4. DATABASE

4. DATABASE

4.1 Existing Condition of Data Arrangement

(1) Well inventory

Prior to the present study, no systematic arrangement of well inventory data had been undertaken by MIEM, despite its responsibility for compiling these data in a central file. Some data (like well depth, groundwater level, casing diameter, water quality, etc.) are recorded on index cards which contain no information on drilling logs and pumping test results. Nevertheless, well locations were plotted on 1:100,000 topographical maps.

In the field survey of this study, wells in these records were visited to determine the precise location of each well, to fill in gaps in the data where possible, and to measure the groundwater levels for the preparation of a groundwater contour map.

Well inventory forms used to update and collect data from existing wells during the first field survey are attached in Supporting Report(1). All inventory data for each well, including a sketch map of the site, shall be arranged with the database system established under this project.

(2) Meteorological data

For understanding the hydrological environment, especially groundwater recharge potential, meteorological data at required stations shall be stocked and updated periodically in MIEM. Most of meteorological data can be collected from the Directorate of Meteorology, Antananarivo. However, systematic data collection and arrangement procedure has never been introduced.

4.2 Introduction of the Database Management System

(1) Database Management System Categories

A database management system(DBMS) is a collection of related programs for loading, accessing, and controlling a database. The database is independent of the programs that process the information, and a system may have several databases within one database management system. Hierarchical, network, and relational database management systems are three DBMS models that have achieved widespread popularity.

- Hierarchical database management system (HDBMS)

In a HDBMS, data are orgainzed like an inverted tree with a series of nodes connected by branches. These nodes and branches form what is described as a parent-child relationship; each parent may have many children but each child may have only one parent. Data go through the tree from top to bottom until they reach their appropriate destination. The hierarchical structure assumes that certain data are more important than others; therefore, these systems are created to work within a specific application.

- Network database management system (NDBMS)

In a NDBMS model, data are organized similarly to those of a HDBMS, except that each node may have more than one branch; therefore, data can come from several different sources. In the network structure, records are linked by a complex system of pointers that frequently must be updated, making the network model more flexible than the hierarchical model. A disadvantage of the network approach is that some structures begin to have pointers going off in all directions. In the event of failure, such a structure can be difficult to comprehend, modify, or reconstruct.

- Relational database management system (RDBMS)

The most fundamental property of a relational database management system is that data are presented to the user as tables. Thus, the data consist of rows and columuns, with the rows corresponding to traditional database records or segments and the columuns representing fields within the records.
"Join" is a RDBMS operation capable of combining relational tables. Another relational operation is "selection", creating a subset of all the records in a table. A relational operation always produces new tables. This makes it possible to provide very powerful and concise languages for

the manipulation of relational data structures.

For the database development based on hydrogeological view point, RDBMS (dBASE III) is adaptable because of some advantages over the HDBMS and NDBMS concerning access control, operation of implementation, tabular representation, etc.

(2) Hardware and software

Three sets of personal computers and some application programs were provided for this system during the first field survey.

- Toshiba model J3100 (IBM compatible type)
  - GX021 (32 bits, 40 Mbyte hard disk) -- 1 unit
  - SL021 (16 bits, 20 Mbyte hard disk) -- 2 units
- Dual mode printer -- 3 units

- Word Perfect (French word processor)
- Word Star professional (English word processor)
- Lotus 123 (Multipurpose tabulation software)
- dBASE III Plus (Database software)

All other data required for groundwater development planning and management are entered into this system. Data include hydrological and meteorological data (like streamflow, rainfall, temperature, humidity, wind velocity, etc.), groundwater level data from both simultaneous and continuous observations, and water quality data.

A major application of the database system shall be in the future groundwater monitoring program of the Government of Madagascar.

4.3 Hydrogeological Database

An outline of the hydrogeological database system is shown in Fig.4.3.1 and the working flow is shown in Fig. 4.3.2. This program is composed of the following functions.

(a) Data entry function

To enter the following information and records

(i) Information of monitoring unit

- Meteorological station
- Gauging station
- Well (borehole, dug well)

(ii) Collected records (monthly and/or daily)

- Rainfall
- Discharge
- Groundwater level
- Temperature
- Evaporation
- Humidity
- Sunshine hours
- Wind velocity

(iii) Water quality analysis

(iv) Results of pumping test

(v) Groundwater level

(b) Search function

To search information and records by specified range

(c) Display and print function

To display on a screen and output to a printer

(d) Location map function

To show the Study Area with locations of wells and monitoring units

(e) Assist function

To arrange records graphically on the screen

For the sake of simplicity of the data entry, some information, such as organization and station name, shall be given code number such as "Well", "Station", "Agency", "River", "Aquifer", "Water Use".

Detailed operation is explained in the "Operation Manual" attached to Volume 4, Supplementary Report (2).

4.4 Operation and Maintenance

Because of the short experience, the Hydrogeological Section is yet to be accustomed to the routine use of personal computers. Therefore, it is recommended to establish a Unit to be specialized in computer service.

The objective of the Unit will be the system development for hydraulic, hydrological and hydrogeological analyses, as well as education and popularization of computer use within MIEM.

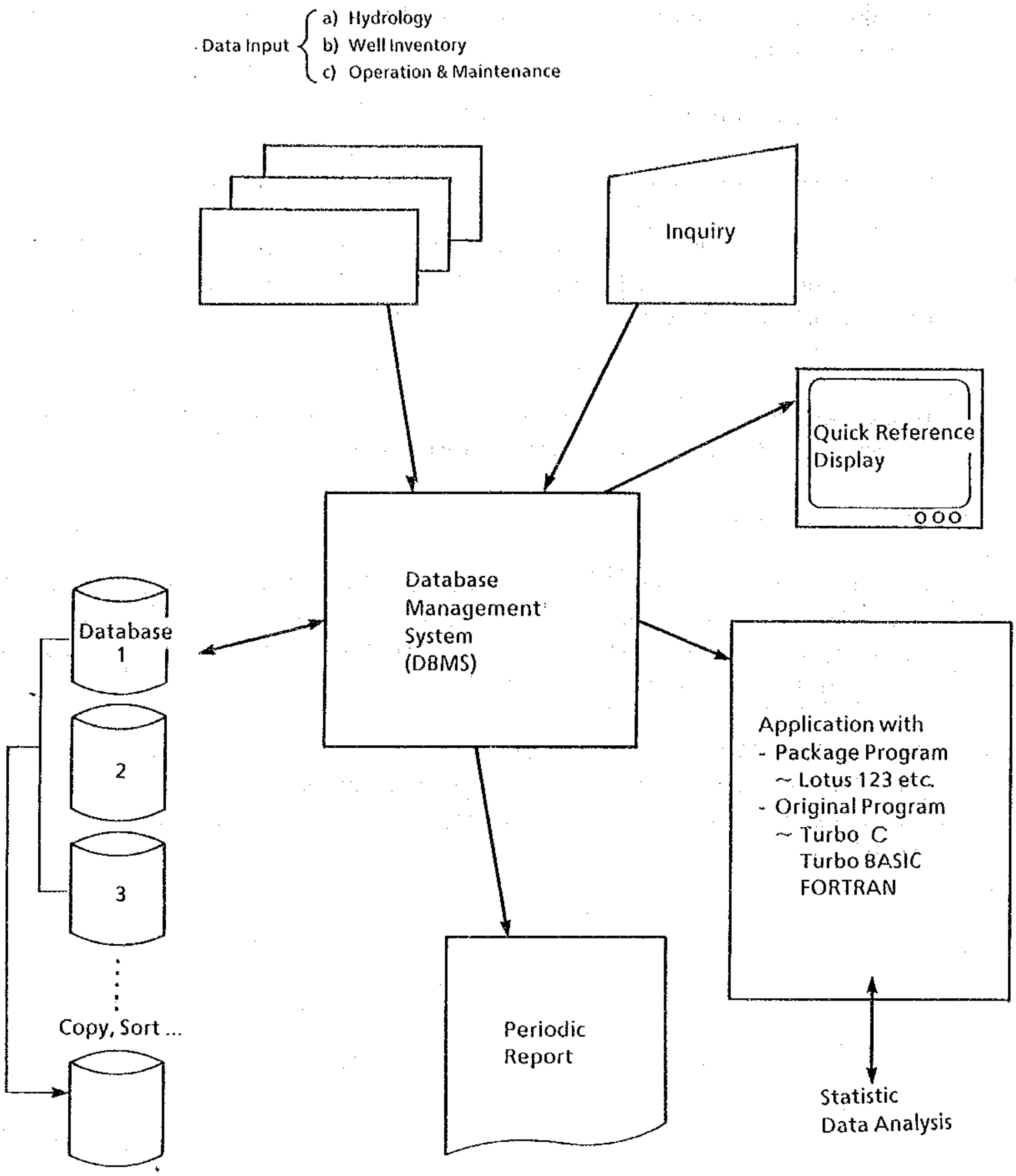


Fig. 4.3.1 Outline of Database System

WORKING FLOW

PRINT APPEND/ MODIFY

- MAIN MENU
  - APPEND/MODIFY
    - INFORMATION OF STATION/BOREHOLE
      - METEOROLOGICAL STATION
      - GAUGING STATION
      - WELL/BOREHOLE
    - DAILY DATA
      - PRECIPITATION
      - DISCHARGE
      - WATER LEVEL
    - MONTHLY DATA
      - PRECIPITATION
      - DISCHARGE
      - WATER LEVEL
      - TEMPERATURE:MAX,MEAN,MIN
      - EVAPORATION
      - HUMIDITY 9:00, 15:00
      - SUNSHINE HOUR
      - WIND VELOCITY: MAX,MEAN,AVG
    - DISCHARGE OBSERVATION
    - CHEMICAL QUALITY
    - PUMPING TEST
    - GROUNDWATER LEVELING
  - SEARCH
    - DESIGNATE AN EXTENT OF LAT. & LONG.
      - DAILY PRECIPITATION
      - MONTHLY PRECIPITATION
      - DAILY DISCHARGE
      - MONTHLY DISCHARGE
      - WATER LEVEL
      - TEMPERATURE:MAX,MIN,AVG
      - EVAPORATION
      - HUMIDITY: 9:00,15:00
      - SUNSHINE
      - WIND VELOCITY:MAX,MIN,AVG
      - SIMULTANEOUS DISCHARGE OBSERVATION
      - ALL
    - ALL DATA
  - DISPLAY & PRINT
    - INFORMATION OF STATION
    - DAILY DATA
    - MONTHLY DATA
    - DISCHARGE OBSERVATION
    - CHEMICAL QUALITY OF WATER
    - PUMPING TEST
    - GROUNDWATER LEVEL
  - LOCATION MAP
    - METEOROLOGICAL STATION
    - HYDROLOGICAL STATION
    - WELL & BOREHOLE
  - ASSIST FUNCTION
    - APPEND & MODIFY INDEX
    - CODE
    - GRAPH

Fig. 4.3.2 Flow of Hydrogeological Database

5. REHABILITATION SURVEY

5. REHABILITATION SURVEY

The rehabilitation survey was initially planned in nine villages. However, the existing water supply system in TANANDAVA has been maintained in a very good condition, so that the detailed survey was found unnecessary in this village.

Among the remaining eight candidate villages, the survey in BEROROHA was also omitted, because the access to this village is limited to a small ferry boat which was not able to carry the survey equipment and heavy vehicles. Instead of BEROROHA, MAHABOBOKA was added, and the rehabilitation surveys were undertaken in the following villages.

Befandriana
Betsioky
Andranohinaly
Andranovory
Sakaraha
Ankazoabo
Bereketa
Mahaboboka (for Beroroha)

The model rehabilitation works were carried out in BEFANDRIANA.

5.1 Results of Rehabilitation Survey

The results of rehabilitation survey for the above eight villages are summarized as follows.

BEFANDRIANA :

a. Borehole

The condition of the well differs from the well record as shown below.

Item	Actual condition	Record
Well depth	64 m	36 m
Casing diameter	6", 4"and 3"telescopic	6"
Static water level	12.6 m B.G.S	25.0 m B.G.S
Pumping rate	25-30 liter/min	233 liter/min

Activities for borehole rehabilitation :

1. Removal of riser pipes
2. Repetition of air lifting and air surging for 2.5 hours
3. Brushing by use of 4" wire brush, which was useless, because the casing diameter becomes smaller at screen portion

In spite of air lifting/surging, the well yield could not be improved, its maximum discharge rate being less than 30 liters/min.

b. Condition of other facilities

- Elevated tank : A steel cylindrical tank with a volume of 21 cubic meters and 3 m high above ground surface is fit for use for several years more. Minor problems are a small amount of leakage from the joint and a damaged valve on outlet pipe.

- Communal faucet : One stand pipe with one tap near the tank has been damaged for many years.

- Reservoir tank: Brick made tank with a dimension of 1.2 m W x 6 m L x 0.7 m H can not be used as is, since mortar facing has mostly been stripped off, and the tank has no drain.

- Motor pump : The worn out motor has been removed, and a new pump is required.

- Generator : Cannot be used without thorough overhaul and repair.

- Generator house : Old shed made of used zinc sheet.

BETSIOKY :

a. Borehole and pumping system

The following conditions were found by removal of riser pipes, cylinder and 3" screen.

- Well depth :	90 m
- Screen diameter and locations :	6" : 75.75-79.75 m
	3" : 79.75-89.75 m
- Static water level :	59.35 m B.G.S.
- Discharge :	144 liters/min.
- Drawdown at pumping rate of 144 l/min :	10 m
- Water quality :	EC : 2,800 pH :7.0
- Pump cylinder :	worn out
- Motor for pump :	worn out and removed
- Screen, 3" Johnson type :	filled up with mud

b. Other facilities

- Reservoir tank :
  Steel made cylindrical type with a volume of about 16 cubic meters and a bottom height of 2.2 m. Joint should be sealed to prevent leakage
- Distribution pipes :
  The PVC pipes are damaged and the pipeline should be replaced.
- Communal faucet base :
  It seems to be worn out, so that it had better be reconstructed.

It is recommended that all of the facilities except the reservoir tank be replaced. As for the borehole well, the results of electrical sounding suggests that a 150 m deep well will produce more quantity of better quality water.

ANDRANOHINALY :

The existing water supply system, which has not been working since 1975, is comprised of the following.

- Reservoir tank : Steel made cylindrical type with a volume of about 11 cubic meters.
- Communal faucet base near the tank with 3 faucets.
- Borehole : Depth 220 m, static water level 207 m, 6"casing, equipped with motorized cylinder type pump.

The tank and faucet base seem to be in good condition for future use, but the pumping system is not repairable. The capacity of the well could not be confirmed, because some pieces of stone were thrown into the well before pumping test. The welded well cover had been broken and the depth of the well had decreased to 209 m (no variation of water level) when the survey team visited the village for the second time. A new well should be drilled in the implementation stage.

ANDRANOVORY :

a. Borehole

The borehole drilled in 1964 has not been functioning since 1984 because of piston and motor problems.
- Depth : 136 m, static water level 116 m.
- Capacity : 40 liter/min.

At the beginning of the air lifting/surging, water was coming up minimally like a spray, but with time, water amount increased gradually to 40 liters/min. Pumping test by use of submersible motor pump confirmed that constant yield of the well was 40 liters/min.

However, since most of 3" screen under riser pipe was left in the well bottom at the time of removal work, no more recovery will be expected in this well.

b. Other facilities

- Reservoir tank : A cylindrical steel tank, with a volume of about 15 cubic meters is still usable. The concrete foundation, however, should be reconstructed because of big cracks.

- Communal faucet base : One faucet base was found near the tank, but it is insufficient for the village population.

