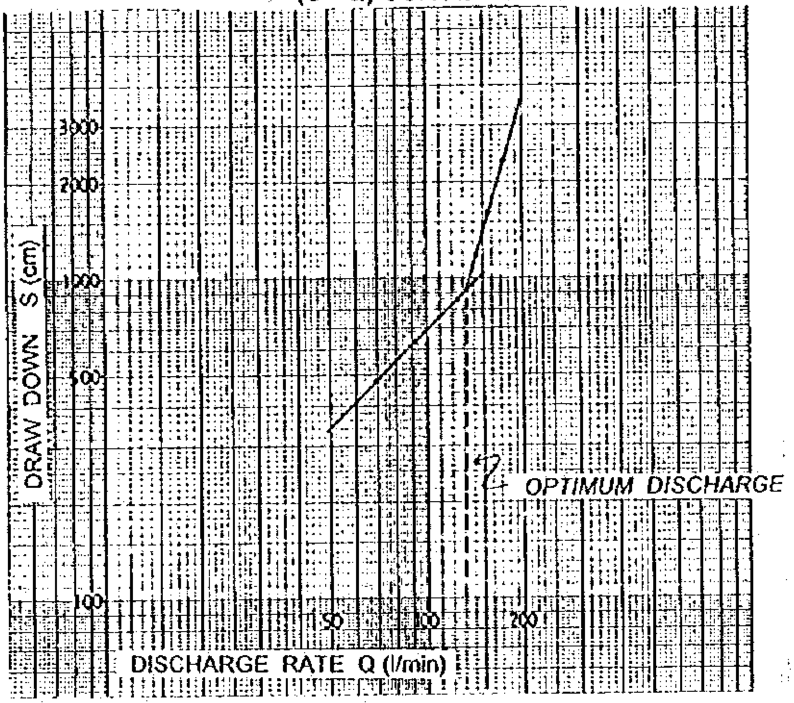
STEP DRAW DOWN TEST
(S - Q) CURVE



CONTINEOUS PUMPING TEST
(110 l/min)

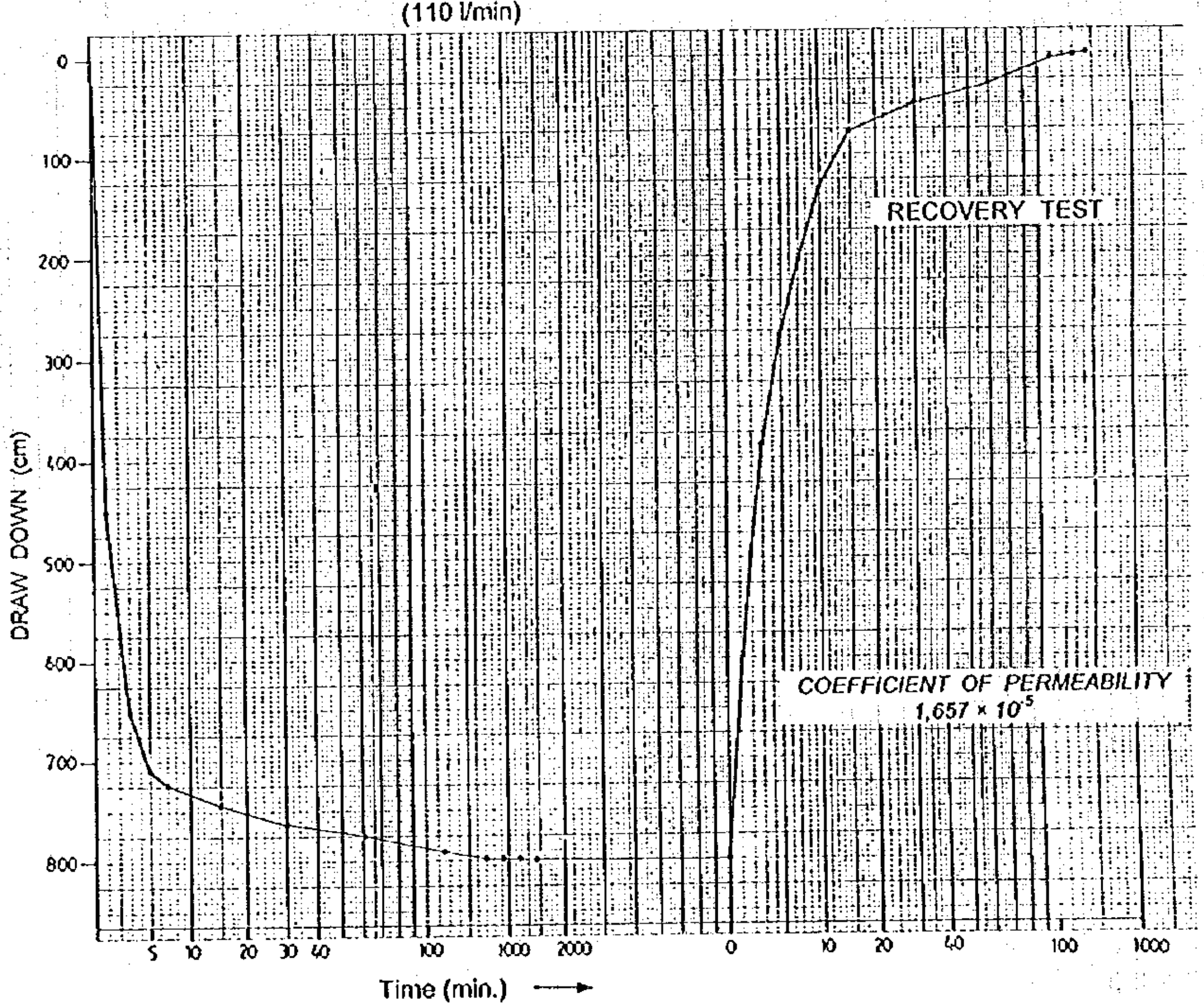
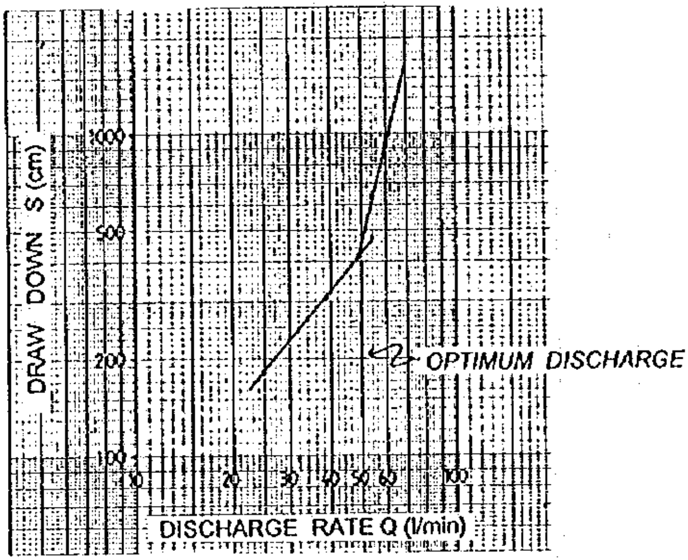


