of all the drilled holes. This suggests that the occurrence of fissures is poor in the basaltic rock masses of this region.

Test well TW009 was built at Drumasi in the southeastern side of the region, penetrating fresh, compact, olivine basalt. Unfortunately, the test well did not meet a fissure zone which it could tap. Little water could be pumped out over a short duration of time. The poor existence of fissure zones has been confirmed in this region.

The quality of water in wells is generally good. However, some of these wells in the northern coastal area have a high electrical conductivity of 600 MS/cm. Hazardous constituents such as cadmium, arsenic, and chromium were detected in some of the water samples collected in this region. Owing to the poor occurrence of fissures in the rock masses and the hazardous constituents of the water, the potential for groundwater development is poor in this region.

4.2.10 Rabul Coastal Plain

Rabulu Coastal Plain is located between the Tavua Basin region and the Yaqara River Basin, and is bounded in the north by the sea and by the Mountainous Area in the south. This region consists of basaltic volcanic rocks belonging to the Ba series. These rocks are chiefly hard, fresh basalts and volcanic agglomerates. About $21m^3$/day of groundwater is abstracted by 15 existing boreholes, mainly from the fractured volcanic agglomerates in the coastal area. Clarified lineaments and hot springs are located along the Drumasi road. Therefore, the drilling of test well (TW010) was carried out along the Drumasi road about 2 km from the coast in order to confirm the permeability of volcanic rocks in the area. However, it was observed that transmissivity of the rocks was poor. Therefore, the potential for groundwater development in this region is poor.

4.2.11 Yaqara River Basin

The Yaqara River Basin is located along the middle to lower reaches of the Yaqara river, and comprises a mountainous area in the south and undulating hills in the north, which are dissected by the Yaqara river and its tributaries. Basalt and basaltic breccia of the Ba series are common in this region. The mountainous area is covered with forest and the undulating hills are covered with pasture.

A spring flowing about 50 l/sec, is found in the upper part of the mountainous area located in the southern part of this region. The spring water is used throughout the year by the inhabitants of Nananu village.

There are several existing MRD boreholes. Tidal fluctuations are detected in the water level of the existing boreholes, even though the water level is located far higher than the mean sea water level. It is presumed that the rock masses in this region possess many fissures forming a good water bearing bed.

The pumping test carried out on GW254, showed that this test well possessed the greatest yield and transmissivity in the Study Area, 15 l/sec and 2,672 m^2/day, respectively. It is, however, noteworthy that the drawdown curve at a constant pumping rate become steeper 5 hours after pumping started. It is suggested that a less pervious rock mass surrounds the pervious mass where the borehole was drilled.

In addition, water level recovery almost ceased 20 cm below the original level, 6 hours after pumping stopped, due to an inferior recharge and the limited distribution of a good water bearing bed. In order to maintain groundwater levels, the possibility of artificial recharge is to be considered in future studies. This is because, the pumping test results in the Yaqara river basin showed high porosity with a permeability zone in a concentrated area, and moreover, the annual water level fluctuation between 7 and 9 m in depth from surface responds to the rainfall pattern suggesting the fissure water bearing bed has more storage space for artificially recharged water. The quality of the pumped water is good for drinking. Thus, the potential for groundwater development in the limited fissure zones in this region is excellent.

4.2.12 Wailevu - Narewa Coastal Plain

This region is a narrow coastal plain which is bounded on the north by the sea, in the west by the Yaqara River Basin region, in the east by Penang River Basin, and in the south by the mountainous area located along the Kings road. According to the well inventory survey, only 4 production boreholes with a total daily estimated discharge rate of 3 m^3 were confirmed. This region consists of mainly chloritised trachy basaltic volcanic rocks which exist together with dioritic intrusive rocks in the center of the region. Transmissivity is 1 m^2/day. The average electrical conductivity of groundwater ranges from 320 to 630 MS/cm. Hot water enters the sea from the bottom of the coral reef near the intrusive rocks. The groundwater potential in this region is poor.

4.2.13 Penang River Basin

The region of the Penang River Basin is situated in the western part of the Study Area and extends along the Penang river. It is composed of a gentle mountainous slope in the southern area and undulating hills and alluvial plain in the northern area. The basement of the region consists of chlorotised trachy basalts, basaltic breccia, and tuff of the Ba series from the Tertiary period. Alluvial deposits cover the basement rocks in the lower reaches of the Penang river. A thermal spring, with a temperature of around 35°C, is located on a tributary of the Nakauvadra river 2 km upstream of the Nakauvadra river pumping station.

PWD's water supply system only supplies the town of Rakiraki and the surrounding area. However, the water supply was insufficient in the dry season due to the shortage of surface water at the Nakauvadra river pumping station. Groundwater is only utilized in a limited area such as Wairuku, where villagers abstract water from dug wells. Several boreholes were drilled at Ellington in the coastal area, however, the majority were unsuccessful because they were unproductive or produced saline water.

