社会開発調査部報告書

No. 42

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

ARUSHA REGIONAL DEVELOPMENT DIRECTORATE
THE UNITED REPUBLIC OF TANZANIA

THE FEASIBILITY STUDY ON MONDULI TOWN AND THE SURROUNDING AREA WATER SUPPLY IN ARUSHA REGION

FINAL REPORT

SUPPORTING REPORT

[illegible]

SANYU CONSULTANTS INC.
JAPAN ENGINEERING CONSULTANTS CO., LTD.

[illegible]

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

ARUSHA REGIONAL DEVELOPMENT DIRECTORATE
THE UNITED REPUBLIC OF TANZANIA

THE FEASIBILITY STUDY ON MONDULI TOWN AND THE SURROUNDING AREA WATER SUPPLY IN ARUSHA REGION

FINAL REPORT

SUPPORTING REPORT

MARCH 1996

SANYU CONSULTANTS INC.
JAPAN ENGINEERING CONSULTANTS CO., LTD.

CONTENTS

CHAPTER A HYDROGEOLOGY AND GROUNDWATER

LIST OF TABLE

CHAPTER A HYDROGEOLOGY AND GROUNDWATER

CHAPTER B PROJECT ENGINEERING

LIST OF FIGURE

CHAPTER A HYDROGEOLOGY AND GROUNDWATER

CHAPTER B PROJECT ENGINEERING

CHAPTER A HYDROGEOLOGY AND GROUNDWATER

A - 1 NATURAL CONDITIONS

A-1-1 Topography

The United Republic of Tanzania is situated between the great lakes of Central Africa and the Indian Ocean and lying just south of the Equator. Tanzania lies on the east African coast between and 1° and 11°45' south, and 29°20' and 40°35' east. It is bordered by Kenya and Uganda to the north, Rwanda, Burundi and Zaire to the west, and Zambia, Malawi and Mozambique to the south. It covers an area of 945,166 km², which is one of the largest countries in sub-Saharan Africa.

The study area, a part of Monduli District, has roughly a rectangular feature located in between latitude 3°14' and 3°40' south, and longitude from 35°55' to 36°35' east. The average axes are approximately 70 km in east-west and 85 km in north-south, with approximate total area of 5,950 km².

The northern part of the study area is bordered by three major volcanic mountains of Monduli (2,660 mamsl), Burko (2,140 mamsl) and Essimingor (2,300 mamsl). The eastern part is bordered on Arumeru District where an remarkable escarpment with north southerly direction extend on the western edge of the Engare Olmotoni river basin. The southern part is bordered by the Hill Oldonyo Lolkisale (2,130 mamsl) and the western part is bordered by the Great North Road.

The physiographic features of Monduli District is mainly related to volcanic activity, and only the southern part of the district is characterized by an elevated plateaus of Precambrian rocks. The Neogene Lake Sediments were deposited in a former wide extension of Lake Manyara and occupy much of the southwestern part of the district.

Pronounced volcanic mountains; the Monduli, Burko and Essimingor; drain several number of ephemeral rivers to the south. These river system join each other near Makuyuni and discharge into Lake Manyara.

A major part of the study area is characterized by the flat lava plateau with associated volcanic cones. The plateaus are edged with the tectonic scarps extending north southerly direction.

A remarkable fault-scarp with east westerly direction locates in the

northern edge of the plateau. A large scale broad valley were cut in the north of the scarp that is the Ardai Basin, where a bare land extend between the scarp and Monduli mountains. The land is subject to recharge from the mountains.

A-1-2 Geology

The study area is underlain by four major geological units, the Basement, the Older Extrusives, the Younger Extrusives and the Manyara Lake Beds.

The Basement is referred to the Usagaran Group of the Precambrian. It is composed of a varied type of gneisses, granulites, amphibolites, quartzites, meta-calc-silicates rocks, marbles and meta-igneous rocks, and occupies the southern part of the study area.

The different type of volcanic activity have resulted into different topographical feature in the northern half of the study area. The Older Extrusives comprise the Monduli Mountain and the faulted terrain of the lava plateau. The former forms forest covered dissected mountains of olivine basalt, basaltic conglomerate and trachyte rising 2,660 m height and the latter forms lava plateau of basaltic lava and pyroclastic beds with fault scarps in the edges of plateau.

The Younger Extrusives are associated with the main phase of faulting. The Essimingor and the Burko are main center of this extrusives with chiefly of nephelinitic and phonolitic lavas associate with pyroclastic beds. The small volcanic cones less than 200 m height are located in the lava plateau.

The Manyara Lake Beds were deposited in the southwestern part of the study area. The beds are composed of fine grained calcareous mudstone, marls and calcareous sandstones with mainly horizontal beddings.

A-1-3 Hydrogeology and Groundwater

Four hydrogeological units underlie in the Monduli District; the Basement, the Plateau Lava, the Colluvial Deposits and the Lake Manyara Beds. The Basement is chiefly composed of metamorphic rocks and their weathered and fractured facies are expected for the aquifers. Depth to groundwater table show quite deep, more than 60 mbgs based on the exploratory wells drilled by RDD and the Study Team. Tested data in Tukusi reveals that well yield was 1 ℓ /min. by aquifers of weathered gneiss.

The Plateau Lava is composed of an alternating layers of basaltic lava, volcanic cinders (scoria), tuff and tuff breccia. Although fresh lavas underlie in the plateau, they are subjected to heavy weathering in broad wide valley. Groundwater is probably developed in these weathered beds. An exploratory well, EX-2 in Mbuyuni shows that depth to groundwater table in fractured volcanic rock indicates more than 60 mbgs.

The exploratory well drillings reveal that the Ardai and Eluanata Basins are underlain by same lithological beds of the Plateau Lava which are composed of alternating layers of heavily weathered basaltic lava, scoriatic lava, tuff and volcanic breccia with several meters thickness of single bed. Seven exploratory wells in the Ardai and Eluanata Basin were encountered cavern lavas rich in gas with non-flammable, non-radio-active and non-poisonous natures resulted on in-situ test by Tanzanian Pesticide Resarch Institute. Depth to these cavern lavas ranges from 85 to 150 mbgs in the Ardai Basin and it is shallower, 44 mbgs in the Eluanata Basin.