Fig. C. 2. 3 RESULT OF PUMPING TEST (1/4), TB - 2


STEP DRAW DOWN TEST
(S - Q) CURVE

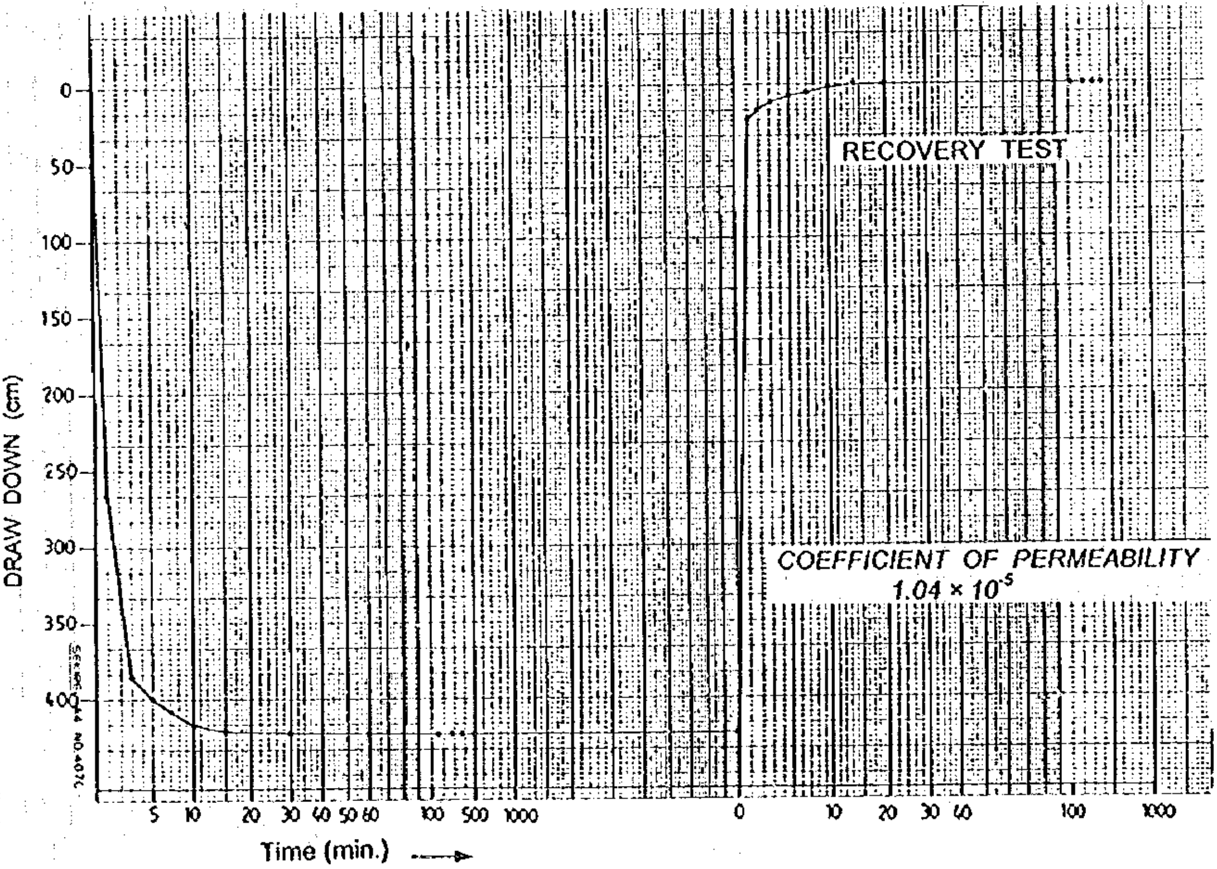
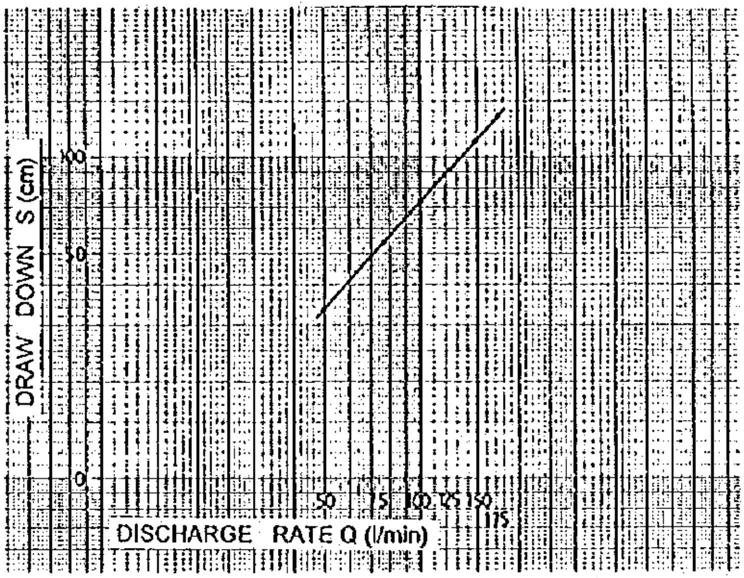

CONTINEOUS PUMPING TEST
(50 l/min)

Fig. C. 2. 3 RESULT OF PUMPING TEST (2/4), TB - 3

STEP DRAW DOWN TEST
(S - Q) CURVE



CONTINEOUS PUMPING TEST
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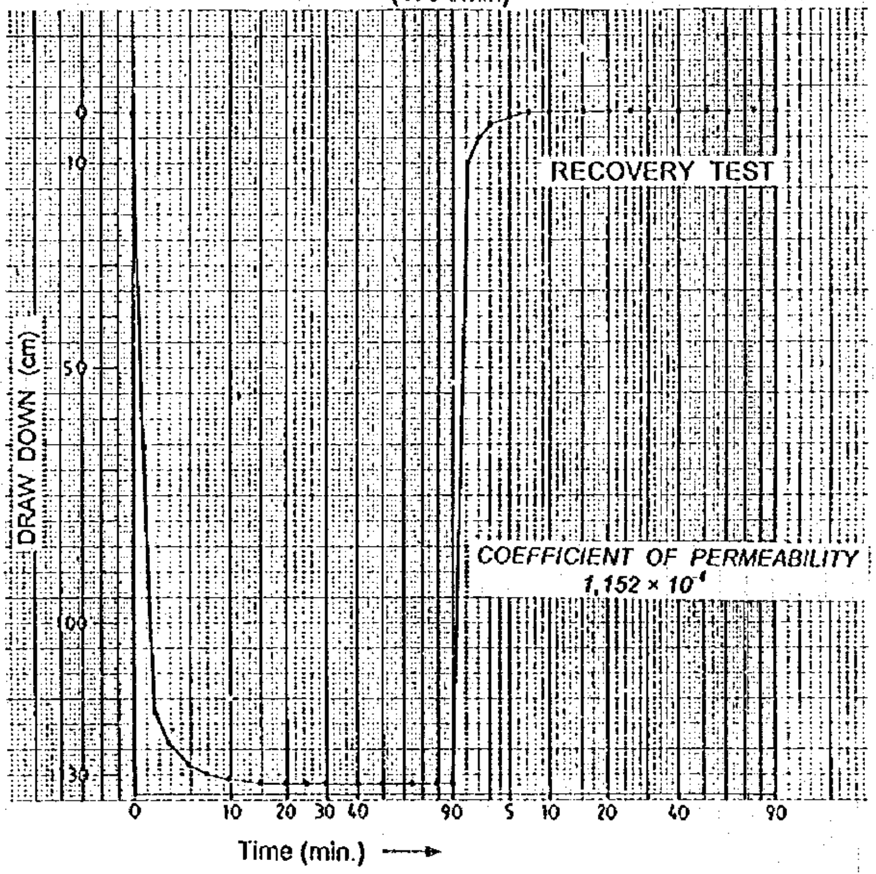
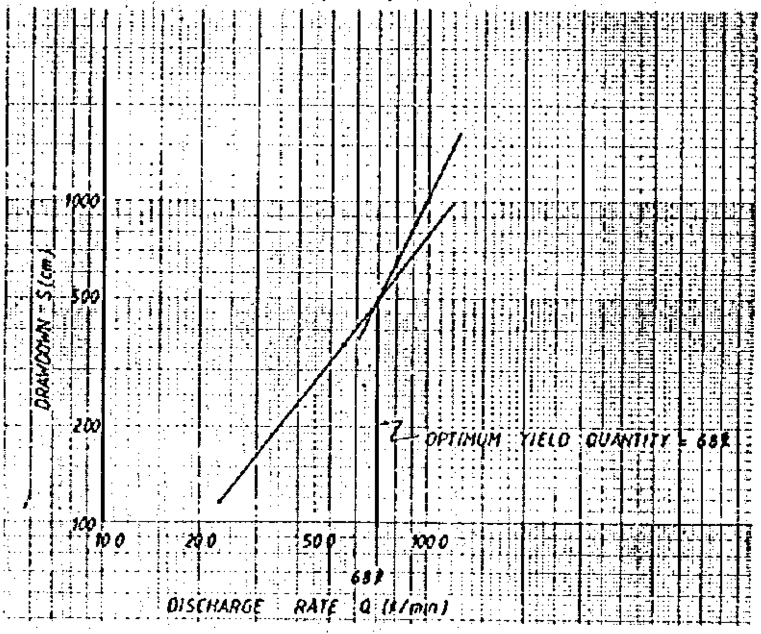
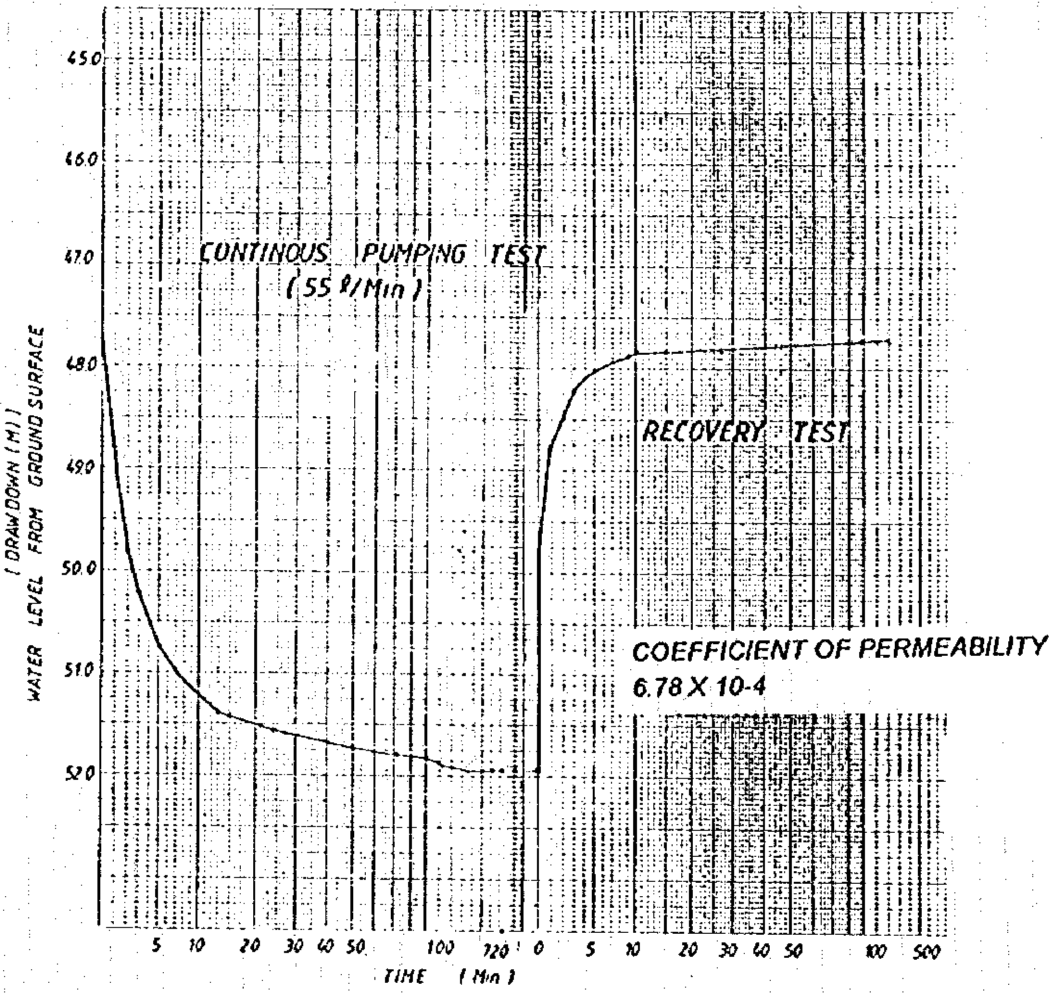