The drilling of two test wells, TW011 and TW012, was carried out in this region in order to find the water bearing zone. However, both of those test wells were unable to locate good fissure zones in the basement of the rock masses. Test well TW012 produced water at a rate of 1 l/sec and test well TW011 yielded less during the pumping test. The quality of the pumped water at TW012 is good for drinking. However, the water at TW011 contains aluminum ions, the concentration level of which, slightly exceeds WHO standards.

It is observed that sea water enters the upper reaches of the Penang river about 3 km from its estuary. A FSC Mill borehole, located along the Penang river, was abandoned 10 years ago due to salinization of the groundwater.

It is inferred that the occurrence of fissures in the basement rock masses is low and that sea water enters the area along the lower reaches of the river. Thus, the potential for groundwater development in this region is considered poor.

4.3 Groundwater Simulation

4.3.1 General

(1) Purpose

The main purpose of groundwater simulation in this Study is to quantitatively evaluate groundwater resource potential which will be utilized for the formulation of the Project. In addition, transfer of knowledge to the counterpart personnel was also achieved through on-the-job training (OJT) by the JICA Study Team.

(2) Scope of works

The entire Study Area is located in the northern coastal zone of Viti Levu and is bounded by the southern watershed, when the Ba river originates and flows from south to north, the coastline in the north, the watershed of the Penang river in the east, and the east end of the Lautoka water supply system in the west. The Study Area is estimated to cover an area of 1,567 km^2.

The Ba Uplands in the lower basin on the right bank of the Ba river were selected for the groundwater simulation, based on the groundwater evaluation study in Section 4.2. An area of some 75 km^2 surrounded by the northern coastline, the Ba river from the west to the south, and the Navisa creek from the south to the east, was finally defined as the area for groundwater simulation.

(3) Procedure

It is well known that mathematical models are the most useful tools for groundwater simulation. There are two types of mathematical models, the analytical model and the numerical model. Since the complicated nature of subsurface conditions can rarely be completely explained using the analytical model, the numerical model is generally introduced for this Study. In the Project, two kinds of numerical models were used for the evaluation of the recharge amount and the study of the groundwater flow system.

Both numerical model simulations are realized through the following steps and are shown in Fig. 4.3.1.

1) Construction of a numerical model
    a. Computer coding
    b. Approximation of its real nature; conceptualization of the recharge and groundwater flow
2) Calibration and validation of the model
3) Model prediction

4.3.2 Hydrogeological Background

In order to determine the topography, subsurface geology, and parameters, etc., required for modeling, the hydrogeological backgrounds are discussed/summarized in this section.

(1) Topography

The Ba river basin is surrounded by steep mountainous slopes in the east which extend to the south and west, and a mangrove coast in the north. Flat and gentle hilly plains are widespread in the basin. The elevation of the plains is around 100 m on an average, except for the lower terraces along the Ba river.

Although the Ba river is the only stream with a perennial water flow, many tributaries and creeks also exist along depressions caused by the undulation of plains. In the Study Area flat plains and low hills are mostly used for sugar cane fields.

(2) Hydrological condition

In the Ba basin, the infiltration of rain water is considered on essential groundwater source, since groundwater inflow from the mountainous areas rarely occurs due to the geological characteristics. Therefore, maximum groundwater development potential should be limited to the total infiltration of rain water.

A recharge study, discussed in more detail in Sub-section 4.3.3, was carried out using a lumped parameter model, otherwise known in Japan as the Tank Model. It is obvious that the characteristics and statistical conditions of precipitation are extremely important for the recharge study.

Annual precipitation of 1,000 mm to 3,000 mm is recorded in the northern part of Viti Levu island, while a relatively higher precipitation of 2,000 mm to 4,800 mm is predominant in the southern part. There are clearly two different seasons, the dry season from May to November and the wet season from December to April when an increase in precipitation is expected.

Hydrological standard years, on the other hand, should be obtained for the prediction of future groundwater flow under certain recharge conditions. Annual precipitation for the last 23 years was calculated as a weighted mean using Thiessen polygons, and the probability of precipitation in various return periods was examined graphically using Hazen plots. As a result, the hydrological standard years are defined below:

Hydrological Conditions	Year of Occurrence	Annual Precipitation
Drought over a 10-year period	1992	1,430 mm
Mid-point (average year)	1991	2,018 mm
Rain over a 10-year period	1989	2,917 mm

(3) Geology

Basalt and basaltic breccia of the Tertiary period are common in the Ba Uplands. Recent deposits such as silt, sand, and gravel have been found on terraces along the Ba river course, and have a maximum thickness of 20m.

From a hydrogeological viewpoint, potential aquifers are only expected to exist in basaltic volcanic rocks, based on the existing wells.

