REPUBLIC OF BOLIVIA

FINAL REPORT FOR THE STUDY ON GROUNDWATER DEVELOPMENT PROJECT ON EL ALTO DISTRICT IN LA PAZ CITY

MAIN REPORT

DECEMBER 1987

JAPAN INTERNATIONAL COOPERATION AGENCY

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PREFACE

In response to the request of the Government of the Republic of Bolivia, the Government of Japan has decided to conduct a Study on the Groundwater Development Project on El Alto District in La Paz City in the Republic of Bolivia and entrusted the study to the Japan International Cooperation Agency (JICA).

The JICA sent to Bolivia a study team headed by Mr. Masaaki Shindo of Kyowa Engineering Consultants Co., Ltd. from January to March 1987 for the study of the rainy season and from July to August 1987 for the study of the dry season.

The team had discussions on the study with the officials of the Government of Bolivia and conducted a field survey. Further studies were made after the team returned to Japan, and the present report has been prepared.

I hope that this report will be useful for the development of the Project and contribute to the promotion of friendly relations between our two countries.

I wish to express my deep appreciation to the officials concerned of the Government of the Republic of Bolivia for their close cooperation extended to the team.

December, 1987

Keisuke Arita
President
Japan International Cooperation Agency

December, 1987

Mr. Keisuke Arita
President
Japan International
Cooperation Agency
Tokyo

Dear Sir,

LETTER OF TRANMITTAL

It is our pleasure to submit to you the Final Report of the Study on Groundwater Developement Project on El Alto District in La Paz City in the Republic of Bolivia prepared for consideration by the Government of Bolivia in implementing development of groundwater in the Project area.

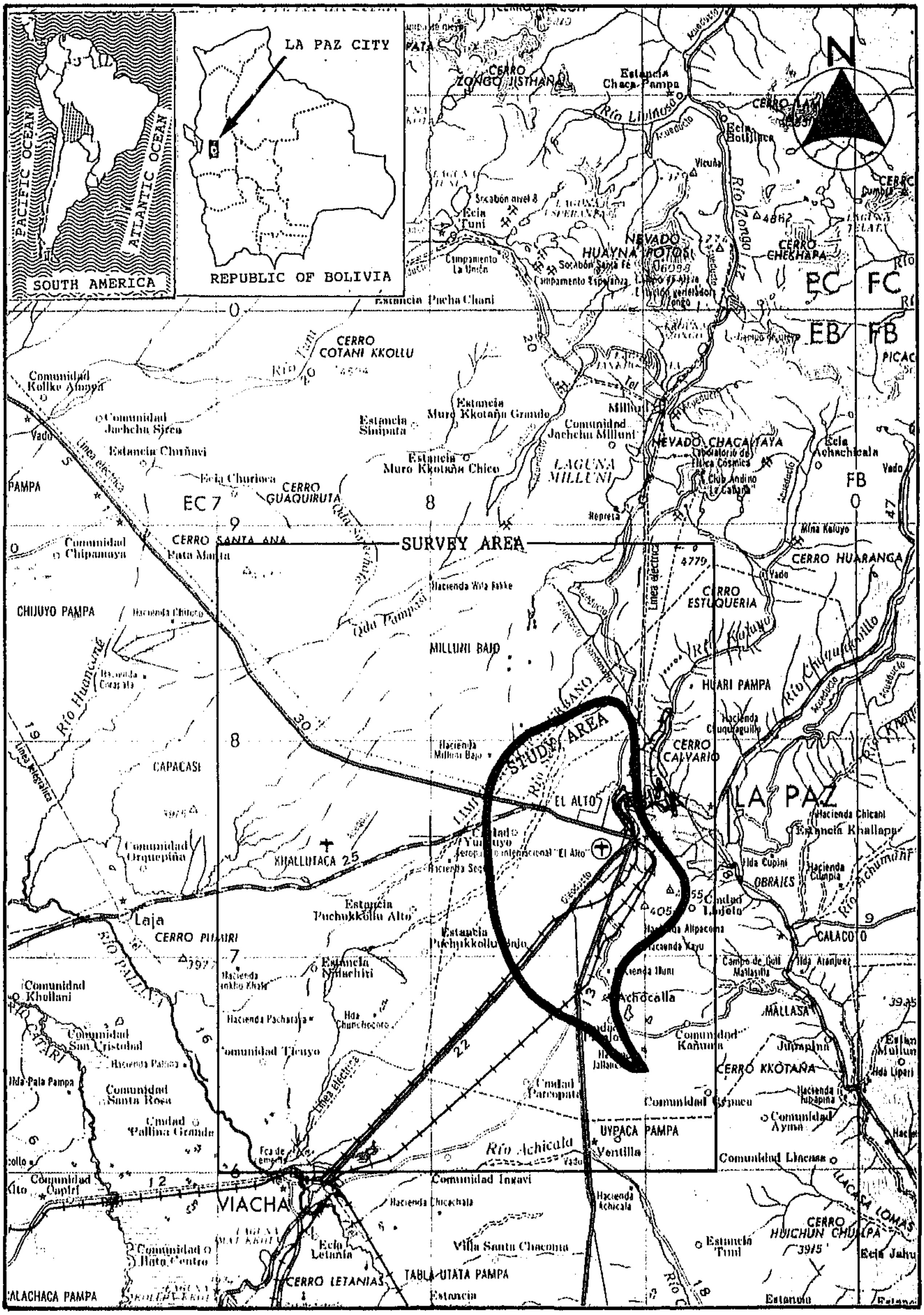
The final report consists of two separate volumes: Main Report summerizes the results of the survey and presents the conclusion and recommendations; Annexes provides detailed informations and data.

All members of the study team wish to express grateful acknowledgement to the personnel of your Agency, Ministry of Foreign Affairs and Embassy of Japan to the Bolivia as well as officials and individuals of the Bolivia for their assistance extended to the study team. The study team sincerely hopes that the results of study would contribute to socio-economic development and well-being in general.

Yours sincerely,

M. Shindo

Masaaki Shindo
Team Leader



LOCATION MAP SCALE 1:250,000

0 5 10 15 20 Km.

SUMMARY

1. INTRODUCTION

This report presents the results of field investigation and the home analysis made during the period from January, 1987 to January, 1988, and deals mainly with the finding on the present conditions , analysis of groundwater balance and development concept for utilization of groundwater in and around El Alto area.

Servicio Autonomo Municipal de Agua Potable y Alcantarillado (SAMAPA), who is the responsible Government Agency for the water supply of La Paz, had been studying the extending and reinforcing of the existing surface water supply system from Lago Tuni. SAMAPA had reached a result that it is impossible to extension of the existing water supply system due to water rights, huge cost of construction, long construction period and so on. SAMAPA, although, had ensured that the groundwater development for the new towns in El Alto district had very high potentialities hydrogeologically and technically based on the existing data of aquifers. Consequently, SAMAPA had requested the Government of Japan to prepare the study on groundwater development project on El Alto district in La Paz city including the identification of hydrogeological entity of the exploitable concealing water table.

The scope of work for the study contains three major programs as follows:

Part 1. Data collection and review
- Socio-economic background
- Existing development plans
- Natural conditions
- Water supply system and facilities
- Previous study on groundwater

Part 2. Field survey
- Field reconnaissances
- Geological condition
- Borehole pumping test

Part 3. Analyses and evaluation
- Groundwater hydrology and potential

Facilities' plan for water collecting
Forecast of water demand
Rough cost estimation and evaluation of the project
Recommendation

2. BACKGROUND

La Paz city is the biggest and a time-honored city in the Republic of Bolivia and has been developed in the basin of Rio choqueapu. The urban population in Bolivia is rapidly increasing recently. La Paz city is already over-populated. Therefore, the people who intend to live in La Paz cannot help dwelling in surrondings of El Alto Airport. Consequently, the functions of the city can not control it. Especially, water supply from the existing system is not sufficient to answer the demand. As a result of above circumstances, the shortage of water is imminent in El Alto district.

The study area where is formed as town in El Alto district is approx. 70 Km2. Population of 240,000 are living in there. These people are benefited of water supply by the surface water distribution system from Lago Tuni which is 37km far from El Alto district. The present capacity of this water suppply system is 28,000 m3 daily. Water from the system is served by the individual house's connections and the public taps.

This existing water supply system is affected by seasonal fluctuation of rainfall. And more, Bolivia also is being affected by the recent worldwide climatic changes which is characterized by decrease of precepitation. Serious water shortage occured many times in the past as the dam storage descend below the intake limit.

On the other hand, new towns are under development in the outskirts of formed towns in El Alto district where are receiving above mentioned water supply system. The people who are living in the new town area are, recieving daily water only by water tank lorry.

3. PROJECT AREA

The project area covers about 700 km2 including the proposed water supply area of about 70 km2 of El Alto district in La Paz city.

4. OBJECTIVES OF THE STUDY

The objectives of the study are to evaluate the possibility of the groundwater recsource development of El Alto district in La Paz city and to perform transfering of groundwater development technology to Bolivian Government personnel in the course of the study.

5. CONTENTS OF THE STUDY

The study consists of two phases: Phase 1 in rainy season, Phase 2 in dry season. Contents of the each study were as follows:

Phase 1 study
- Field Works
  - Field Reconnaissance Survey
  - Collection of data
  - Inventory on existing wells (43 wells)
  - Electric exploration (64 points)
  - Observation of groundwater level
  - Observation of surface water
  - Soil and water Sampling
- Home works
  - Water quality test
  - Soil mechanical test
  - Preparation on simulation of water balance analysis
  - Formulation of the phase 2 study

Phase 2 study
- Field Works
  - Pumping test (3 wells)
  - Observation of groundwater level
  - Observation of surface water
  - Soil and water Sampling
  - Cost investigation for construction works and materials

Home Works
- Water quality test
- Soil mechanical test
- Water quality test
- Tritium test
- Water balance analysis
- Plan for proposed facilities
- Rough cost estimation
- Evaluation on the project

6. RESULT OF THE SURVEY

The followings was clarified from the survey

Aquifers;

Groundwater intake from the Moraine layers should be preferable. Groundwater development area should be confined a triangle zone formed by Kalle Chuani on the north, Tacachira on the west, and Junthuma Pampa on the east.

Water Quality;

The northern part of the El Alto district, the area near Rio Seco, and the existing town area should be preferable for use. Deep well, which reaches to La Paz layer and intake from any area where groundwater begins to return flow, should not be preferable.

Therefore, well field should be proposed in consideration of above mentioned conditions.