Fig. C. 2. 3 RESULT OF PUMPING TEST (3/4), TB - 4

STEP DRAW DOWN TEST
(S - Q) CURVE



CONTINUOS PUMPING TEST
(55 l/min)



COEFFICIENT OF PERMEABILITY
6.78 X 10-4

Fig. C. 2. 3 RESULT OF PUMPING TEST (4/4), TB - 5

APPENDIX D
GEOLOGY AND HYDROGEOLOGY

THE STUDY
ON
GROUNDWATER DEVELOPMENT
IN
WANGDUEPHODRANG DISTRICT OF BHUTAN

FINAL REPORT

VOLUME III: SUPPORTING REPORT

APPENDIX-D GEOLOGY AND HYDROGEOLOGY

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APPENDIX-D GEOLOGY AND HYDROGEOLOGY

D.1 PHYSIOGRAPHY

D.1.1 General

The land-locked mountainous kingdom of Bhutan constitutes an important segment in the geology of the Eastern Himalaya. It is flanked in south-west, south and east respectively by the states of Sikkim, West Bengal-Assam and Arunachal Pradesh of India and in north by Tibet. Bhutan is believed to have derived its name from the Sanskrit word "Bhutttan or Bhot-ant", the former means sudden rise in elevation, while the latter conveys the end of Tibet. For locals the name of this spectacularly beautiful country is Druk Yul --- Land of the Thunder Dragon.

Geometrically it is roughly an oval shaped country and lies between latitude 26°45' to 28°10' north and longitude 88°45' to 92°10' east. The east-west length is approximately 320 km and the north south width is about 175 km.

Bhutan is compartmentalized into different units by north-south flowing rivers. However, the terrain rises abruptly from the Indo-Bhutan border and reaches different elevations in different parts.

Elevation-wise Bhutan can be classified into three units:

- Southern foot hill region (South)

  The southern foot hill region lies at the edge of the Brahmaputra river basin. The Bhutanese part of the terrain is found mostly in the river fans which are delta shape after emerging from the mountains.

- Mountain and valley belt (Middle)

  In the mountain and valley belt where the study area is situated, nature has made deep gorges in the southern part and wide river valleys in the northern part like Paro, Thimphu, Wangduephodrang etc., of elevation 1300 to 2500 meters.

- Himalayan chain (North)

  The Himalayan chain lies in the north and forms an arc shape from east to west. Himalayan peaks as high as more than 7000 meters are found in this chain.

The attitude of the terrain controls the climatic pattern which varies from hot humid summer, heavy monsoon to pleasant winters in the south, pleasant summer, normal monsoon to moderately severe cold during winters in the middle part and pleasant summer, meagre monsoon and severe cold in the northern most and higher altitude terrain. The hills in the southern and middle parts rise up to an elevation of 3500 meters and support a thick forest cover.

The study area is accessible by the East-West Highway from Thimphu within three hours. Motorable all weather road other than the E-W Highway is the paved Punakha road running the right bank of the Chang Chhu, the main drainage of the area. Other graveled all weather roads branch out from the highway connecting villages to major towns.

In and around the study area, Wangduephodrang and Punakha are the only towns where the public markets are open once a week.

D.1.2 Regional Geomorphology (Fig. D.1.1)

The regional study on the drainage system in the Himalayan Mountains has revealed a distinct difference between the Nepal Himalayan and Bhutan Himalayan.

The pattern of the river system in Bhutan is that of the antecedent river system, which transverses and dissects the mountain range forming deep valleys. This pattern means that the mountain range, which was formed by the collision of the Indian subcontinent and Asian continent, is cut by rivers running toward the south.

It is interpreted that the river system has been keeping its flow course during the time of uplift causing the formation of deep valleys The reason for this phenomenon is that the uplift speed of the earth crust in this region has been relatively slow, therefore, the speed of the river erosion and dissect has been faster than the uplift speed.

On the other hand, the uplift speed of the earth crust in Nepal has been faster than that of river erosion and dissect, therefore, the rivers have been temporarily prevented their ways by the uplifted mountains, and several rivers have emerged forming a huge lake, then made a flow-out way. This type of topography is geomorphologically called "subsequent river".

It is readable from their drainage patterns that the uplift speed in Bhutan has been slower than that of Nepal. The mountains in Bhutan has many flat and forested areas on their tops, resulted from the slow uplift speed. Some of these forest areas situated over 3,500 meters above the sea level are under the deforestation.

These forests contribute to the water recharge system in the area, therefore the outskirts of the mountains are so productive as to that a rice crop is possible in high elevation areas over 2,500 meters.

The difference of the uplift speeds of the earth crust so significantly affects formation of their topography and vegetation. Accordingly, flat areas on the crests of the mountains are common, and forests are distributed in such crests areas up to the elevation of 4,000 meters. These forests are composed of needle-leaf trees. The mountains in Bhutan show significantly different landscapes from those in Nepal, naked steep mountains.

D.1.3 Geomorphological Study

Topography of a certain area is a product of its land-forming geological history, that is the sum of the amount of movement (uplifting) of the earth crust and the amount of deposition or erosion. Accordingly, it is necessary to study a large area including a whole uplifting unit, rather than to study a small area including only small-scale topographic units.

Following geomorphological maps have been prepared in the survey.

Drainage system map	1 to 50,000 and 1 to 10,000
Geomorphological land-classification map	1 to 50,000 and 1 to 10,000
Summit level map	1 to 50,000
Relative relief map	1 to 50,000
Drainage density map	1 to 50,000

These maps have been made for the studies of geological structure and geological hazards as well as hydrogeology.

(1) Drainage System Map (Fig. D.1.2)

Drainage system map shows the distribution of the present erosion energy, and include general information which should be regionally interpreted at the first stage. The most predominant physiographic feature in the study area is the Chang-Chhu River following down to the south-south-east (SSE) and forming river terraces on both banks of upper reaches of Wangduephodrang and steep gorges in the down stream. All streams in the study area are tributaries of the Chang Chhu. Major tributaries in and around the area are Dang Chhu and Limti Chhu on the left bank, and Nabe Rongchhu and Tabe Rongchhu on the right bank. The Dang Chhu has its headwaters in the mountain area about 5000 meters high located around 27°45'N and 90°15'E. The river flows to the south and gradually changes its course to the west to join the Chang Chhu. Limti Chhu originates its course near Limkha village which is situated about 10 kilometers north-north-east of the Bajo sub-area. The river flows down to the south-south-west and joins to the Chang Chhu near Bajo. The Tabe Rongchhu rises in the mountain area that is east of the Doche-La, and flows roughly to the east to join the Chang Chhu at the Lobeysa. The Nabe Rongchhu approximately flows due east from the mountain pass of the ancient main trail to Thimphu, and joins the Chang Chhu at around 2 kilometers south of the Wangduephodrang bridge. Tributaries on the left bank generally flow down to the south-west while the tributaries on the right bank form west-to-east streams. The pattern of the river system of these tributaries is mostly dendritic which generally indicates homogeneous and compact underlying rocks. There are some limited areas of a parallel drainage pattern which indicates loose and inclined geological formations in some degree. (Drainage System Map) The mountain area is generally very steep forming many landslides throughout the area. The flat land or gentle sloped land in the elevated area has mainly resulted from landslide or mud-flow debris. As a topographic element, two beautiful cuesta are observed on the left bank of the Chang Chhu, Talo Gonpa questa on the north bank of the Tabe Rong Chhu and Khujula Gonpa cuesta on the north bank of the Nabe Rong Chhu. Both of the cuesta are in the area of highly foliated rocks dipping roughly to north-east causing the north-east inclined gentle slope and very steep slope facing to the south-west.

(2) Geomorphological Land Classification Map (Fig. D.1.3)

Since the geomorphology is the product of geo-historical processes such as weathering, erosion, deposition, landslide and so on, careful study on the geomorphology may reveal the geological history of the area. Using the air-photograph and the topographic map of 1:50,000 and 1:10,000, the Geomorphological Land Classification Map has been prepared by the following procedure.