(4) Aquifer system

As a result of the well inventory survey and simultaneous observations of the groundwater level, it has been concluded that two aquifers with different groundwater levels might exist in the Ba river basin. Although the groundwater level of shallow aquifers is usually higher than that of deep aquifers, a confining layer was not clearly defined by any of the drilling results.

Consequently, in the present Study, an aquifer system consisting of two aquifers with one confining layer was conceived. Therefore, a quasi-three dimensional model which can evaluate not only the groundwater flow in aquifers but also the interaction between upper and lower aquifers, was applied for the numerical simulation.

(5) Aquifer properties

The Study included test well drilling work. The characteristics of the aquifer were examined through the pumping tests carried out on the test wells. According to the results of these field investigations, transmissivity of the deep aquifers ranges from 0.1 to 150 m^2/day. Considering the hydrogeological conditions in the Study Area, it is conceived that transmissivity of the deep aquifers will be around 5 m^2/day on an average. Hydraulic conductance of the shallow aquifers ranges from $1*10^{-2}$ cm/sec to $1*10^{-4}$ cm/sec, even though data are not available due to the small number of field tests carried out.

(6) Groundwater level

During the early stages of the Study (late 1993 and early 1994) when a survey on water supply, demand and use was carried out, the groundwater levels of the existing wells were also measured.

1) Water table of shallow unconfined aquifers

The watershed of the unconfined groundwater is the northern coastline, the Ba river in the west to the south, and the Navisa creek in the southeast. The unconfined groundwater generally flows in the direction from the eastern mountains to the Ba river and/or the sea coast (southwest) in concordance with the topography of the area.

Although the trend of the groundwater movement is rather simple, local undulations such as a mound in the Vunisamaloa area and a depression in the eastern part of Ba city, are observed which characterize the contour map.

2) Piezometric head of the deep confined aquifers

Deep wells were not available for measuring groundwater levels because the casing tops of all the existing tube wells have been closed. Therefore, the groundwater levels of 20 existing wells, measured when the wells were installed, are collected and used to analyze the piezometric head of the confined groundwater.

The trend of the groundwater movement of the deep confined groundwater is almost the same as that of the shallow unconfined groundwater, indicating a flow direction from the mountains to the Ba river and then to the coastline. When the shallow and deep groundwater contours were compared, it was observed that the hydraulic gradient of the deep groundwater was more gentle and the head was generally lower than the shallow groundwater.

(7) Groundwater usage

According to the well inventory survey, a large number of shallow and/or deep wells are located in the Study Area and are being utilized mainly for domestic purposes.

The maximum depth of the shallow dug wells most of which are not equipped with pumps, is about 15 m. In general, these shallow dug wells were constructed for emergency use, therefore, they are rarely used. It is estimated that the total amount of water used from the shallow dug wells in the area is, at the most, 34 m^3/day.

Deep wells (boreholes) are about 40 m deep and are drilled by boring machines. Submersible motor pumps are generally installed in these wells. The total amount of water discharged from the deep wells in the area is estimated at about 490 m^3/day, out of which 420 m^3/day is pumped from PWD wells (boreholes).

4.3.3 Recharge Model Study

(1) Tank model

The tank model has normally been utilized for simulating surface runoff, e.g. runoff from mountainous areas under the present Study (see Chapter 2), but may, with some modifications, also be used to estimate aquifer recharge as discussed below.

1) General description of the Tank Model

The original Tank Model was developed by Sugawara et al (1974) under the auspices of the National Research Center for Disaster Prevention in Japan. Models of varying complexity were calibrated against observed discharge records for catchments in the USA, Australia, USSR, Japan, Cameroon, and Thailand, representing a wide range of climatic conditions. The basic model and hybrid versions have since been applied widely in many countries, particularly in Southeast Asia but, as evidence of the model's flexibility, also in arid regions.

The basis for the model is the "tank" which may be considered as a storage unit of variable capacity. An individual tank is characterized as follows:

- storage capacity expressed in mm;
- inflow to the top of the tank;
- lateral outflow through one or more side outlets located at different levels;
- vertical (downward) outflow from the base of the tank, representing inflow to the tank below, if one exists;
- losses which may result from natural phenomena such as evapotranspiration or capillary rise, or from abstractions, for example by pumping (from an aquifer).

By combining several tanks, each with its own storage, outlet, and loss parameters, a realistic model of the hydrological cycle can be devised. The basic concept is to combine tanks vertically with each tank representing a discrete storage unit, say the surface or soil moisture storage. However, tanks can also be added laterally to represent the different soil or land use characteristics of the catchment area, or perhaps to simulate channel storage to attenuate surface flows.

Although the basic outflow function is linear, the effect of combining more than one lateral outlets at different levels is to create, for the tank in question, a non-linear outflow response which reflects more accurately the actual storage-dewatering relationships, combined with original storage levels. Furthermore, outflow for an individual outlet can be expressed as a non-linear storage function, though this option was not utilized in the present Study.