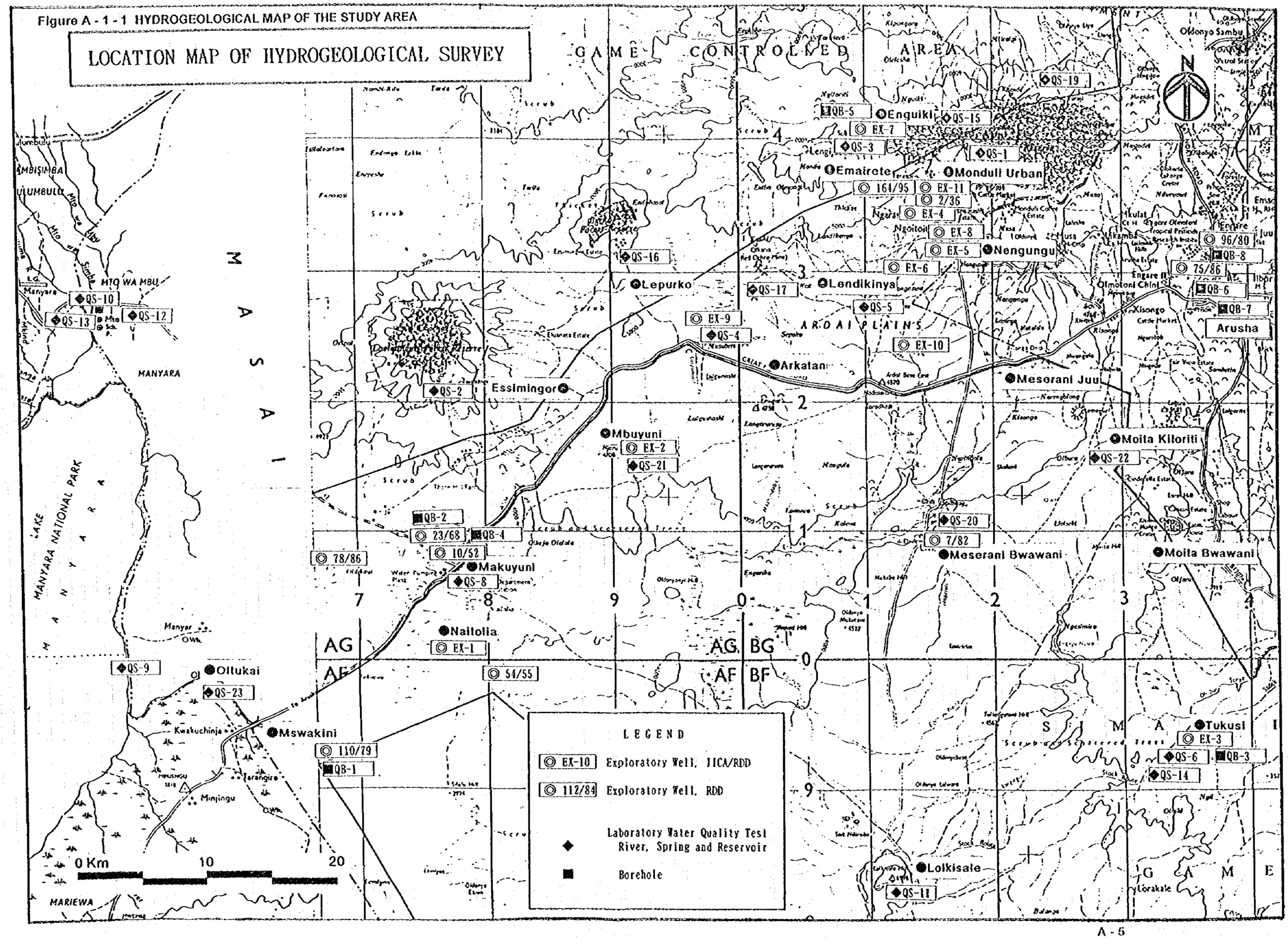
The Colluvial Deposits underlie in foot hill of the Younger Extrusives, in Monduli Juu, and in the Ardai and Eluanata Basins. The deposits are composed of unconsolidated pervious and impervious beds and have a thickness of less than ten meters in the Ardai Basin and more than one hundred meters in Monduli Juu. Depth to water level in Monduli Juu shows 72 mbgs and tested well yield, specific capacity and transmissivity in EX-7 indicate 20.7 ℓ/min., 6.3 ℓ/min./m and 10 m^2/day respectively.

The Lake Manyara Beds is mainly composed of unconsolidated pervious beds and groundwater potential in the beds is comparatively good according to the exploratory wells drilled by RDD in Mswakini and Makuyuni. Depth to water levels ranges from 24 to 31 mbgs and average specific capacity and transmissivity show 12 ℓ/min./m and 23 m^2/day respectively.

Hydrogeological Map of the study area is shown in Figure A-1-1.

Figure A - 1 - 1 HYDROGEOLOGICAL MAP OF THE STUDY AREA

LOCATION MAP OF HYDROGEOLOGICAL SURVEY



A - 2 HYDROGEOLOGY AND GROUNDWATER

A-2-1 Objectives of the Survey

Prior to the geophysical prospecting and exploratory well drilling, hydrogeological survey was conducted to obtain the following:

1) to understand the geology of the study area,
2) to identify the hydrogeological units based on the geology and existing well information,
3) to evaluate the groundwater potential of respective hydrogeological units and
4) to prepare the hydrogeological map of the study area.

Location of hydrogeological study and prepared hydrogeological map are shown in Figure A-1-1 and A-2-1.

A-2-2 The Hydrogeological Units of the Study Area

Four hydrogeological unit was identified based on the field survey, these are the Basement, Plateau Lava, Colluvial Deposits and Lake Manyara Beds.

(1) The Basement

The Basement is composed of chiefly various type of gneisses associate with quartzite and meta-igneous rocks. These rocks underlie in the south of Naitolia in the west, Lolkisale in the south and Tukusi in the east of the Area.

Main aquifers in these rocks are fractures and heavily weathered geologic material in the upper part of the rocks. In general, granite and granitic metamorphic rocks are easily altered to loose sandy material by superficial weathering.

The area which is underlain by the Basement, is subjected to low rainfall, however, aquifers can receive recharge by the surface runoff from forest covered areas of Lolkisale Game Controlled Area and Tarangire Game Reserve where subjecting large amount of rainfall in the rainy season. Tukusi and Lolkisale villages are located in the basement area.

(2) The Plateau Lava

Geological sequence of the plateau lava is complex with wide variety of volcanic lithological facies. Outcrops reveal that the lava flow consists mostly of basaltic rocks with few meters thick, but contains some intercalated tuff and pyroclastic rocks.

In general, the plateau lava forms gentle undulated hills extending north-southerly direction with the escarps in both sides of edges. Broad and shallow valleys were cut between the escarps.

Main aquifer in the Plateau Lava seems to pyroclastic rocks, however, fractures in basaltic rocks also can be expected an aquifer if the rocks are heavily subjected to fracturing by tectonic movement.

The area is located between volcanic mountains and the Basement. The aquifers are mostly subjecting recharge by surface river runoff from the mountainous area, but magnitude of it depend on the distance from the mountains.

The results of exploratory well drilling reveals that groundwater table in the plateau lava indicates so deep, more than 250 mbgs, according to EX-6 in the Ardai Basin.

The following eight villages are located in the plateau lava area; Arkatan, Lepruko, Lossimingor, Mbuyuni, Meserani Juu, Meserani Bwawani, Moita Kiloriti and Moita Bwawani.

(3) Colluvial Deposits

The small scale colluvial deposits underlie in the areas of Basement and the Plateau Lava, however, thick and widely extended beds is only underlain in Monduli Juu. The exploratory well of EX-7 and existing wells reveal that total thickness of unconsolidated colluvial beds which derived from volcanic material, exceeds more than 100 meters in Monduli Juu.

The colluvial deposits consists mostly of clay and volcanic sand with volcanic rock fragments which were derived principally from the extrusives.

An expected aquifers in the deposits are volcanic sand, according to a record

of exploratory well of EX-7. Emaireti village is located on Monduli Juu.

(4) Lake Manyara Beds

A broad flat land extend from the south of Makuyuni to District Boundary along the Highway. The distribution of the Lake Manyara Beds is in good agreement with the area of this flat land. It consists of weak consolidated calcareous mudstone, marls and calcareous sandstone with few ten centimeters thickness of single beds. Existing well record in Mswakini reveals that total thickness of the formation is more than 100 meters(see Figure B-1, Exploratory Well Log in ANNEX).