- Delineate river bed
- Classify river terraces into high, middle and low terraces
- Delineate fan, colluvium, gentle sloped mudflow plane
- Draw erosion front line connecting the convex knick points
- Delineate the crest plane which may be a relict peneplane covered by thick soil and weathered zone formed during "interglacial warm period".
- Classify the slope into stable, active or other category

The geomorphological land classification map is the most important basic data for physiographic study on environment, geo-hazards, and land utilization. Many topographic relieves such as three levels of river terraces and fans along both sides of the Chang Chhu river exist in the area. In addition, the topographic reliefs such as peri-glacial planes and peri-glacial colluvium cause by glacial movement, landslide blocks, and mud flow zones caused by other factors are recognized on the map. Other topographic characteristics recognized in the area are flat crests on the tops of the mountains as a relic topography formed during the time being peneplane. Also it can be read from the existence of the convex knick point or erosion front on the both sides of the Dang Chhu and Tabelong Chhu rivers, that an abrupt uplifting occurred in the recent geological age.

(3) Summit Level Map (Fig. D.1.4)

A summit level map is a hypothetical topographic map, for which contour lines are drawn by connecting summits and ridges as if the small valleys and depressions are completely buried and filled up. Heights of mountains represent the final results of uplift movement and erosion in those areas. The amount of erosion on the height of the mountains is negligible in areas having flat crests on their mountain tops as a relic of uplifted peneplanes. Accordingly, it is interpreted that the relative height of the flat crests in the area represent actual amount of uplifting from the ancient peneplain level.

(4) Relative Relief Map (Fig. D.1.5)

Relative relief, indicator of status of dissection, is the difference of the elevation between the highest and lowest points within certain area. The figure has made to investigate and discuss the history of topographic formation, measuring hights of topographic reliefs applying same method as in summit level maps. One kilometer grid pattern has been drawn on 1:50,000 topographic maps, and the relative relief of each block has been read by counting the number of contour lines. As shown on the map, the mild relief blocks are observed along the major drainage system, Chang Chhu river, and the mountain ridges. The latter may represent a relict peneplain. If so, to make a relative relief map is quite useful for interpretation of distribution of peneplanes, as well as geomorphological land classification map.

(5) Drainage Density Map (Fig. D.1.6)

Drainage density generally reflects intensity of dissection, therefore a drainage map of one kilometer grid pattern using 1:50,000 topographic map has been made. The numbers of the creeks crossing the four sides of the grid have been counted on the map and treated as drainage density index. The drainage density has been classified into four groups. The result shows that the least drainage density in the study area is distributed on a ridge suggesting that it is a relict peneplain. Generally, drainage density is great in impermeable rock areas, and low in permeable rock areas consisted of massive, porous layers such as tuff layers. These areas of low density are being considered as the possible recharge areas for groundwater. In the survey area, gently sloped crest and ridge areas covered by forest may function as recharge zones for groundwater.

D.1.4 Photogrammetric Mapping

A new map, scaled 1:10,000, made by photogrammetric drawing for the study has prepared by the Survey of Bhutan. Areal photographs used for the study are a part of 848-A series, which was taken in 1978 with approximate scale of 1:35,000.

The photogrammetric mapping instruments used for the study are as follows.

- AMH TA-Table and /or AGI for drawing
- EK 22 for coordination and elevation measurement

All these are the products of the Wild Heerburg of Switzerland

Symbols and marks used have been adapted from those of the topographic map of Bhutan. During the field verification, a theodolite (RKI) with staves, and a rule and plane table with tripod have been used. Contour line interval is set as 10 meters in steep terrains and 2 meters in flat terrains. Thick contour lines, index contours, have been drawn for every 50 meters.

D.2 GEOLOGY

D.2.1 General Geology

The first geological information pertaining to Bhutan came from Godwin-Austin (1868) in connection with mineral assessment. He was followed by Maliet (1875) and Pilgrim (1906). Lahiri (1941) provided details of the foot-hill geology especially of his 'Buxa Series". The geological investigations got an impetus after 1961 when the Geological Survey of India set up a unit at Samtse (old spelling Samchi). Results of the early geological survey were published by Nautiyal et al, (1964). This was followed by a crisp account of Bhutan geology by Gansser (1964), Jangpangi (1974, 1978) and Jangpangi et al, (1975) dealt in detail the regional geology of parts of Bhutan. After Nautiyal et al, (1964), except for the publication of a geological map (Anon, 1984) no attempt has been made to synthesize divergent views contained in numerous unpublished reports of the Geological Survey of India. The emphasis had shifted to mineral exploration. The results of mineral investigations have been summarized by ESCAP (Anon, 1991) under United Nations in an Atlas of Mineral Resources of Bhutan along with a map. Those existing geological data, although limited, are accessible at the library of the Division of Geology and Mines, Ministry of Trade and Industry, Bhutan. The publication of the Indian Geological Survey often contains field reports on the Bhutan geology and those are available in Japan.

The outline of the regional geology is as follows.

Like other sectors of the Himalaya, the Bhutan Himalaya can also be divided into physiographic sub-divisions of the Siwalik Hills, the Lesser Himalaya and the Higher Himalaya where topography is essentially controlled by geological formations. As would be evident in the following pages, the Siwalik Group is only locally developed and the Lesser Himalayan formations below the Thimphu Thrust Sheet are highly attenuated and tectonically telescoped. As a result the Simalik hills area only discretely developed and the topography corresponding to the Lesser Himalayan terrain of western and central Himalaya is present only as a narrow zone. In most part specially where the Simalik Group is absent, the hills abruptly rise from the plains of India and physiography, beyond a narrow zone of the Lesser Himalaya near the foothills, is rugged and comparable with that of the Higher Himalaya of the western Himalaya. The highest terrain which is abode of several glaciers is located in the northern most part of Bhutan.

Based on rock types and tectonic style, the Bhutan Himalaya can be broadly divided into two geological zones: below and above the Thimphu Thrust.

Below the Thimphu Thrust Sheet, largely unfossiliferous Lesser Himalayan formations are present. The Lesser Himalayan sequences, so well developed as distinct tectonic belts in the western Himalaya, have been reduced to a narrow width in the Bhutan Himalaya. The reduction in width is due to more southward translation of the Thimphu Thrust Sheet and tremendous tectonic telescoping suffered by the Lesser Himalayan rocks. The intense tectonics has completely disrupted the original stratigraphic order to these unfossiliferous sequences.

The following table shows the general Tectono-stratigraphic order of superposition in Bhutan.

Tectono-stratigraphic order of superposition in the Bhutan Himalaya

Tethyan succession	Conglomerate, shale, siltstone, sandstone, limestone, volcanics
	------------------ Unconformity ------------------
Thimphu Group	Gneiss, migmatite, amphibolite and high grade metasediments
	------------------ Thimphu Thrust ------------------
Jaishidanda Formation	Biotite-garnet ±staurolite schist with tectonic slivers of granite gneiss
	------------------ Jaishidanda Thrust ------------------
Shumar Formation	Quartzite, phyllite and chlorite-mica schist, Rirsong limestone, a few tectonic silvers of granite gneiss in lower part
	------------------ Shumar Thrust ------------------
Diuri Formation	Diamictite, phyllite, quartzite
	------------ Unconformity ? - locally tectonised ------------
Buxa Group	Gritty feldspathic quartzite, limestone, dolomite, quartzite, conglomerate, slate, quartzite, phyllite, tectonic scales of Permian Setikhola Formation
	------------------ Buxa Thrust ------------------
Damuda Subgroup	Sandstone, siltstone, shale, coal beds
	------------------ MBT ------------------
Siwalik Group	Sandstone, siltstone, shale, clay, conglomerate
	------------------ Fault ------------------
Quaternary succession	Sand, conglomerate, silt, clay

The Jashidanda Formation and Shumar Formation are referred for the Paso Series, respecting to the previous name. The most important thrust within many thrusts, which separate each geological unit, is the Thimphu thrust. Based on rock types and tectonic style, the Bhutan Himalaya can be broadly divided into two geological zones: below and above the Main Central Thrust. As described by Molnar (1986) the Main Central Thrust is not a single, clearly defined plane separating two different kinds of rocks, but a wide zone of ten or more kilometers in width where all of the rocks have been severally sheared. The highly metamorphosed sequence above the Main Central Thrust is the Thimphu Series, and the weakly metamorphosed sequence below the thrust is named the Paro Series. The Thimphu Series was referred to the Takhtsang Gneiss by Gansser (1983).

The Regional Tectonic Setting is summarized as follows.

The Bhutan Himalayas are composed of a sequence of major geo-tectonic units which express themselves geomorphologically as the following three zones; namely Sub-Himalayan zone mainly composed of the Siwalik Formation, Lesser Himalayan zone mainly composed of the Midland Meta-sediments, and Greater Himalayan zone composed of the Himalayan Gneiss and the Tethys sediments. These zones are separated by major faults. Among the physiographic belts mentioned above, the Himalayan Chain as well as the Mountain and Valley belt belong geologically to the Greater Himalayan zone. As mentioned above, the Greater Himalaya area is mainly underlain by highly metamorphosed crystalline rocks with the Tethys sediments distributed to the north. The study area physiographically in the Mountain and Valley belt of the metamorphosed crystalline rocks accompanied by thin cover of the weathered blanket and the Quaternary river terrace deposits at places.

D.2.2 Geology of the Study Area (Fig. D.2.1)

The geological formations in and around the study area could be divided into following units.

- Phyllite, meta-sediments	(Chekha Formation)
- gneiss group	(Thimphu Series)
- phyllite, schist group	(Paro Series)

In addition, small intrusive bodies in the area are scattered.