The tank model utilized for the present Study is schematically shown in Fig. 4.3.2, corresponding to the configuration and inflow/outflow assumptions. This three tank configurations might be conceptualized as representing from top to bottom, the surface, topsoil and/or subsoil and aquifer, though it is stressed that these are not rigid definitions. The former two tanks correspond to the unsaturated zone and the latter one to the saturated.

2) Basic calculation concept

Inflow to the top tank is from rainfall. Heavy rain falling on a single day will produce surface runoff, the amount depending on the rainfall intensity and the current storage and infiltration capacity of the topsoil/subsoil, represented by the tank below. These can be simulated by adjusting the height and dimensions of the outlets and the tank storage capacity. For example, setting A1 = 0.5 and H1 = 50 results in 50 percent of daily rainfall in excess of 50 mm (including any residual storage in the top tank remaining from the previous day), flowing out of the side outlet as surface runoff. If residual storage plus rainfall is less than 50 mm then clearly there will be no outflow through A1, but outflow might occur through the base outlet.

Outflows through side and bottom outlets are, in the simplest case, controlled by a linear relationship as follows:

$$Q = A1 \times (H - H1) \qquad H>H1$$

$$Q = 0 \qquad H \leq H1$$

Where

Q : outflow

H : current depth of storage in the tank

H1 : height of outlet above base of tank

A1 : size of outlet.

Evapotranspiration is derived from the top tank if the precipitation on a certain date is less than 5 mm. In the present recharge study, groundwater abstraction was not considered since the total usage from the shallow groundwater is quite limited as discussed above.

The same principles, except for the evapotranspiration in the second and third tanks, are applied to derive the initial outlet characteristics of each tank, relating these if possible to actual physical parameters of the storage unit concerned. Model coefficients are then adjusted during calibration.

3) Model modification for the recharge study

Groundwater recharge, in the tank model simulation, is obtained as vertical outflow of the second tank, say the inflow to the saturated zone from the unsaturated zone. It is also important to evaluate the groundwater runoff amount to understand the groundwater balance.

There are two types of groundwater runoff in the Study Area: outflow to a different groundwater basin and outflow as surface runoff. In the actual calculation, both of these are obtained as outflow from the side outlet of the third tank. They are described by the following relationships:

a) Outflow to a different groundwater basin (Fig. 4.3.3 (a))

$$Q = A1 \times (H - h)$$
$$Q = 0$$

b) Outflow to surface (Fig. 4.3.3 (b))

$$Q = A1 \times (H - H1) \quad H>H1$$
$$Q = 0 \quad H \leq H1$$

As apparent from the above formulations, the outflow to a different groundwater basin depends on the storage of the connected tank, while the outflow to the surface is independently defined by its own tank specification. For convenience sake, the term "groundwater runoff" will be used for the outflow to a different groundwater basin and the term "spring" for the outflow to the surface.

(2) Calibration results

Data used for the calibration are summarized below:

Data & Description	Content & Explanation
Precipitation	Evaluated from the Thiessen Polygons
Evapotranspiration	Derived from the monthly pan evaporation
Calibrated Area	Right bank of the Ba river
Calibrated Data	G/W hydrograph of GW003 (dug well)
Calibration Period	1993.1.1 to 1994.5.31

The final result of calibration is shown in Fig. 4.3.4. As seen, the constructed numerical model can calculate satisfactorily the actual groundwater level fluctuation of the GW003 well. Water balance during the calibration period is shown in Table DATA BOOK-D (D-4). Within one and half years, precipitation totals 2,750mm, 36% (990mm) evaporates, 37% (1,030mm) directly runs off, and 26% (730mm) infiltrates as groundwater recharge.

(3) Recharge during the hydrological standard year

For necessity of the prediction run of the groundwater flow model, recharge in the hydrological standard year was estimated supposing the converged condition under the Mid-point (the year of 1991) rainfall equals the recharge of the hydrological average year. Furthermore, successive calculations from the converged conditions from rainfall with a 10-year return period (the year of 1992) yield a recharge equal to the hydrological drought year (shown in DATA BOOK-D (D-5)). Final results are summarized below.

Hydrological Standard Year	Annual Recharge in mm/year
Mid-point (average year)	554
Drought in a 10-year period	296

4.3.4 Groundwater Flow Simulation

Although aquifer response was examined through a numerical model study, it has to be stressed that insufficient data left many uncertainties in understanding the hydrological condition of the Study Area. Therefore, the model should be revised upon receiving additional data.

(1) Numerical model

1) Introduction

Considering a model is a tool designed to represent a simplified version of reality, properly constructed groundwater models can be valuable predictive tools for the management of groundwater resources. Analytical and numerical groundwater models are commonly used nowadays to study groundwater flow systems.