Expected lithology of aquifer is calcareous sandstone and electrical conductance of groundwater from this aquifer shows ranging from 1,000 to 1,400 μ S/cm.

A-2-3 Selection of Potential Five Villages

Five potential villages were selected according to following selection criteria;

- appropriate groundwater potential can be expected for the exploratory well drilling,
- sufficient potable water sources are not found near by villages within several kilometers and
- selected villages shall be located on different hydrogeological units.

The hydrogeological condition of selected villages is summarized as follow:

Name of village	Hydrogeological Unit	Expected Aquifer
Naitolia	Lake Manyara Beds	Sandstone
Mbuyuni	Plateau Lava	Fractured rocks
Tukusi	Colluvial/Plateau Lava	Pyroclastic rocks
Lendikinya	Colluvial/Plateau Lava	Pyroclastic rocks

Prior to the exploratory well drilling, geophysical prospecting were conducted in the selected villages. Objectives of the prospecting are to confirm and to identify the aquifer conditions and to locate drilling sites.

A-2-4 Hydrogeology of Monduli Town

Monduli town is located on a foot hill of Monduli Mountain and is underlain by colluvial deposits derived from the Older Extrusives of Monduli Mountain. Three exploratory wells, No. 2/36, 3/36 and EX-11, were drilled by RDD and JICA in Tarosero area in northwestern part of the town and their yield were 38 ℓ/min., but no drawdown were recorded. The geological well log in EX-11 reveals that unconsolidated colluvial bed as much as 39 meters thick covers fractured volcanic rocks. The former act a part of aquifer, but not good potential, and the latter contains pressure gas in an cavern volcanic rock.

An interpretation of an aerial photograph estimates that the depth to the extrusive thickens abruptly in the south of the Monduli Mountain due to east-westerly faulting. The exploratory well record of EX-4 which was drilled near Ngarash, supports this estimation. The record indicates that the well didn't encountered distinct hard volcanic rocks until 150 mbgs. Water level in EX-4 indicates 122 mbgs in aquifers of volcanic sand.

A-2-5 Hydrogeology of Monduli Juu

Monduli Juu is composed of two calderas, inner and outer ones with diameter of 3 and 7 km respectively. The inner caldera has a distinct caldera wall, but it of the outer one is not clear due to dissected and eroded works.

A test well of 87/79 was drilled up to 91 mbgs by RDD in the outer caldera but it was dry. Thick unconsolidated beds of clay with gravels and clayey rock fragments underlie in the hole and it was encountered volcanic rocks at 88 m depth where circulation mud was lost.

The drilling log of EX-7 in the inner caldera reveals that the upper part of log consists of colluvial deposits of clayey beds with thickness of about 68 m, and the lower part of it consists of medium to coarse sand with more than 30 m thick which play an aquifer. Tested specific capacity and transmissivity are 6.34 ℓ/min./m and 8 m^2/day respectively.

A-2-6 Hydrogeology of 18 Villages

(1) Oltukai Village

The village is located in few kilometers east of Lake Manyara, the southwestern part of the study area and is underlain by Lake Manyara Beds more than 100 meters thick. A sand-floored plain slopes gently westward to Lake Manyara.

The villager are dependent surface river for their water source during rainy season. Water quality in terms of electrical conductance is excellent, that is 400 μ S/cm, but with high rate of turbidity. A reservoir was constructed in the Oltukai River near by village, but it was flushed out due to inadequate construction technique.

The groundwater potential of Lake Manyara Beds seems excellent but the analysis of water quality indicates that it has a high concentration of dissolved solids(ARWMP, 1994). Results of resistivity prospecting in the village supports the qualitative inferiority.

(2) Mswakini Village

The village is located in the east of Oltukai village and is underlain by Lake Manyara Beds more than 100 meters thick. A sand-floored plain slopes gently westward to Lake Manyara same as Oltukai and the east and southeast are bordered by Tarangire Game Reserve and Lolkisale Game Controlled Area which act a part of recharge area.

An exploratory well of RDD, No.110/79 reveals that tested yield was 527 ℓ /min. at 43 m drawdown and calculated specific capacity is 12.3 ℓ /min./m(see Table A-2-1, Successful Boreholes in the Study Area). Although electrical conductance of groundwater in the well shows 1,400 μ S/cm which exceed limitation of WHO drinking standard, but concentration of other chemical items is within the standard.

Groundwater quality in Lake Manyara Beds in the south and eastern part of village have been improved by the fresh water flowing from the forest covered reserved areas. The villagers will be depend on their drinking water by groundwater, however, it is required power driven pump because of water level indicates more than 30 mbgs.

(3) Naitolia Village

The village is located in the east end of Old Lake Manyara depositional plain and is underlain by Lake Manyara Beds in lowland. The lake Manyara Beds is underlain by the Basement in undulated hill. Depth to the basement in the lowland was confirmed by the exploratory well drilling of EX-1 that was 80 mbgs near a Charko(see Figure A-4-1, Exploratory Well Log of Naitolia).

Major aquifers in the lowland is sandy material of the Lake Manyara Beds and water quality of the aquifers infer have high concentration of total dissolved solid.

Groundwater potential in the Basement was not precisely evaluated in the study area, but an exploratory well No. 54/55 reveals that it was struck groundwater at about 150 mbgs and yield was 18 ℓ /min. with static water level of 104 mbgs, but no record of drawdown(see Table A-2-1 Successful Boreholes in Monduli District).

(4) Makuyuni Village

The village is located in the east fringe of depositional plain of the Lake Manyara Beds where the Makuyuni River flow out from hilly area to the plain. The Lake Manyara Beds is restricted in distribution due to the Plateau Lava surrounding the village except the west.

Three exploratory wells were drilled by RDD and they are utilizing for the villagers.

Major aquifers underlie in calcareous bed of the Lake Manyara Beds according to the exploratory wells of RDD. Tested yield and static water level range from 37 to 76 ℓ /min. and 24 to 31 mbgs respectively, however drawdown were not observed(see Table A-2-1 Successful Boreholes in Monduli District). The study team carried out pumping test in the exploratory well of 10/52. The test reveals that discharge, specific capacity and transmissivity are 78.2 ℓ /min., 10.4 ℓ /min./m and 11 m^3/day respectively.

(5) Mbuyuni Village

The village is located on the Plateau Lava and the Buani River flows from the Essimingor drainage area in the east of it. Although record of existing wells are

not available near the area, fractured volcanic rocks and intercalated tuff breccia are possibly developed for the aquifers.

Resistivity prospecting reveals that a center of the Buani River course is underlain by low resistivity layers which is a sign of clayey impervious beds or highly concentrated total dissolved solid in the beds. The prospecting and geological features suggest that there is a zone of fractured volcanic rocks in the west of river bed(see Figure A-3-15 and A-3-16, Resistivity Profiles in Mbuyuni).

The exploratory well of EX-2 reveals that tuff breccia underlies with 3 m thick and heavily fractured volcanic rock is overlain by it. Depth to static water level was 57 mbgs, but no enough discharge is observed by the test.

(6) Lossimingor Village

The village is located in foothill of Mt. Essimingor and is underlain by colluvial deposits and volcanic rocks. An exploratory well was drilled to 56 m depth by RDD near the village, but it was unsuccessful.