7. WATER BALANCE

In oder to calculate obtainable quantity of groundwater, module for water balance in the El Alto district and its neighborhood was set up based on the collected data of hydrologic, meteorologic and hydrogeologic, and the result of field surveys. It was assumed that the groundwater flow and flow speed at the planned well point would badly be changed because the east side of the study area is formed a curved steep cliff. Therefore, computer simulation was carried out by the three-dimensional method taking the planer factors into account.

According to the results of the computer simulations, the groundwater level will be lowered by continued water intake year by year. This decrease of groundwater level was estimated as 25 m in 1995 and 35 m in 2000 at the well point, and it is assumed that a range of about 1.5 km from the well point is infuluenced in 2000. Therefore, in consideration of these conditions, the annual obtainable quantity should be set up to insure the stable intake at least up to the target year of 2000.

The average thickness of the Moraine layer is about 80 m. Thus, by adding a well soil and sand retaining thickness of 10 m, the well depth will be taken as 90 m. The groundwater will be taken at 26,700 m3/day which is the target for 1995 from the well field in the south-east area of Rio Seco. It was resulted that water intake at 26,700 m3/day can be safe in total of 27 wells of 1,000 m3/day up to year of 2005.

8. PLANNING OF THE PROJECT

Planned Water Supply Population

Considering the natural population increase, domestic immigration measures for mine laborers, etc., the population of El Alto in 1995, the intermediate target year of this project, is assumed as 385,000, and in 2000, the final target year as 495,000, in El Alto district.

Planned Water Supply Quantity

The daily maximum water supply quantity is assumed as 155 lit/day/person for 1995, and 160 lit/day/person for 2000. Total quantity of supplying water is totally assumed as follows:

1995	26,700 m3/day
2000	46,200 m3/day

9. DRAFT PLAN FOR THE PROJECT

The area, where groundwater development can be done in El Alto district, is 22 km in total of about 12 km on the south-east side of Rio Seco and 10 km on the north-west side from the hydrogeological conditions.

Considering from the water balance and technical feasibility of groundwater development, the obtainable water intake quantity is 30,000 m3/day on the south-east side and about 25,000 m3/day on the north-west side.

10. PLANNED FACILITIES

The major proposed facilities are as follows:

Water intake well
Water conveyance facilities
Pump station
Power recieving facilities
Construction machines and materials
Fuel for construction works

11. PROJECT COST

The Project is set up to carry out the work in two separate phases: the 1st phase up to the target year 1995, the second phase up to the target year 2000.

The cost of water intake facilities is estimated approximately as about Japanese-yen 1,800,000,000 for the 1st phase work and Japanese-yen 1,100,000,000 for the 2nd phase work.

The overall project cost is fixed by adding the cost of water distribution facilities to this cost of water intake facilities.

12. EVALUATION OF THE PROJECT

The project was evaluated socially, technically and economically, and environmental impact assessment was also carried out.

The wells proposed in the 1st phase on the south-east side of Rio Seco, including the existing water supply facilities, will supply water to the predicted dwelling popuration of 385,000. In addition to above mentioned facilities, the wells planned in the

2nd phase on the north-west of Rio Seco will be sufficient quantity for the water demand in 2000. However the water quality might be affected by the Milluni mines.

Existng water supply sources depend on the surface water which has already been sufficiently utilized. In oder to obtain newly water resources, dam construction or water conveyance from lake Titikaka by pumping is considered as a drastic solution. However, these are impossible by topographical and financial problems and infeasible from the point of veiw of prompt implementation.

On the other hand, groundwater development is rather economical for the construction and maintenance, and also its construction term is shorter than the above mentioned development. Accordingly, the project of ground water development is preferable for this area. In combination with the existing water supply system, the proposed water supply can be stable to this area throughout the year and useable as emergency measures for the entire La Paz area.

As a result of the evaluation, it can be said that the "Groundwater development project" is most recommendable to the said district. And the implementation of the project as promptly as possible will contribute much to the stabilization of poeple's life, which is one of the major targets of the gorvernment of Bolivia.

CONTENTS

1. Flow of Study

1.1 Preliminary Study

In response to the request of the government of the Republic of Bolivia dated June 23, 1986, it was decided to make a study to set up the groundwater development project intended to supply living water in the El Alto district of La Paz City, and prior to the final survey, field investigations, field data collections, and conference and signing for S/W were done.

The survey mission was headed by Mr. Hiroshi Matsutani of the Second Development Survey Division, Social Development Cooperation Department, Japan International Cooperation Agency (JICA) and was dispatched to Bolivia from September 29 to October 16, 1986. Based on the results of the field survey, conference for S/W was done with Servicio Autonomo Municipal de Agua Potable y Alcantarillado (SAMAPA), and an agreement was reached between both. Then, on October 10, in the vice-minister's room of the Planning and Coordination Ministry, the minutes of the meeting were exchanged between the survey mission and SAMAPA.

The major items of the conference for S/W are as follows.

① Study area

The study area shall be about 71.5 km^2 of the El Alto district less the airport area. The survey area shall be about 700 km^2 around the study area. (Refer to the location map.)

② Participation in the survey by Servicio Geologico de Bolivia

③ Geophysic prospecting

For geological survey, geophysic prospecting shall be done, and its method shall be electrical prospecting.

④ Tube top level survey and groundwater level observation of existing wells

The tube top level survey of existing wells for the groundwater level observation shall be done by the Bolivia side, and the guidance shall be given by the Japan side.

⑤ Preparation of survey vehicles

Regarding the vehicles (4-wheel driven vehicles) required for survey, those owned by SAMAPA are insufficient, and from consideration of the operating conditions, they shall be prepared by the Japan side.

⑥ Implementation in the future

In response to the question from the Bolivia side about the implementation after finishing of the final study, the Japan side suggested that, if the Bolivia side would request the implementation to the Japan side after finishing of the final study, there should be a possibility of consideration on it.

⑦ Power source for groundwater intake facilities

When the power sources for the water intake facilities are investigated in the study, both internal combustion engine and wind energy shall be taken up.

⑧ Time of study start-up

The time of study start-up shall be a time as early as possible in 1987.

1.2 Final Study

The final study consisted of the rainy season survey for 60 days from January 31 to March 31, 1987 and the dry season survey for 40 days from July 1 to August 8, 1987.

The implementing body of this study on the Bolivia side is SAMAPA. The organization of SAMAPA is shown in Annex 16. The head of the organ is the mayor as shown in the chart, but the substantial head is the Gerencia General (general manager). The engineering department has 8 senior engineers specialized in hydraulics, sanitation, electronics and mecahnical engineering, and nearly 20 middle class engineers alloted in the department. There are about 400 laborers engaged in the construction work. Moreover, there are two chemists in the central test room and each 1 middle class chemist in each water purification plant.

In this study, the Gerencia Technica and the Dpto Planificacion were the responsible persons for the counterparts. The counterpart for geology, groundwater and electrical prospecting was undertook by SAMAPA and GEOBOL. The organization of GEOBOL is as shown in Annex 17. Moreover, water level surveys of the tube top height for water level measurements of existing wells, and the ground height at electrical prospecting points were made by SAMAPA.

2. Survey Area

The study area is the El Alto district situated on a plateu west of La Paz City. This area has the El Alto airport, and its neighborhood is surrounded by the dwelling land developed in the 1970s. Further on the outside, new dwelling lands developed recently have extended. The study area is about 70 km^2 except the airport. The evaluation of groundwater resources, made in the final study, was carried out for the survey area.

The survey area is about 660 km^2 extending west of the study area, and its most part belongs topographically to a plateu. This area was set up in order to grasp the geological, groundwater, hydrological and other natural conditions of the study area. In this area, houses are scattered. Most of the area is unutilized, and only a small part is agricultural field. However, the ability of agricultural production is low because of poor irrigation and gravel-riched soil. Especially, in the dry season, the surface water mostly infiltrates underground, and cannot be utilized for irrigation. Therefore, that part of the survey area, which has been developed in a comparatively large proportion, is only the southern part near Viacha.

2.1 Topography and Geology

The survey area corresponds to the peripheral part of Altiplano and presents a very slowly sloping topography which is at about 3,900 to 4,200 m altitude for the most part. Roughly speaking, this area is divided into three areas by the steep cliff east of the study area and the road extending from El Alto towards west: valley area, mountain foot easy slope and mountain area, alluvial plain (plateau plain).

As to geology of the survey area, the base consists of Catavi strata of the Paleozoic Silurian period, covered with distributed tertiary La Paz strata, quaternary glacier-river deposit unsectioned strata, and glacier deposit strata, etc. The Catavi strata show the geological structure in the north-north-west to south-south-east direction and are not exposed in the La Paz town area. From these features, it is estimated that these strata are distributed at depths of 500 to 600 m or more in the El Alto district. The La Paz strata consist of fine sandy rock and silty rock mainly, and show a nearly horizontal geological structure. The quaternary strata are mainly gravel layers, and there are partially sand layers and clay layers included in them. The glacier-river deposit unsectioned strata, exposed to the earth-cut surfaces of Auto Pista, are comparatively consolidated, but the glacier deposit strata and alluvial strata over them are generally loose.

2.2 Meteorology and Hydrology

The northern plateau, including the El Alto district, belongs to the river system basin flowing out into Lake Titicaca. In these river systems, rivers Khullu Cachi, Sehuenca, Huancase, Seco, etc. flow out from the northern mountain areas towards south-west. Nearly all of these rivers combine with Rio Castari at their downstream, and then flow out into Lake Titicaca. The hydrological conditions of the plateau have the following features.

- Water systems from northern mountains towards south-west

  The water of rivers origanates in the glacier of the mountains, thawed water of perpetual snow, and rainfall, and the water quantity of river is stable throughout the year. However, in the plain area, the surface water infiltrates underground, and as a result, marshes dry up.

- Water systems towards north-west

  The direction of rivers is affected by the geological structure of tertiary strata or palaeozoic strata. The water of rivers in this area originates in rainfall and groundwater, and the water quantity of rivers is also stable throughout the year.

The amount of rainfall and evaporation is being observed by SAMAPA at Mulluni, Tuni, Condoriri, water reservoirs, etc.

The precipitation in the plateau is generally high in the northern parts and decreases towards south (above 700 mm/year in the northern mountain areas and about 550 mm/year in the southern parts). The amount of evaporation is 100 to 130 mm/month.

2.3 Water Supply Systems

At present, water supply in the El Alto district of La Paz City is implemented by SAMAPA. The water supply system of La Paz City consists of three systems: El Alto, Achachicala, Pampahasi. Each system is supplied water from dam which stores the surface water, and each system is as follows.