SAKARAHA :

The existing water supply system in this town is comprised of 1 source (borehole), 2 elevated tanks, 16 communal faucets and distribution pipeline of more than 1,500 m total length.
However, these facilities have not been working for many years, because of worn out pumping facility and pipeline.

a. Borehole

- Depth : 30.8 m (existing record : 32 m)
- Casing diameter : 6"
- Static water level : 10.66 m (record 10.35 m)
- Discharge before development : 100 liters/min
- Discharge after development : 144 liters/min
  Drawdown 10.97 m (Former pumping rate was 566 liters/min)

b. Other facilities

- Diesel engine for cylinder type pump : Worn out

- Elevated tank No. 1, near the source :
  Volume : 24.6 cubic meters
  Elevation : 6 m above ground surface. Steel made and cylindrical type.
  Plenty of leakage from the joint, and it is not easy to repair.

- Elevated tank No.2, about 1 km from the source
  Cylindrical steel tank with a volume of about 10 cubic meters.
  Elevation : 4 m above ground surface, (ground elevation is 3.60 m higher than that of No. 1). The pipe between water source and this tank is broken.

- Distribution pipeline and communal faucets : All of the faucets are broken and abandoned.
  The distribution pipes and transmission pipes to No. 2 elevated tank are broken and/or lost.

ANKAZOABO :

The existing water supply system in this town is equipped with 5 communal faucets and distribution pipeline of more than 1,500 m total length.
However, these facilities have not been working for many years, because of worn out pumping facility and pipeline.

a. Condition of the water source and well rehabilitation

- Depth of the well : 27.25 m (record : 31 m)
- Static water level : 12.36 m (5 m)
- Discharge : max 80 l/min (120 l/min)
- Drawdown at 50 l/min pumping : 0.94 m

The development of the well was undertaken by the method of air lifting/surging for more than 3 hours. At the beginning of the air lifting, a small amount (40-50 l/min) of muddy water came up, but the amount gradually increased to 80 l/min of clean water.

The brushing did not increase discharge, because a smaller diameter screen under riser pipe was left in the well bottom when removal work was conducted.

b. Condition of other facilities

- Elevated tank : A big cylindrical steel tank with a volume of about 40 cubic meters and 3 m above ground surface has been maintained in a good condition except for a small leakage from the joint.
- Communal faucets : All of the faucets and one concrete base have disappeared.

- Distribution pipeline : The 2" PVC pipes are damaged, especially where the pipes are not buried deep enough due to hard ground surface of limestone.

BEREKETA :

Water used to be pumped from 2 dug wells by a ground level centrifugal pump, up to the elevated concrete tank and distributed to 2 sets of washing bases and 12 communal faucets. This distribution system has not been functioning for many years, and the faucet bases within the village seem to be inconveniently located for the users.

The biggest problem in this supply system is the limited amount of water, especially in the dry season.
Condition of the two dug wells is as follows.

	Diameter	Depth	Water level	Well capacity
No.1 dug well	0.8 m	8.27 m	7.25 m B.G.S.	drying up in 2 hours at a pumping rate of 45 liters/min.
No.2 dug well	1.0 m	7.92 m	7.39 m B.G.S.	drying up in 5 minutes at a pumping rate of 70 liters/min.

MAHABOBOKA :

There are two boreholes in the village. According to the village people, one is equipped with hand pump, but since water quality is poor, this well has not been used for drinking water.
The other well was drilled several years ago at a place where the water quality was expected to be better. However, this well has not been utilized, being kept capped, probably due to the limited amount of water, especially in the dry season.

The air pipe was lowered to the dried up bottom (10 m B.G.S.) intending to remove the settled mud/soil from the bottom and from the screen. Lowering of the air pipe, however, stopped at 10.2 m B.G.S. due to stiff soil. Thus, the recovery of this well was not successful, and a new well should be drilled in this village.

5.2 Conclusions of the Rehabilitation Survey

The findings from the detailed rehabilitation surveys on the above 8 villages are summarized as follows.

(a) Borehole

Many of the wells were drilled by the "cased hole drilling method" (Jetted well, driven well). The wells constructed by this method usually have shorter life span compared with the drilled wells, because the gravel packing to the annular space surrounding the screen is difficult and sometimes impossible. (Ex. : Befandriana, Betsioky, Andranovory, Ankazoabo and Mahaboboka). Also, the rehabilitation works to recover the well are difficult or almost impossible, because the screens are found to be completely clogged or filled with mud.
The cased hole drilling method occasionally blinds the good shallow aquifer, which will result in smaller capacity (Ex.: Befandriana).
By the reasons mentioned above, most of the existing wells cannot be utilized in the future. An exception is Sakaraha's well, but one new well should be drilled in

this town in the future, because the recovery of the well was not enough.

(b) Other facilities

The reservoir tanks except that of Sakaraha can be used in the future by sealing against leakage. Most of the other facilities like pumping systems, distribution pipelines and communal bases should be replaced or reconstructed.

5.3 Model Rehabilitation Works

Based on the rehabilitation surveys conducted in Phase II, the village BEFANDRIANA was selected as a model site among eight(8) surveyed villages. One local contractor was hired, and the model rehabilitation was carried out in Phase III in accordance with the technical specification prepared by the Study Team, which is attached in APPENDIX.

The initial plan for the rehabilitation works in this village was limited to the replacement of the pumping system and the reconstruction of the worn-out faucet base, intending to utilize the rehabilitated borehole. However, since the rehabilitation survey revealed that the existing borehole could not be recovered, a new well was constructed beside the existing well by the drilling crew of the Study Team.

The comparison of new and old wells is shown below.

	New well	Old well
Drilled depth :	53.0 m	64.0 m
Casing diameter :	6"	6" 4" 3" telescopic
Drilling method :	Open hole (rotary)	Cased hole (?)
Discharge rate :	300 liter/min	30 liters/min

The other works done under the contract basis in Befandriana are listed below.

- Installation of a new submersible motor pump in the new

- Installation of a new submersible motor pump in the new well
- Construction of the generator house, and installation of a new diesel engine generator (12.5 KVA)
- Construction of a new faucet base with one faucet
- Repair of the existing reservoir tank (mortar facing, drainage, one faucet)
- Cleaning and repair (putty sealing) of the existing tank, and replacement of the outlet pipe and valve
- Piping works from the new well to the elevated tank including water meter installation
- Test run of all of the facility

6. PILOT FACILITIES

6. PILOT FACILITIES

Three pilot facilities for water supply system (Type A, B and C) have been constructed during Phase III.

Some test boreholes drilled in Phase II were converted to production wells as water sources of the pilot facilities. The technical specifications for local contractors are attached in Supporting Report(1).

6.1 Pilot facility Type A:

This is a model water supply system equipped with an elevated tank, branch type distribution pipelines and three communal faucet bases. The system was constructed in Mahasoa, which is the major residential area of TRANOKAKY, with a population of about 1,000.

The pilot facility is composed of the following:

- Elevated tank : Reinforced concrete, 16 cubic meters, bottom height 2.6 m above ground
- Distribution pipeline : Galvanized iron pipes, 48 mm diameter, total length 36 m.
- Communal faucet bases : Brick with mortar facing, 3 bases with 12 faucets
- Generator /Storage house : Brick wall and slate roof, 18 square meter
- Borehole with submersible motor pump : 181 m deep, 6 inch FRP casing, static water level 16.24 m, pump position 106 m B.G.S.

6.2 Pilot facility Type B:

This facility is similar to type A, with the addition of a solar energy pumping system.

The major purpose of this system was to monitor the effectiveness of photovoltaic power generation for pumping system. Since the solar power generation system requires very high investment cost, the sites for solar pumping system are limited to areas where the groundwater level is comparatively high, less than 50 m below ground surface. Therefore, Soahazo was selected as the site for this experiment, since its static water level was found to be 36 m B.G.S.

The pilot facility is composed of the following:

- Electricity generating system : 18 pcs of solar panel, inverter for 220 V-4A
- Monitoring system : 2 pcs. of solar panel, flow meter, solar meter, data logger
- Elevated tank : Reinforced concrete, 10 cubic meters and bottom height 1.2 m A.G.S.
- Communal faucet base : 1 base with 4 faucets about 25 m from the elevated tank
- Generator/storage house : Brick wall, slate roof, 15 square meters
- Borehole with submersible motor pump : 76 m deep, 4 inch casing, static water level 36 m, pump position 42 m

6.3 Pilot facility Type C:

Bottom cylinder type manual pumps have been installed in 16 test boreholes and reinforced concrete bases have been constructed. Some of them are temporary facilities prior to the higher level water supply system to be implemented by a future project, while others are permanent facilities. Some local made and some Japanese made pumps were installed for the purpose of comparing life span, convenience of use and relative difficulty of maintenance.

The sixteen villages where the hand pumps have been installed are as follows:

Japanese pump [NISSAKU] Local pump [SOMECA]

Japanese pump [NISSAKU]	Local pump [SOMECA]	
- Namaboha	- Manoy	- Manombo
- Ampasikibo	- Ampoza	- Benetsy
- Belitsaka	- Sihanaka	- Ankilimalinika
- Analamisampy	- Basibasy	- Manoroka
- Analatelo	- Mangotroka	- Analamary
	- Ampihamy	

7. EVALUATION OF GROUNDWATER RESOURCES

7. EVALUATION OF GROUNDWATER RESOURCES

7.1 Water Balance Analysis

7.1.1 Water Balance Equation

Water balance analysis of the groundwater basin as well as estimations of recharge in the aquifer system shall be performed in order to evaluate the potential areas for groundwater development.

Water balance analysis of the Study Area

The water balance analysis is performed in the tributary areas of Mangoky and Onilahy Rivers (i.e., those inside the Study Area), in the catchment areas of Manombo and Fiherenana Rivers, and in the coastal area between Manombo and Mangoky Rivers.

In this analysis, the input of water from precipitation P is being equated to the outflow of water by evapotranspiration E, groundwater recharge W, and runoff O.

$$P = O + E + W \tag{1}$$

This water balance analysis shall provide some general understanding of the amount of natural groundwater recharge to the aquifer systems in the Study Area.

Estimation of groundwater recharge for unconfined aquifers

The concept of water balance shall be extended to the estimation of groundwater recharge into unconfined aquifers. Here, the groundwater system is recharged by rainfall infiltration, influent seepage from river beds, inflow from the upstream of the aquifer, and leakage from other aquifers. On the other hand, groundwater is discharged as effluent seepage into streams or springs, by abstraction, outflow at the downstream of the aquifer, and as leakage to other aquifers. Aside from these factors, the change in storage must also be taken into account in the water balance equation which is given as:

$$SdH/dt = (Q_1 - Q_2)/F + W \qquad (2)$$

where,

SdH/dt	:	Change in groundwater storage
S	:	Storage coefficient (For unconfined aquifer, S is the specific yield.)
dH	:	Change in water level
dt	:	Time increment
$(Q_1 - Q_2)/F$	:	Groundwater flow
W	:	Groundwater recharge
F	:	Water balance area

The groundwater inflow Q_1 includes the inflow from the upstream of the aquifer, recharge from the river bed, and leakage from other aquifers, while the groundwater outflow Q_2 is composed of the outflow to the downstream of the aquifer, effluent seepage into streams or springs and leakage to other aquifers. When shallow groundwater is involved, evapotranspiration loss is part of the groundwater outflow.

When surface runoff O in Eq. (1) is estimated to be proportional to precipitation, the groundwater recharge by precipitation infiltration G becomes:

$$W = P' - E \qquad (3)$$

$$P' = (1 - C_1) \cdot P \qquad (4)$$

where C_1 is a constant assumed equal to the runoff coefficient.

Considering an ideal unconfined groundwater basin where groundwater inflow and abstraction are negligible, Eq. (2) can be expressed as

$$SdH/dt = -Q_2/F + W \quad (5)$$

In the dry season, when the infiltration of precipitation is negligible, Eq.(5) becomes

$$SdH/dt = -Q_2/F \quad (6)$$

Water level and change in water level in the dry season can be assumed to have a linear relationship as follows

$$dH/dt = a \cdot H + b \quad (7)$$

where H = water level and a, b = constants.

The constants can be determined by analyzing a recession curve of shallow groundwater level in the dry season.

Replacing Eq. (7) into Eq. (6),

$$-Q_2 = S \cdot F \cdot (a \cdot H + b) \quad (8)$$

If Eq. (8) is substituted into Eq. (5), then the basic formula for shallow groundwater balance becomes

$$SdH/dt = S \cdot (a \cdot H + b) + W \quad (9)$$

7.1.2 Recharge Estimation for Unconfined Aquifers

(1) Water balance calculation, based on equations (3)-(9), was carried out following the procedure described below.

- Initial water level is chosen from the water level record. Time step one is set. Parameters (S), (C) and (Mdmax) are carefully chosen and given in the equation.

- P and E at each time step are given and W is calculated as follows:

$$M_{dt}=M_{dt-1} + P'-E$$

$$W=0$$
$$W=M_{dt} - M_{dmax} \quad (M_{dt}>M_{dmax})$$
$$M_{dt}=M_{dmax} \quad (M_{dt}>M_{dmax})$$

where, M_{dt-1} --- Water content in the saturated zone in previous time step

M_{dt} --- Water content in the saturated zone in present time step

- By assigning arbitrary values to W in equation 9, dH/dt is calculated.

- H of next time step is calculated as H=H+dH

- If the time step comes to the end, then computation stops, otherwise repeat the procedure.

Parameters S, C and Mdmax are changed on a trial and error computation, until the calculated water levels match the actual groundwater levels.

(2) Computation of the Recharge Analysis

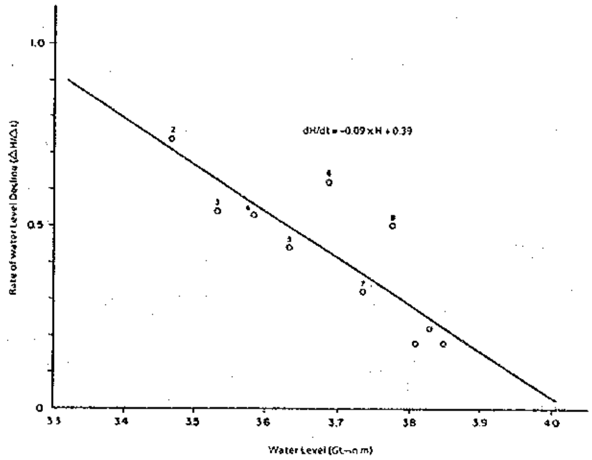
The water level monitoring results in Ambatolily is chosen for this calculation. However, results are considered to be rough estimations because the monitoring period is limited to 10 months, from December 1989 to September 1990.

(a) Rainfall and Evapotranspiration

Rainfall record at Ankaraobato station is chosen for the calculation. Potential evapotranspiration is calculated by the Thornthwaite method as discussed in Section 3.3.

(b) Constants for Equation

From the water level recorded in Ambatolily and substituting five-day for dt, the linear relationship between H and dH/dt is recognized as the following figure.



Constants a and b are calculated by the least square method as follows.

$$dH/dt = -0.09 * H + 0.35$$

However, the term b is modified to 0.35 with calibration because data are not enough to arrive at accurate constants.

(c) Results

Results of the water balance calculations for shallow groundwater are shown in Table 7.1.1. A comparison between actual and computed groundwater levels is shown in Fig 7.1.1. Parameters determined with this procedure are as follows.

- Storage coefficient: 4 %
- Runoff coefficient: 20 %
- Water holding capacity: 10 mm

The estimated balance is as follows.

Raifall	525 mm	(100%)
Runoff	105 mm	(20%)
Evapotranspiration	325 mm	(62%)
Groundwater Recharge	94 mm	(18%)

7.1.3 Water Balance in Basins

Using formula (1)-(4), rough water balance of each basin is calculated as follows.