The area is drained by the streams from Mt. Essimingor which is well reserved forest area, and groundwater potential is promising considering from hydrogeological point of view. Two reservoirs are located in the village, but one of them was flushed out by a food.

(7) Lepruko Village

The village is located on the volcanic plateau, south of Mt. Burko and is underlain by the Plateau Lava. No existing information of the exploratory wells near the village, however, it is difficult to obtain groundwater resources in the Plateau Lava from hydrogeological point of view.

There is a large possibility to develop groundwater in the Eluanata Basin, east of the village. Nevertheless an exploratory well of RDD was unsuccessful. It might be inferred that the area is drained from the catchment of Mt. Burko and Kosiki Mountains which discharge into the Eluanata Nanja Swamp. The swamp can drain to the Loikumashi River when water level rise more than the river floor.

It can be inferred that a depth to the volcanic rocks in the Eluanata Basin estimates so deep resulted on faulting along the northern edge of the plateau.

Water sources for the village can be supplied by a reservoir in the upper part of Eluanata Basin.

(8) Arkatan Village

The village is located on the volcanic plateau and is underlain by the Plateau Lava. It is difficult to obtain groundwater resources in the plateau, but there is a possibility to develop groundwater in the Ardai Basin, the north of it, but depth to aquifer estimates more than 250 m.

A reservoir in the Ardai Basin is the only major water sources for the village. However, a plan to introduce water from TMA by pipe is under construction by the villagers but progress is too slow due to financial constraint.

(9) Lendikinya Village

The village is located on the southern slope of Lendikinya Mountain to the west of Monduli Mountain and is underlain by the alternating beds of scoriatic volcanic rocks and pyroclastic beds. Although hydrogeological information is not obtained by the existing well, only the groundwater sources is available in the Ardai Basin based on the hydrogeological point of view, however depth to the aquifer system seems more than 200 m.

Ngamuriaki and Ardai Dams are their water sources but the latter was flashed out by a flood on 1995.

An exploratory well of EX-5 reveals that it was not struck groundwater up to 250 meters depth but was encountered volcanic cave at 114 meters.

(10) Nengungu Village

The village is located to the south of Monduli Town and is underlain by the Plateau Lava. No exploratory well drilling was tried by RDD, but the villagers are receiving domestic water by a diverted pipe water from TMA.

Expected aquifers is in the Plateau Lava. The exploratory well, EX-5 and EX-8 near the village reveals that it was no sign of groundwater up to 200 meters depth.

(11) Emairete Village

The village is located in the inner caldera and is underlain by colluvial deposits. Two exploratory wells of RDD were drilled in the inner caldera and one well was drilled in the outer caldera. Tested data of well in the inner caldera reveals that well depth and static water level were 29 and 5.2 mbgs respectively, and discharge was 36 ℓ /min. from colluvial beds, but no drawdown was recorded. A well in the outer caldera had a 92 m depth and heavy water loss was encountered at 87 m depth and the well was abandoned.

An exploratory well, EX-7 was drilled in the inner caldera up to 100 m depth. Tested data indicate that static water level, discharge, specific capacity and transmissivity are 72 mbgs, 20.7 ℓ /min., 6.34 ℓ /min./m and 8 m^2/day respectively.

Based on these information of existing wells, depth to volcanic rock was more than 100 meters and volcanic sand was expected as an aquifer.

(12) Enguik Village

The village is located on the mountain slope of Mt. Monduli and is underlain by volcanic rocks. No available information of drilling wells except in the outer caldera as stated in Emairete Village. A spring from the northern slope of Mt. Monduli is the only water sources to the village. Measured discharge of the spring was 0.76 ℓ /s on September, 1995.

Groundwater development in the village is difficult based on hydrogeological point of view.

(13) Meserani Juu Village

The village is located in the lowest part of Muso river and is underlain by pyroclastic rocks. The Muso River is drained from the eastern part of Monduli Mountain joining several number of tributaries.

Although no drilling record is available, there is a great possibility for groundwater development because the area is subjected to recharge from the Musa River.

A reservoir and TMA pipe are supplying domestic water to the village.

(14) Meserani Bwawani Village

The village is located in the alluvial plain of Loolera River, which is the down stream of Muso River and is underlain by unconsolidated alluvial beds and pyroclastic rocks of the Plateau Lava. Depth to volcanic rocks is more than 60 meters according to existing wells No. 7/82 and 129/84.

Tested data of well No. 129/84 indicates that well depth and static water level are 107 m and 90 mbgs respectively, and discharge is 28 ℓ/min. by 7.3 meters drawdown.

Broad shallow valley of the Ardai and Loolera Rivers narrows at Liviseki where a range of volcanic cones intercept their river courses. The topographic feature described above suggests that the streams are stagnated and stored in the upper part of this volcanic range. Distribution of swamp and marshy land support this inference. Groundwater potential seems excellent in the upper part of the volcanic range.

(15) Moita Kiloriti Village

The village is located in the western slope of the volcanic plateau and is underlain by the Plateau Lava. Record of existing wells was not available near the village, however, there is a possibility of groundwater development near the Nadaare River basin.

A reservoir in tributary of the Nadaare River can be stored water all the year around.

(16) Moita Bwawani Village

The village is located in the eastern edge of the volcanic plateau and is underlain by pyroclastic rocks and Plateau Lava. The plateau is bordered by tectonic scarp to the Engare Olmotoni River. Although record of existing wells was not available near the village, it is difficult to develop groundwater resources because of limited recharge area.

A reservoir near the village can be stored water all the year around.

(17) Tukusi Village

The village is located in the undulated hill and is underlain by Basement Rocks. The exploratory well of EX-3 reveals that depth to the Basement is about 90 meters and is overlain by unconsolidated clayey and sandy material as a result of weathering of the Basement Rocks.

Tested data shows that well depth and static water level are 79 m and 54.56 mbgs and obtained yield is 1 ℓ /min. respectively.

Water sources for the village is an underflow in Oloibor river which drains from the Basement. Measured discharge was 0.89 ℓ /s on September, 1995. The most of rivers in the Basement Rocks have a perennial stream because drainage area is covered by thick forest and it act a part of recharge area.

(18) Lolkisale Village

The village is located at the foot hill of Mt. Lolkisale and is underlain by the Basement Rock. Two exploratory wells were drilled up to more than 150 meters near the village, but obtained discharge was so little, 1.5 ℓ /min. Groundwater potential of the aquifer in the fractured gneiss seems not enough for development.

Two spring sources in Mt. Lolkisale are major water sources of the Village. Measured discharge of these springs is 0.45 and 0.1 ℓ /s respectively.

A-2-7 Hydrogeology of Ardai Basin

The Ardai Basin covers about 130 sq.km in the south of Monduli Town and includes moderately sloping alluvial surface and nearly level wide valley floor. All streams in the Monduli and Lendikinya mountain ranges drains into the basin and it filled with drained water because the southern edge of the basin is limited by the uplifted lava plateau. Only two outlets drain into the lava plateau. From this topographic feature it may be inferred that groundwater can be stored, transmitted and released in colluvial beds and heavily fractured volcanic rocks aquifers in the zone of saturated subsurface. But the exploratory well drillings reveal that they couldn't attain the zone of saturated subsurface until 250 meters in EX-6, the middle course of the basin. Lithology of well log indicates that there are several beds which can act a part of aquifer in fractured scoriatic rocks.