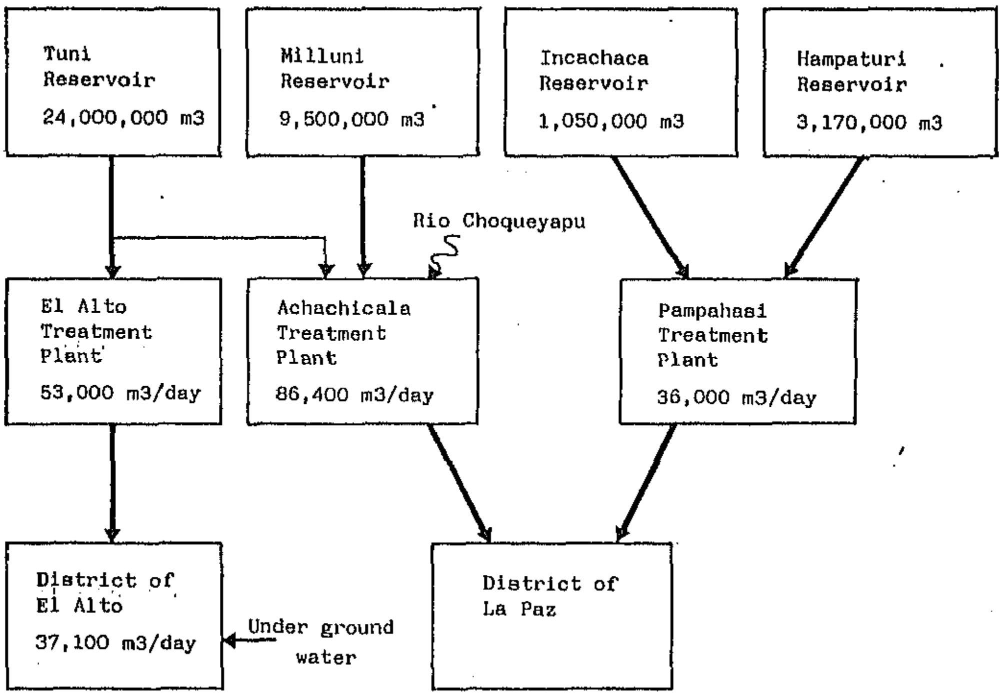


Fig.2.3-1 Water supply system of La Paz City

The water system, which is related to the study area, is the El Alto system. The other systems supply to La Paz City. In the area where the distribution pipes are unfurnished, the drinking water is available by private wells, springs and water tank lorry.

The La Paz district is supplied water from Achacicala, Pampahasi, and El Alto treatment plant. However, the quantity of water supply is insufficient. In a part of the district, water supply is time-restricted, and other parts are not supplied water.

The raw water to the Mulluni storage reservoir is affected by mine waste waters and has poor water quality, and in order to purify this, much electric power and chemicals are used. These costs press the finance of SAMAPA, so that SAMAPA has no allowance to invest money into new undertakings. Moreover, river waters flowing into four storage reservoirs have already been sufficiently utilized. In the present condition, if any attempts were made to construct new storage reservoirs so as to increase the water storage capacity, or further to increase water sources, they would involve large undertaking costs. From the present economic state of Bolivia, these attempts could not be realized immediately. Threfore, in El Alto district, the development of groundwater is only an efficient measure to solve the problem of water shortage caused by the rapid increase of population.

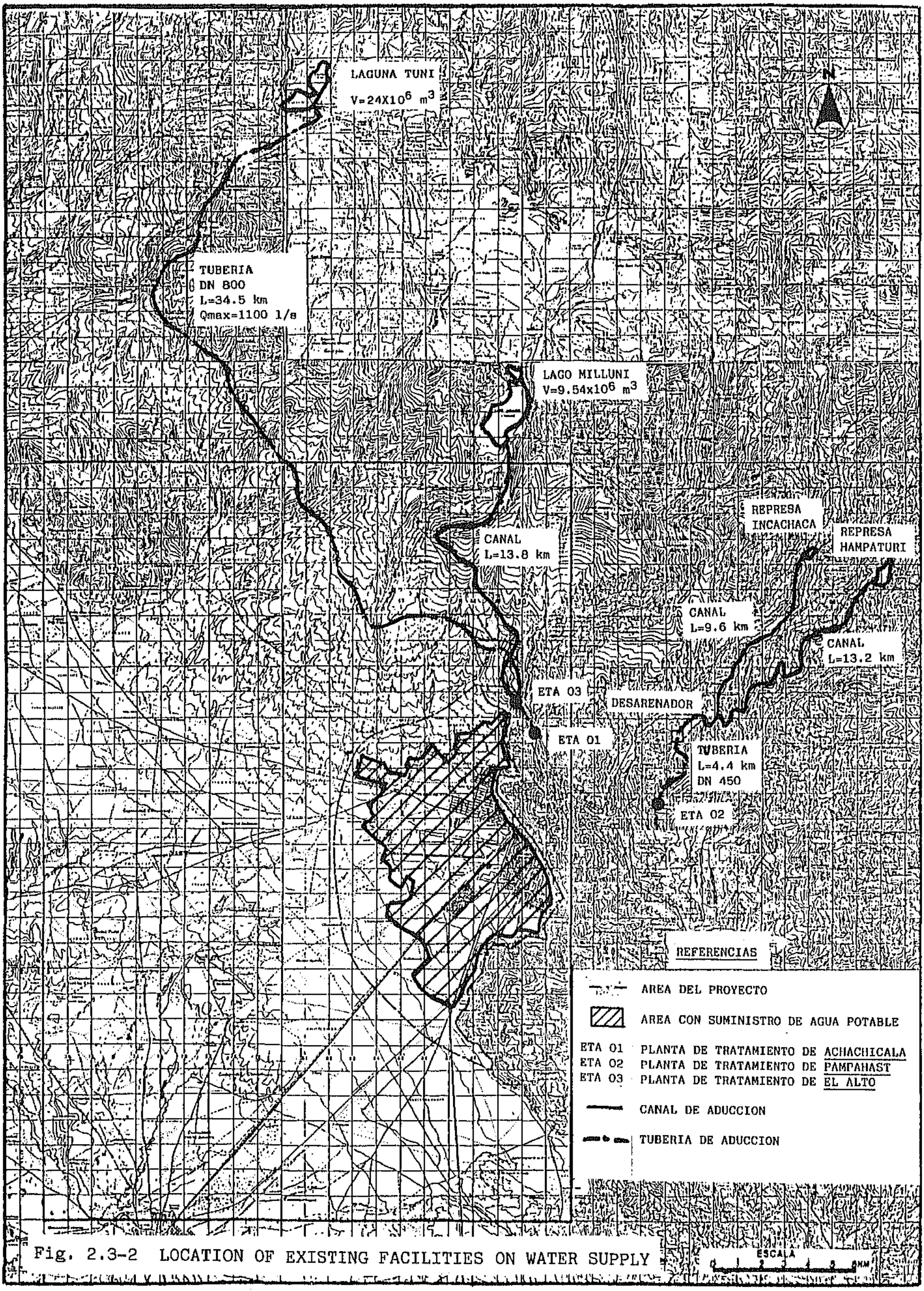


Fig. 2.3-2 LOCATION OF EXISTING FACILITIES ON WATER SUPPLY

2.4 Existing Groundwater Utilizing Systems

Regarding the groundwater survey at the plateau including El Alto district in the survey area, GEOBOL investigated on the groundwater resources in the northern plateau and Oruro in cooperation with UNDP (United Nations Development Plan) and published "Los Recursos de Agua del Altiplano Norte y del Area de Oruro". This report describes the topology, geology, water quality, and the potential of the groundwater development in this area. According to the conclusion of this report, this area has a high feasibility of groundwater development.

GEOBOL constructed about 40 deep wells in El Alto district based on the results of above-mentioned report. However, GEOBOL has not yet had adequate technical capabilities regarding groundwater development, and for example, it was experienced many times that after completing of wells, the expected water quantity could not be secured, or for the water quantity available, the well life was short. Therefore, it cannot but be judged that GEOBOL cannot accomplish planning groundwater development based on a long-ranged view.

For these reasons, it is significant to transfer the technology on the groundwater development to Bolivia through this study.

3. Results of the Survey

3.1 Topography, Geology and Hydrogeology

3.1.1 Topographical and Geological Survey

The topographical and geological survey was made by investigating the ground surfaces by reference to existing topographical maps (1/50,000) and geological maps "La Paz" (1/100,000, 1967, Bolivia Geological Research Institute). Especially, outcrops in the steep cliff which demarcates the eastern edge of the study area were surveyed, and the geological map (Fig.3.1.1-1) and the geological profile (Fig.3.1.1-2) have been prepared.

The survey area is a flat plateau at about 4,000m altitude, and the La Paz Town area develops in the valley of River Chakuabu formed on this plateau. Regarding geology, the base consists of the Paleozonic Silurian and Devonian strata, covered with the distributed Cenozoic Neogene tertiary Pliocene La Paz strata. The La Paz strata are exposed in the valley zone around La Paz City, and are generally fine sand-riched aquicludes. On the La Paz strata, the glacier deposits and the deposits by thawed and running water of the quaternary Pleistocene glacier period are distributed. Of them, the gravel layers, which are included in the glacier deposit unsectioned strata at the lowest level, form aquifers. The geological structure of the survey area is as shown in the Geological Map of the El Alto District.

This map is slightly different from the La Paz neighborhood geological map, which was already published. But, it was prepared in consideration of the following points and in cooperation with Engineer Alfredo Soria of GEOBOL.