A mathematical model consists of a set of differential equations that are known to govern the flow of groundwater. Since the assumptions necessary to solve a mathematical model analytically are fairly restrictive, numerical techniques are generally used. This creates more realistic situations than those often assumed from analytical models, e.g. homogeneous and isotropic.

There are two types of numerical models: the finite difference and the finite element. In each case, a system of nodal points is superimposed over the problem area. In the finite difference method (FDM) which was used for the proposed groundwater potential evaluation of the Study Area, the concept of discretization into mesh form was fundamental in the development of the equations.

Although the groundwater model study usually deals with steady-state flow and transient flow, only the application of the FDM to the transient flow equation is discussed below because this equation also covers the steady-state flow equation. In steady-state flow, the spatial problem domain is subdivided into a mesh of blocks. However, in transient flow, the value of groundwater heads (h) in cells is not limited to the spatial problem domain, but is a function of time.

2) Derivations of the finite-difference equation

(a) Mathematical model

The three-dimensional movement of ground water through porous material may be described by the following equation

$$\frac{\partial}{\partial \gamma}\left(K_{\gamma\gamma}\frac{\partial h}{\partial \gamma}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=Ss\frac{\partial h}{\partial t} \qquad (1)$$

Where

$Kxx,\ Kyy,\ Kzz$	:	values of hydraulic conductivity (Lt^{-1})
h	:	the potentiometric head (L)
W	:	a volumetric flux per unit volume and represents sources and/or sinks of water (t^{-1})
Ss	:	the specific storage of the porous material (L^{-1})
t	:	time (t)

Equation (1) constitutes a mathematical representation of a groundwater flow system if flow and/or head conditions at the boundaries of an aquifer system and initial-head conditions are specified.

As already mentioned above, analytical solutions of equation (1) are rarely possible, so various numerical methods must be employed to obtain approximate solutions. One approach is the finite-difference method, wherein the continuous system described by equation (1) is replaced by a finite set of discrete points in space and time, and the partial derivatives are replaced by terms calculated from the differences in head values at these points.

This process leads to systems of simultaneous linear algebraic difference equations, and the solution yields values of head at specific points and times.

(b) Discretization

Fig. 4.3.5 shows a spatial discretization of an aquifer system in the Study Area, that uses a mesh of blocks called cells, with their locations described in terms of rows, columns, and layers. In the present Study, the width of a cell was set to 500 m for both row and column.

In equation (1), the head, (h) is a function of time as well as space so that, in the finite-difference formulation, discretization of the continuous time domain is also required.

(c) Finite-difference equation

Development of the groundwater flow equation in finite-difference form follows from the application of the continuity equation, i.e. the sum of all flows into and out of the cell must be equal to the rate of change in storage within the cell. The continuity equation expressing the balance of flow for a cell is

$$\sum Qi = Ss \frac{\triangle h}{\triangle t} \triangle v \qquad (2)$$

Where

- Qi : a flow rate into the cell (L^3t^{-1})
- Ss : specific storage equivalent to Ss in equation (1) (L^{-1})
- V : the volume of the cell (L^3)
- Δh : the change in head over a time interval of length

The term on the right hand side is equivalent to the volume of water taken into storage over a time interval of Δt given a change in head of Δh. Equation (2) is stated in terms of inflow and storage gain. Outflow and loss are represented by defining outflow as negative inflow and loss as negative gain.

Consequently, a backward-difference equation which can be used as the basis for a simulation of the partial differential equation of ground water flow, equation (1), is expressed by:

$$CR_{i,j-1/2,k}(h^{m}_{i,j-1,k} - h^{m}_{i,j,k}) + CR_{i,j+1/2,k}(h^{m}_{i,j+1,k} - h^{m}_{i,j,k})$$

$$+ CC_{i-1/2,j,k}(h^{m}_{i-1,j,k} - h^{m}_{i,j,k}) + CC_{i+1/2,j,k}(h^{m}_{i+1,j,k} - h^{m}_{i,j,k})$$

$$+ CV_{i,j,k-1/2}(h^{m}_{i,j,k-1} - h^{m}_{i,j,k}) + CV_{i,j,k+1/2}(h^{m}_{i,j,k+1} - h^{m}_{i,j,k})$$

$$+ P_{i,j,k}h^{m}_{i,j,k} + Q_{i,j,k} = SS_{i,j,k}(\Delta rj, \Delta ci, \Delta vk)\frac{(h^{m}_{i,j,k} - h^{m-1}_{i,j,k})}{t_{m} - t_{m-1}} \quad (3)$$