The formation names in the blankets are used in the study report. However, it is necessary to study furthermore whether or not the name of "the Paro Series" for the Phyllite schist group is adequate as a proper terminology. The crystalline rock sequence in the study area has been tentatively classified into two series, namely the Thimphu Series and Paro Series. The Thimphu Series is composed of highly metamorphosed rocks such s garnet gneiss, para-gneiss and schists, marbles and quartzites with granitic intrusives. The Paro Series is composed of less metamorphosed pelitic and psammitic rocks such as phyllite and schist with minor showings of stratabound copper layers. In the field, the highly metamorphosed Thimphu Series lies as a vast sheet covering the less metamorphosed rocks of the Paro Series. This reversed metamorphism is a well known fact with regards to other parts of the Himalaya mountains but still remains a major future research item. The petrographic study indicates great break in continuity of the metamorphic grade suggesting fault contact of the two geological series.

(1) Paro Series

A sequence of metasedimentary rocks, composed mainly of phyllite, slate, limestone, fraggy and massive quartzite, and biotite schist was designated as the Paro Series in the study area. Individual lithorlogical units of this series do not have a regional spatial extension. Beside the less metamorphosed sequence in the area, a similar metasedimentary sequence crops out in west-central Bhutan occupying a considerable aerial extent around the Paro. Out of these, the largest one is present around the Paro-Simtokha areas and was named the Paro Series. Lithologically, the Paro Series is composed of an alternating sequence of quartzite and phyllite/mica schist with impersistent bands of carbonate and lenses of gypsum. Basic sills are common mainly towards the upper part of the sequence. Concordant sheet-like bodies of mylonitised granite gneiss are present at different levels within the sequence, particularly towards the basal part. In the studied area, the stratigraphic succession of the less metamorphosed sequence below the thrust consists of phyllitic schist quartzite and quartz-biotite schist (quartzose member herein after), green schist and thin bed of marble in ascending order.

Although the ground check on the continuity of the proper Paro Series has not been conducted, the less metamorphosed stratigraphic sequence observed in the study area is tentatively named the Paro Series.

PHYLITIC SCHIST

The schistose phylilite overlies the garnetiferous schist in the outside of the study area. The Schistose phyllite contains porphyroblasts of biotite which develop generally near the granite contact. The origin of the porphyroblast may have a genetic relation with deep-seated metamorphism, according to Gansser (1983). The Schistose phyllite contains biotite chlorite, quartz and feldspar as essential constituents with garnet and iron minerals as subordinate minerals. Two types of biotite, bleached pale brown variety and brown variety are seen in specimens. The brown biotite occurs as a porphyroblast which is riddled with quartz grain. Chlorite, quartz, feldspar and magnetite are the common constituents of the rock.

QUARTZOSE MEMBER

The Quartzite or quartzitic phyllite and quartzose-biotite schist in the study area are grouped into one member. This quartzite member overlies the schistose phyllite. This quartzite consists of quartz, mica and chlorite as the prominent minerals and magnetite, tourmaline and zircon as subordinate minerals. The color of quartzite is depends on the minerals; i.e., green quartzite contains chlorite and biotite makes gray quartzite. The Quartzose biotite schist is pale brown top gray in color and composed mainly of quartz, feldspar garnet and tourmaline. The rock is medium grained, and minerals in the rock are aligned parallel to the bedding plane. Micaceous quartzite commonly occurs as intercalatory bands within the garnetiferous mica schist. The quartzite is medium grained, greyish white and thinly bedded. Colour bands, defining the bedding, are conspicuous and commonly associated with bedding joints. The dominant mineral constituents are quartz, muscovite and comparatively rare biotite. Accessories include tourmaline and opaques. However, within the calcareous zone in addition, carbonate and epidote grains are found. With the increase in phyllosilicate component, this quartzitic unit commonly grades into mica schist.

GREEN SCHIST

In the study area, a around 10 meters thick bed of dark green colored hornblende schist has been found as one of the uppermost members to he Paro Series. The essential constituents are hornblende, feldspar, quartz, chlorite magnetite and biotite. The hornblende is green to bluish in color. Epidote occurs as granular aggregates and yellow green to colorless. The basic rock occurs as concordant sill-like body with a sharp contact with the adjoining country rocks. Concordant as well as foliated nature of the sills may indicate an early tectonic emplacement of these rocks.

MARBLE

The marble or crystalline limestone occupies the top horizon of the Paro Series and is overlain by the gneiss of the Thimphu Series. Close association of carbonate and calc-silicate units is common and the former is mainly represented by medium to coarse grained, thinly bedded grey to greyish white coloured limestone/marble. Well developed colour bands are observed in some areas. Occasionally within the impure zones banding is defined by alternation of carbonate and hornblende-epidote rich layers. Main mineralogical constituents of the limestone/marble are carbonate and little quart with a few muscovite flakes. Biotite is rare. Accessories include apatite and opaques. Incidence of base metal (mainly Pb-Zn) associated with the carbonate unit is known in other areas. Within the calc-silicate unit colour banding is excellently developed. This banding is defined commonly by amphibole and carbonate quartz rich layers. However, at places epidote as well as garnet (grossular variety) form rich layers and thin lenticular pockets. Dominant minerals are tremolite/actinolite, epidote, biotite, carbonate and quartz. The marble/limestone bed is thinly banded in texture and grey to whitish grey in colour. This bed is well exposed along the foot path connecting Umtekha Village to Punakha. But the contract between the Thimphu Series and Paro Series which is the most important geological unknown, is not clearly observed in the field.

GRANITE

Concordant, sheet-like bodies of mylonitised granite gneiss is common within this series. Thickness of these bodies generally varies between 5m - 50m. However in some places one body attains a thickness of about 100m. The granite gneiss exhibits sharp and highly sheared contact with the enveloping garnetiferous mica schists. No thermal effect and apophyses are observed within the adjoining country rocks. Phyllonitic rock is almost invariably present along the contact of these gneisses. At several localities, a distinct reduction in size and number of augen related to the intensity of deformation is found towards the margin of the granite bodies. In other words the granite with protomylonitic texture gradually becomes mylonitic towards its margin. The granite gneiss is highly deformed and is protomylonitic to mylonitic type. The dominant minerals are quartz, K-feldspar, plagioclase, muscovite and biotite. Epidote, apatite, tourmaline and opaques constitute the main bulk of the accessories. All the granite gneiss bodies are highly deformed and exhibit mylonitic texture. The dominant minerals in the granite gneiss are quartz and perthite. K-Feldspar and plagioclase are rare. Feldspar grains are commonly clouded due to alteration. Common mafic mineral is biotite which is present as tiny flakes, forming thin laminae parallel to the mylonitic foliation which is continuous with the schistosity of the enveloping metasediments.

(2) Thimphu Series

The vast sheet of highly metamorphosed sequence, structurally located above the Thimphu Thrust and comprising garnet-kyanite-sillimanite-para-gneisses and schists, augen gneiss, and flaggy quartzites with granitic intrusions, and occupying about half of the country, is named the Thimphu Series after the capital of Bhutan. In the studied area, the biotite gneiss interbedded with garnetiferous schistose gneiss, augen gneiss with minor quartzite band and quartz veins, pegmatites and granite constitute the Thimphu Series. The stratigraphy of the Thimphu Series is repeating alternation of biotite-gneiss, garnetiferous schistose gneiss and augen gneiss in general. Judging from the great discontinuity in the metamorphic grade with the underlying Paro Series, the Thimphu Series are considered as a thrust-up sheet on the Paro Series but no definite field evidence of fault contact has been found so far. In contrast to the lower tectonic contact marked by the Thimphu Thrust, the Thimphu Group is overlain by low grade metasedimentary rocks referred to as the Chekha Series. The contact between rocks of the Thimphu Series and the Chekha Series is variously interpreted as conformable, disconformable and in one instance unconformable. Based on the present detailed surveys in the study areas and various reports dealing with the Central Crystallines, the Thimphu Group in the present work, has been divided into Sure, Naspe and Takhtsang Formations. Though not always coinciding with these proposed lithostratigraphic division, there is a distinct perceptible increase in the metamorphic grade from south to north. A short description of the major rock types of the Thimphu Series will be given in ascending order.

BIOTITE-GNEISS

The basal member of the Thimphu Series consisting of biotite gneiss is well exposed in the study area. The rock is gray colored, uniformly banded but schistose at places, hard and compact, and medium to coarse grained in texture. Quartz, feldspar, biotite, sillimanite and garnet are the main rock forming minerals of the gneiss. Sillimanite occurs as knots and sheaves along the foliation plane and at the contact of quartz vein and quartz-feldspathic intrusions. On the weathered surface, sillimanite knots show characteristic white color with silken luster. Biotite, together with a minor amount of muscovite occur as flakes in parallel orientation and are concentrated at the contact of quartz vein, showing well marked lineation on foliation planes. Other accessory minerals are garnet, apatite, magnetite, zircon and chlorite.