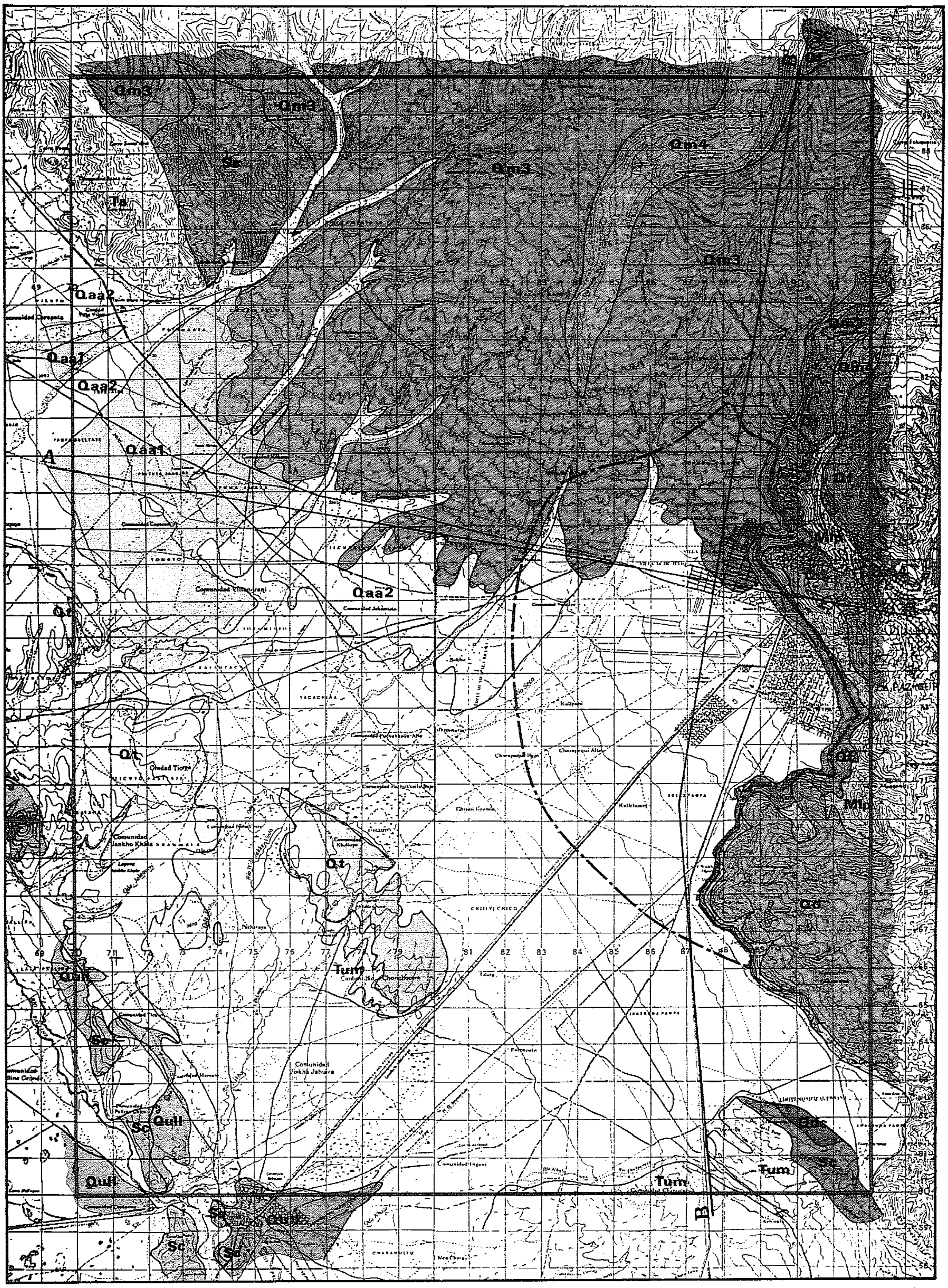
- o Study of existing data

  The existing data were studied to grasp the geological distribution, rock quality, geological structure and geographical outline of the survey area.
- o Observation of aerial photos

Aerial photos taken in 1987 were stereoscopically observed to grasp the topographical sections, collapsed areas, linearment, etc. of the survey area.

- o Survey of surface geology

On the main outcrops in the survey area, the rock quality, strike and dip structure, presence or absence of sectional areas, etc., were examined to prepare the route map. The important outcrops were reconfirmed by photographing.



REFERENCIAS

CUATERNARIO

Qa	Depositos aluvials
Qd	Deslizamientos de terreno
Qdc	Detritos y canchales
Qt	Terrazas
Qaa2	Abanicos aluviales modenos (2)
Qaa1	abanicos aluviales antiguos (1)
Qm4	Morrenas de la IV graciacion
Qm3	Morrenas de la III graciacion
Qf	Glacial y fluvio-glacial no diferenciado
Qull	Formacion Ulloma (Terrazas del antiguo Lago Bollivian, intercaloiones de arcillos, arenas, localmentz gravas y turva)

TERCIARIO

Tum	Formación Umala (Arcillas margosas y arenitos cremas con intercalaciones de tobas)
Mlp	Formación La Paz
Ta	Formación Aranjues (Conglomerados y areniscas rojas)

SILURICO

Sc	Formación Catavi (Alternancia de areniscas cuarciticas lutitas)

SIGNOS CONVENCIONALES GEOLOGICOS

A —— A´ Perfil geologico transversal

Fig 3.1.1-1 GEOLOGICAL MAP

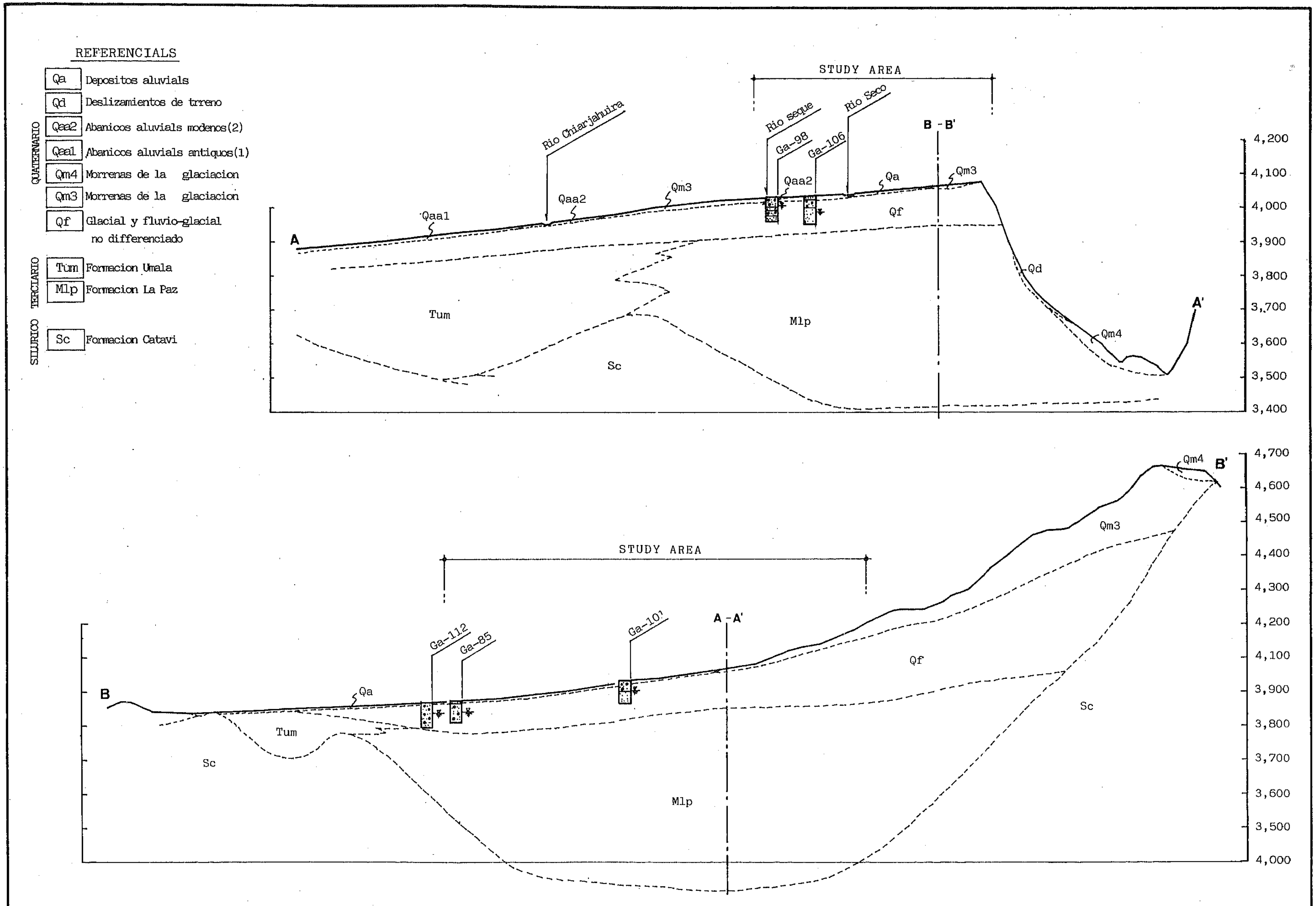


Fig. 3.1.1-2 GEOLOGICAL PROFILE (scale H=1:100,000 V=1:10,000)

3.1.2 Geophysic Prospectig

In the 470 km^2 area of east-to-west 17 km and north-to-south 28 km of the study area, electrical prospecting was done at 64 points.

The electrical prospector of low frequency square wave type having a prospecting depth of 200m was prepared by the Japan side, and was used to perform vertical prospecting by the Schlumberger 4-electrode method.

Current electrode interval:

2, 4, 7, 10, 15, 20, 30, 40, 50, 70, 100, 120, 150, 200, 300, 400(m)

Potential electrode interval:

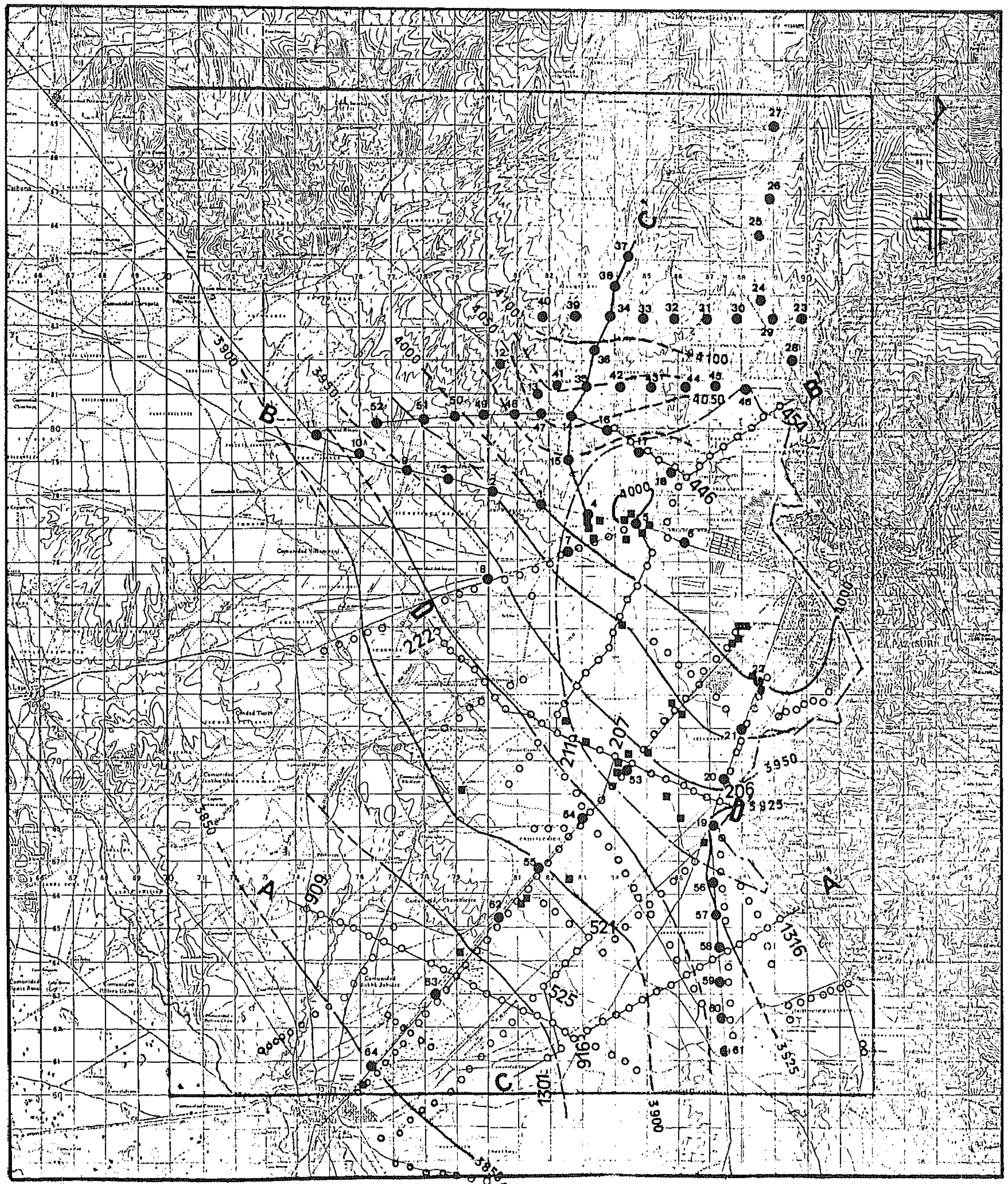
1, 3, 10, 25(m)

After the survey mission entered the country of Bolivia, they discussed with GEOBOL engineers and examined the related data. As a result, a detailed report could be found, which was prepared in 1977 by the joint work of GEOBOL and BRGM by performing electrical prospecting in the southern part of the El Alto district.

The southern part of the El Alto district has few existing wells. Since 1977, extensive developments had not been performed there. The results of field surveys indicate that there are little changes in the groundwater level between the value measured in 1973 and the present value.

However, regarding the northern part, which is the groundwater supply source, no survey data are available. Therefore, it was impossible to grasp the groundwater level trends of the entire area of the El Alto district. The survey points were selected by discussion with GEOBOL engineers. As a result, it was decided to survey the northern part with priority in this study. Several points in the southern part were selected to measure in order to grasp the changes or differences from the survey results of 1977. The survey points by electrical prospecting are as shown in Fig.3.1.2-1.

It was expected that the groundwater level in this district was parallel to the slope of the ground surface. However, from the survey results, it was found that the groundwater level has nothing to do with the slope of the ground surface, and it is near the horizontal plane, although slightly higher in the El Alto district. Therefore, it is judged that this district is within the range of the groundwater basin with Lake Titicaca as its center.



LEGEND

● 40	ELECTRIC PROSPECTING SURVEY (1987)
○	ELECTRIC PROSPECTING SURVEY (1977)
■	EXISTING WELL
—4000—	CONTOUR LINE OF GROUNDWATER

Fig. 3.1.2-1 MAP OF CONTOUR ON GROUNDWATER

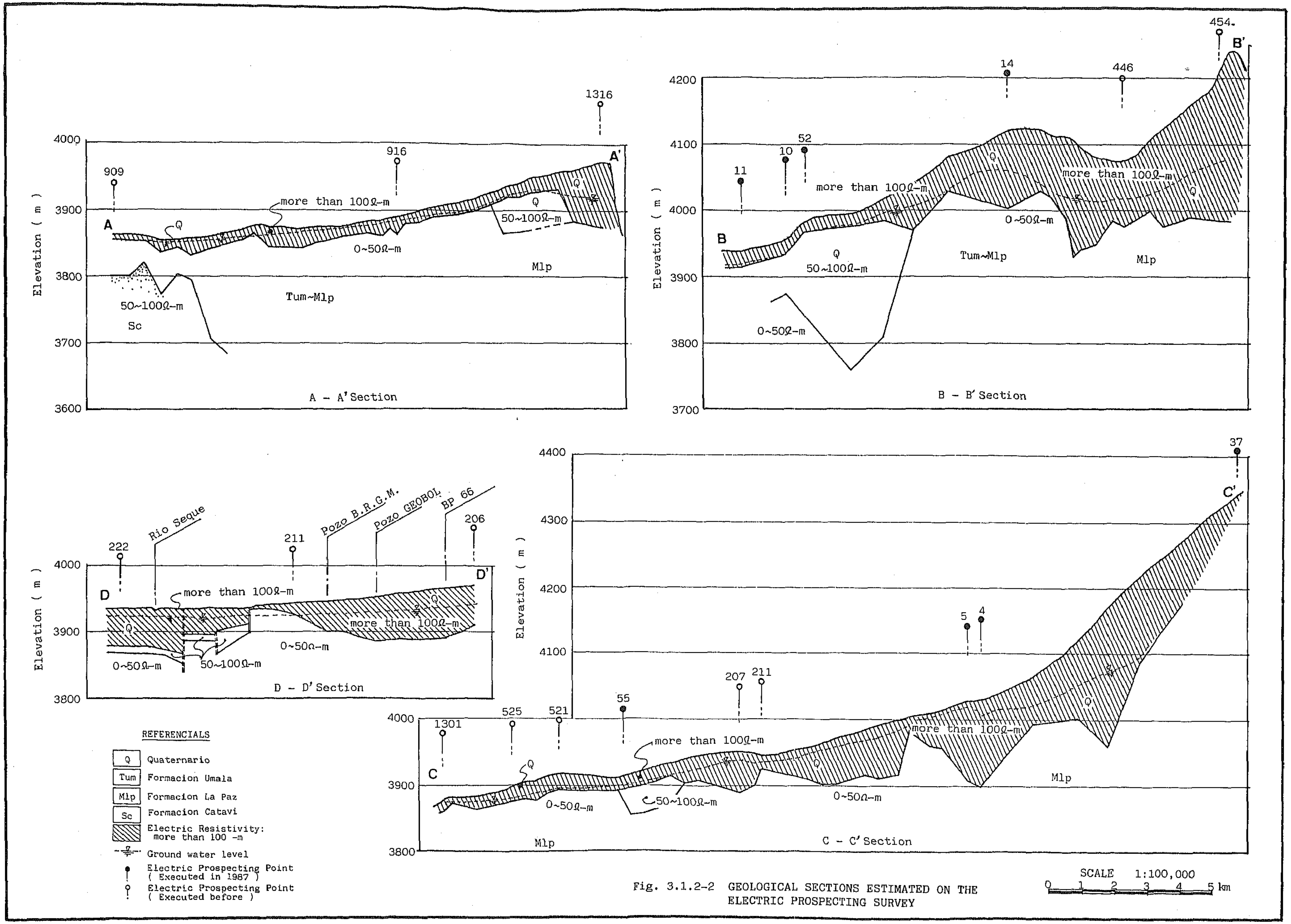


Fig. 3.1.2-2 GEOLOGICAL SECTIONS ESTIMATED ON THE ELECTRIC PROSPECTING SURVEY

3.1.3 Pumping Test

1) Purpose and Method of Pumping Test

The pumping test is conducted to obtain the permeability coefficient of the ground required to determine the proper pumping quantity of a well. The pumping test may include step drawdown test, aquifer test, group well test, etc., and in this study, the step drawdown test was conducted to obtain the permeability coefficient of the aquifer.

In this method of test, the pumping quantity is divided in several steps, pumping is continued for a certain time until the water level stabilizes, and by repetition of this work a number of times, the relation between the pumping quantity and the water level decrease is obtained as a plotted graph. Usually, the obtained curve has an inflection point, and the pumping quantity corresponding to this inflection point is called "marginal pumping quantity". From the merginal pumping quantity, it is possible to find a pumping quantity, for which pumping can be performed for a long time wihtout disturbing the water balance in the groundwater basin of the well, that is, the safe pumping quantity. The pumping test was performed at existing wells. If the capacity of the aquifer is in excess of the test pump capacity, the curve does not show any inflection point, and the marginal pumping quantity cannot be obtained. However, even in such a case, the permeability coefficient can be obtained. Therefore, by making use of the hydraulic parameters obtained by this test, it will become possible to calculate the pumping quantity on assumption of the bore of the well to be planned, and taking into account the planned intake quantity, specific capacity, etc., to suppose the bore of the planned well and the capacity of the test pump.

2) Preparations

Selection of existing wells for pumping test:

Before commencement of the test, the existing wells at the site were examined. The wells to be selected for pumping test should be determined from the hydrogeological and water quality fluctuations, and also taking into account the general precautions given below.

General precautions in selecting wells:

- o The groundwater surface should not be too shallow.
- o A space as wide as possible should be available.
- o As remote from water channels, lakes and marshes and banks, as possible and easily drainable.
- o There should be no pumping well in the neighborhood.
- o Electricity should be easily available.

The site examination indicates that all the wells are owned by private or juridical persons, and the wells for which the pumping test can be done were seven shown in Table 3.1.3-1.

Table 3.1.3-1 List of wells for which the pumping test can be done

Well No.	Owner ship	Dia	Depth	Water Level	Supply of Electricity	Pump	Conditions of Function	Execution of Pumping Test
22	INFOL	8 5/8"	52m	−12.9m	○	○	△	○
29	CENACO	6 5/8"	64m	−19.4m	○	−	○	○
31	INSA PP-1	8 5/8"	62m	− 9.0m	−	−	○	
38	CORDEPAZ	8"	48m	− 1.7m	−	−	○	
39	SAMAPA	6"	40m	−13.3m	−	○	○	○
41	AASANA	8"	53m	− 2.4m	−	−	△	
42	CONVIPET	6"	60m	−25.0m	○	−	○	

In the above table, well Nos.31, 38 and 41 are considered most desirable for the pumping test to grasp the characteristics of this area. However, for the reasons shown below, the survey at these wells was unavoidably given up.

- o This area has no electric power supply.
- o The generator prepared by the Bolivia side was operated at the site, but their capabilities were insufficient.
- o Generators owned by other governmental organs were checked, but all were insufficient in capabilities.

Well Nos.22, 29, 39 and 42 have commercial power supply, and of them, well Nos.22, 29 and 39 were selected for the pumping test.