Where

CR	:	Hydraulic conductance in the row direction which is the product of hydraulic conductivity and the cross-sectional area of flow divided by the length of the flow path (the distance between the nodes.)
CC	:	Hydraulic conductance in the column direction
CV	:	Hydraulic conductance in the vertical direction
P, Q	:	General external flow term
Δrj, Δci, Δvk	:	Width of a cell in the row, column and vertical directions

The coefficients of the various head terms including the term $Q_{i,j,k}$ in equation (3) are all known when the head is at the beginning of the time step, $h^{m-1}_{i,j,k}$. The seven heads at t_m, the end of the time step, are unknown because they are part of the head distribution to be predicted. Thus equation (3) cannot be solved independently, since it represents a single equation in seven unknowns. However, an equation of this type can be written for each active cell in the mesh. Accordingly, there is only one unknown head for each cell resulting in a system of "n" equations with "n" unknowns which can be solved simultaneously.

3) Vertical discretization

It is inferred that the aquifer system in the Study Area consists of two aquifers with one confining layer. In this system, it may also be assumed that storage release occurs only in the aquifers, flow in the aquifer is essentially horizontal, and flow in the confining layer is essentially vertical. In this case a single model layer may be used to represent each aquifer, while the confining layer may be represented simply by the vertical conductance between layers. This approach to vertical discretization is known as the "quasi three-dimensional" approach and is applied to the present aquifer modeling.

4) Modeling software

The "3D MODFLOW: A Modular Three Dimensional Finite Difference Groundwater Flow Model" (MacDonald and Harbaugh, 1988) will be used for the quasi-three-dimensional finite-difference model. This model is useful for perennial-yield planning of a large, complex, unconfined/confined aquifer system.

In principle, MODFLOW can simulate flow in three dimensions. The model may be used for either two or three-dimensional applications. Physical and mathematical concepts are incorporated in the modular structure of the computer program. The modular structure consists of a Main Program and a series of highly independent subroutines called "modules". The modules are grouped into "packages". Each package deals with a specific feature of the hydrologic system which is to be simulated, such as flow from rivers, or with a specific method of solving linear equations which describe the flow system, such as the Strongly Implicit Procedure.

Groundwater flow within the aquifer is simulated using a block-centered finite-difference approach. Layers can be simulated as confined, unconfined, or a combination of both. Flow associated with external stresses, such as wells, area recharge, and evapotranspiration can also be simulated.

(2) Model construction

Hydrogeological data, including the top and bottom of aquifers and the confining layer in the form of a contour map, were manipulated into a computer code as shown in DATA BOOK-D (D-6 TO D-12). Remarks for the model construction, including aquifer characteristics, are summarized below.

Data	Manipulation Method/Characteristics
Aquifer Characteristics	
T of the deep aquifer	0.1 to 150 m^2/day
K of the shallow aquifer	$1*10^{-2}$ to $1*10^{-4}$ cm/sec
Storativity (deep aquifer)	0.001
Storativity (shallow aquifer)	0.07

Hydrogeological Condition	Manipulation Method/Characteristics
Ground surface	Reading from topographical map (1:50,000)
Top of the confining layer	Inferred from the depth of shallow dug wells
Bottom of the confining layer	Inferred from the screen design of deep tube wells
Hydrogeological basement	Inferred from the depth of deep tube wells
Groundwater table of the shallow aquifer	Result of the field investigation conducted in this project
Piezometric head	Refer to the existing data of the deep wells measured during construction
Groundwater usage	Utilized in the inventory survey result
Recharge	Utilized in the recharge study result
Others	
Calibrated data	GW003 for the shallow G/W level, and TW004,TW005,GW035 for the deep G/W level
Calibration period	1993.1.1 to 1994.5.31

(3) Calibration results

1) Procedure of model calibration

The model is test-operated into a computer by inputting recharge and pumping, and outputting the simulated groundwater table fluctuation in each cell. The simulated groundwater table will be compared with the actual records of the continuously monitored wells. The model then will be modified/adjusted until final agreement between the simulated and the actual water level fluctuation is achieved. Thus the model is calibrated and ready to use for water table simulation under various development situations.

Generally, model calibration is carried out in the following steps:

- Calibration of the steady-state flow
- Calibration of the transient flow

As known from its terminology, the first step of model calibration requires an assumption of the steady-state conditions for all constituents of groundwater flow, including recharge, discharge, boundary conditions, and aquifer characteristics. The steady-state flow should indicate a stable water table, though this is considered to be an ideal condition. By monitoring data of the whole Study Area to date, rather obvious water level fluctuations, due to a seasonal increase/decrease in recharge volume and groundwater abstraction are noticed. Assumption/simplification, therefore, will be based on recharge, discharge, water table, etc., in order to achieve the first step of calibration. The target of this step is to clarify the approximate hydraulic conductivity or transmissivity of the aquifers.

In the second step, the non steady-state flow or the time dependent flow will be simulated and/or calibrated in the manner explained above. The second step calibration aims to fix the aquifer parameters consisting of hydraulic conductivity or transmissivity and storativity or storage coefficiency.