Basin	A(km^2)	P(mm)	ET(mm)	O (mm)	W (mm)
Manombo	508	760	494	152	114
Fiherenana	6755	780	507	156	117
Sakanavaka	3070	750	488	150	113
Isahena	1870	810	527	162	122
Malio	2040	870	566	174	131
Sakondry	730	750	488	150	113
Taheza	1600	770	5501	154	116

Areal rainfall is calculated from annual isohyet. Evapotranspiration and annual runoff is calculated by the ratio of rainfall in Section 3.3, i.e., 62% for evapotranspiration and 20 % for annual runoff.

The next table shows the results of spot discharge measurement in the dry season (baseflow as discussed is Section 3.4) considered as recharge potential.

unit:(l/min/km^2)

Basin	A (km^2)	Spot Measurement	Water Balance
Manombo	508	150	217
Fiherenana	6755	30	223
Sakanavaka	3070	360	214
Isahena	1870	144	231
Malio	2040	378	248
Sakondry	730	66	214
Taheza	1600	924	220

Results of spot measurements are considered as groundwater recharge potential. In consideration of both results, re charge potential is roughly estimated as 100-300 l/min/km^2 depending on the local hydrogeological condition.

Table 7.1.1 Water Balance Calculation

1. Initial water level 3.22
2. Runoff Coefficient 0.2
3. Mdmax 10
4. Initial Md 10
5. Storage Coeff. S 0.05

6. Coefficient of decline
a : -0.09
b : 0.35

STEP	MONTH	P	E	P*C	M'	W	dif H	H	M''	M
0								3.22	10	10
1	DEC	60	22	48	36	26	-0.45	2.760	10	10
2		10.6	22	8.48	-3.52	0	0.101	2.861	-3.52	0
3		15.4	22	12.32	-9.68	0	0.092	2.954	-9.68	0
4		47.6	22	38.08	16.08	6.08	-0.03	2.916	10	10
5		0	22	0	-12	0	0.087	3.004	-12	0
6		1.1	26.4	0.88	-25.5	0	0.079	3.083	-25.5	0
7	JAN	73.1	22	58.48	36.48	26.48	-0.45	2.626	10	10
8		29.7	22	23.76	11.76	1.76	0.078	2.705	10	10
9		39	22	31.2	19.2	9.2	-0.07	2.627	10	10
10		55.6	22	44.48	32.48	22.48	-0.33	2.291	10	10
11		0	22	0	-12	0	0.143	2.435	-12	0
12		61.3	26.4	49.04	22.64	12.64	-0.12	2.313	10	10
13	FEB	0	20.5	0	-10.5	0	0.141	2.455	-10.5	0
14		36.2	20.5	28.96	8.46	0	0.129	2.584	8.46	8.46
15		2.2	20.5	1.76	-10.2	0	0.117	2.701	-10.2	0
16		0	20.5	0	-20.5	0	0.106	2.808	-20.5	0
17		13.5	20.5	10.8	-9.7	0	0.097	2.905	-9.7	0
18		0	12.3	0	-12.3	0	0.088	2.994	-12.3	0
19	MAR	0	19	0	-19	0	0.080	3.074	-19	0
20		0	19	0	-19	0	0.073	3.147	-19	0
21		0	19	0	-19	0	0.066	3.214	-19	0
22		0	19	0	-19	0	0.060	3.275	-19	0
23		0	19	0	-19	0	0.055	3.330	-19	0
24		8.2	22.8	6.56	-16.2	0	0.050	3.380	-16.2	0
25	APR	0	15.5	0	-15.5	0	0.045	3.426	-15.5	0
26		0	15.5	0	-15.5	0	0.041	3.468	-15.5	0
27		0	15.5	0	-15.5	0	0.037	3.506	-15.5	0
28		7.2	15.5	5.76	-9.74	0	0.034	3.540	-9.74	0
29		17.1	15.5	13.68	-1.82	0	0.031	3.571	-1.82	0
30		6.9	15.5	5.52	-9.98	0	0.028	3.600	-9.98	0
31	MAY	10	12.5	8	-4.5	0	0.025	3.626	-4.5	0
32		0	12.5	0	-12.5	0	0.023	3.649	-12.5	0
33		0	12.5	0	-12.5	0	0.021	3.671	-12.5	0
34		0	12.5	0	-12.5	0	0.019	3.691	-12.5	0
35		0	12.5	0	-12.5	0	0.017	3.708	-12.5	0
36		0	15	0	-15	0	0.016	3.725	-15	0
37	JUN	0	10.5	0	-10.5	0	0.014	3.739	-10.5	0
38		0	10.5	0	-10.5	0	0.013	3.753	-10.5	0
39		0	10.5	0	-10.5	0	0.012	3.765	-10.5	0
40		0	10.5	0	-10.5	0	0.011	3.776	-10.5	0
41		4.4	10.5	3.52	-6.98	0	0.010	3.786	-6.98	0
42		0	10.5	0	-10.5	0	0.009	3.795	-10.5	0
43	JUL	0	11.5	0	-11.5	0	0.008	3.804	-11.5	0
44		0	11.5	0	-11.5	0	0.007	3.811	-11.5	0
45		0	11.5	0	-11.5	0	0.006	3.818	-11.5	0
46		0	11.5	0	-11.5	0	0.006	3.825	-11.5	0
47		0	11.5	0	-11.5	0	0.005	3.830	-11.5	0
48		22.6	13.8	18.08	4.28	0	0.005	3.836	4.28	4.28
49	AUG	0	15.5	0	-11.2	0	0.004	3.840	-11.2	0
50		0	15.5	0	-15.5	0	0.004	3.845	-15.5	0
51		0	15.5	0	-15.5	0	0.003	3.849	-15.5	0
52		0	15.5	0	-15.5	0	0.003	3.852	-15.5	0
53		0	15.5	0	-15.5	0	0.003	3.855	-15.5	0
54		0	18.6	0	-18.6	0	0.002	3.858	-18.6	0
55	SEP	3.7	20.5	2.96	-17.5	0	0.002	3.861	-17.5	0
56		0	20.5	0	-20.5	0	0.002	3.864	-20.5	0
57		0	20.5	0	-20.5	0	0.002	3.866	-20.5	0
58		0	20.5	0	-20.5	0	0.002	3.868	-20.5	0
59		0	20.5	0	-20.5	0	0.001	3.870	-20.5	0
60		0	20.5	0	-20.5	0	0.001	3.871	-20.5	0

P:5-day rainfall; E:5-day Evapotranspiration;
M:Remained depth; M':M+P*C-E; M'':Converted with MD

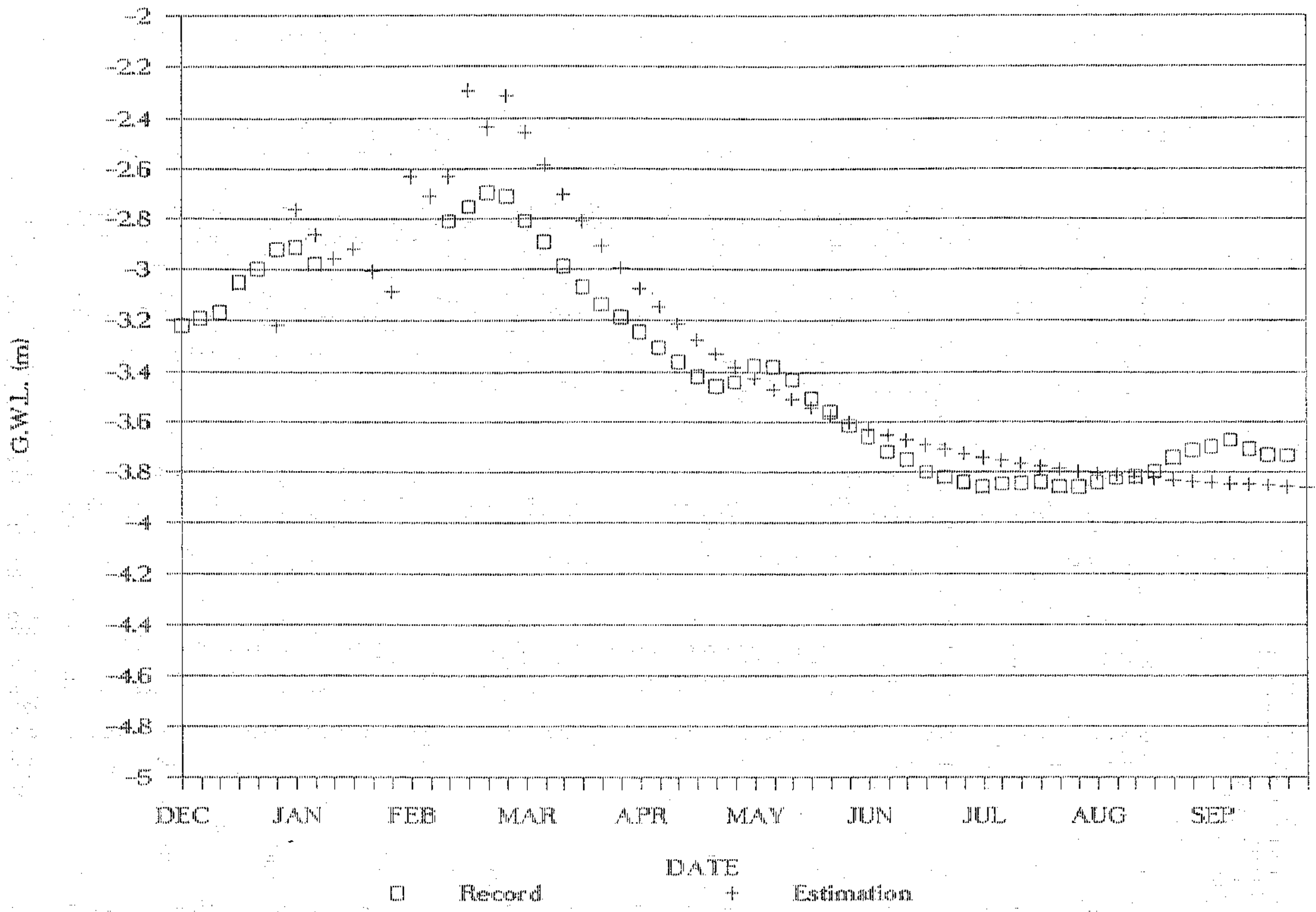


Fig. 7.1.1 Water Balance

7.2 Groundwater Model Simulation

7.2.1 Background of Analysis

(1) Basic Concept

In order to recognize groundwater flow patterns, a two dimensional simulation model is applied to the Study Area. Basically, since groundwater flow in rocks is due to primary openings formed within rocks and secondary openings created after the rock formation, flow condition is different from general porous media. However, it is possible to treat the flow in rocks by assuming that the hydraulic conductivity is applied to such a zone with some density, depth and property of rock opening condition. In view of this, groundwater flow simulation can be treated as in the porous media.

As the steady groundwater in the porous homogeneous media flows by the fluid potential of topography, hydraulic head potential ϕ is simply presented as the following equation.

$$\phi = h \cdot g \qquad (1)$$

where, h:groundwater level
g:gravity acceleration

The distribution of hydraulic head in the section can be calculated by topographic condition and groundwater level. Equipotential lines can be drawn using the distribution of hydraulic head. Finally, flow lines can be drawn with equipotential lines because both lines are coordinated. This map is called "Flow Net", and is useful to understand visually the groundwater flow condition.

When two adjacent layers have different hydraulic conductivities, both equipotential and flow lines are deflected at the boundary. Hubbert presented a groundwater flow system in homogeneous section with the same hydraulic conductivity in 1940(See Fig. 7.2.1(1)). Toth presented a mathematical model by Laprus formula for the steady flow system (See Fig.7.2.1(2)).

Depending upon the drainage basin topography and geometry, flow systems have regional, intermediate and local components.

- A regional flow system has the recharge area in the basin divide and the discharge area at the valley bottom.
- An intermediate flow system has at least one local system between their recharge and discharge areas.
- A local groundwater flow system has the recharge area at a topographic high spot and its discharge area at an adjacent topographic low.

Freeze & Witherspoon conducted numerical analysis on the hydraulic potential distribution in a multi-layer structure with different hydraulic conductivities, and presented three flow patterns. Fig.7.2.1(3) shows the three flow patterns: (1) underlying layer has high permeability, (2) homogeneous layer, (3) some parts of layers have higher permeabilities.

All the above mentioned approaches rely on manual drawing of equipotential and flow lines after calculation of hydraulic potential. Therefore, it is very difficult when the section has complicated topographic and geological structure.
The groundwater flow analysis by the flow function has been researched only for simple geological conditions, like flow lines in dam basement.
Friend & Matanga conducted numerical analysis by the finite-element method in 1985, discussing the accuracy of the method.

(2) Hydraulic Head and Flow Function (Bear,1979)

Flow line can be defined as a tangent curve to many points of flow vector of groundwater. Therefore, the direction of a flow line is the same as the groundwater flow.
On the basis of this definition, quantity of a flow is stable without interference from other flows.

The equation of a flow line is

$$q \times ds = 0 \tag{2}$$

Where, $\times$: an alternant production
ds : unit flux vector

In the rectangular coordinates system, (2) is

$$q_y \cdot dx - q_x \cdot dy = 0 \quad \text{(Fig. 7.2.1(4))} \tag{3}$$

Acordingly, a function $\psi = \psi(x,y)$ is defined as steady amount on flowline,

$$d\psi = 0 = \partial\psi/\partial x \cdot dx + \partial\psi/\partial y \cdot dy \tag{4}$$

The following formula is obtained by equation(3) and equation(4).

$$q_x = 0 = \partial\psi/\partial y \qquad q_y = \partial\psi/\partial x \tag{5}$$

is formed as flow function (dimension is L2/T).
From Darcy's law,

$$q_x = -K_x \cdot \partial\phi/\partial x \qquad q_y = -K_y \cdot \partial\phi/\partial y$$

are read, so that the following relationship can be obtained.

$$q_x = -K_x \cdot \partial\phi/\partial x = -\partial\psi/\partial y$$
$$q_y = -K_y \cdot \partial\phi/\partial y = \partial\psi/\partial x \tag{6}$$

As shown in Fig.7.2.1(5), the groundwater flow sandwiched in 2 flow lines is given.

$$\Delta Q = \int_{\psi_1}^{\psi_2} d\psi = \psi_2 - \psi_1 \tag{7}$$

Quantity A is the difference between two flow functions located on the flow.

(3) Basic Equations

The basic equation of continuity of the steady groundwater flow is obtained by a hydraulic head ϕ in the section of 2 dimensions.

$$\frac{\partial}{\partial x}\left(K_x \cdot \frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \cdot \frac{\partial \phi}{\partial y}\right) = 0 \qquad (8)$$

and the flow function ψ is as follows (Bear, 1979)

$$\frac{\partial}{\partial x}\left(\frac{1}{K_y} \cdot \frac{\partial \psi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{K_x} \cdot \frac{\partial \psi}{\partial y}\right) = 0 \qquad (9)$$

In a Dirichlet Condition, boundary (known head) is at the boundary of the flow region

$$\phi = \phi_B \quad (\Gamma 1) \qquad (10)$$

$$\psi = \psi_B \quad (\Gamma 2) \qquad (11)$$

Where ϕ_B (Γ 1) is the known head in boundary Γ 1, and ψ_B (Γ 2) is a flow function in boundary Γ 2.