The most striking feature of subsurface geology is the presence of pressure gas in the cavern volcanic rocks. The drilling is required to seal the cave by cementing when it try to drill more deeper part. Four exploratory drillings reveal that the pressure gas find at the depth ranging from 86 to 150 mbgs which is equivalent at a horizon ranging from 1,190 to 1390 mamsl.

The Ardai Basin is underlain by alternative beds of tuff, tuff breccia, scoriatic lava and basalt with few meters of the colluvial beds in the surface according to the exploratory well drilling. It appears from the above that the geology in the basin is same as the lava plateau, that is the Plateau Lava.

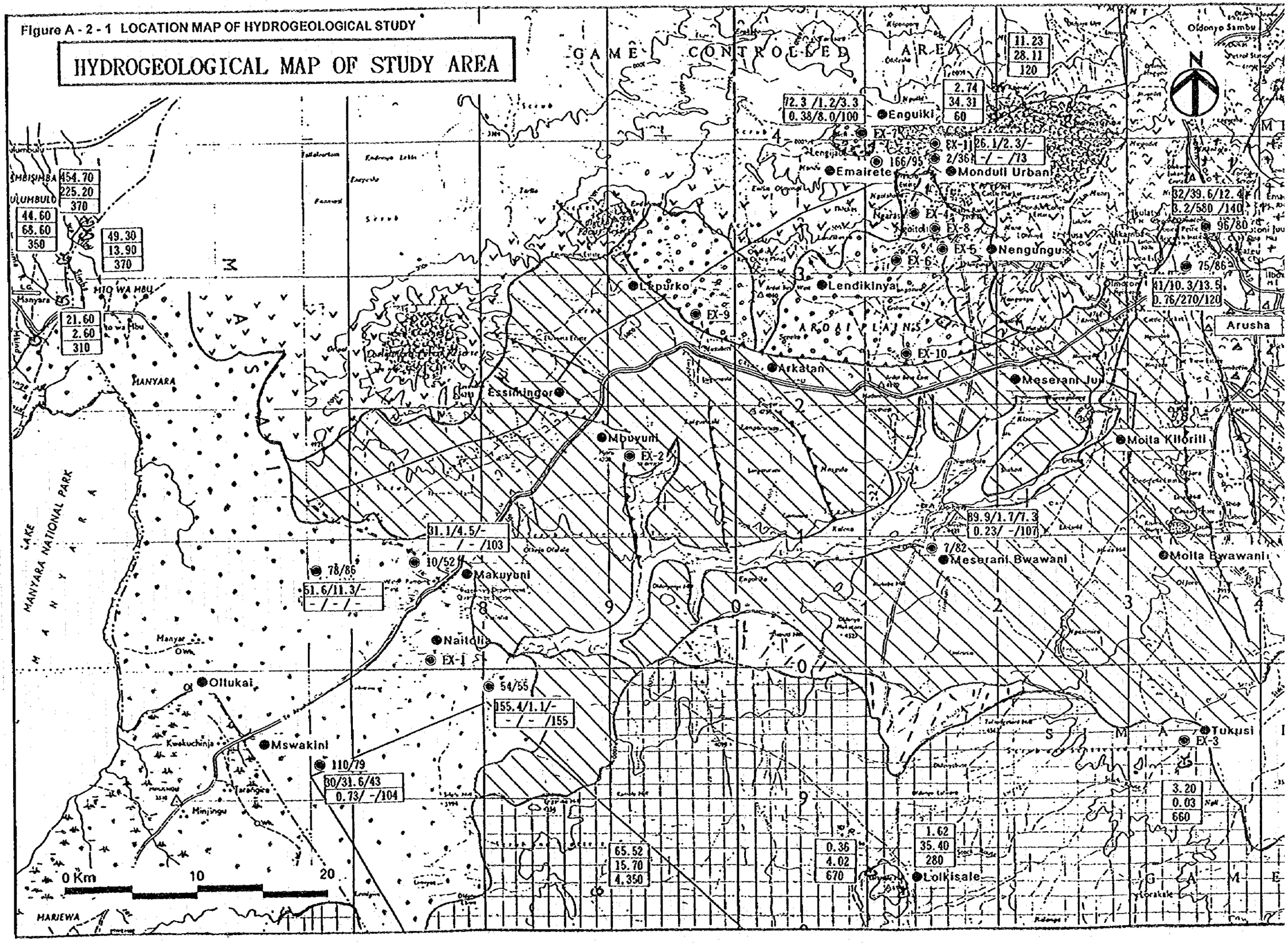
Table A-2-1 SUCCESSFUL BOREHOLES IN THE STUDY AREA, MONDULI DISTRICT