2) Calibrated model

Simulated groundwater level hydrographs are shown in Fig. 4.3.6, and the water table map and the piezometric head map are presented in Figs. 4.3.7 and 4.3.8. These figures are the final outputs of the model calibration. As observed from these figures, the fluctuation trend shows good agreement between the observed and calculated, and the reliability of this numerical model is very good. Consequently, it is concluded that this model is ready to predict the aquifer response under future groundwater usage. Final agreement on the model calibration has also defined the aquifer characteristics, as shown in Figs. 4.3.9 and 4.3.10.

Alternatively, water balance of inflow and outflow during January 1993 to May 1994 (17 months) is summarized below. According to the table, almost all of the recharge flows out as springs and/or groundwater runoff. Supposing that the groundwater resource potential is limited to leakage from the shallow aquifer to the deep one, the maximum amount is expected to be 26.3 mm in depth or 1.97 million m^3 in volume.

Constituent	Water Balance in mm	in $*10^6 m^3$	in $*10^3 m^3/day$
Recharge	756.8	56.76	111.3
G/W runoff & Springs	710.0	53.25	104.4
Pumpage	2.8	0.21	0.4
Leakage	26.3	1.97	3.9
±Storage	+44.0	+3.3	+6.5

4.3.5 Optimization and Prediction

(1) Optimization procedure

1) Perennial-pumping strategy

"Perennial-yield" is the maximum quantity of water that can be continuously withdrawn from a groundwater basin without adverse effects. A "perennial-yield pumping strategy" is a specific pattern of spatially distributed pumping that causes the evolution and maintenance of an appropriate potentiometric surface. Thus a perennial-yield pumping strategy assures a certain amount of water to the user over a long term.

A common management goal in the Study Area is to fully utilize water resources to produce economic and social benefits. A groundwater management plan should satisfy specified objectives while considering the physical constraints of the aquifer system and legal and economic constraints.

To effectively achieve this goal the optimization technique adopting a linear programming algorithm is used. These models can predict the behavior of a given aquifer and determine the best management and/or the perennial pumping strategy for the specified objectives and constraints/bounds.

2) Mathematical models for the optimization

(a) Objective function

The objective function of the model is to maximize total steady groundwater extraction.

$$\text{maximize Qtotal} = \sum_{i=1}^{N} Qi,j \tag{1}$$

where

Qi, j :groundwater pumping in a cell located in row i and column j, (L^3/T)

N : total number of cells with potential pumping wells

The optimization problem is linear as long as the objective function and the constraints/bounds stay linear. The standard problem of linear optimization is solved using the simplex-algorithm. In this Study, it is supposed that the relation between the groundwater level fluctuation and well discharge is linear and therefore the optimization problem might be linear.

(b) Constraints and/or bounds

For the planned optimization model, constraints and/or bounds on the pumping rate and head are described as:

$$h^L_{ij} \leq h_{ij} \leq h^U_{ij} \tag{2}$$

$$Q^L_{ij} \leq Q_{ij} \leq Q^U_{ij} \tag{3}$$

Where

L and U denote lower and upper bounds, respectively.

In the present Study, the lower bounds on head are used solely to avoid or minimize problems caused by unacceptable drawdowns, while the bounds on pumping are primarily included in the exploitation strategy based on the future water demand.

(2) Constraints on the model prediction

Groundwater resources potential in the Study Area was examined under the following constraints and/or assumptions:

Items	Constraints/Assumption
Constraints and others	
Recharge Condition	Two years a hydrological average year and drought year in a 10-year period, and a hydrological average year.
Groundwater Level	Piezometric head of the deep aquifer should be higher than sea level to avoid sea water intrusion
Drawdown	Maximum drawdown in a well should be up to the mid-point of the screen section.
Exploitation Strategy	TW004, TW005 (test wells) and GW035*(owned by MRD) will be fully utilized as production wells
Assumptions	
Groundwater Usage	Same amount as present for the existing wells, different for the new production wells (see Table 3.3.10)
Initial G/W level	Converged Groundwater level after a 10-year iterative run under the recharge of the hydrological average year

* According to the field survey, water demand is very high in the vicinity of the GW035 well.

(3) Model prediction

1) The relationship between the calculated water level and the drawdown in a production well

Since the mesh width of the discrete model is 500 m, drawdown in a mesh, calculated by the numerical model is considered equal to an image well with a 250 m radius. The relationship between drawdown in a mesh and drawdown of the actual radius of a well should be considered, as it is necessary to confirm the detailed utilization/construction plans of the existing and/or newly drilled wells.