In a Neumann condition, boundary is (flux across boundary of the flowregion)

$$g_n^{\phi} = K_x \cdot \frac{\partial \phi}{\partial x} n_x + K_y \cdot \frac{\partial \phi}{\partial y} \cdot n_y \qquad (12)$$

$$g_n^{\psi} = - \frac{\partial \phi}{\partial x} \cdot r_x - \frac{\partial \phi}{\partial y} \cdot r_y \qquad (13)$$

Where g_n^{ϕ} ϕ, g_n^{ψ} are known flow (inflow is +) and a known flow function coordinates to boundary, n_x and n_y are co-sines of normal lines at boundaries with $n_x = - r_y$, $n_y = r_x$ (See Fig.7.2.1(6)).

A typical boundary condition is shown in Fig.7.2.1(7) (Friend & Matanga, 1985).

(4) Numeric Analysis

As the numeric analysis, Finite-Element Method (Galerkins' method) is used to solve equation (8) and (9).
A approximate value of ϕ and/or ψ is defined as follows

$$\gamma = \gamma = \sum_{j=1}^{n} \gamma_j W_j (x,y) \tag{14}$$

Here, γ is a point of contact of ϕ or ψ, γ_j is also a point γ, W_j is a base function, presented by a triangular elment (See Fig. 7.2.1(8) as follows,

$$W_j (x,y) = \frac{1}{2\triangle} (a_j + b_j x + c_j y) \quad j = 1,2,3 \tag{15}$$

Where, $\triangle$: area of triangle

$$\begin{aligned} a_1 &= x_2 y_3 - x_3 y_2, & b_1 &= y_2 - y_3, & c_1 &= x_2 - x_3 \\ a_2 &= x_3 y_1 - x_1 y_3, & b_2 &= y_3 - y_1, & c_1 &= x_3 - x_1 \\ a_3 &= x_1 y_2 - x_2 y_1, & b_1 &= y_1 - y_2, & c_1 &= x_1 - x_2 \end{aligned} \tag{16}$$

Where, x1~x3 and y1~y3 are coordinates of nodes.
In the Galerkin's method, the difference between the lts by equation (8) and (9) converted by eq. (14) is made to zero as average. The following equation is obtained with these results.

$$[R] \{\gamma\} = \{F\} \tag{17}$$

Components of [R] are as follows for potential ϕ and flow function ψ.

$$R^{\phi}_{ij} = \sum_{e} \iint (K_x \frac{\partial W_i}{\partial x} + \frac{\partial W_j}{\partial x} + K_y \frac{\partial W_i}{\partial y} \cdot \frac{\partial W_j}{\partial y}) \, d\,x\,dy \tag{18}$$

$$R^{\psi}_{ij} = \sum_{e} \iint (\frac{1}{K_y} \frac{\partial W_i}{\partial x} + \frac{\partial W_j}{\partial x} + \frac{1}{K_x} \frac{\partial W_i}{\partial y} \cdot \frac{\partial W_j}{\partial y}) \, d\,x\,dy \tag{19}$$

Σ means an element to be added. Equations (18) and (19) are

$$R^{e}_{ij} = \frac{1}{4\triangle} (C_x b_i b_j + C_r c_i c_j) \quad i, \quad j = 1,2,3 \tag{20}$$

Where, $C_x = K_x$ or $1/K_y$, $C_y = K_y$ or $1/K_x$

{F} includes Neumann condition. When a known flow qn is given, equation (12) becomes

$$F_i^{\phi} = \Sigma_e \quad qn \frac{\ell}{2} \tag{21}$$

Where, qn is vertical flow to the boundary, ℓ is length of element (See Fig.7.2.1(9).
In the flow function, equation (13) is

$$F_i^{\psi} = \frac{\phi_{i-1} \quad \phi_{i+1}}{2} \tag{22}$$

ϕ_{i-1} - and ϕ_{i+1} are the potential at both sides of i.

7.2.2 Modeling

(1) Model Section

Fig.7.2.2 and Fig.7.2.3 show the selected sections for a two-dimensional model simulation, both sections located in the coastal area.

The reasons to choose these sections are:

- Coastal area is the driest part in the Study Area.
- The fault system in this area is characterized by the North-South direction. These faults are considered to greatly influence the groundwater flow system.

(a) Andoharano-Manombo-Atm Section

The eastern boundary coincides with the watershed of Manombo river basin. Toliara Fault is located in the middle of section. Geological condition of upstream side of this fault is mostly composed of porous or fissured limestone and marly limestone of the Lower Eocene.

Condition of downstream side is estimated as alternation of compact or porous limestone, marly limestone, marl and fine to coarse grained sandstone with partial intrusion of gravelly coarse sandstone of the Middle to Upper Eocene.

(b) Befandriana-Lake Ihotry Section

The eastern edge coincides with the watershed of the Befandriana river basin, and ground level is continuously inclined to Lake Ihotry.Some faults exist in the middle of the section. Geological feature in the downstream side is estimated to be principally of three kinds according to the results of deep drilling at Befandriana in the 1970's.
From the upper part to the lower part, they are composed of neritic sediments of the Middle to Upper Eocene, neritic sediments of the Lower Eocene and neritic sediments of the Upper Cretaceous. Detailed composition is discussed in Chapter 3.

The finite-element cells made in both sections are shown in

Fig.7.2.3(2) and Fig.7.2.3(2).

(2) Boundary condition

Boundary conditions are given as follows:

(a) groundwater level is the same as the ground elevation

(b) bottom, left and right boundaries are impermeable, and

(c) no flow is interrupted with these directions.

(3) Hydraulic conductivity

Hydraulic conductivities of model layers are determined from collected records and results of pumping test. Table 7.2.2 shows hydraulic conductivities and lithofacies. Aquifer properties in the Study Area were discussed in Chapter 3.

The following cases are adopted.

Case I: Same hydraulic conductivity

Case II: Estimated conductivities of model layers

Combinations of hydraulic conductivities are shown in Fig. 7.2.2 (2) and 7.2.3 (2).

4) Results and discussion

(a) Andoharano - Manombo Atm section

When the section is homogeneous porus media, groundwater flows like Case I. Regional flow can be drawn from the watershed in the east to the Route 9 in the west. Four intermediate flows are shown in the above regional flow, especially concentrated around the branch of Manombo river. Case II is drawn with the fault system and different hydraulic conductivities. It is very clear that the regional flow from the eastern side is dammed up by the existence of the fault. If this fault zone is completely impermeable, all flows come out to the eastern side of the fault. Intermediate flow around the fault is especially influenced by it.

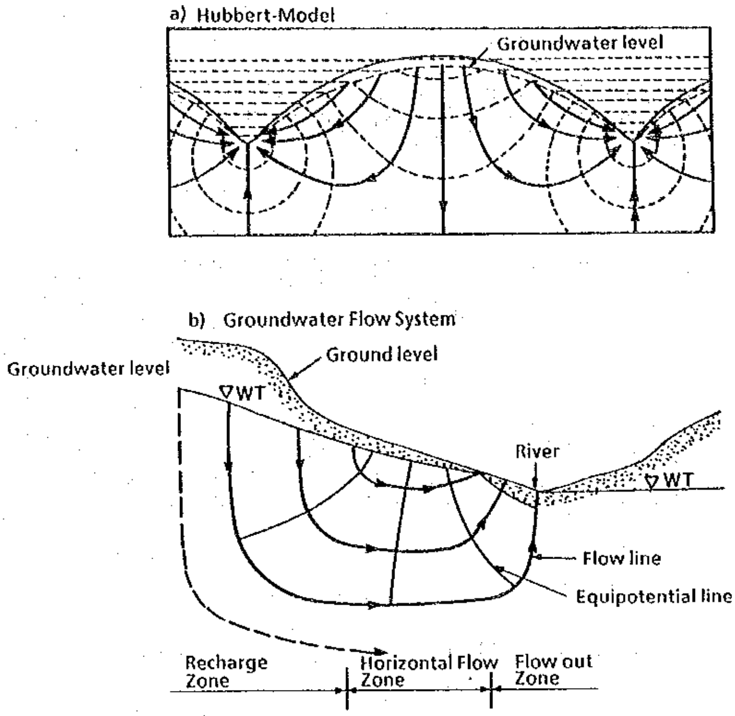
(b) Befandriana - Lake Ihotry section

Case I shows the flow pattern in the homogeneous media. Regional flow system occurs from the watershed in the Mountain range toward the Lake Ihotry direction. Three intermediate flows are seen in some dry streams.
Case II is drawn with the fault system and different hydraulic conductivities. It is clear that the regional flow from the eastern side is dammed up by the existence of the fault. Two intermediate flow systems are shown in mountainous zone. Flow systems in mountainous area and flat area are basically separated now. Antanimeva was observed in the time of fieldouruey sandwiched by two.
The existence of artesian well in Antanimieva was observed in the time of field survey sandwiched by two faults with N-S direction. The eastern fault is the one considered in the model section. For the Antanimieva well, the influence of the eastern fault is not so severe. On the other hand, the western fault has a big role to stop and dam up groundwater flow.

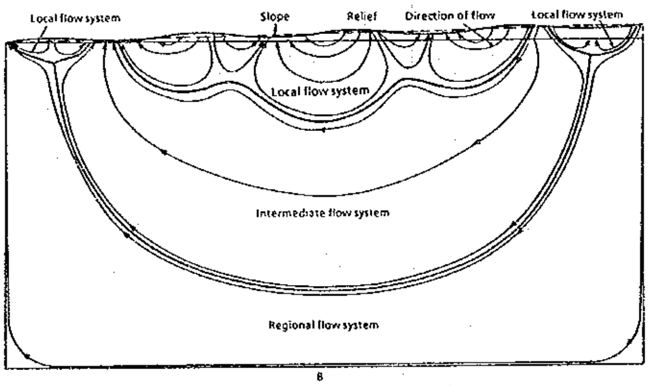
Table 7.2.1 Hydraulic Conductivity

Location	T/Jacob(m^2/min)	L(Screen)(m)	K(cm/sec)	Lithofacies
1 Manoy	4.34×10^{-2}	20	3.6×10^{-3}	Sandstone(M~C)
2 Ampoza	4.71×10^{-2}	24	3.3×10^{-2}	Sandstone(M, M~C)
3 Siharalca	4.32×10^{-1}	20	3.6×10^{-2}	Sandstone(M~C)
4 Basibasy	9.76×10^{-3}	28	5.8×10^{-4}	Sandy Marl&Sandy Limestone
5 Analatero	----	20	----	Sandy Marl&Sandy Limestone&Limestone
6 Mangotroka	1.14×10^{0}	24	7.9×10^{-2}	Sandstone(M~C)
7 Soahazo-1	1.13×10^{0}	16	1.2×10^{-1}	Sandy Marl
8 Soahazo-2	4.69×10^{-2}	12	6.5×10^{-3}	Sandstone(M~C)&Sandy Marl
9 Analamisampy	3.20×10^{-3}	24	2.2×10^{-4}	Sandy Limestone&Sandstone(M)&Sandy Marl
10 Belitsalco	1.08×10^{-2}	20	9.0×10^{-4}	Sandstone(M&C)&Sandy Marl
11 Ampasikibo	8.71×10^{-2}	20	7.3×10^{-3}	Sandy Marl
12 Namabaha	3.10×10^{-2}	18	2.8×10^{-3}	Sandstone(M~C)&Sandy Marl&Sandy Limestone
13 Ampihamy	3.45×10^{-1}	28	2.1×10^{-2}	Sandstone(M~C)
14 Ankaraobato	1.67×10^{-1}	28	9.9×10^{-3}	Sandstone(M~C&C)&Sandy Marl&Limestone
15 Manombo Atm	2.36×10^{0}	12	3.3×10^{-1}	Sandstone(G~M~C)&Limestone
16 Tsefanolca	1.18×10^{-1}	20	9.8×10^{-3}	Marly Limestone&Sandstone(C)&Limestone
17 Benetsy	2.33×10^{-1}	16	2.4×10^{-2}	Sandstone(C)thire marly Sandstone
18 Ankilimalinika	3.02×10^{-1}	20	2.5×10^{-2}	Sandy Marl&Sandstone(C)
19 Anovoka	----	20	----	Sandstone(C)&Limestone
20 Befoly	----	14+open Lole	----	Limestone
21 Tranokaky	5.05×10^{-3}	56	1.5×10^{-4}	Basalt&Sandstone(f)
22 Tandrano	8.45×10^{-2}	24	5.9×10^{-3}	Sandstone(F~M)
23 Berenty-Betsileo	3.55×10^{-3}	32	1.8×10^{-4}	Marly Sandstone&Sandstone
24 Maninday	8.23×10^{-2}	28	4.9×10^{-3}	Sandstone(G~C)
25 Analamary	5.06×10^{-2}	36	2.3×10^{-3}	Sandstone(C~f)
Befaudriana	6.54×10^{-1}	16	6.8×10^{-2}	

Sandstone (7.9×10^{-2}~2.3×10^{-3}) Mean=1.3×10^{-2}
Sandy Marl (1.2×10^{-1}~7.3×10^{-3}) Mean=3.0×10^{-2}
Sandy Marl & Sandstone (2.5×10^{-2}~6.5×10^{-3}) Mean=1.3×10^{-2}
Sandstone & Limestone (3.3×10^{-1})
Sandy Marl & Limestone (9.9×10^{-3}~2.2×10^{-4}) Mean=1.5×10^{-3}
Basalt & Sandstone (1.5×10^{-4})

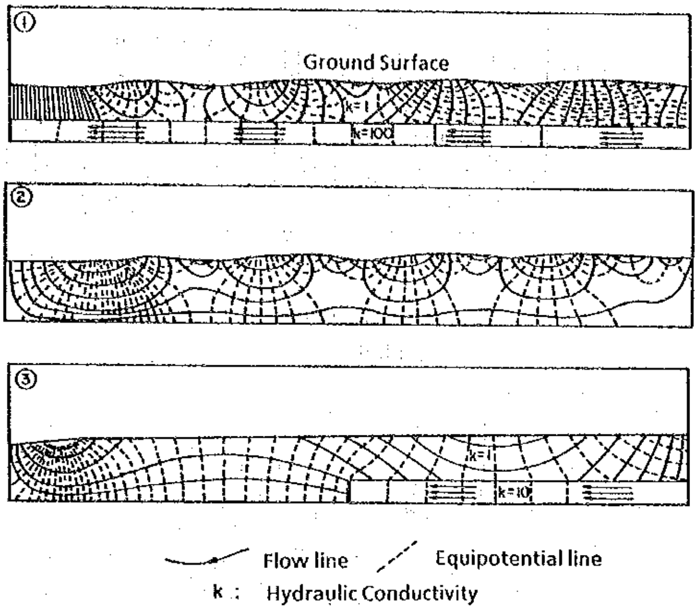


(1) Flow Pattern (Hubbert, 1940) and
Typical Grondwater Flow System

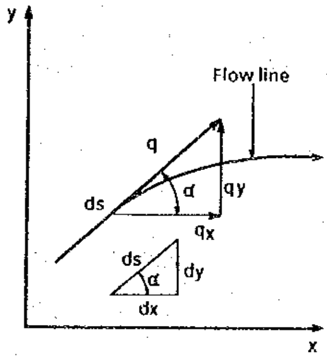


(2) Regional, Intermediate and Local Flow system
(Toth, 1963)

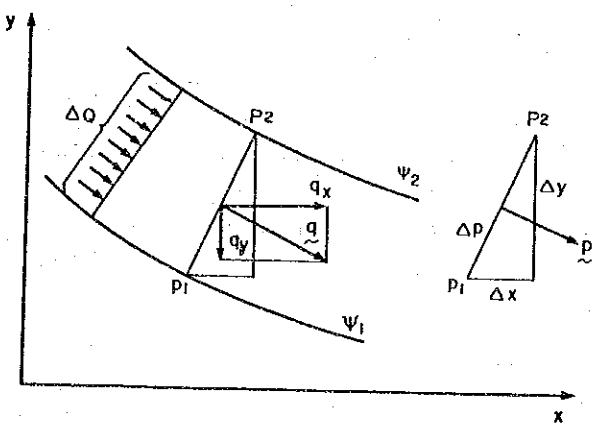
Fig. 7.2.1 Some Pictures for Theoretical Background (1)-(2)