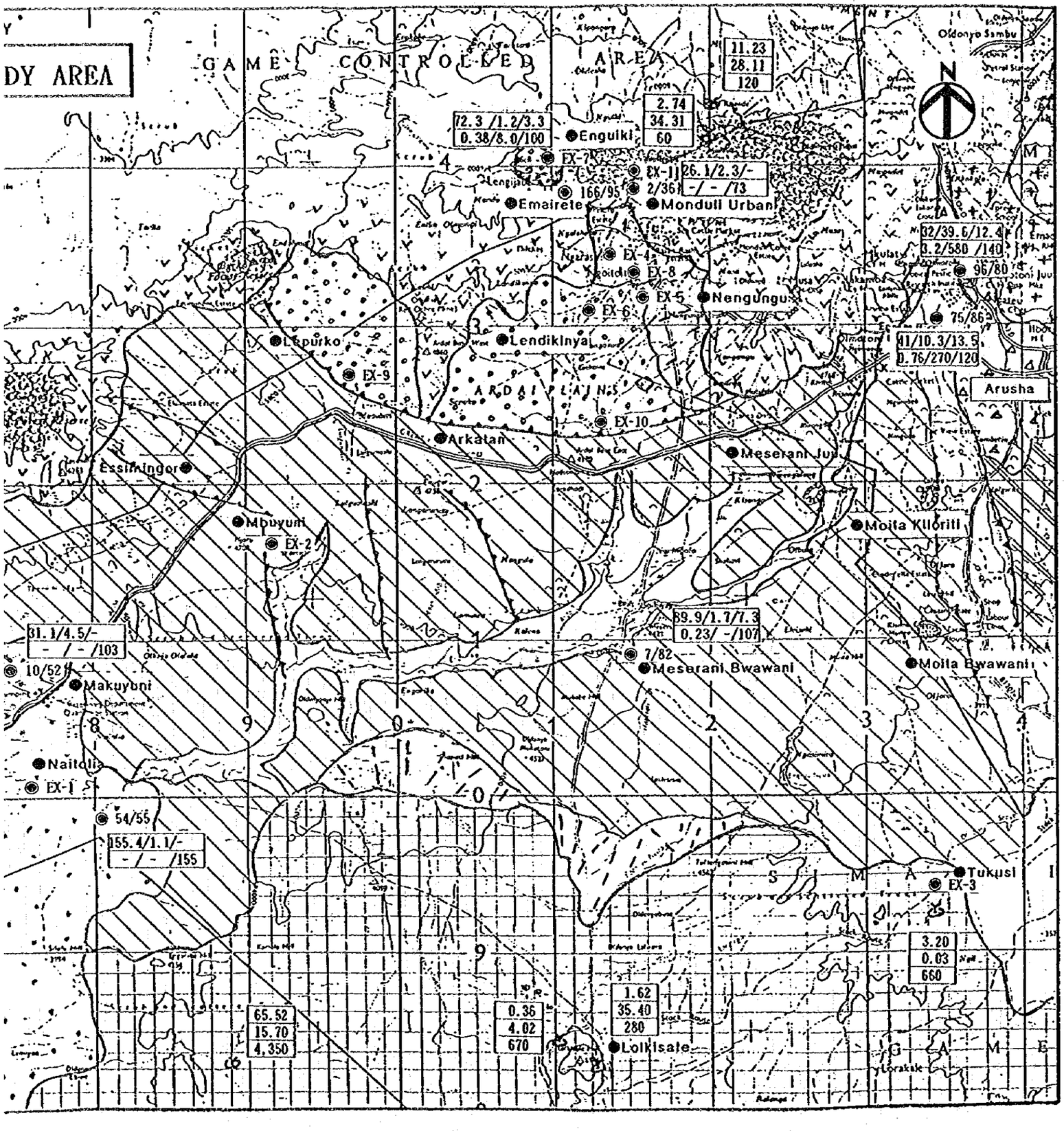
BH. No.	Depth (m)	SWL (mbgs)	DWS (mbgs)	Yield (m3. hr)	D/d (m)	S. C. (l/min/m)	Dep. to H. Rock	Aquifer	Location	Alt. (mamsl)	Long. Lati.
2/36	72. 7	26. 1	36. 4	2. 30	-	-	-	w. lava	Tarasero	1, 546	3° 16. 816' 36° 26. 305'
3/36	73. 2	26. 2	36. 6	2. 30	-	-	-	w. lava	Tarasero	1, 530	3° 16. 816' 36° 26. 305'
10/52	103. 6	31. 1	34. 1	4. 50	-	-	-	w. dike	Makuyuni	1, 095	3° 33. 302' 36° 05. 461'
54/55	155. 4	104. 0	152. 7 154. 0	1. 10	-	-	-	w. gneiss	Naitolian	1, 105	3° 38. 195' 36° 07. 331'
23/68	144. 6	24. 0	95. 0	2. 20	-	-	-	w. basement v. ash	Makuyuni	1, 105	3° 32. 362' 36° 04. 262'
110/79	103. 7	30. 0	42. 7 85. 4	31. 60	43. 0	12. 2	103. 0	calcareous	Mswakini	1, 055	3° 40. 775' 36° 00. 553'
7/82	106. 8	89. 9	-	1. 70	7. 3	3. 9	-	c. sand grav, granu.	Meserani *Bwawani	1, 220	3° 32. 071' 36° 25. 900'
112/84	29. 0	5. 2	9. 5 20. 1 25. 0	2. 18	-	-	28. 9	soft soil clay	Engwiki	1, 730	3° 15. 040' 36° 23. 453'
78/86	-	51. 6	-	11. 30	-	-	-	w. basalt	Manyara ranch	1, 030	3° 32. 976' 36° 00. 841'

Remark : DWS = Depth water struck SWL = Static water level D/d = Drawdown
SC = Specific capacity Alt = Altitude

Figure A - 2 - 1 LOCATION MAP OF HYDROGEOLOGICAL STUDY

HYDROGEOLOGICAL MAP OF STUDY AREA





LEGEND

Symbol	Lithology	Hydrogeology
	RECENT River beds Clay, sand and gravels	Small scale shallow groundwater
	Fan, Talus Clay, volcanic sand & fragments	Small scale shallow groundwater
	Volcanic talus Clay, volcanic sand & fragments	Large scale groundwater in Engare Olmoton
	Colluvium Clay, volcanic sand & fragments	Large scale groundwater only in Monduli Juu
	NEOGENE Lake Nanyara Bed	Large scale groundwater, but inferior quality in EC and fluorine
	Younger Extrusive	Fractured aquifer with small scale quantity
	Plateau Lava	Fractured aquifers and pressure gas in volcanic caves. Depth to water level is more than 250 m
	PRECAMBRIAN Basement Rocks Gneiss, migmatite, granulite and metaigneous	Aquifer in weather part of Basement rocks
	Escarpments	

Explanation of Symbol and Figure		Remark
◉ 7/82	Exploratory Well of RDD	SWL=S.W.L. in mbgs Q =Well discharge in m3/hr Dd =Drawdown in m SC =Specific capacity in m3/hr/m T =Transmissivity in m2/day WD =Well Depth in m S.R=Specific discharge
◉ EX-10	Exploratory Well of JICA/RDD	
19.3 /4.7/7.5 0.62/10 /36	Well Potential SWL/Q/Dd SC/ T/WD	
	Spring	
3.2 0.032 300	Spring discharge Q (m3/hr) S.R(mm/ann) E.C.(μS/cm)	

A - 3 GEOPHYSICAL PROSPECTING

A-3-1 Methodology

(1) Resistivity Prospecting

Two method of electrode array, Wenner and Schlumberger were applied for the prospecting. The former was applied in Monduli Town and the latter was applied in the rest of study area.

A maximum spacing of current electrodes for Wenner array was 230 m. The prospecting in the Ardai and Eluanata Basins was conducted by Schlumberger array with 1,000 m of maximum 2/AB spacing. An instrument applied prospecting was SYSCAL-R2, BRGM.

Inversion analytical method were applied for interpretation of resistivity models which were approximated by the observed VES curves.

(2) Magneto-Telluric Prospecting(PLMT)

Electro-Magnetic Prospecting by VLF-MT method was initially programmed to detect rock fracture in the study area, however, it has not effective in the area because the thickness of overburden attains more than a prospecting limitation and resistivity was too low to construct the model. An attempt was made to verify the use of VLF-MT method in Mbuyuni village where thinner overburden was detected by the resistivity prospecting. The prospecting show that no proper interpretation of resistivity structure couldn't made because of the extremely high deviation of the observed data due to weak signal from GBR.

On the other hand, PLMT method was introduced to study large-scale resistivity structure in the Ardai Basin where potential aquifer system is expected for Monduli Town and neighboring villages. PLMT system is to explore subsurface electrical resistivity distribution by measuring both electric and magnetic fields generated by electric power line.

Although the signal source of the method depends on both electric and magnetic fields from a commercial high-voltage power line it was so weak and often interrupted, therefore, artificial power sources by a generator was introduced in the Ardai and Eluanata Basins. The generator emits high signal in frequencies of at 60 Hz and its harmonics, e.g. 120, 180, 240, 300, 360, 420, 480, 540, 600 and 660 Hz.

Prospecting sites are covered the Eluanata and Ardai Basins in a grid approximately of every 2 ㎞. The total number of prospecting is at 95 sites (Figure A-3-25 Location Map of PLMT Prospecting).

Of the measured data obtained by PLMT, are analyzed by the one-dimensional inversion method to derive the theoretical curve which fits to apparent resistivity and frequency.