GARNETIFEROUS SCHIST

The schist of the Thimphu Series differs from the tectonically underlying schist of the Paro Series in having profuse granite-pegmatite intrusions apart form containing high grade minerals like kyanite and rare sillimanite. In general, kyanite is more widespread in the Thimphu Series than Sillimanite. Despite subordinate in amount to garnet, kyanite can be considered as an index mineral of the schist of the Thimphu Series. Where these two high grade minerals are absent, the schist in Thimphu Series is little different from the garnetiferous mica schists of the Paro Series. The garnetiferous schist crops out on the east wing of the synform. The bed is overlain by biotite gneiss and is underlain by biotite gneiss and crystalline limestone. Thickness of the bed is roughly measured as 500 metes more or less. The garnetiferous schist consists essentially of quartz, feldspar, mica and garnet. A number of leucocratic veins and pegmatitic lenses are observed intruding or intercalating the schist. Segregation banding of quartz and mica rich layers are quite prominent. The feldspar is fairly abundant and some of the schist is highly feldspathised. Biotite is pale brown to deep brown in color and altering to light green chlirite. The garnet in the schist is spotted and well developed having a diameter from 1 centimeters to more than 10 centimeters at places. Porphyloblast of garnet is also common. Tiny tourmaline and iron minerals occur as accessory minerals.

AUGEN GNEISS

Augen gneiss occurs as compact slabs or sheets in the biotite gneiss and is considered to represent the thrust-up slab. In Nepal, the Main Central Thrust (MCT) borders the augen gneiss and underlying schistose phyllite. Porphyroblasts of the feldspar in the gneiss are rectangular, square and "augen". These augen are surrounded by small quartz grains and separated by interfoliar biotite flakes.

(3) Chekha Series

Adjacent to the east and the south of the study area, a late Pre-Cambrian to Phanerozoic sequence of metasediments is distributed. The sequence is represented by garnetiferous schist and quartzite; schistose phyllite with porphyroblasts of biotite; green and grey coloured quartzitic phyllite and siliceous marble; grey schistose phyllite with grey to white quartzite and limestone with acid and basic intrusive. These sediments are litholiogically very similar to the rocks of Chekha Series exposed in the type locality and have been mapped as the local variants of the Chekha Series which is a member of the Tethyan Sequence. The contact between the underlying garnetiferous mica schist of the Thimphu Series is marked by profuse granitic intrusion. Due to this intrusion, the boundary between these two series is not distinct, and oftenly an intimate mixture of the two rock types is formed. A slate bed with well defined slaty cleavage intercalated in the series is being mined for the roofing slates at the upper reaches of the Pe Chhu, a tributary of Dang Chhu. The bed is overlain by a impure slate bed and underlain by a sandstone bed in the mine site. In the mine site, the slate is black to dark grey in the upper member, and shaly in the lower member. The slate of the upper member has clear slaty cleavage which is nearly parallel to the original bedding of the formation. The cleavage plans are not buckled or curved and form smooth plane surface. Because of its characteristic slaty cleavage, it can be readily split into thin slabs. The common size of the slate slabs is 10 centimeters by 70 centimeters, but even larger ones can also be extracted. The thickness of these slabs varies between one to 1.5 centimeters, but slabs of less than 0.5 centimeters thick are common. The slates are uniform in composition, maintaining its colour and fineness throughout the upper part of the mine site. The slate can be used for roofing, as school slate, for billiard tables and blackboards. Since the distribution of the Chekha Series is outside of the study area, on detailed field investigation was conducted.

(4) Quaternary Geology

Location of the Quaternary system in the study area are limited in the scattered river terraces and mud flow deposits of the slope. These two types of the Quaternary system, river terraces and mud flow deposits, form gentle sloped terrain utilized as farmland.

1) River Terraces

a) High terrace

The relative height of the high terraces in this area are situated more or less 130 meters above the present river. So far observed, the high terraces are developed mainly in an around the Wangduephodrang town. The high terraces are mainly underlain by mudflows and boulder beds at the Wangduephodrang bridge, gravel beds and massive coarse-grained sands beds at the middle Bajo, and partly laminated sand beds and gravel beds in the upstream area.

b) Middle terrace

The middle terraces have a relative height of 25 meters from the riverbed. The terraces are widely scattered on both banks of the Chang Chhu. The terraces are mainly composed of boulder beds with thin intercalation of well sorted sand beds.

c) Low terrace

The low terrace with a relative height of 5 to 8 meters from the river bed is the most widely distributed terrace along the Chang Chhu river. The terrace is mainly composed of gravel beds with minor bands of cross-bedded sands. The original topographic relief such as ancient river channels is well preserved.

2) Mud-flow deposits

The cultivated gentle slope in Lobeysa is composed of thick mudflow deposits. Also, adjacent to the south of Lobeysa is another mudflow deposit forming a gentle slope where the camp of the Road Department is located. Aside from these major landslides, several mud flow deposits are observed in the study area. These mudflow are quite uniform in constituent material and composed of loose, unsorted, brown colored massive muddy sediments with angular blocks and fragments of rocks from the flow origin.

3) Fan deposit

Small but clear fan deposits are observed in some places. The typical fan with a considerably large size is only located adjacent to the south of the Lobeysa mud flow where the perennial spring at the terminal fan is observed. The debris of the fan is mainly less sorted with sandy and/or muddy lenticular band.

D.2.3 Geological Structure and Tectonics (Fig. D.2.2)

The most parts of the study area are occupied by the highly metamorphosed rocks, and these are tentatively classified into two series, the overlying sequence mainly composed of gneiss and underlying sequence composed of schist and metasediments. Just for the sake of convenience of field work, the popular name s for the geological formation. The Thimphu Series and Paro Series have been assigned. Although great breaks of metamorphic grade have been observed between the two series, the observed schistosity and stratification of the two series are quite comformable and parallel. In other words, mostly the original bedding of the rocks is in conformity with the schistosity. The Thimphu Series has witnessed several deformation and complex folding as revealed by the frequent change in the attitudes and dips of foliation and dislocation of the lands of calc-silicate rock and crystalline limestone, occurring as intercalations in the metamorphic rocks. A land of limestone has formed a synform with a north to south trending axis at the center of the study area. The regional trend of foliation is formed to vary NW-SE in the west wing, to NE-SW in the east wing, with corresponding dips of 10° to 40° to form a synform. At the west bank of the Chang Chhu river, the structural trend is almost east to west with dips of about 10° to either direction. Two major faults, (i) a transverse fault along the Chang Chhu river, and (ii) a small fault along the Pe Chhu are found in the study area. The former transverse fault is evidenced by the marked change of the dip and strike in the west and east of the fault. The small fault, trending NE-SW, is evidenced by the abrupt change of rock facies and a sheared zone founding two rock types. The north-east extension of this fault is mapped as the boundary between the Thimphu Series and Chekha Series. The rocks of the Chekha Series are undulating to form an isoclinal folding structure.

D.3 HYDROGEOLOGY

Hydrogeological survey has been conducted in the study area during the course of the field study. Those sites to be surveyed geophysically and the sites for the test boring area selected hydrogeologically.

Since no previous systematic hydrogeological study had been carried out in the area, no hydrogeological report was obtainable.

D.3.1 General hydrogeology

Because of the mountainous terrain, there is a wide variety of local groundwater conditions; nevertheless the hydrogeological condition of the study area could be generalized as an area of two-layered geological model, i.e., impermeable basement rock and more or less permeable cover of the Quaternary age.

The basement rocks, probably Pre-Cambrian in age, are mainly composed of massive gneiss and foliated schist. The porosity of these basement rocks is generally in the form of foliation and/or interconnected fractures which vary considerably in size and frequency. The amount of fracturing in rock depends on both rock type and geologic structures such as folding or faulting. In the areas of massive garnet gneiss, fractures are less developed

while in the areas of quartzite and schist fracturing is often best developed. These fractures become less frequent with depth and as a rule, drilling deeper than 10 meters after encountering the less fractured fresh rock is not advisable.
No important water yield from the basement rock was so far observed in the study area.

Perennial yield of minor quantity of spring water is often observed at the toe of landslides in the study area. This landslide related ground water is a sort of "perched ground water" on the black coloured landslide-clay, and the best yield of water is just above the black clay. This type of spring is the most important water source in the area of the Phangyul block.

Deeply weathered rocks with thick soil cover forming gentle sloped area on/near the crest of mountains may have important roles in recharging the groundwater, however the water is unlikely to be exploitable on the crest plane.

Quaternary covers in the study area are river terraces, landslide debris and less permeable mudflow deposits.

Quaternary river terraces along the Chang Chhu and other large rivers are the most important aquifer in this study area. Since the area is located in the mountainous area, no impermeable bed/layer is intercalated in the terrace deposits, suggesting that the ground water in this area is unconfined one.

By two drill holes groundwater was found between the basement rock and overlying impermeable mudflow deposits in Lobeysa. The geological model for these groundwater is the two model, as with the case of the river terrace.

D.3.2 Classification of Groundwater in the Study Area

The main part of the Study area is situated in the steep mountain area, which is geologically composed of metamorphic rocks, and small-scale river terraces are distributed along the principal river in the area, the Chang Chhu.

Generally, groundwater resources are poor in the mountain areas. The groundwater in the mountain is stored and flowing down in fracture and joint zones in the hard metamorphic rocks, and its volume for utilization is limited.

In some places, springs are scattered for the length of several kilometers in a same level of mountain slopes. It suggests that a continuous groundwater table exists in the mountain.

In such case, large areas of gentle slopes are situated in the summit or crest areas of the mountains, and thick vegetation is commonly seen in those areas. Also thick debris and talus are commonly seen in the mid-slope areas. These areas provide good conditions for the percolation of the precipitated water in the study area.

This type of mountains generally have a large preservation capacity for water, and many spring waters are commonly seen in mountain slope and foot areas.

No spring waters from the basement rock areas is seen in the survey area, however, it is presumed that the mountains have a large preservation capacity for water, judging from the topographic condition and vegetation there.