The Thiem equation, for measuring steady radial flow to a well in a confined aquifer is shown below;

$$h_w = H - \frac{(H-h_m)}{\ln (R/250)} \times \ln(R/r_w)$$

Where

Q : Pumping rate (L^3/T)

T : Transmissivity (L^2/T)

= K * b

K : Hydraulic conductivity (L/T)

b : Thickness of aquifer (L)

H : Static water level (SWL) in a well (L)

(Equivalent to SWL of a mesh where the well is located)

h_o : Pumping water level (L)

R : Radius of influence (L)

r_w : Radius of pumping well (L)

Supposing the radius of an imaginary well, which corresponds to the discrete mesh in the simulation model, is 250 m and the radius of an actual production well is 0.076 m (7.6 cm), drawdown of the mesh (imaginary well) can be converted into that of the actual well by the equation below:

$$h_w = H - \frac{(H-h_m)}{\ln (R/250)} \times \ln(R/r_w)$$

Where

h_w : Pumping water level in an actual well (L)

h_m : Pumping water level in a mesh; i.e. imaginary well (L)

According to the result of the test well drilling executed in this project, well loss is estimated at about 50 % of aquifer loss, equivalent to the theoretically obtained drawdown h_w. Consequently, the equation above can be modified to the following equation:

$$h_w = H - \left[\frac{(H-h_m)}{\ln (R/250)} \times \ln(R/r_w)\right] \times 1.5$$

Alternatively, considering the hydrogeological condition of the Study Area, the radius of influence was inferred to be about 3,000 m, therefore conversion from h_m to h_w was done supposing R of 3,000 m.

2) Prediction case

Ten cases of model prediction are prepared as follows.

Unit : m^3/day

Case No.	Pumping rate of each well				Remarks
	TW004	TW005	TW000	GW035	
0	0	0	0	0	No additional pumpage Hydrological average year
1	0	0	0	0	No additional pumpage Hydrological drought year
2	209	166	0	346	Discharge rate at the pumping test
3	104	83	0	173	Half of the above pumping rate
4	70	83	0	115	Two thirds of the above for TW004 and GW035
5	70	126	0	115	1.5 times of the above for TW 005
6	70	83	209	115	Additional pumpage from TW000 (new well) on the Case 4
7	70	83	83	115	Same as the above, but the pumping rate of TW000 was decreased
8	70	102	0	115	Optimum plan using existing three wells
9	70	77	150	115	Optimum plan using existing wells and the newly drilled wells

Within the above trials, the discharge rate of the optimum plans in Case 8 and 9 was obtained form the optimization study discussed in section (2).

3) Prediction results

Figs. 4.3.11 to 4.3.12 show contour maps, that is the optimum Cases 8 and 9, of the groundwater level in December of the drought year in a 10-year period. Figs. 4.3.13 to 4.3.14 are prepared as drawdown maps of the groundwater level of optimum Cases 8 and 9. Other non-optimum cases are shown in DATA BOOK-D (D-13 to D-16).

Although it is difficult to find any obvious change in the contour maps, depressions like a cone centered by the production wells are indicated in the drawdown maps. In Case 2, for example, drawdown reaches a maximum of 6 m, violating the assumed constraints and indicating that pumping strategy in this case is not acceptable.

Even though acceptable pumping strategies are chosen, it is judged that a drawdown of about 1.5 m will be experienced 500 m from the production wells. Although it is known from the inventory survey that a deep tube well is located near TW005, no serious influence is inferred from the saturated thickness of more than 10 m and the limited discharge rate. In addition, a few MRD water wells are located about 1.5 km from TW005. Since the influence from this distance is estimated at about 50 cm at the most, no serious damage is expected.

As a result of additional pumping from the deep aquifer, the maximum drawdown of about 15 cm was reasonably estimated for the shallow groundwater. Therefore, no serious problems, in regard to the magnitude of the estimated drawdown, are expected during daily usage of the shallow dug wells.

The water balances of 10 cases are explained in Table 4.3.1. A schematic diagram of the annual water balance of optimum Cases 8 and 9 are shown in Fig. 4.3.15. Other non-optimum case are shown in DATA-BOOK-D (D-17). As shown, almost all the recharged amount flows out to the sea and the river, however, an increase in pumpage from the deep aquifer is supplemented by an increase in leakage from the storage and/or outflow of the shallow groundwater.

Furthermore, even though the recommended pumping is continued throughout the drought year, the ground water level of the deep aquifer is expected to increase in Case 8 and Case 9 if hydrological conditions of the following year equal the average

(4) Conclusion

The optimization study and the model prediction have consequently clarified and optimized the best two pumping strategies, shown below:

Plan 1

- Use of existing three tube wells
- Discharge rate

TW004	70	m^3/day
TW005	102	
GW035	115	
TOTAL	287	

Plan 2

- Use of existing three tube wells and one newly drilled well
- Discharge rate

TW004	70	m^3/day
TW005	77	
TW000	150	
GW035	115	
TOTAL	412	