A-3-2 Results of Resistivity Prospecting

Resistivity prospecting were made in the following town and villages:

Name of Village	No. of Site	Max. AB/2 (m)	Array
Monduli Town	17	230	Wenner
Monduli Town	37	200	Schlumberger
Monduli Juu	30	200	"
Ardai Basin	21	200	"
Tukusi	4	200	Wenner
Tukusi	12	200	Schlumberger
Naitolia	15	200	"
Mbuyuni	15	200	"
Arkatan West	17	200	"
Arkatan East	18	200	"
Oltukai	2	140	"
Mswakini	5	200	"
Makuyuni	5	200	"
Ardai and Eluanata	7	1,000	"
Total	205		

(1) Monduli Town

Seven prospecting lines with east westerly direction were set up from the northern edge of the town to the Ardai Basin(see Figure A-3-1, Location Map of Resistivity Prospecting in Monduli Town and Ardai Basin). The results are shown in resistivity profiles and these interpretation is summarized as follows:

<Line No.1 and No.2 in Figure A-3-2>

The profiles are composed of 3 to 4 resistivity layers, but they can be divided into upper, middle and lower resistivity layers for the convenience of interpretation. Results is summarized in the following table:

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	10 - 490	2 - 30	clayey, coarse sandy material
Middle	10 - 30	40 - 150	clayey impervious material
Lower	80 - 370	-	fractured volcanic rocks, scoria, pyroclastic beds

A depth to surface of the lower layer thickens to the east in opposition to gradient of surface topography.

<Line No.3 in Figure A-3-2>

Three to six resistivity layers were observed in VES curves, but interpretation was made by two layers.

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	6 - 70	50 -180	sand, pyroclastics material
Lower	80 - 570	-	fractured to compacted volcanic rocks, scoria, pyroclastic beds

The upper layer is virtually divided into two to four layers, but their thickness seems very thin. An extinct underground valley is found in site 11 where depth to surface of the lower layer shows 175 mbgs. Depth to the lower layers thins to west.

Resistivity of the lower layer indicates comparatively higher in both sides of the line.

<Lines No.4, 5 and 6 in Figure A-3-3 and A-3-4>

The lines were set up just the south of the town. An interpretation of the profiles were made by two resistivity layers, however, VES curves are composed of three to five resistivity layers. Results of interpretation is summarized in the following table:

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	5 - 50	25 - 120	clayey, coarse pyroclastics beds
Lower	50 - 510	-	fractured to compacted volcanic rocks, scoria, pyroclastic beds

The middle layer are found in sites 18 to 22 with 5 to 25 Ω-m resistivity. The profiles shows typical two resistivity layers in the southern part of the lines. Resistivity of the lower layer increase to the south where consolidation of layer become more hard and compact. The exploratory well, EX-4 and EX-8 were located near sites No.23 and No.27 to expect fractured aquifers in 180 and 110 Ω-m layers.

<Line No. 7 in Figure A-3-4>

The line was set up the southeasterly direction and east end of the line connect with the line which was conducted by RDD on 1981(see Figure A-3-1, Location Map of Resistivity Prospecting in Monduli Town).

An interpretation of the profiles were made by two resistivity layers, however, VES curves are composed of two to four resistivity layers. Results of interpretation is summarized in the following table:

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	5 - 30	25 - 120	clayey, coarse pyroclastics
Lower	45 - 260	-	pyroclastics in central to east part and vol. rocks in west edge

As easily visualized from Figure A-3-4, resistivity of the lower layer is quite different between west group of sites 52,53 and 54 and east group of sites 47,48,49,50,

and 51. The west group indicates more than 200 Ω-m, however the east group ranges from 35 to 64 Ω-m. The former can be correlated with fractured volcanic rocks and the latter is correlated with unconsolidated pyroclastic material.

An exploratory well, EX-6 was located on No.39 to expect fractured aquifer in 130 Ω-m layer.

(2) Ardai Basin

Two prospecting lines of Ardai Basin are set up to connect with seventh line of Monduli Town(see Figure A-3-1, Location Map of Resistivity Prospecting in Monduli Town and Ardai Basin). The results are shown in resistivity profiles and interpretation is summarized as follows:

<Line No.1 and 2 in Figure A-3-5>

Although observed VES curves are composed of 3 to 5 resistivity layers, the interpretation was made by two layers.

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	5 - 60	30 - 100	clayey, impervious material is dominant
Lower	20 - 430	-	pyroclastics and/or heavily fractured volcanic rocks

Undulated surface is observed in the lower layer and it shows less fractured lithology compared with central and eastern part of the lines. An exploratory well, EX-5 was located on No. 5 to expect fractured aquifer in 75 Ω-m layer.

(3) Monduli Juu

Three prospecting lines were set up in Monduli Juu, one in the inner caldera and two near reservoir in the outer caldera(see Figure A-3-6, Location Map of Resistivity Prospecting in Monduli Juu).

<Line No.1 and No.2 in Figure A-3-7>

The line No.1 is in upper part of reservoir and No.2 is in lower part of it in the outer caldera. The profiles are composed of 2 to 4 resistivity layers, but interpretation was made by three layers. Results is summarized in the following table:

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	5 - 20	10 - 30	clayey material
Middle	10 - 40	20 - 120	clayey impervious material
Lower	50 - 650	-	sandy or pyroclastics, hard rocks in upper part of reservoir

The upper layer thickens in the center of a valley. The middle layer shows transitional lithological facies from the upper to lower. The lower layer can be correlated with hard volcanic rocks in the upper part of reservoir.

<Line No.3 in Figure A-3-8>

The line was set up in the inner caldera. Depth to the lower layer ranges from 40 to 110 m with an average of 60 m.

An exploratory well, EX-7 was located on site No. 25 to expect sandy aquifer in 120 Ω-m layer.

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	10 - 30	5 - 30	clayey material
Middle	25 - 40	20 - 100	clayey to semi-pervious material
Lower	55 - 120	-	sandy or pyroclastics, and/or fractured volcanic rocks

(4) Tukusi Village

The site is located in the undulated hill with three prospecting lines(see Figure A-3-9, Location Map of Resistivity Prospecting in Tukusi). As shows in Figure A-3-10 and A-3-11, three to 6 resistivity layers were observed in VES curves, but interpretation was made by three layers. Results is summarized in the following table:

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	20 - 140	10 - 50	sandy material
Middle	80 - 500	35 - 105	weathered and fractured basement rocks
Lower	11 - 300	-	weathered and fractured basement rocks

An exploratory well, EX-3 was located on site No.4 to expect aquifer in weathered basement of 83 Ω-m layer.

(5) Naitolia Village

Three prospecting lines were set up with east-westerly direction, near reservoir to the west part of the village(see Figure A-3-11, Location Map of Resistivity Prospecting in Naitolia). Although VES curves are composed of 3 to 4 resistivity layers, they were divided into two layers for the interpretation. Results is summarized in the following table:

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	2 - 50	15 - 90	clayey to sandy material
Lower	10 - 130	-	sandy and heavily weathered basement rocks

The upper layers indicate very low resistivity in the western part of lines due to salty water in the aquifers of Lake Manyara Beds. As shown in Figure A-3-13, Resistivity Profile in Naitolia, there is large difference of depth and resistivity in the lower layers between sites 13 and 14, and 7 and 8. It presumably resulted from the faulting.

An exploratory well, EX-1 was located on site No.1 to expect aquifer in 130 Ω-m layer.