(3) Steady Flow Systems in Some cases

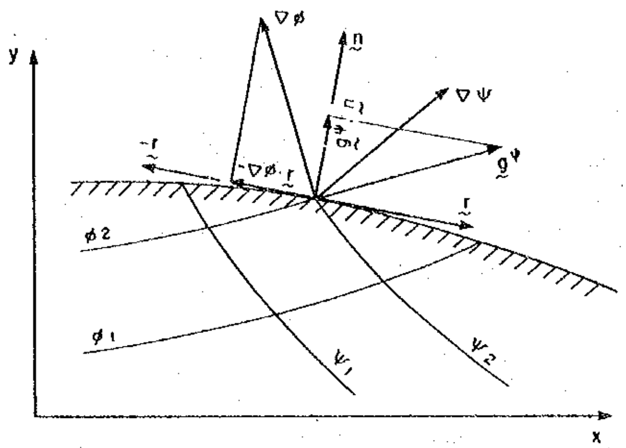


(4) Flow line (Bear, 1979)

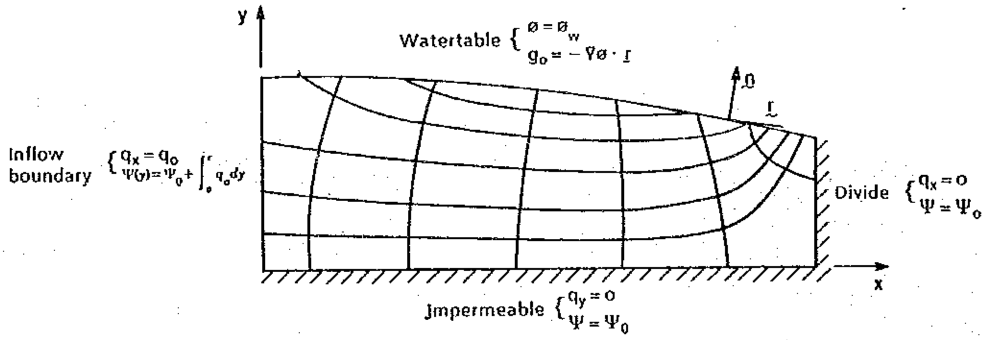


(5) Flux on Flow line (Bear, 1979)

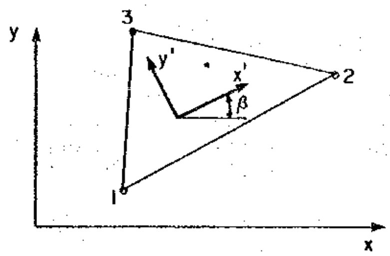
Fig. 7.2.1 Some Pictures for Theoretical Background (3)-(5)



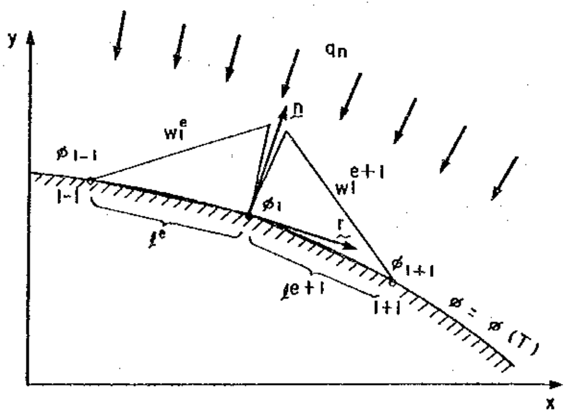
(6) Hydraulic Potential and Flow Function on the Boundary (Friend & Matanga, 1985)



(7) Boundary Condition (Friend & Matanga, 1985)

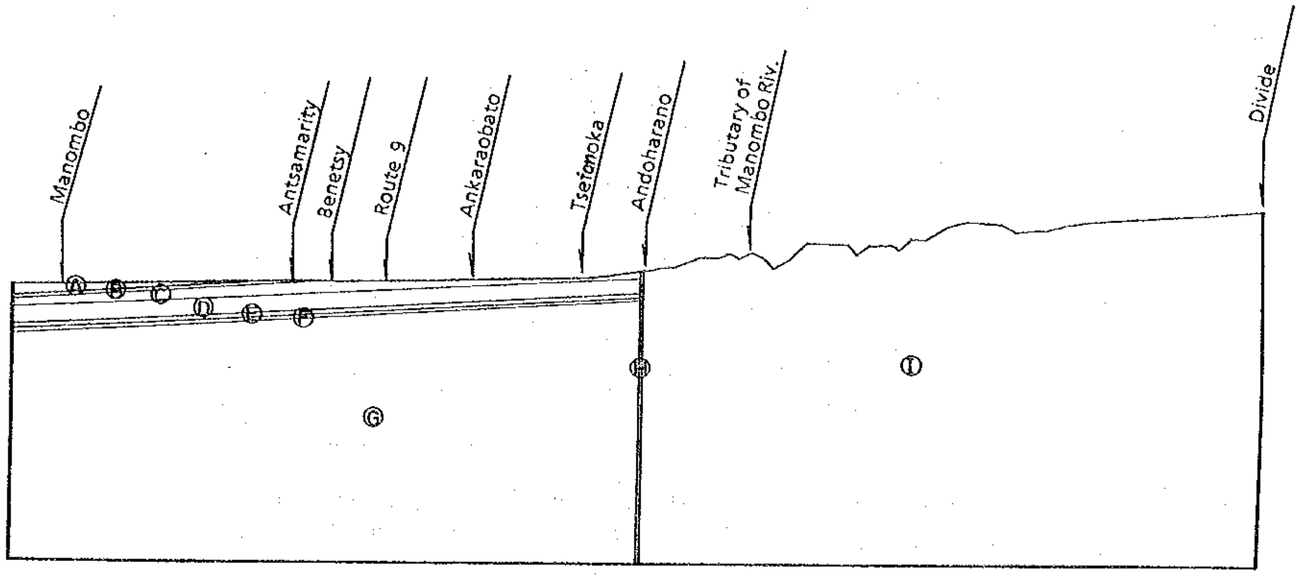


(8) Triangle Element

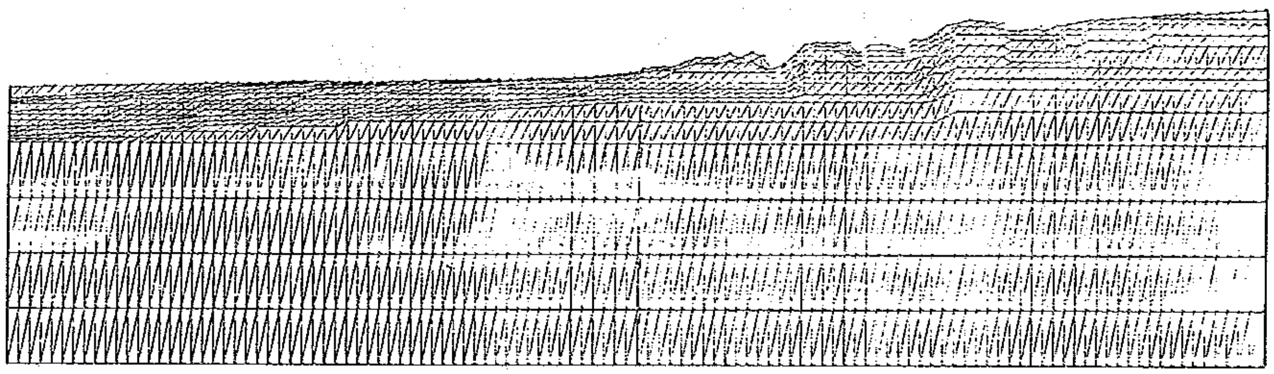


(9) Boundary Condition of Finite Element Method (Friend & Matanga, 1985)

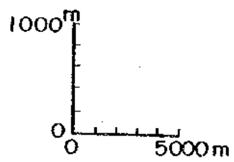
Fig. 7.2.1 Some Pictures for Theoretical Background (6)-(9)



(1) Selected Section



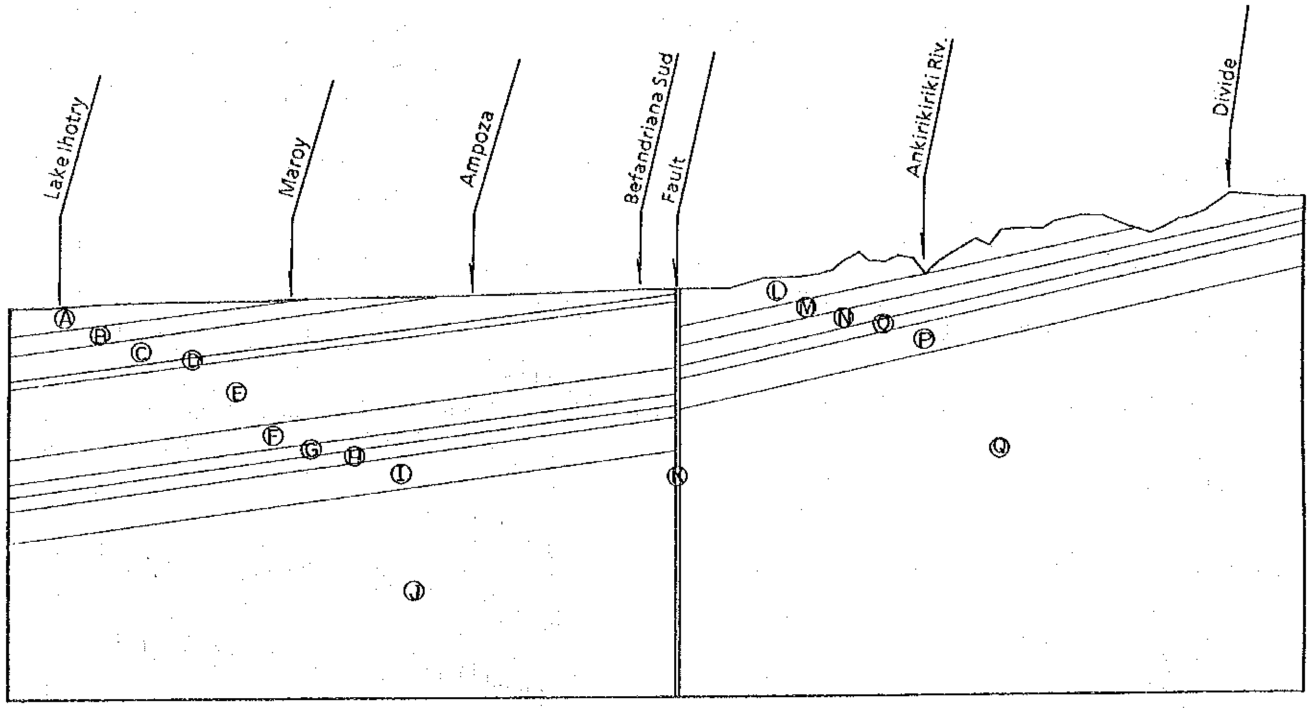
(2) Triangle Element



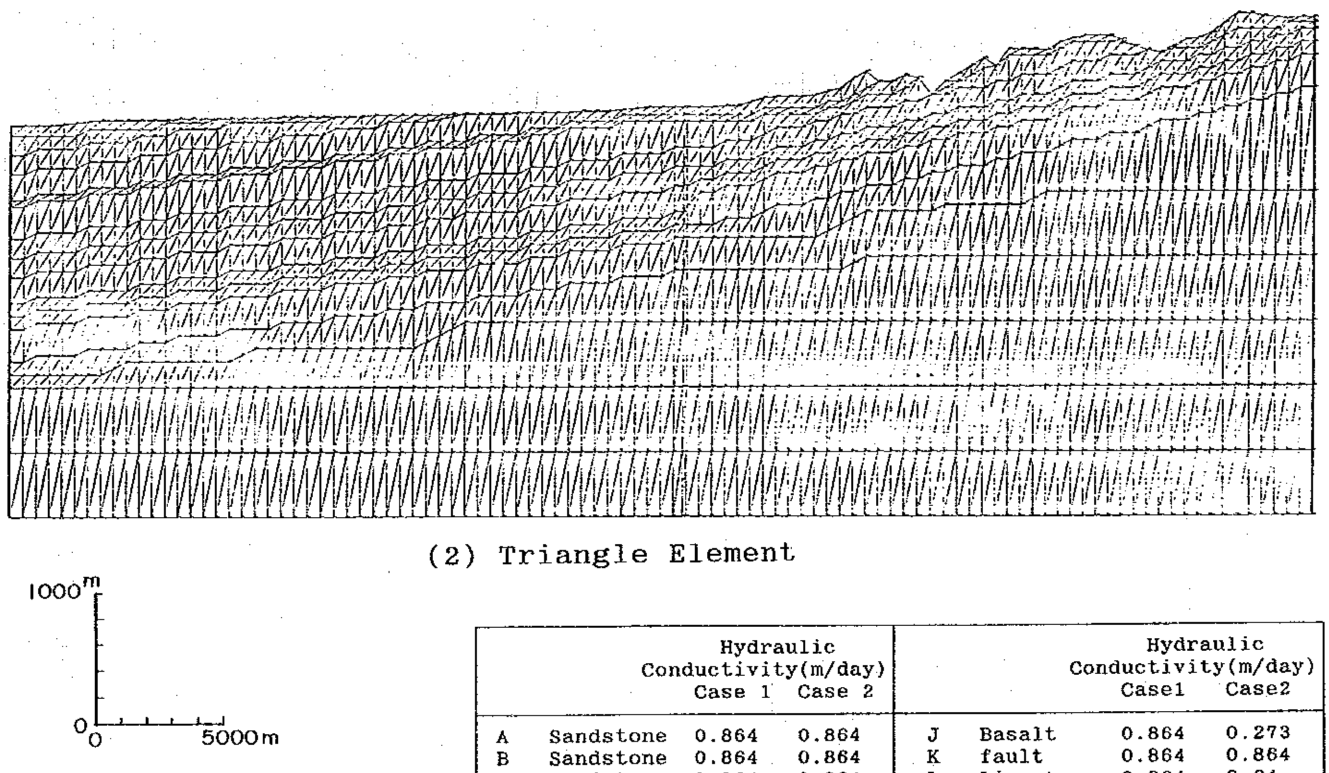
		Hydraulic Conductivity(m/day) Case 1	Case 2
A	Sandstone	0.864	0.864
B	Sandstone	0.864	0.864
C	Sandstone	0.864	0.864
D	Limestone	0.864	8.64
E	Sandstone	0.864	0.864
F	Marl	0.864	0.864
G	Limestone	0.864	8.64
H	Fault	0.864	0.0864
I	Limestone	0.864	8.64

(3) Hydraulic Conductivity

Fig. 7.2.2 Simulating Condition (Andoharano-Manombo Atm)