On the other hand, in the areas of no flat areas on top of summits and poor in vegetation, its preservation capacity for water might be low. Accordingly its potential for groundwater development should be low and not sustainable for long time utilization. A forced development should bring a serious unrecoverable environmental impact such as dead trees, disaster of farmland soil erosion caused by decreasing soil moisture.

Even in cases spring waters exist in mountain slopes, if locations of those springs are not in same level and irregularly scattered, then it is presumed that those springs do not come from a same groundwater body.

Many landslide blocks exist in the survey area, and stores perched water, which sustained by a black clayey seam at the bottom of sliding blocks. Most of the springs located in the mountain slopes are of water squeezed out from landslide blocks.

The groundwater in the landslide blocks is recharged by infiltrated precipitation and intercalation in the background mountains, however, since the volume of landslide is limited the available quantity for exploitation is also limited. It is necessary to take adequate process for development, for instance to prevent destruction of black clayey seams on the bottom.

The mountain slopes in the Study area is unstable due to the recent abrupt uplift movement, and landslides occurred in many places. In cases relatively large-scale landslides with some water contents occurred, mud flows will occur and run down in valleys and drainage, then mud flow deposits will fill out those depressions. Those mud flow areas show gentle flat slopes, and the water under-flows subsurface of the mud flow areas. Running surface water in mudflow area can be seen only during heavy rainfalls.

The mud flow deposits are composed of huge rock blocks, boulders to fragments, and muddy matrix, and its permeability is generally low. The boundary between the mudflow deposits and basement rocks, specially in buried ancient channels, however, is commonly the best yielding zone for groundwater. The groundwater in such parts are supplied from the background mountains, in where water is stored as fissure water and pore water in mud flow deposits.

The survey area is situated in the mountain area, and only few small flat lands such as river terraces exist between these mountains. Therefore, the state of the groundwater in the area is much different from that of large-scale plains or sedimentary basins.

The low terraces having relative height of 2 to 10 meters are rich in subsurface water, so called underflow, and its water table is almost same as nearby river water level, fluctuating their levels simultaneously.

The middle terraces have the relative height of 25 meters, and the groundwater level in the terraces is about 5 meters higher than that of the river. It is resumed that the water here is recharged from the background mountains and small tributaries.

The high terraces are deeply dissected, and its distribution is limited to small areas. The high terraces, therefore, are not potential targets for groundwater development.
Based on the survey results, the groundwater in the area can be classified as follows.

- Groundwater in mountains : Fracture water in basement rocks
  Groundwater in landslide blocks
- Groundwater in valleys : Groundwater in mud flow deposits
- Groundwater in flat lands : Groundwater in middle terraces
  Groundwater in low terraces

D.3.3 Groundwater in the Study Area (Fig. D.3.1)

With in the Study area, significant exploitable water resources comprise sub surface water and groundwater. On the basis of mode of occurrence, groundwater can be classified into (I) river terrace related groundwater, (ii) landslide related groundwater and (iii) mudflow related groundwater.

Water potential for each sub-area is summarized in the following table.

(unit : l/min)

Sub-area	Subsurface water	Groundwater			Total
		River terrace	Landslide	Mud-flow	
Lobeysa	nil	-	450	2,450	2,900
Bajo	1,000	800	400	-	2,200
Phangyul	-	-	1,000	450	1,450
Rubeysa	-	-	450	900	1,350

(1) Groundwater in mountains

1) Fracture water in basement rocks

Generally, rain water first reaches groundwater tables vertically penetrating through soil and nearsurface layers, then moves to some direction by the gravity depending on subsurface structures and states of groundwater tables. Finally, the water comes back to the surface through various routes or processes. Positions and forms of groundwater tables depends on states of subsurface lithology, structure and hydrogeology, however the most important controlling factors are its global permeability and quantity of precipitation. In cases its meteorological condition is stable for years, sources or origin of rivers keep almost same positions in every stream, and positions of springs are also in certain small ranges. In cases no rain falls long time, surface run-off is drained, and only base run-off which is supplied by water spring flows into rivers. Accordingly, quantity of base run-off corresponds to its porosity of rocks composing mountain bodies. A quantitative repeating measurement at a certain point of streams in each geological unit has not been performed in this survey, however, the quantity of the water flow in a small stream through the dry season has kept same level, less than 10 liters/sec/km^2. In Japan having similar states of precipitation and vegetation, the base run-off in metamorphic rock areas is 7.6 liters/sec/km^2. The same figure, therefore, has been applied for this study. The volume of about 8 liters /sec/km^2 is quite important recharge source for the survey area. The base run-off in the area appears as rather a little seepage forming small streams than clear springs.

2) Groundwater in landslide blocks

Gently sloped farmlands are scattered several places in the area. A house or several houses are situated in the highest places of each farmland. This kind of landscapes is very common in Bhutan, and these gently sloped areas have genetically been formed by the landslide blocks. The farmers living there depend their water for domestic use on the springs nearby the areas, normally yielding about 10 liters per minutes. All these springs are situated in the edges of the landslide blocks, so called "toe", and accompanied with black clayey layers. Also these springs, in some places, have formed marshes. The black clay has been formed from landslide material during their slide movement, by crashing and grinding of rock fragments and soil. The clay material has formed impermeable seams or layers. The landslide blocks have been highly fractured during its movement, and as a result, it has become porous blocks. The blocks have formed perched groundwater reservoir systems within the bodies together with underlying impermeable clay seams. It is presumed that the water of the landslide blocks have been recharged from the fracture water in the background mountains, despite of details of that have not been studies. Scarps are commonly seen on the tops of the landslide blocks, therefore it is presumed that the bottoms of the slide blocks are in spoon-shape. It is interpreted that the state and size of clay seams in the upper parts and lower parts are different, thick clay seams in the lower and poor in the upper. This interpretation suggests that the clay seams, which sustain the perched groundwater, should be impermeable in some degree. Also it is reasonable to think that the upper parts of the landslide blocks are being recharged from the fracture water in the background mountains by subsurface run-off. As described in other chapter, the groundwater in the landslide blocks is recharged from the rain water and subsurface run-off from the background mountains. The volumes of the recharge from both sources are roughly same, 200 millimeters per year from the rain water and 200 millimeters per year from the fracture water. Accordingly, the volume of the recharged water in the landslide blocks can be calculated applying following formula.

Q (cubic meters) = Area (square meters) × 0.4 meter

The observed quantity of spring waters as natural run-off water are only a small portion of recharged water, therefore, can be utilized double or triple amount of present yielding by improving existing intake facilities in the most of places.

(2) Groundwater in valleys

1) Groundwater in mud flow deposits

The mud flow deposits, which form gentle sloped lands burring ancient valleys, are scattered in the area, and springs are sometimes seen at the lowest edges of the mud flow slopes. Two test wells have been drilled in the Lobeysa sub-area situated in the right bank of the Chang Chhu river in this study. The wells hit groundwater at the near bottom of the mud flow deposits, and the groundwater there seems to have enough quantity to be utilized as domestic water supply sources. The mud flow deposits topographically form wide gentle slope flat lands burring ancient valleys, and can easily distinguish in aero photographs using a stereo-scope. The deposits include various size of fragments of metamorphic rocks, from huge blocks over 2 meters in diameter to fine granules, and its matrix is commonly composed of reddish brown adhesive muddy silts. The fragments are not arranged in a same horizon, and separately scattered each other in many cases. This phenomenon indicates that the specific gravity of the matrix was high, and fragments were not sorted and suspended within the dense muddy matrix during the transportation. This occurrence is quite different from that of river terrace deposits transported by river water and deposited. It is therefore very easy to classify these tow types of deposits in the field. The mud flow deposits in the area have high porosity but low permeability.

The data of the test drilling TB-4 and TB-5 are as follows.

TB-4	Depth:	
	Optimum Discharge:	110 liters per minute
	Coefficient of Permeability:	1.65×10^{-5}
TB-5	Depth:	81 meters
	Optimal Discharge:	68 liters per minute
	Coefficient of Permeability:	6.78×10^{-4}

The catchment area of TB-4 and TB-5 is expected as about 8 and 2 km^2 respectively. Those mud-flow area is expected as about 2.5 and 0.14 km^2 respectively. Comparing the amount of yield from the catchment area and mud-flow area for each drill holes, it is concluded that the size of catchment area is a more significant factor controlling ground water volume than either mud-flow area. Applying the values set out in the previous section, specific discharge of metamorphic rock is roughly calculated as 7.6 l/s/km^2 (450 l/min/km^2). If 40% of this is considered exploitable, 180 l/min/km^2 of groundwater is expected to be exploitable from the catchment area.

These holes have been drilled in a buried creek suggested based on the results of an electric prospecting. These mud-flow deposits have completely covered the pre-existing topographic relief, forming new drainage or creek patterns which are entirely different from the buried drainage pattern. The groundwater in these areas, however, is still flowing down to buried creeks as mentioned before. This is the main reason why dry creeks are often observed in the mud-flow area.

(3) Groundwater in flat areas

1) Groundwater in middle terraces

The middle terraces composed of M1 and M2 terraces are situated in the level of 30 to 50 meters above the river, M1 terraces, and 10 to 20 meters above the river, M2 terraces.