(6) Mbuyuni Village

Three protecting lines were set up in Buani valley with northeasterly direction, east of the village(see Figure A-3-14, Location Map of Resistivity Prospecting in Mbuyuni). An interpretation of the profiles were made by two

resistivity layers, but VES curves are composed of 2 to 4 layers(see Figure A-3-15 and A-3-16, Resistivity Profiles in Mbuyuni). Results of interpretation is summarized in the following table:

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	1 - 300	8 - 60	clayey and fractured volcanic
Lower	10 - 4000	-	weathered and fractured volcanic, hard compacted volcanic rocks

The upper layer has considerable variation in resistivity and they thicken to the west. The lower layer also has considerable variation in resistivity, especially a high resistivity zone at sites 4, 9 and 15 ranging from 2,600 to 4,000 Ω-m near the plateau. The zone extend to northwesterly direction along the plateau.

An exploratory well, EX-2 was located on site No.13 to expect fractured aquifer in 130 Ω-m layer, but it was dry.

(7) Arkatan West

The prospecting site is located in the Eluanata Nanja Swamp, to the west of Ardai Basin where the Looloikumashi river is discharging from the Swamp. Three prospecting lines were set up in the swamp, the first two lines have a trending northwesterly direction and the last line was set up with northeasterly direction(see Figure A-3-17, Location Map of Resistivity Prospecting in Arkatan West.

<Line No.1 and No.3 in Figure A-3-18, Resistivity Profile>

These two lines are located at the central part of the Swamp and VES curves are composed of 2 to 4 resistivity layers. An interpretation was made by three resistivity layers as shown in Figure A-3-18, Resistivity profile Line No.1 and No.3. Results of resistivity profile No. 1 & No.3 is summarized in the following table:

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	3 - 11	5 - 45	clayey material
Middle	5 - 20	10 - 100	clayey, saturated by salty water
Lower	10 - 150	-	clayey, fractured volcanic

Resistivity of the upper and middle layers show low because of high electrical conductance of groundwater water in these layers.

<Line No.2 in Figure A-3-19, Resistivity Profile>

The line is located at the upper stream of Nanja Dam. An interpretation was made by two resistivity layers and results is summarized in the following table:

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	3 - 90	40 -105	clayey material and fractured volcanic
Lower	400 - 900	-	hard compacted volcanic rocks

It is easily assumed by Figures of Resistivity Profiles that resistivity of the lower layer is quite different between the line No.1 and No.2. The former shows low resistivity ranging from 12 to 120 Ω-m and the latter shows high resistivity ranging from 430 to 710 Ω-m due to lithological change from the Swamp to the Eluanata Nanja Dam.

An exploratory well, EX-9 was located on site No. 7 to expect a fractured aquifer in 77 Ω-m layer, but it was encountered pressure gas in cavern volcanic rock at 48 mbgs, and hole was abandoned.

(8) Arkatan East

The site is located in an outlet of the Ardai river which drain from the Ardai drainage area including the Monduli Mountain(see Figure A-3-20, Location Map of Resistivity Prospecting in Arkatan East). Three lines were set up with northeast by easterly direction. First line set up in river basin and second and third line in the plateau. Although VES curves are composed of 3 to 5 resistivity layers, interpretation was made by two resistivity layers. Results is summarized in the following table:

<Line No.1 in Figure A-3-21, Resistivity Profile of Line No.1>

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	9 - 140	20 - 90	clayey material and fracture volcanic or pyroclastics rocks
Lower	100 - 700	-	fractured and compacted volcanic rocks

The lower layer can be correlated with volcanic rocks which have been probably subjected to fracturing except site 1 in the east end of Line.

<Line No.2 and No.3 in Figure A-3-22, Resistivity Profile No.2 and No.3>

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	10 - 100	20 - 120	clayey material and fractured volcanic or pyroclastics rocks
Lower	20 - 700	-	fractured and compacted volcanic rocks

The lower layer can be correlated with volcanic rocks which have been probably subjected to fracturing in the western part of lines. Great difference of resistivity is observed between sites 12 and 13, and 8 and 9 which might have been resulted in faulting.

An exploratory well, EX-10 was located near site No. 2 to expect fractured aquifer in 250 Ω-m layer, however drilling was encountered pressure gas in cavern rock at 44 and 152 mbgs.

(9) Oltukai Village

The site is located in the old Lake Manyara depositional plain (see Figure A-3-23, Location Map of Resistivity Prospecting in Oltukai). Two prospecting were tried to verify resistivity of saturated water in the aquifers. Results are shown in VES curves that resistivity of layers 2 to 3 mbgs indicate below 2 Ω-m which is equivalent to more than 5,000 μ S/cm of electrical conductance (see Figure A-3-24, VES curve in Oltukai).

(10) Ardai and Eluanata Basin

Schlumberger prospecting with 1,000 meters electrode spacing was conducted in the Ardai and Eluanata Basin to verify the resistivity models constructed by PLMT prospecting. Prospected sites show in Figure A-3-25.

Five sites are located in the Ardai Basin and two sites are in the Eluanata Basin. Results of interpretation is shown in the Table 3-3-1, Interpretation of VES curve in Ardai-Eluanata.

Resistivity profiles resulted by Schlumberger and PLMT prospecting are shown in Figure A-3-26 and A-3-27.

As shown in above figures, the basin is mainly underlain by resistivity layers with 100 to 150 Ω-m and it can be correlative with the Plateau Lava according to the obtained drilling record of the exploratory wells. Although lithology of a low resistivity layer with 13 Ω-m at site S4 is not confirmed by the exploratory well drilling, it may be correlative with the heavily weathered Basement. Depth to the low resistivity layer ranges from 210 to 370 mbgs(see Figure A-3-26 and A-3-27).

(11) Mswakini

The purpose of prospecting is to identify location of production well for potable water supply in Mswakini village.

The site is underlain by the Lake Manyara Bed and is located in an outlet of a river which is discharging from the Lolkisale Game Reservoir where play a part of recharge area of the Bed(see Figure A-3-28, Location Map of Resistivity Prospecting in Mswakini).

Although VES curves are composed of 3 to 4 resistivity layers in detail, three major resistivity layers are underlain in the area. Results of interpretation is summarized in the following table:

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	3 - 58	10 - 42	clayey material and unsaturated calcareous sand
Middle	2 - 16	43 -	calcareous sand & gravel, saturated by groundwater
Lower	2 - 68	90 +	calcareous sand & gravel, weathered granite and gneiss

The middle layer play a part of aquifer according to a well data of production well for Phosphate Factory in Minjingu.

(12) Makuyuni

The purpose of prospecting is to identify resistivity of aquifers in the production wells of Makuyuni village. The site is underlain by the Lake Manyara Bed(see Figure A-3-29, Location Map of Resistivity Prospecting in Makuyuni).

Although VES curves are composed of 4 to 5 resistivity layers in detail, three major resistivity layers are underlain in the area. Results of interpretation is summarized in the following table:

Layers	Resistivity (Ω-m)	Thickness (m)	Lithological correlation
Upper	15 - 96	1 - 17	sand and gravel, unsaturated
Middle	4 - 9	15 - 23	clayey material
Lower	6 - 61	160 +	calcareous sand & gravel, saturated by groundwater

The lower layer play a part of aquifer according to a well data of production wells for Makuyuni village.

(13) Engare Olmotoni

The purpose of prospecting is to identify resistivity of aquifers which were screened by the existing production wells in Burka Coffee Estates and Arusha Seed Farm near by Arusha Airport area. Six sites, No.1, 2, 3, 5, 6 and 7, are located in the