(1) Selected Section



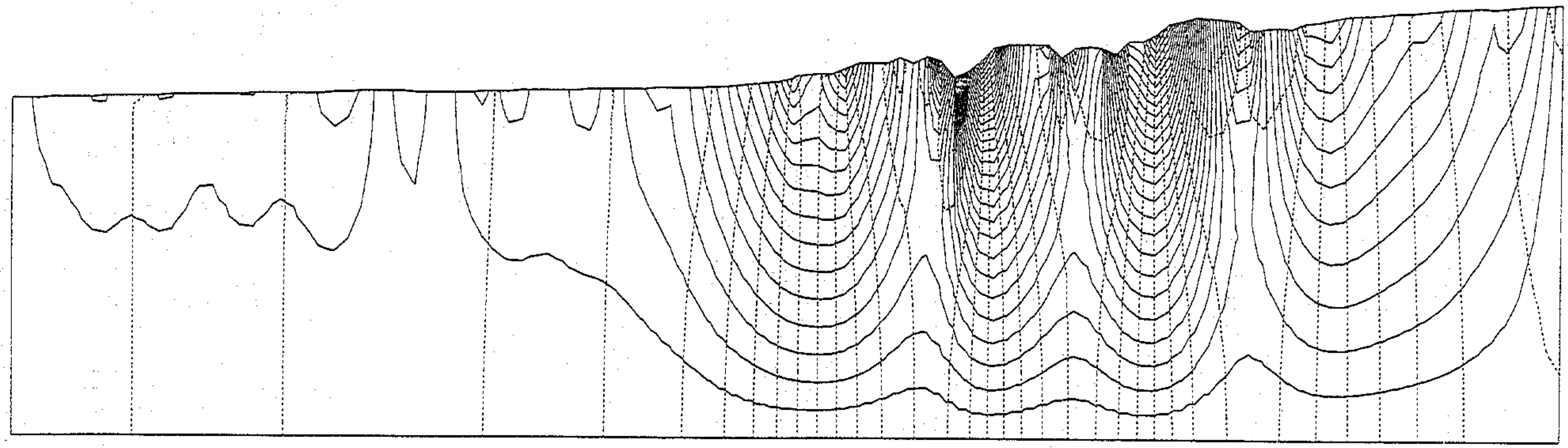
(2) Triangle Element

		Hydraulic Conductivity(m/day) Case 1	Case 2			Hydraulic Conductivity(m/day) Case1	Case2
A	Sandstone	0.864	0.864	J	Basalt	0.864	0.273
B	Sandstone	0.864	0.864	K	fault	0.864	0.864
C	Sandstone	0.864	0.864	L	Limestone	0.864	8.64
D	Marl	0.864	0.273	M	Marl	0.864	0.273
E	Limestone	0.864	8.64	N	Marl	0.864	0.273
F	Marl	0.864	0.273	O	Sandstone	0.864	0.864
G	Marl	0.864	0.273	P	Mudstone	0.864	0.273
H	Sandstone	0.864	0.864	Q	Basalt	0.864	0.273
I	Mudstone	0.864	0.273				

(3) Hydraulic Conductivity

Fig. 7.2.3 Simulating Condition (Befandriana-Lake Ihotry)

Case I



Case II

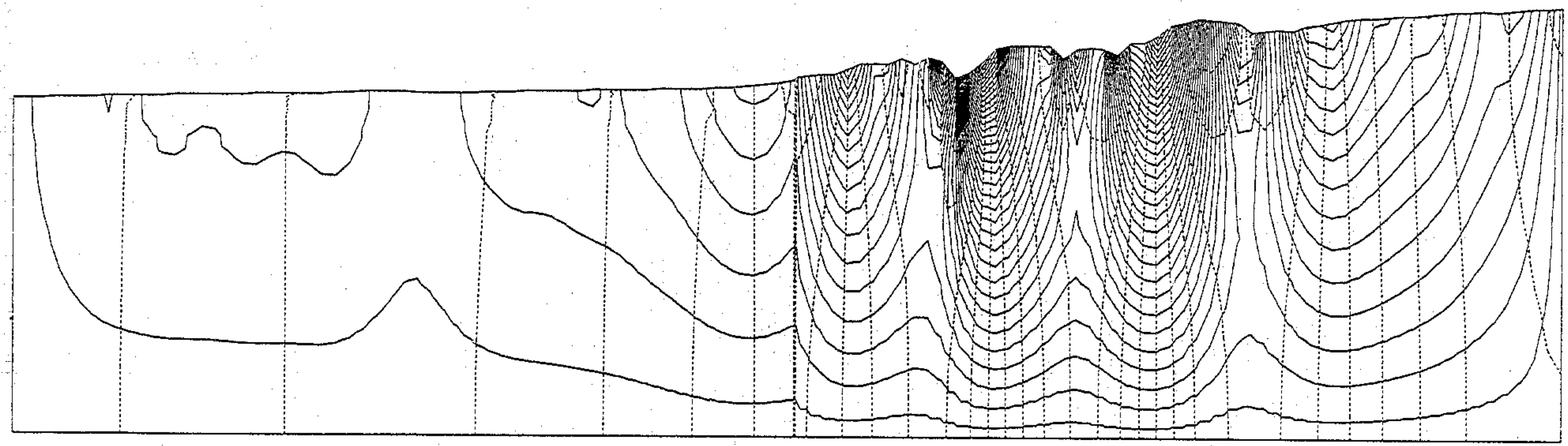


Fig. 7.2.4 Results of Simulation (Andoharano-Manombo Atm)

Case I

Case II

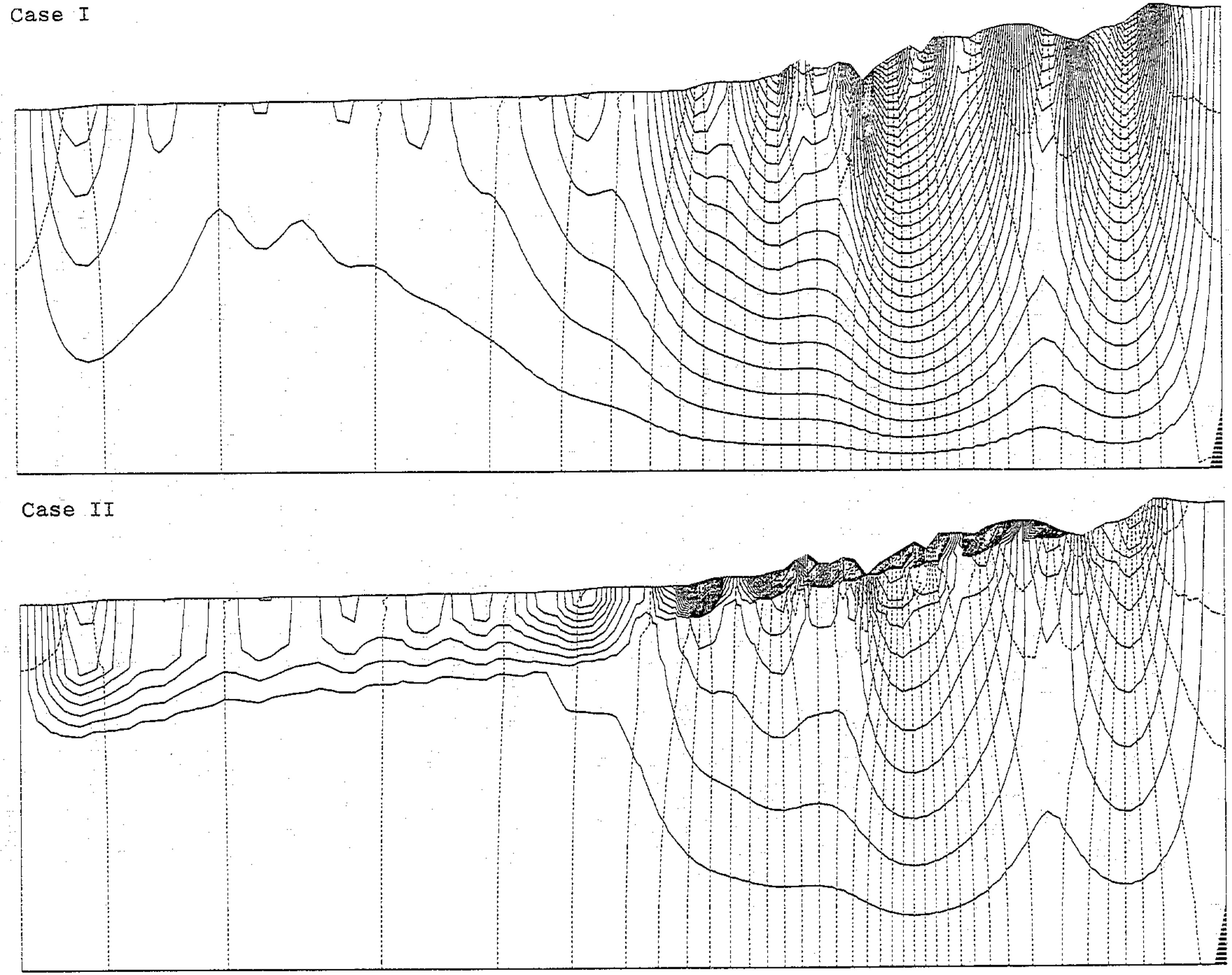


Fig. 7.2.5 Results of Simulation (Befandriana-Lake Ihotry)

7.3 Potential for Groundwater Development

In order to evaluate potential of groundwater resources, a hydrogeological map (1/250,000) was prepared, including hydrogeological cross sections.
This map embodied the potentiality for groundwater development from the standpoint of comprehensive analysis based on the results of satellite image and aero-photo analysis, geological field survey, geophysical prospecting, test drilling, pumping test and water quality analysis.

Analysis of groundwater balance and groundwater model simulation described in the above subsections used and verified the hydrogeological map and hydrogeological cross sections.

As shown in the hydrogeological map, groundwater of the Study Area is found in the Continental and Marine deposits with a thickness 5,000-8,000 m belonging to the Precambrian basement, which is distributed within Morondava basin with gentle slope to the west.

Target depth of the Study is about 300m below ground surface, judged from the technical and economic viewpoints.

Most of aquifers belong to Isalo group of the Middle Jurassic continental sandstone, continental or marine sandstone, limestone and basalt of the Cretaceous (base rock), limestone, muddy limestone, sandstone, sandy mudstone of the Eocene.

These aquifers are divided by new and old faults, mainly of N-S or NNE-SSW directions, interrupting the regional groundwater flow system which is very complicated.

Additionally, delta deposits, alluvial-fan deposits, sandstone and fluviatile deposits are locally found as Quaternary aquifers in the Study Area.

According to the water balance analysis, it is estimated that annual precipitation of 400-800mm results in a groundwater potentiality of approximately 100-300 $l/min/km^2$.

Additionally, the groundwater flow simulation, ion component and tritium analysis results show that aquifer characteristics are influenced not only by the rainfall in the surrounding area but also by regional recharge of 20-45 years flow circulation period. These study results closely match the field experience, with plenty of groundwater outflow observed in the coastal zone and high productivity of the test wells.

Accordingly, groundwater development potentiality is evaluated very high in the Study Area except for some unsuitable part with water quality and hydrogeological problems. The groundwater development will contribute not only to drinking water supply but also to agricultural and industrial development.

Some shallow aquifers existing at less than 30m below ground surface are sometimes not suitable for drinking because of the salty tastes. By the study results, the reason of the salty taste is ***** confined in the mudstone. And, it was confirmed by the test wells that deeper confined aquifers can be development as suitable water for drinking. Main high potential areas which were confirmed from the results of test drilling in this Study are as follows.

Area	Specific capacity(m^3/day/m)
Befandriana	438.58
Sihanaka	232.26
Analatelo	7224.00
Mangotroka	281.35
Soahazo	173.33
Manombo Atm	609.23
Toliara*	3057.00

* Limestone aquifer in the eastern area of Toliara such as Miary and Manoroka

Detailed evaluation of hydrogeologic characteristics of major basins in the Study Area is as follows.

7.3.1 Mangoky Delta

(1) Topography

Mangoky delta with about 1,100km^2 in area has its apex near Nosy-Ambositra and the base on the north-west coast. It is divided from Lake Ihotry Basin by gently undulating hills of about 80 meters in elevation and SE-NW direction.

The apex of the delta is 53 meters in elevation and its surface is inclined northwestwardly with a mean gradient of less than 1/1,000. Innumerable old river beds existing in the outside area of the present river bed are interpreted on satellite images and aerophotos. On this delta, villages located in the upper reaches are on the foot of the above mentioned hill, and villages located in the lower reaches are on the natural level developed between old river beds.

(2) Geology

Mangoky river cuts the northern end of Mikoboka massif in a deep valley. Mikoboka massif, on this point, consists of marly limestone and calcareous sandstone of Upper Cretaceous at the lower part, and limestone of Lower Eocene at the upper part. These strata dip westwardly with 2 or 3 degrees as a whole. Calcareous sandstone of Upper Cretaceous is hard but porous with reddish color. Cross-bedding develops in this formation and thin hard layers rich in iron are often intercalated. Limestone of Lower Eocene is dark gray colored, massive and hard, but with abundant irregular fissures.

The hill which extends from southeast to northwest on the southern side of the delta, on the other hand, mainly consists of reddish brown and loose coarse-grained sandstone with cross-bedding. This formation is inclined toward the west with less than several degrees. In addition to continental sandstone, marine sediments such as alternation of yellow medium-grained sandstone and greenish gray siltstone or siliceous siltstone are also found in this hill. The lowest part of this series is yellowish gray porous limestone. As the geologic age of this series is not confirmed, here it is called Middle and Upper Eocene.

The thickness and facies of Alluvium which forms this delta has not been known until now. Test drilling were not carried out on this delta by the Study, but the thickness of Alluvium is presumed to be at the most 110 to 120 m, judging from the result of the electric prospecting conducted by this study. Some layers with high resistivity are found in Alluvium, and it is presumed that these layers consist of sand bed. Existing literature reports that the thick formations with low resistivity lie beneath Alluvium. Therefore, Middle and Upper Eocene in this area should mainly be marl or marly clay.

(3) Groundwater level and flow pattern

Wells for drinking water confirmed in this area are listed in Table 7.3.1. Most of them are located on sites lower than 25 meters in elevation, and they are less than 10 meters in depth. These wells use unconfined groundwater in sand beds intercalated in Alluvium, but some wells use unconfined groundwater in continental sandstone beds of Middle and Upper Eocene which form the hill extended on the left bank of Mangoky river.

The static water level of these wells is less than 4 meters below the ground surface. Residents report that in the rainy season it is 1 to 3 meters higher than that of the dry season. Unfortunately, such difference could not be confirmed in this Study.

The flow pattern of the unconfined groundwater could not be clarified in detail because the groundwater level was measured in only a few wells in the Study. Roughly speaking, however, two flows of unconfined groundwater are presumed to exist in this area. One is the major flow which runs from southeast to northwest in accordance with the gradient of the delta through the sand bed of Alluvium. The other one is a subordinate flow, which runs along the furrows in the hill through the continental sandstone of Middle and Upper Eocene.

The existing literature reports that there is a large scale confined groundwater body stored in the Lower Eocene limestone around Nosy-Ambositra, the apex of the delta. Though this groundwater body was not confirmed by the Study, it is highly possible that the marsh around Nosy-Ambositra is recharged by the confined groundwater seeping from the Lower Eocene limestone.

Near Tsiarimpioke, east of Nosy-Ambositra, hot water of about 45 degrees Celsius springs out from the Upper Cretaceous limestone bed cropped out on the Mangoky river bed. Local residents use this hot spring for bathing.

(4) Groundwater quality

The water quality type of the groundwater samples collected from the wells in this area is shown in Fig.7.3.1. All of them are samples from unconfined groundwater and most of them belong to type I. But some samples (3,4,9) collected from wells near the coast belong to type IV. This fact suggests that they are affected by the sea water.