Pumping quantity measuring equipment:

Generally, to measure the water quantity, 60^{o} notch or 90^{o} notch is used according as the water quantity. In this study, 90^{o} notch was used because of the capacity of the pump prepared by Japan side. And, in accordance with the design drawing brought by the survey mission, a notch box with a measure for each 1 lit/s was fabricated.

The formaula used for the measure is as follows.

$$Q = CH^{5/2} \qquad \text{---Eq.1}$$

were Q: quantity lit/s

C: coefficient 0.014

H: overflow depth m

Water level measuring equipment:

To measure the water level, the electric water level meter using a magnet bell, brought from Japan, was used.

Test pump:

Basically, the test pump, which is prepared by Japan side, was used. Necessary measures were taken, such as addition of seal water, and thread cutting of connecting pipes. Before commencement of the pumping test at the site, confirmations were made, such as pump performance test (at the El Alto purification plant), check of valve flow control, check of pressure gauge, check of circuit breaker for water level decrease, etc.

3) Observation Work and Its Procedure

The observation work was done at three wells: No.22 INFOL, No.39 SAMAPA, No.29 CENACO. At No.22 INFOL and No.39 SAMAPA, where pumps had been installed, the existing pumps were used, and at No.29 CENACO, the pump prepared by the Japan side was used. At both INFOL and SAMAPA, the sluice valve, pressure gauge, etc. were defective, and therefore, for the pumping test, the bend pipe, air valve, pressure gauge, and sluice valve, all prepared by the Japan side, were installed and used. The sluice valve was fully closed, and after confirmation of the pressure, the valve was gradually opened and closed. Both the water quantity and the pressure were observed using the notch. This procedure served to uniform the pumping quantity by valve operation.

INFOL

The observation work was done during holidays, because the factory was under contruction. On Saturday, reconnection of pipes, construction of drainage canals, removal of mud water, and preliminary observations were done. On Sunday, the pumping test was done for permitted hours. It was tried to remove the existing pump, but the well was just below the overhead water tank base and the pump could not be drawn up. Thus, unavoidably, it was decided to use the existing pump. In the preliminary observation, it was confirmed that the maximum pumping quantity by the pump capabilities was 5 lit/s. Therefore, in the final observation, the pumping quantity was increased by 1 lit/s from 1 lit/s until the final value of the maximum possible pumping quantity of the pump was reached. The recovery test should be done. The results of the pumping test are shown in Fig.3.1.3-1.

CENACO

The site is used as the national storehouses at present, and the pump has been removed and left on the ground. The test pump was installed, and a preliminary observation was conducted. Sludge drainage, cleaning and the preliminary observation were done at first, because the well has been unused for long time. The test pump was installed to the strainer position at a level 37m down. The lowest water level (37m) was the target, and the step drawdown test was done by the same operation as INFOL. The pumping quantity at about 37m was taken as the pumping quantity at the final step in the pumping test. The running water level at final step was 36.9m, and sand drained out was confirmed. The results of the pumping test are shown in Fig.3.1.3-2.

SAMAPA

Pipe connection works were done at that time. This well is located at a measure bed in the channel of Rio Seco. It was judged that the quantity of influent fine sand is smaller than in others. Inspite of the strainer being set at GL - 27m, the pump was set at GL - 30m. The step drawdown test was done by the same operation as other sites until the maximum pumping quantity for influent sand was reached. At the final stage, the pumping quantity was 4.21 lit/s, and the water level was -25.5m. The results of the pumping test are as shown in Fig.3.1.3-3.

4) Results of Observations

In accordance with the equilibrium equation for the full penetrated non-confirmed water well, the permeability coefficient of each well is obtained. The pumping quantity in the pumping test of each well was taken as the critical pumping quantity, and its 70% is taken as the proper pumping quantity in the calculation.

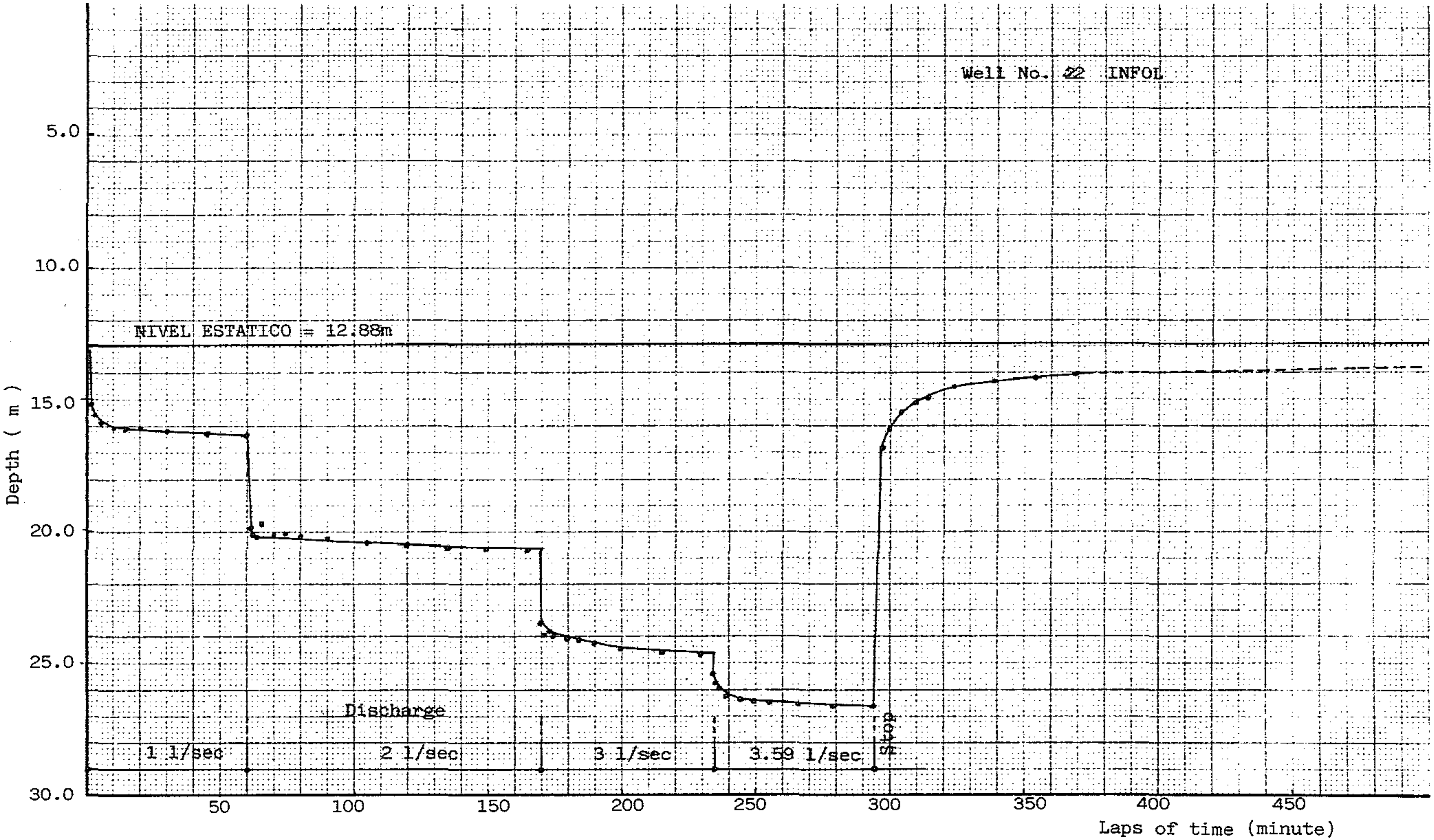


Fig. 3.1.3-1 RESULT OF PUMPING TEST (1)

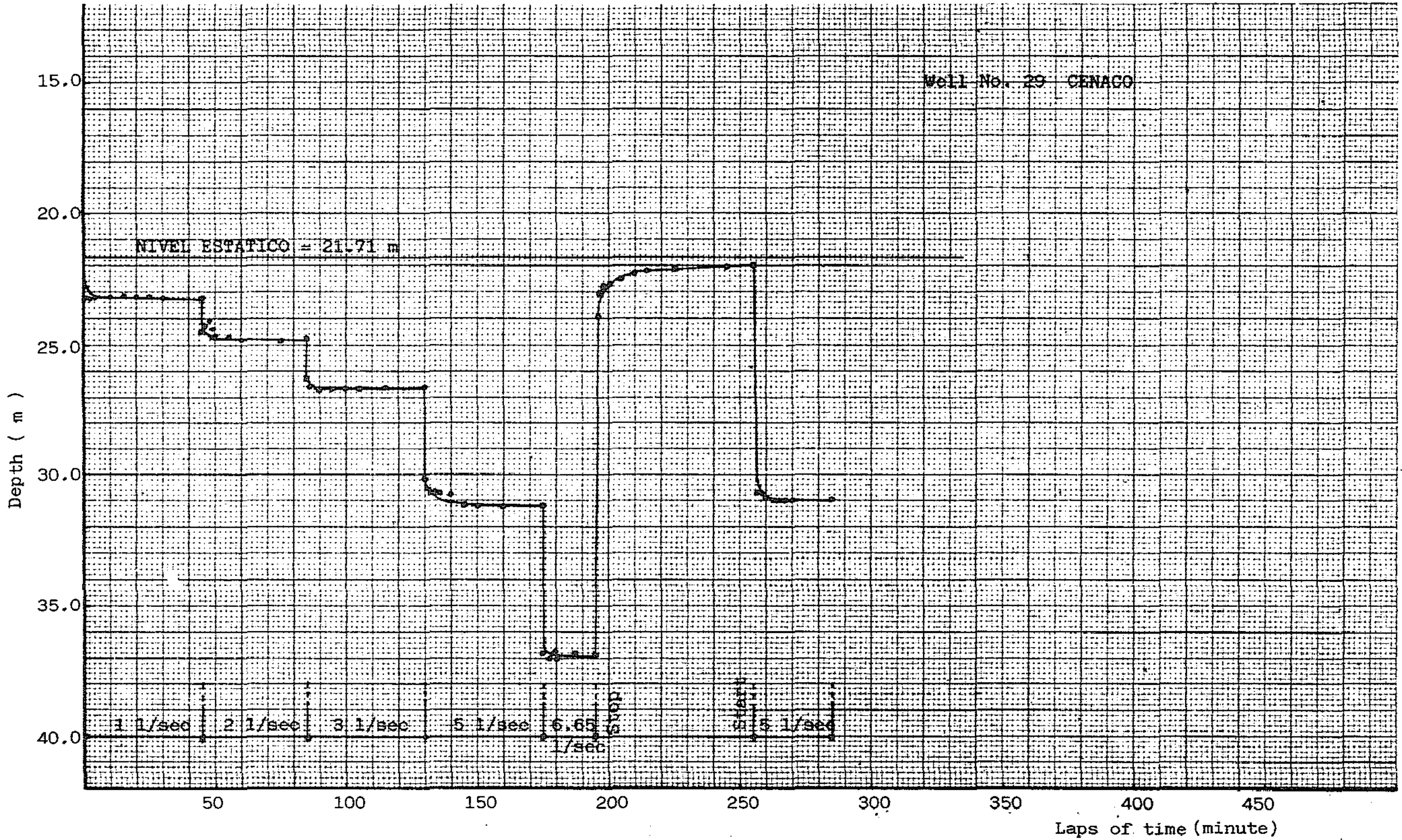


Fig. 3.1.3-2 RESULT OF PUMPING TEST (2)