(5) Groundwater development potential

The aquifer widely used in this area is sand bed intercalated in Alluvium and lies shallower than 10 meters below the ground surface.
Though no pumping test was done by the Study, the existing literature reports that the well of Tanandava (29 meters in depth) yielded $12m^3/h$ from the sand bed intercalated in Alluvium, and the specific capacity was 26.46 l/min/m.

Though the groundwater stored in Alluvium has no problem in terms of water quality, the static water level draws down remarkably in the dry season. In addition, there are some cases in the coastal area where chlorine ion concentration of the groundwater is rather high.

As it is presumed that the Middle and Upper Eocene, the basement of Alluvium, mainly consist of marl and marly clay, there is little possibility that the productive confined aquifer be found in it.

It is highly possible that the confined groundwater stored in the limestone of Upper Cretaceous or Lower Eocene will be developed in the neighborhood of Nosy-Ambositra where Mangoky river cuts Mikoboka massif.

7.3.2 Lake Ihotry Basin

(1) Topography

This basin consists of the lowland, 50 to 300 meters high and 20 km wide, extending from north to south adjacent to the west of Mikoboka massif, and is characterized by three alluvial fans and the water system converging to Lake Ihotry.

The alluvial cone of Befandriana fan, the northernmost fan, is 200 meters above the sea level and the gradient of its surface is 1/40 to 1/250. On the other hand, alluvial cones of Ankoro fan and Andranodambo fan, south of Befandriana fan, are about 300 meters above the sea level. The latter two can be distinguished on LANDSAT image, but they are not so clear on the topographical maps.

Lake Ihotry is a large salt lake (chlorine concentration is more than 3,000 ppm) with about 50 meters of lake surface height and about 100km^2 in area. This lake receives inflow of fresh water supplied by the water system flowing on the above mentioned fans, and the water course is also open to Mangolovolo in the rainy season. On the contrary, during the dry season, the water system disappears and the lake shrinks.

(2) Geology

Many wells for groundwater exploration have been drilled in this basin because it is judged that this area has the highest potentiality for groundwater development in the southwestern region of Madagascar. Seven test drillings with about 50 meters in depth were also carried out in the Study. The subsurface geology of this basin was made fairly clear by these data (Fig.3.8.6).

The surface of this basin is mostly covered by the Middle to Upper Eocene. Below this series, at a depth of 100 to 150 meters, there are other series, the Lower Eocene and the Upper Cretaceous, which form the Mikotoka Massif in the east. The Lower Eocene mainly consists of limestone in Mikoboka massif, but it consists of marl at Andavadoaka on the west coast. It was presumed that the zone of abruptly changing electric resistivity values, extending from NEE to SWW along the road connecting Befandriana and Bemoka, coincided with the boundary between limestone facies and marl facies.

A zone of discontinuous electric resistivity values, with a NNW to SSE direction, was also found in the west side of the road connecting Befandriana and Andranomena. This zone may consist of a fault because it coincides with the continual lineament found on LANDSAT image, and also with the anomaly zone of VLF magneto-telluric survey carried out in the Study. The Lower Eocene may consist of marly sediments in the west side of this fault.

In the northern part, Middle and Upper Eocene mainly consist of reddish brown coarse grained continental sandstone. In the southern part, however, it is marine sediments mainly consisting of alternation of marl and limestone with sandstone.

The depth of the boundary between Lower Eocene and Middle and Upper Eocene was confirmed at some point west of the National Road 9 by the drilling survey of the past. Fig. 3.8.6 shows the shape of this boundary plane drawn with the above mentioned data. The boundary plane is represented as two furrows controlled by faults, and the river-bed is the crossing point of this plane and the ground surface.

Fig.7.3.2 shows the constitution of Middle and Upper Eocene in this basin according to the results of the Study and the existing literature. In the northern part, Middle and Upper Eocene mainly consist of reddish brown coarse to medium grained continental sandstone rich in quartz grains with only 5 meters of marl bed on the top. In the southern part, on the contrary, they consist of marl or alternation of marl and limestone.

Though three alluvial fans were distinguished in this basin on the topographical maps and the satellite image, alluvial fan deposits could not be confirmed by the test drilling carried out during the Study.

(3) Groundwater level and flow pattern

The fact that most wells in this area are less than 10 meters in depth suggests that the aquifers widely used in this area lie generally deeper that those of Lake Ihotry basin.

The groundwater table can only be drawn around Befandriana, and its level is 5 to 10 meters below the ground surface. As there are some wells with water level difference of more than one meter between the dry season and the rainy season, it is presumed that the groundwater is not confined.

At the working well of Antanimieva, confined groundwater stored in the Lower Eocene limestone springs out from the depth of 126 meters below the ground surface. Ten(10) wells drilled in this area, where elevation is 100 to 200 meters, by the United Nations in 1966 and 1967 reached the confined groundwater stored in the lower Eocene limestone at 35 to 160 meters below the ground surface, and four(4) of them were artesian wells. In addition, a large quantity of groundwater springs out from the lower Eocene limestone in Mandevy, where residents utilize the water for domestic use.

The above mentioned confined groundwater is recharged in Mikoboka massif, which is high and rich in precipitation, and flows down along the bedding plane of the lower Eocene inclined gently to the west. The static pressure of this groundwater becomes high and springs out within the 3 km wide zone extended from NE to SW. The reasons for the static pressure of the confined groundwater to become high within this zone are the facies change of Lower Eocene and the existence of the fault. That is to say, the Lower Eocene mainly consists of impermeable marl in the western and northern side of this zone, and the faults with NE-SW and N-S directions stop the groundwater flow to the west.

Many non-protected ditches dug to get water for irrigation are found in the sandy lowland of lower than 70 meters above the sea level in the southeastern side of Lake Ihotry. They extend from NE to SW with 2.5 to 3 meters in depth and the water seeping from them is salty. The water level in these ditches in the rainy season is more than two(2) meters higher than that in the dry season. These ditches are the facilities to catch the widely unconfined groundwater which flows southeastward to Lake Ihotry.

(4) Groundwater quality

Both unconfined and confined groundwater in this basin mostly belong to type I of water quality as shown in Fig.7.3.1. In addition, the values of chlorine ion concentration and the electric conductivity are low. The groundwater of Manoy and Basibasy, however, is different in water quality type and ion concentration of chlorine, sodium and magnesium. Judging from the fact that the marly sediments are on top of Middle and Upper Eocene in Manoy, and they are both on and beneath the lower Eocene limestone bed in Basibasy, the reason for the ion concentration to be so high is that the salts adsorbed in these marly sediments are dissolved by the groundwater in these areas.

(5) Groundwater development potential

The three aquifers used in this basin are sand layer of Alluvium, sandstone bed of middle and upper Eocene and limestone bed of lower Eocene, in descending order.

The sand layer of Alluvium crops out on the ground surface around Lake Ihotry and the unconfined groundwater stored in this layer is used for irrigation because of its shallow level. However, the irrigation use of this water is limited because of its salt content.

The sandstone bed of Middle and Upper Eocene is most widely used in this region. It lays 15 to 50 meters below the ground surface and coarser in the lower part. Seven test drillings were carried out in the Study and the yield was 200 to 300 l/min, and the specific capacity was 30 to 200 l/min/m. As the water quality is good, this aquifer has high utilization value.

However, in areas where Middle and Upper Eocene accompany marly sediments, the specific capacity is relatively small and the water quality is bad because of salty taste. Therefore, the utilization value of the groundwater is low in

such areas.
The lower Eocene limestone bed storing the groundwater is an aquifer with a very high utilization value. The Antanimieva well yielded 110 l/sec of artesian flow at the time of its completion, and the yield of the natural spring in Mandevy is 620 l/sec. The artesian groundwater springs out in the above mentioned 3km wide zone extended from NE to SW, and the static water pressure becomes lower toward the northwest.

According to the results of pumping tests reported in the existing literature, the specific capacities of the confined groundwater stored in the Lower Eocene are 2,621 l/min/m and 3,061 l/min/m.

7.3.3 Manombo Basin

(1) Topography

Manombo basin is a 15-20 km wide lowland area extending in the South-North direction, sandwiched by Mikoboka massif and a part of Belomotra-Vineta plateau in the east, and by a 100-200 m gentle hill in the west.

Of the three fans existing in this basin, Sakamana fan is the northernmost and biggest. Elevation of the top of fan is around 300 m, and the fan is extended in the West- East direction with a 1/150 slope called Bevary plateau. Amboboka fan is 200 m in elevation, but it cannot be seen clearly on a map.
Manombo fan is located in the south, with an elevation of around 125 m, and average slope of 1/150. Manombo river flows 10-20 m lower than the basin from North-East to South-West. Andraka river, which is a tributary of the Manombo river in the downstream, flows along the mentioned three fans.

Many independent hills exist in and around the watershed between this basin and Lake Ihotry basin. Their diameter is almost 500 m and relative height is 10 m. Four hills exist on a straight line around Betsioky in the NNE-SSW direction. Sand dune is developed in the coastal area. Limestone outcrop is seen in some areas.

(2) Geology

Mikoboka massif and Belomotra-Vineta plateau surrounding this area is composed of limestone of the Lower Eocene. This limestone is covered by the alluvial deposits in the vicinity of Manombo fan with E.L. 100-125 m.

There is another outcropping of limestone in the hill located on the western side of National Road 9. This limestone is more porous and with smaller specific gravity than the one in the Lower Eocene period. According to test drilling results of the Study, this hill is composed of porous limestone, sandy marl and coarse sandstone. Facies of the hill are very changeable. Collected geological map shows this layer as belonging to the Middle to Upper Eocene Period. Since the same type of limestone outcrops on the left bank of Manombo river, the Quaternary deposits covering the Middle to Upper Eocene are very thin.

(3) Groundwater level and flow pattern

The groundwater level of 41 existing wells studied in this area is as follows: 6 of them less than 10 m, 16 of them between 10 m and 20 m, 14 wells between 20 m and 30 m, 5 wells more than 30 m.
Aquifer location is deeper than in the Lake Ihotry basin. The wells with water level deeper than 20 m are concentrated in the North of Namaboka and South of Milenaka. Wells with water levels exceeding 50 m are located only in the North of Betsioky Nord.

Simultaneous groundwater leveling was performed in wells deeper than 20 m during this Study. Groundwater level contour drawn by this survey shows unconfined aquifer. This map shows groundwater level declining from North to South along Androka river valley.
Ambatolily is located in top of Manombo fan, and continuous groundwater leveling was performed in this palce. The level is variable with rainfall, being higher in the rainy season than in the dry season. Therefore, this can be said to be unconfined aquifer.

The wells existing in the North of Namaboka and in the South of Ambatolily are more than 20 m in depth, and use the aquifer in sandstone of Middle Eocene. Since this sandstone layer is sandwiched by impermeable marl layer, aquifer is confined.

Deeper aquifer was confirmed by two well logs drilled at Sakamana fan by the United Nations in 1966-1967. According to the well logs, the upper portion of Lower Eocene is at a depth of 30 m and 106 m, and static groundwater level at a depth of 18 m and 37 m. From this result, unconfined aquifer of Lower Eocene is presumed to flow from Northeast to Southwest in Sakamana fan.

Many springs exist in this area. Ample water from Amboboka spring, originating from limestone in Lower Eocene,is utilized for drinking and irrigation. Other springs exist west of Androka river, having the same confined aquifer as Amboboka because of their similar geological structure.

Spring area exists in the coastal zone south of Monombo river mouth. Since sandy sediments of Quaternary on the impermeable marl of Middle Eocene are the principal aquifer in this area, groundwater flows up to the surface through detrital deposits of the upper portion. It is confirmed on LANDSAT image that groundwater flows out as fresh water from this aquifer directly into the sea.

(4) Grounwater quality

Water quality of this area is classifed as Type-I and IV as shown in Fig-7.3.1. Type IV is more productive than in the Lake Ihotry basin.

This Type IV is generally characterized by high ion concentration of Chlorine, Sodium, Magnesium, etc., and is called "salty" by village people. This aquifer is basically from the Middle to Upper Eocene, except for the water sources in villages numbered 69 and 76 which are influenced by sea water.

There are three existing wells and two wells drilled by the Study in Soahazo. Shallow wells (28 m and 34 m) have high Chlorine ion concentration. Water quality at different depths can be compared in the section from Benetsy to Ankilimalinika. Chlorine ion concentration and electric conductivity are high in the water from sandstone sandwiched by thick marls in the upper portion. Their values were low in the water from sandstone layer thicker than 3 m (Fig. 7.3.3).

As described above, the problem of lower quality groundwater in Middle and Upper Eocene is caused by dissolved salt from marl layer in the upper portion.

On the other hand, water quality of the Amboboka spring from Lower Eocene is the same as the spring in Mandevy and artesian well in Antanimieva, having very low values of Chlorine ion concentration and electric conductivity.

(5) Groundwater development potential

The potentiality for groundwater development is considered in two aquifers in the coastal zone sand dune and sandstone or limestone in Middle to Upper Eocene.
As the aquifer in sand dune is like a lens formed on sea water, the water quantity is very limited and not in stable condition.

The aquifer in Middle to Upper Eocene is classified into two groups. One is composed of marly limestone and middle to coarse sandstone with more than 3 m in thickness. This aquifer is more than 40 l/min/m in specific capacity. The other group is composed of thin sandstone sandwiched by sandy marl, marly sandstone and thick marl, and specific capacity is less than 40 l/min/m. Since the former is generally deeper than 30 m below ground level, it is necessary to drill more than 30 m for production well.

Amboboka springs originate from the aquifer of a limestone in Lower Eocene. Discharge from these springs is almost 3,100 l/sec. Additionally, existing data of pumping test in Sakamana fan have the following range: 32.4-139.2 l/min/m. Therefore, this aquifer has very high productivity and no problem of water quality. However, as its distribution is very deep in the west of Toliara fault, its utilization is very difficult.

7.3.4 Fiherenana Delta

(1) Topography

This delta was formed in the place that Fiherenana river comes out from Belomotra-Vineta plateau. This is a small delta, measuring only 10km from the western edge of the plateau to the river mouth. Therefore, the area is only 150 km2 including the coastal plain continuing to the South and the North. Belomotra-Vineta plateau, the delta and coastal plain are clearly divided by a straight steep cliff, 50 m in height.

The coastal plain continuing South and North of the delta is covered by new and old sand dune. This sand dune is cut and flattened artificially in the center of Toliara.

(2) Geology

There used to be some production wells in the dry river bed of Fiherenana river, where Fiherenana river comes out from Belomotra-Vineta plateau, as drinking water sources for Toliara City.
According to their well logs, sand exists up to 10 m below surface, followed by clay. The well logs of existing deep wells(depth 34 m) near the river shows porous limestone of Middle Eocene at 6 m below ground level.

According to the electric prospecting in Befanamy, 3km downstream from the above point, limestone of Middle Eocene is estimated to be at 10-15 m below ground level.
On the other hand, the location of limestone is deeper in Tsonoabary, near the river mouth, and high resistivity values of thick marl and clay sediments are distributed between limestone and alluvium sand.

A test drilling of 2195 m for oil prospecting was conducted North of Toliara City, where ground elevation is around 10 m above sea level. According to the well log of drilling, Middle Eocene marl was found 159 m below ground, and marl with thin limestone was found at 300 m.

The depth of Middle Eocene and the facies of sediments of this Eocene in Fiherenana delta is completely different in the west and the east of Befanamy. By this reason, it is estimated that there is a fault with South to North direction. On the results of VLF magneto-telluric survey of the Study, some abnormal condition is found around there, but no corresponding lineament was found on the satellite image.

Toliara fault, first class fault in the Study Area, corresponds to a steep cliff of 50 m relative height in the eastern margin of the Fiherenana delta. According to VLF magneto-telluric survey, abnormal condition is confirmed, but the result is narrower than in the west of Befanamy (See Fig 3.7.2).