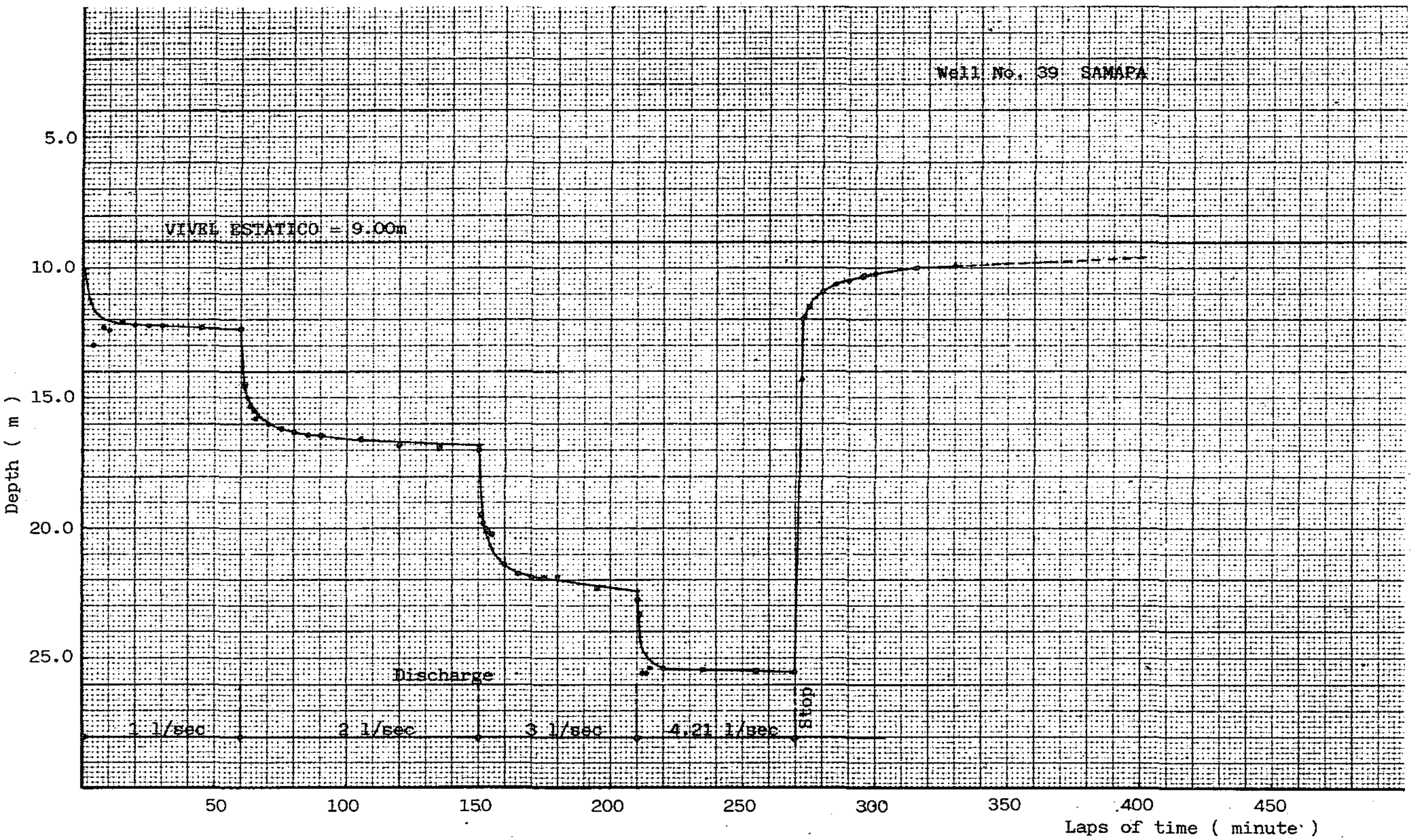


Fig. 3.1.3-3 RESULT OF PUMPING TEST (3)

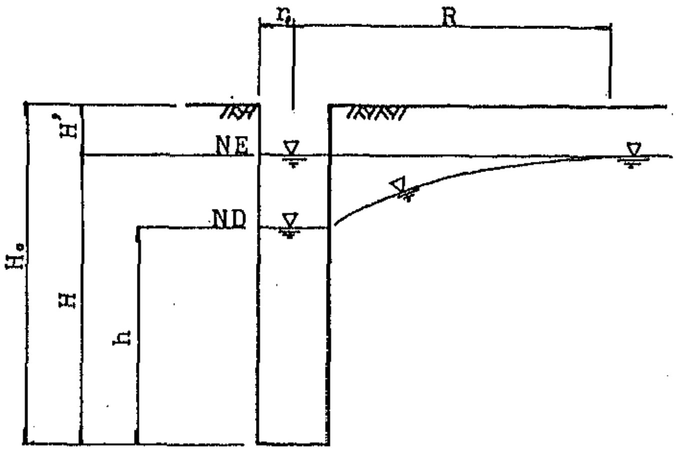


Fig.3.1.3-4

Equilibrium equation

$$Q = \frac{\pi k(H^2 - h^2)}{2.3\log R/ro} \qquad \text{---Eq.3}$$

where Q: pumping quantity (m^3/min)

H_o: well depth (m)

H': natural water level N.E (m)

H: depth of natural water level (m)

h: running water level N.D (m)

ro: well radius (m)

R: influence range radius (assumed as 400m)

k: permeability coefficient (m/min)

Well No.22

$$0.18 = \frac{3.14\ k\ (38.5^2 - 14^2)}{2.3\ \log 400/0.1} \qquad \therefore\ k = 0.3 \times 10^{-3}$$

Well No.29

$$0.3 = \frac{3.14\ k\ (41.9^2 - 10.7^2)}{2.3\ \log 400/0.08} \qquad \therefore\ k = 0.49 \times 10^{-3}$$

Well No.39

$$0.18 = \frac{3.14\ k\ (31^2 - 17.19^2)}{2.3\ \log 400/0.08} \qquad \therefore\ k = 0.7 \times 10^{-3}$$

The permeability coefficient is in a range of 0.3 to 0.7×10^{-3}, and its average value is 0.5×10^{-3} m/min.

Normally, regarding the deep wells for city waterworks, the pumping quantity of 1,000 m^3/day per well or more is taken as the target, by considering construction, maintenance and management costs. As judged from the results of the pumping test, it is considered that the wells to be developed in the future should have larger well depths and larger well bores than those of the existing wells.

However, in the norhtern part of the El Alto district, the pumping quantity was not increased even if the well depth and the well bore were increased. This is because, under the geological influences of mountains, the Moraine depth is about 70m and so, increasing the depth cannot be so effective. This is a point which agrees with the results of electrical prospecting. Therefore, in order to expect larger water intake quantities, it is desired to construct wells in the southern area where the Moraine depth is larger.

Example 1:

In the case of well depth 120m, water level decrease 20m and well bore 300 mm:

$$Q = \frac{3.14 \times 0.5 \times 10^{-3} \times (120^2-100^2)}{2.3 \times \log 500/0.15} = 0.853 \ m^3/min$$

Therefore, the pumping quantity per day is

$0.853 \times 60 \times 24 = 1,228 \ m^3$

Example 2:

In the case of well depth 120m, water level decrease 20m and well bore 300 mm:

$$Q = \frac{3.14 \times 0.5 \times 10^{-3} \ (100^2-80^2)}{2.3 \times \log 500/0.15} = 0.698 \ m^3/min$$

Therefore, the pumping quantity per day is

$0.698 \times 60 \times 24 = 1,004 \ m^3$

Therefore, when the new wells are to be planned, it is desirable to select the area where the Moraine layer of about 100m or more exists.

3.2 Meteorology and Hydrology

3.2.1 Meteorological Parameters

The meteorological and hydrological data have been observed at 5 places: Milluni, Tuni, Condoriri, El Alto, Aero Puerto. Data on the daily rainfall, daily maximum air temperature, daily minimum air temperature, and mean daily air temperature for 1982 to 1986 were obtained. (Refer to Annex 9.)

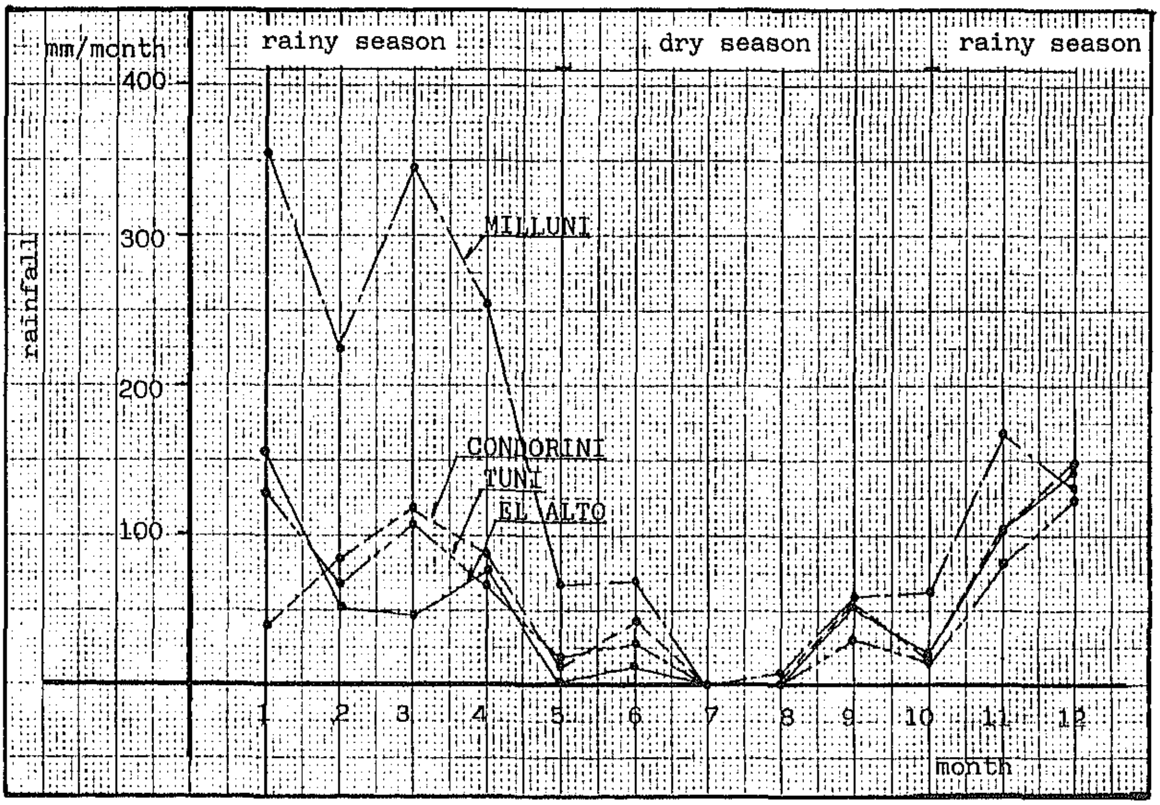


Fig.3.2.1-1 Regional mean annual rainfall (1985)