(3) Grounwater level and flow pattern

There are two types of wells, less than 10 m and deeper than 40 m. Water of the first type of wells is from unconfined aquifer in a sandstone in Alluvium, and their static water level is within 6 m from the ground level, even in the dry season. This unconfined groundwater level is around 20 m above sea level in Miary. It is estimated to be gradually inclined toward the coast, but data are not enough to confirm it.

On the other hand, water of the second type of wells is from limestone or calcareous sandstone of Middle Eocene, and is estimated to be confined aquifer because the water level does not change in dry and rainy seasons.

(4) Groundwater quality

According to conducted research, samples of shallow groundwater and the water from limestone in Middle Eocene are not different in quality, with low salinity except for the coastal area.

(5) Groundwater development potential

Most aquifers for groundwater development in this area are found in deposits of Alluvium sandstone and Middle Eocene limestone, the latter located east of Befanamy.

Pumping tests(3 wells 41-42 m in depth) in Miary pump station show 217.5 l/min/m, 874.0 l/min/m and 4,083 l/min/m. It can be said that Middle Eocene limestone is of extremely high productivity.
This aquifer is considered to be recharged from the whole Fiherenana river basin.

On the other hand, Lower Eocene in this area is composed of marl, which is not expected to contain good aquifers.

7.3.5 Belomotra-Vineta Plateau

(1) Topography

This 60 km wide plateau is extended in the southern side of Analavelona massif, and its topography is different between the eastern and the western sides of the hill near Andranovory.

In Belomotra Plateau west of the hill, the topographic plane inclines westward from 400 m to 200 m above sea level with the mean gradient of 1/100. This topographic plane, however, consists of several flat planes with different height, and doline and uvale are often found on these flat planes and are observable on the aerophotos. Several isolated hills with flat top and steep slope, 50 to 100 m in relative height, are found near the western margin of this plateau. As the water system on the plateau shows a very complicated pattern, characteristic of the limestone plateau, it is difficult to distinguish the divide between Fiherenana river watershed and Onilahy river watershed.

In Vineta Plateau, on the other hand, an almost flat plane, 400 to 450 m above the sea level, extends to the foot of Vineta massif, and the density of the water system is very low. The only deep valley which gathers water from Vineta massif flows down to the west and joins with Fiherenana river. Water sellers come to this valley because it has a certain quantity of water even in the dry season.

(2) Geology

Strata which form this plateau can be seen on the way from the northern margin of this plateau to the valley of Fiherenana river along National Road 7, and they consist of continental sandstone and porous limestone of Upper Cretaceous and intruding basalt sheets.

Two sheets of basalt were found on the test drilling hole carried out at Tranokaky (430 m in elevation) during the Study. The upper sheet is 115 m and the lower sheet is 9 m in thickness. Basalt is compact and hard but abundant in fissure, making the basalt sheet as a whole considerably high in permeability.

Marl bed which covers the upper basalt sheet is distributed only inside the plateau and its surface is flat. Black mudstone lies beneath the lower sheet with more than 30 m in thickness.

At Andranovory (483 m above sea level), the western margin of Vineta Plateau, the Upper Cretaceous consists of sandstone, limestone and sandy or clayly limestone without basalt, from the ground surface to the depth of 137 m. Judging from the result of electric prospecting, the basalt sheet lies at a depth of more than 180 m below the ground surface.

According to the result of test drilling carried out at Befoly (225 m in elevation), near the center of Belomotra Plateau, gray or brownish gray limestone continued to the depth of 226 m, without the top soil of 4 to 5 m in thickness. The upper 50 m of this limestone, identified as Lower Eocene in age, is massive and compact, but the lower part is porous and abundant in fissures. Existing literature reports that the same limestone occurred from the ground surface to the depth of 218 m at Andranohinaly (250 m in elevation), about 5.5 km northeast of Befoly.

According to the existing geologic map, Middle Eocene covers Lower Eocene unconformably in the western margin of Belomotra Plateau. The successive layers of middle Eocene crop out continuously at the cliff around the mouth of Onilahy river, and they consist of limestone and calcareous clastic rocks with changeable lithofacies. Middle Eocene in this area is characterized by a large volume of limestone conglomerate and intercalations of oyster shell beds. Limestone and calcareous clastic rocks, confined from the ground surface to the depth of 60 m according to the test drilling carried out by the Study at Manoroka, corresponds to the lower part of Middle Eocene.

As mentioned above, Upper Cretaceous, Lower Eocene and Middle Eocene are distributed from east to west on this plateau. Therefore, these three formations lie unconformably, and are gently inclined to the west as a whole. It is difficult, however, to grasp the geologic structure correctly because of the low dip of these formations and the displacement by many faults.

(3) Groundwater level and flow pattern

As it is difficult to get groundwater from shallow well on this plateau, most villages have no well and depend on rainfall and water seller.

The exception is non-protected shallow well, locally called "vovo", which is made by digging the bottom of a shallow valley on a tributary of Fiherenana river. This type of well is distributed near National Road 7, about 6 km west of Andranovory, but it is said that the static water level of these wells becomes lower year by year.

There are three wells, about 10m in depth, in Tranokaky and Befoly, but all of them have only a small quantity of water in the dry season. The aquifer of these wells is a sand layer intercalated in the marl bed on the basalt sheet in Tranokaky, while it is sandy deposits on a limestone bed in Befoly. As these shallow wells are not found in other villages on this plateau, the distribution of such an aquifers is presumed to be limited.

Confined groundwater stored in basalt on this plateau was reached by the test drilling hole of Tranokaky, where the static water level of the well was 16.2 m below the ground surface. Here, the mudstone beneath the basalt sheet plays the role of an impermeable layer, and the thick basalt sheet rich in fissure plays the role of an aquifer. It is presumed that the well of Andranovory (136 m in depth, not working now) pumped up the confined groundwater stored in the sandstone bed on the basalt sheet. The static water level of the well was 117 m below the ground surface.

On the other hand, the test drilling at Befoly on the Belomotra Plateau reached the aquifer at 225 m below the ground surface. The static water level was 179 m below the ground surface, which is 46 m in elevation. The depth of the aquifer was 220 m below the ground surface at Andranohinaly, and the static water level was 207 m below the ground surface, which is 63 m in elevation. Therefore, it is presumed that the deep groundwater stored in the Lower Eocene limestone of Belomotra Plateau is hardly confined, and flows from northeast to southwest with hydraulic gradient of about 1/300.

Many natural springs have been found along the right bank of Onilahy river, the southern margin of Belomotra-Vineta Plateau. The springs around Ambohimahavelona flow out from the Lower Eocene limestone, and the water is utilized for irrigation as well as for domestic use. Judging from the above mentioned estimation of the static water level and the direction of deep groundwater, the natural springs along the right bank of Onilahy river are outcrops of this groundwater. Along the seashore north of the mouth of Onilahy river, the groundwater seepage from the Middle Eocene limestone flows into the sea.

On the other hand, natural springs have hardly been found along Fiherenana river. In addition, the gradient of Fiherenana river is steeper than that of Onilahy river and its flowing water disappears around Behompy in the dry season. Judging from these facts and the above mentioned estimation, it is probable that the deep groundwater beneath Belomotora-Vineta Plateau is recharged from Fiheranana river.

(4) Groundwater quality

Almost all the groundwater samples taken from the wells distributed in this area belong to type I of water quality, as shown in Fig.7.3.1, no matter whether it is stored in shallow or deep aquifers. Chlorine ion concentration and electric conductivity are low in value. The fact that the deep groundwater at Befoly, which is stored in the lower Eocene limestone bed, is similar to the Fiherenana river water in terms of water quality, supports the presumption that the former is recharged by the latter.

The groundwater stored in the basalt sheet of Tranokaky is also type I of water quality, but ion concentration of chlorine, sodium and magnesium is rather high. This may be caused by dissolution of salts adsorbed in the marl bed laid on the basalt sheet.

(5) Groundwater development potential

The basalt sheet with abundant fissure is the productive aquifer in Vineta Plateau. This sheet lies 15 m below the ground surface with a thickness of 115 m at Tranokaky. The yield was 110 l/min, and the specific capacity was 11.65 l/min/m at the test drilling hole. As this basalt sheet is almost horizontal in Vineta Plateau, this aquifer has high utility from the view point of its depth and yield. The productivity of this aquifer may be different by places because of the irregularity of fissure density. In addition, it is probable that the water quality is inferior where marl bed lies on this sheet.

Though the sandstone bed of Upper Cretaceous also plays the role of aquifer at the margin of Vineta Plateau, its distribution area is limited. The well of Andranovory draws groundwater from this aquifer and the yield was 150 l/min.

In Belomotra Plateau, the Lower Eocene limestone is the productive aquifer, but its level is more than 200m below the ground surface. The yield was 110 l/min at the test drilling hole of Befoly, and 100 l/min at Andranohinaly according to the existing literature.

As already mentioned, it is estimated that this unconfined groundwater flows from Fiherenana river to Onilahy river with very gentle gradient, but it is not always possible to get the groundwater if the well is drilled to this depth. Since it is probable that the watercourse is limited, as is usual in the limestone area, drilling is necessary to reach the depth of 200 or 300 m after the implementation of electric prospecting and lineament survey.

Middle Eocene limestone is the productive aquifer around the western margin of Belomotra Plateau and the groundwater yield was 158 l/min at Manoroka, without drawdown of well.

7.3.6 Fiherenana Basin

(1) Topography

This area is an intramountain basin with 300-500m elevation, formed in the middle portion of all catchment areas by the contribution of many small branch rivers. Sakaraha is located in the southeastern part of the basin. Fiherenana river from the NE and Ilona river from the NNE flow into this basin. Additionally, Ilona river and many small streams flow parallelly from Analavelona massif in the west, and contribute to main Fiherenana river.

As the topographical feature, there are independent flat top small hills of 30-50 m in relative height around Sakaraha. These hills are distributed in the southeastern direction from Lambosy massif over a 5-10 km wide zone. Special patterns of contour line show easily their location on the map.

(2) Geology

Massifs and hills around the basin are composed of Jurassic system in the west and Cretaceous sytem in the east, separated by the boundary of Ilovo fault having a NNE-SSW direction, parallel with Ilovo river. The Jurassic system is composed of medium to coarse continental sand with rich green mica(Upper Isalo layers), alternation of limestone or calcareous sandstone and siltstone(marine deposit of the Middle Jurassic system) and coarse reddish continental sandstone with rich quartz grain (Middle Isalo layers).
The zone characterized by independent hills coincides with marine deposits of the Middle Jurassic system. Since hard and compacted limestone in the horizontally sedimented alternation is not eroded, manadnocks have been formed with flat tops. Collected geological data describe an atoll fossil, 300 m in diameter, located 6 km from Sakaraha. Therefore, it is estimated that the mentioned manadnock is an atoll fossil.

Test drilling was conducted in Maninday (E.L. 625 m) belonging to the area of Middle Isalo formations. Coarse grain with rich quarz or gravelly red sandstone and red siltstone or silty sandstone were found from the top to 72

m below ground. Marl layer and calcareous sandstone is distributed close to the western side of the Ilovo fault. Lower Cretaceous system, principally composed of continental sandstone, is widely distributed farther west of the above mentioned Ilovo fault.
Fluviatile Quaternary system is sedimented in the bottom of rivers flowing into this basin. The depth is estimated at around 4 m from the results of electric prospecting. According to the collected geological data, deforestation in Analavelona causes plenty of sand, gravel and rock to flow into the Fiherenana river system. Continental sandstone is easily eroded because of weak solidity without diagenesis. Many outcroppings considered as mud flow depoists are found around the basin. It is very difficult to estimate why the fluviatile deposit is not deep in the mentioned process.

(3) Groundwater level and flow pattern

According to drilling results, siltstone or silty sandstone is an impermeable layer which is distributed 4 m below ground in Maninday, and coarse sandstone on the above layer is a good aquifer. Static groundwater level is around 16 m below ground. This aquifer is estimated to be unconfined because the water level varies with rainfall, according to monitoring results.

On the other hand, there are 4 wells varying in depth from 8 to 32m in Sakaraha, and the aquifer is estimated to be in sandstone of Middle Isalo formations. Static groundwater level is 7.5-11 m below ground, and the difference between dry and rainy season is small. Monitoring results from the 32m well shows no variation with rainfall.

(4) Groundwater quality

It is difficult to characterize the water quality in this area because the sample is small and positioned almost in the center of the key-diagram. However, as chlorine ion concentration and electric conductivity are very low, it is suitable for drinking water.

(5) Groundwater development potential

The most productive aquifer is estimated to be in continental coarse sandstone of Middle Isalo formations in the eastern side of Ilovo fault. According to the test drilling in Maninday, yield is 360-480 l/min and specific capacity is 150 l/min/m.

In the western area of Analavelona massif, continental sandstone of Lower Cretaceous is considered as good aquifer. However, since this layer is mostly covered by marine deposit of the Middle Jurassic system, it is difficult to utilize this aquifer. Additionally, this Jurassic system includes marl, causing water quality under this layer to be poor.

7.3.7 Sakondry Basin

(1) Topography

Sakondry basin is a very long and narrow plain, 7-8 km wide, along Sakondry river which flows straight from North to South. This area and Belomotra-Vineta plateau, west of the basin, are divided by a steep cliff of around 100 m relative height, followed by a gentle sloped talus. As the eastern slope is gentle, no boundary between massifs is found.

Little flow was found in the downstream of this river. A ridge from northeast is overhanging on the left bank of the river mouth, narrowing the mouth and forming a swamp.

(2) Geology

It is considered that Sakondry river is regulated by a fault because of straight line characteristics. However, stratigraphic difference of heights exists on both sides of the fault.

Lower Cretaceous system composed of sandstone, calcareous sandstone and limestone with ammonite fossils is found outcropped with a western pitch in the steep cliff west of the river. Basalt sheet exists in this system. On the other hand, yellow calcareous sandstone or limestone of Middle Jurassic Period or white medium sandstone of the middle part of the Isalo Group are distributed with western dip from the river bed to the eastern massif. Calcareous sandstone or limestone of the Middle Jurassic Period is very hard, and the Middle to Upper Isalo Group is poor in solidity.

Alluvial sediments in river bottom is commonly thin. There are many outcroppings of the Jurassic system in the river bed.

(3) Groundwater level and flow pattern

Most of villages depend on the river for drinking water. Therefore, production well is not common. There is an 8.4m deep well, with a broken electric pump, in the upper reach-

es of Bereketa river at E.L. 362 m. Aquifer is unconfined from Quaternary alluvial sediments of Middle Jurassic Period. Groundwater levels during dry and rainy seasons are almost the same.
A swamp on the left bank is recharged by groundwater from the limestone in the Middle Jurassic Period, which forms the overhanging ridge in the NE-SW direction.

(4) Groundwater quality

Only one sample is available from a shallow well located at the divide between Sakondry and Taheza rivers. This is unconfined water originated in the Middle Jurassic Period or topsoil.
Analysis result is plotted in the center of key-diagram. Chlorine ion concentration and electric conductivity are low.

(5) Groundwater development potential

There is no groundwater potential in the west side of Sakondry river, because all layers have west-dip and narrow recharge area. Talus deposits are distributed in the skirt of a steep cliff on the western margin of the plain.

On the other hand, groundwater development potential is good in the mountain west of Sakondry river, where medium to coarse sandstone, expected to be a good aquifer, is found in the middle to upper portion of Isalo Group. The lower part of mountainside is covered by the Jurassic marine deposit. Therefore, borehole must be drilled through this hard Jurassic marine deposit in order to reach a good aquifer in the mountainside.