3.2.2 Observation of Groundwater Level

1) Method of Survey

Data Collection and Rearrangement:

GEOBOL has constructed most of the existing wells in the survey area, and the data necessary for the wells are available. Most of the existing wells constructed by GEOBOL are for factory use. The data for each well include the position, owner, year of construction, personnel, machines used, condition of execution, geological condition, casing and screen installations, and pumping test results, etc. The well inventory is based on these data.

Existing Well Survey:

The existing wells to be surveyed were constructed in 1974 to 1987. In order to know about the changes in the groundwater between the time of construction and the present time, the existing wells were surveyed based on the above mentioned well inventory. The survey items are as follows.

- o Present condition of operation
- o Pipe diameter and kind of pumping pipes
- o Static water level, running water level and water level decrease
- o Pumping quantity per day
- o Operation time per day

Tube Top Level Survey:

On the existing wells, which were selected from the provisional well inventory, the tube top level survey of the wells and the ground height was made. This survey was conducted by two teams of the members of SAMAPA survey and measuring departments.

Preparation of Well List:

The list of the following items, selected from surveyed items, was prepared.

- o Well No.
- o Static water level (altitude)

- o Static water level difference between the time of construction and the present time
- o Well bore
- o Well depth
- o Possible pumping quantity at the time of construction

2) Rainy Season Survey

The present static water level was measured to analyze the recharge mechanism, by observation of water levels at the existing wells.

By the recovery test, it was confirmed that the static water level was recovered after the lapse of 1 hour from stopping the motor, and therefore, the water level was measured on those wells which had been not in operation and those which could be kept at stop for more than 1 hour. On the last day of holidays, the water level was measured in any factory into which entry was permitted, and it was confirmed that there was no change from the water level which was obtained after about 1 hour of stop.

The items which were clarified through the rainy season survey are as follows.

① In the area where the well interval is small, the static water level decreases year by year and produces mutual interference.

② In the area where the well interval is large and the pumping quantity is small, the groundwater level is little changed from the survey in 1973.

③ The results of recovery test and water level decrease observation indicate that the water level reaction time is short.

④ For the well bore, the pumping quantity is small.

3) Dry Season Survey

The dry season survey was made by quite the same technique as in the rainy season survey. In the central area of the El Alto district, the water level in the dry season is in the direction to decrease as compared with that in the rainy season, but in other areas, the values are approximately the same as those in the rainy season. The magnitudes and causes of the fluctuations for each area are as follows.

Central area of the El Alto District (crowded with factories):

This area is crowded with factories. The groundwater level decreased because of the increased water consumption in the dry season. The increased water consumption is caused by water supply for agriculture rather than operation of each factory.

Table 3.2.2-1 Groundwater level fluctuations in the central area of the El Alto district

Well No.	Name of Well	Fluctuation Range of Water Level※
5	LIQUID CARBONIC	−1.50
6	BERA BOLIVIA	+0.34
7	VASCAL	−0.04
24	CENACO	−1.55
27	IMBOLSA	−2.23
28	ARANDO	−2.31
	Total	−7.29
	Mean	−1.22

※ Comparing with the Water Level of the Rainy season

Areas other than the Central Area of the El Alto District (not crowded with dwellings):

In these areas, the water consumption is only caused by drinking and is small. The water level fluctuations caused by pumping are small. Therefore, the level difference of groundwater between rainy season and dry season is small.

Table 3.2.2-2 Groundwater level fluctuations in areas other than the central area of the El Alto district

Well No.	Name of Well	Fluctuation Range of Water Level※
2	FANVIPLAN	- 0.32
3	LABOFARMA	0.00
9	GEOBOL	- 0.06
8	HORMITABOL	+ 0.20
18	BAMVI	- 0.87
17	ELMEC	- 0.53
20	JABONES PATRIA	- 0.16
13	CONVIFAG	+ 1.24
10	Y.P.F.B.	+ 0.46
12	COVIMA	+ 0.69
31	INSA	+ 0.39
	Total	+ 1.04
	Mean	+ 0.09

※ Comparing with the Water Level of the Rainy season

4) Continuous Observation

In this study, the automatic water level recorder was installed at the well of GEOBOL into which entry of dwellers was not permitted, and the measurement of long-term water level fluctuations was started on February 25, 1987. This measurement was continued up to until July 31 when the dry season survey was completed. During this period, the recording paper replacement was done once a month by SAMAPA, and the measurement was interrupted twice by trouble occurrence. The results obtained are almost sufficient to achieve the purpose intended at the first.

Moreover, the daily maximum, mean, and minimum values were read from the measured graphs, and they were processed to prepare graphs and tables by means of the computer prepared by the Japan side. From the results, the following data were found.

Daily mean maximum water level

-13.74m on March 1 (rainy season)

Daily mean minimum water level

-15.34m on July 30 (dry season)

Daily fluctuation maximum value

0.76m on February 28

The normal static water level should have been measured, bcause this well was not in pumping. However, daily fluctuations are large and suggest that it is interferenced with other wells. Around this well, there are HORMITABOL well about 300m, and FANVIPLAN and LABOFARMA wells about 600m, upstream of the groundwater influent point. On the other hand, it is obvious that the daily mean water level is high in the rainy season and low in the dry season. These data can be used as the prediction check data for water balance analysis.

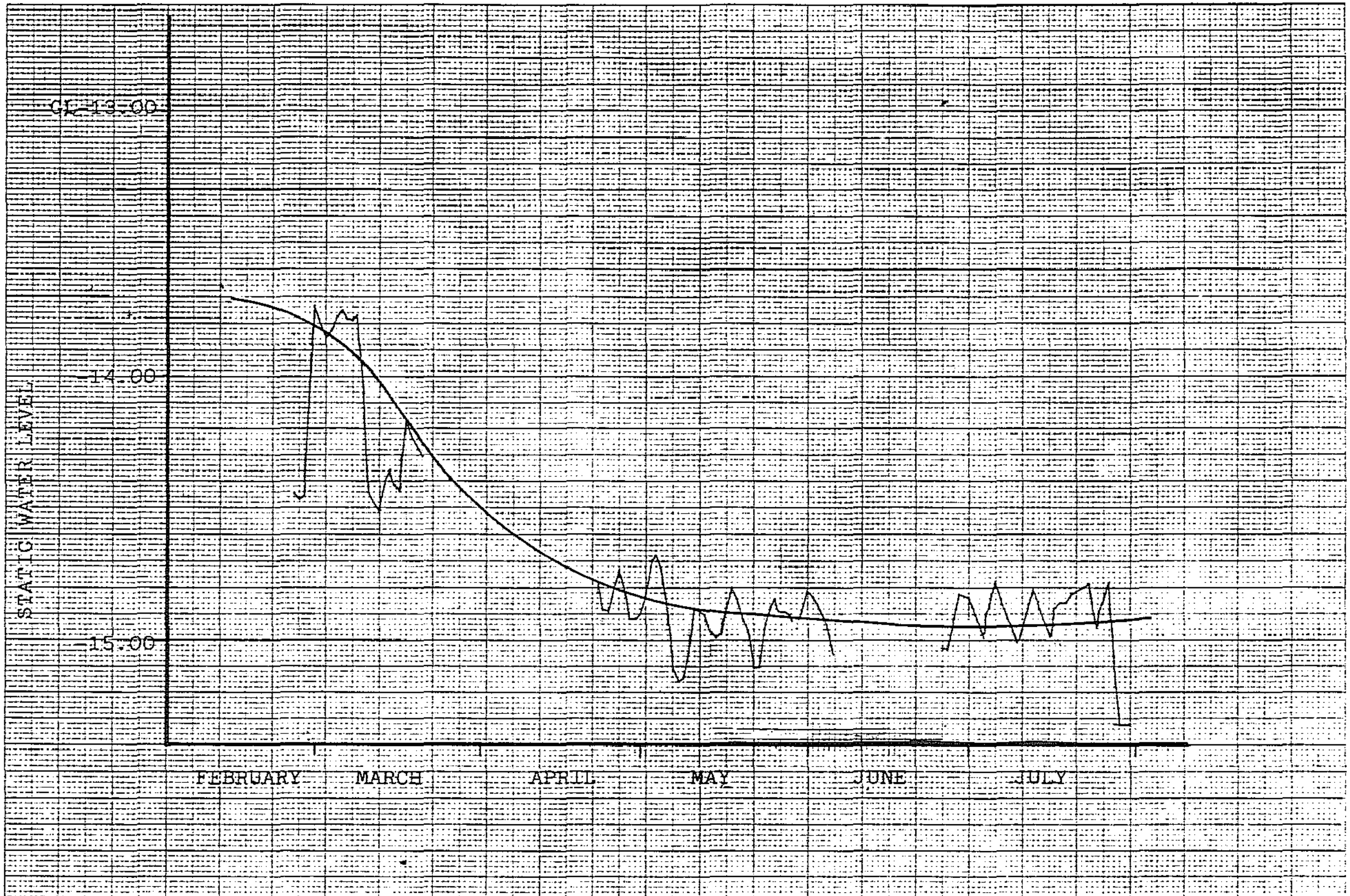


Fig. 3.2.2-1 RESULT ON WATER LEVEL BY AUTOMATIC WATER LEVEL RECORDER