In the survey this time, the electric survey applying the Schlumberger method has been performed. The results of the survey have revealed two crescent-shaped low resistivity zones in the M1 terrace which suggested good potential for groundwater. Presuming from these shapes, these low resistivity zones would be resulted from buried ancient river channels, which would have been formed during the Chang Chhu river run meandering with a width of several hundreds meters (Fig. D.3.2).

Two wells, TB-2 and TB-3, have been drilled in the presumed buried channels. The depth of the groundwater table is about 5 meters higher than the present river level.

While the chlorine content of the groundwater from TB-2 shows 30 ppm, and the spring water from Umtekha village in the mountainous terrain, about 2 kilometers north of the drilled area, shows 46 ppm. No other water sample indicates such as high content of chlorine in the Study Area. Therefore, it is presumed that the groundwater in the M1 area is mostly recharged from the background mountain areas as well as the Limuti Chhu river, adjacent to the north, running water of which shows 15 ppm in chlorine content.

Simply presumed if the water from the mountainous area, which contains 46 ppm of chlorine, is diluted by the water from the Limuti Chhu river, which contains 15 ppm of chlorine, it is estimated that the groundwater from TB-2 is composed of 50 per cent of water from the eastern mountainous area and 50 per cent of water from the Limuti Chhu river.

As discussed above, the groundwater in the area is being recharged from the fissure water in the mountainous area and surface water of the many tributaries. The background area of the Bajo sub-area is about 2 square kilometers, therefore it is estimated that the volume of recharged water in the area is 1.5 liters per second or 900 liters per minute, taking the average 355 day's specific discharge of 7.6 liters/sec/kilometer, same as that of the metamorphic rock areas in Japan of which vegetation and precipitation is similar to the one of the Study Area.

On the other hand, by the study on the chlorine content, it is presumed that the recharge volume from the surface water of the tributaries is about same as that of from the background areas, the total recharge volume in the area can be estimated at 1,800 liters per minute.

2) Subsurface water in low terrace

The low terraces are situate 2 to 10 meters above the present river level, and well preserve micro-topographic relics of ancient river channels, channel bars and banks. These low terraces are widely distributed in the upper Bajo area.

In the survey this time, a dug well with 3.5 meters in diameter has been constructed on a ancient channel in the low terrace.

The result of the water level observation has revealed that the fluctuation of water level of the Chang Chhu river was clearly recognized in cycles of 15 days of time lag, suggesting that the ancient channel is still functioning as subsurface water channel. That is why we suggest to call the ware "subsurface water".

Subsurface water is hydrogeologically connected directly with waters of rivers and can not be separated. Therefore, static water levels of subsurface water are close to or the same as those of river water. Flow velocity of subsurface water is normally slower than that of surface water, but significantly faster than that of nearby groundwater.

Accordingly, exploitable water potential of the subsurface water in the area is extremely high due to the direct water supply from the river. The potential can be related with volume of subsurface water which is calculated by following formula.

$$Q = A \times K \times I$$

Where Q: flowing volume of subsurface water
A: area of cross section
K: coefficient of Permeability
I: hydraulic gradient

If width of subsurface flow is assumed at 200 m, or one hale that of low terrace width, and exploitable depth is assumed at 5 m, then: $A = 200\ \text{m} \times 5\ \text{m} = 1000\ \text{m}^2$. Assuming a hydraulic gradient equivalent to that of the river gradient, or 1/150, and a coefficient of permeability equal to a standard gravel bed, or 2.5×10^{-3} m/s, then: $Q = 1000 \times (1/150) \times (2.5 \times 10^{-3}) = 16.6$ l/s (1 m^3/min).

In conclusion, the area has quite high potential for exploitable water resources from the subsurface water, and the exploitable volume will be decided by number of wells and their depth due to its great recharge capacity.

(4) Water Balance

1) Water balance of subsurface water

Subsurface water is defined as a large-scale flowing water in sand and gravel layers, formed in buried ancient river channels, nearby present river flows. Hydrogeologically, it is directly connected with river water, and impossible to separate from river water. Accordingly, groundwater tables of subsurface water generally coincide with or approximate those of river water.

As mentioned above, subsurface water is essentially same as river water. The Chang Chhu river, which has about 4,800 square kilometers of catchment area and 270 cubic meters per second of mean annual discharge, runs in the survey area. A sub area named "Bajo sub-area", about 1.9 square kilometers, exists beside the Chang Chhu river. A subsurface water runs in this sub-area, therefore, the water volume of precipitation, surface run off, infiltration, and evapo-transpiration in the sub-area is negligible compared with total volume of the river.

Judging from this point of view, the water balance of the subsurface flow in the sub area is negligible from the large-scale water recharge of the Chang Chhu river.

In conclusions, utilization of the subsurface water in the area depends upon its hydraulic conductivity and number of facilities for exploitation of the water.

2) Water Balance of Groundwater in river terrace

As mentioned before, the groundwater in the river terraces is of unconfined, and its water table level is observed 5 meters higher than the river water level of the Chang Chhu river.

The chlorine contents of the groundwater in the terrace are as follows.

- 46 ppm in the Umtekha spring water in the background mountain
- 15 ppm in the Limti Chhu river water originated from the eastern mountain and draining the terrace area
- 30 ppm in the water from the groundwater in the terrace

These contents are much higher than that of water from other areas. Judging from above mentioned fact, the groundwater in the Bajo sub-area is most likely composed of the fracture water from the eastern background mountains and the surface water from the Limuti Chhu river, a tributary of the Chang Chhu river.

In the background mountain area at the north and northeast east of the Bajo sub-area, the groundwater run-off from the fissure water into the terrace, may be existing. In this case, the 355 days' specific discharge is set to 7.6 liters/km2/sec, and the area of background mountain is about 2 km².

Base run-off = 7.6 l/km²/sec × 2.0 km² = 15 l/km²/sec (900 l/min)

This is the volume of the groundwater run off from the eastern mountain. Based on the assumption that the fissure water of the eastern mountain is diluted by same amount of the river water from the Limti Chhu, the water supply of the groundwater in the area is 2,502 cubic meters per day or 1,800 liters per minutes.

In addition to that, the infiltration water in the terrace, 0.9 square kilometers in area, is expected. Assuming the annual precipitation is 1,000 millimeters and 20 per cent of the precipitation water is penetrated in the ground, the volume of 180,000 cubic meters per year, 493 cubic meters per day or 340 liters per minutes, of water is added.

If recharge from rice fields in the area is added, then total flow-in volume would roughly be 3,000 cubic meters per day or 2,000 liters per minutes.

In summary, as a new water source, around 2,000 liters per minutes of groundwater will be able to utilize from the middle terrace. Exploitable volume may be about 40% (800 l/min) of recharge volume as discussed in next section.

3) Water Balance of Groundwater in Landslide areas

The groundwater in the landslide areas is stored in the fractured landslide debris, and small perennial springs, yielding 5 to 20 liters per minutes, are distributed in the landslide areas.

In the chapter 4, it is discussed that the annual infiltration amount to the landslide areas is 200 millimeters from the precipitation and 240 millimeters from the background mountain. Accordingly, the recharge amount in an area of 300 × 300 meters is estimated as follows.

$300m \times 300m \times 0.44m = 39{,}600\ m^3/year$

On the other hand, the volume of the natural discharge of the spring is estimated as 10 liters per minute or 5,250 cubic meters per year.

Accordingly, if the intake facilities are improved to take double or tipple amount of water from the springs, only 30 to 40 per cent of total recharge amount can be utilized. It is concluded that there is no problem to extract such volume of water from those springs.

(5) Quality of Water

1) Seasonal Fluctuations of water chemistry

The spring water in Phangyul, observation point S-5, assay table S-7, has been chemically assayed four times from the end of the dry season to the wet season. The results are as follows.

Date		Apr.25	30-May	4-Jun	19-Jun
Whether		cloudy	fine	fine	fine
1) Physical Exam.					
Appearance		clear	clear	clear	clear
Temperature		15.8	19.1	--	24.2
Conductivity	Us/cm	116.9	125.0	123.4	189.1
Turbidity	mg/l	3	3	3	2
Color	degree	<5	<5	<5	<5
Taste		normal	normal	normal	normal
Odor	at 40C	none	none	none	none
2) Chemical Exam.					
Ph	mg/l as NaCl	8.21	7.60	6.91	7.54
T.D.S	mg/l	58.7	65.0	61.6	95.0
Alkalinity	mg/l	64.0	63.0	62.0	87.0
Hardness	mg/l	38.0	34.0	42.0	44.0
Chloride	mg/l	2	3	6	2
Sulfate	mg/l	<1	<1	<1	<1
Phosphate	mg/l	0.1	0.1	0.2	0.2
Nitrogen					
-Ammonium		nil	nil	nil	nil
-Nitrite		nil	nil	nil	nil
-Nitrate	mg/l	nil	0.8	0.5	0.5
Dissolved Oxygen					
KMnO4	mg/l	5.3	4.8	4.2	5.1
Residual Chlorine					
Iron	mg/l	0.2	0.3	0.05	trace
Manganese	mg/l	nil	nil	nil	nil
Heavy Metal					
-Cu	mg/l	nil	nil	nil	nil
-Cr	mg/l	nil	nil	nil	nil

The reason why the electric conductivity of the water increases time to time, is interpreted that salts precipitated on the surface in the dry season would solved and run out in the wet season.

On the other hand, the pH values decrease from 8.21 to 6.91 then increase to 7.54. This phenomenon is interpreted that the iron sulfide minerals (pyrite; FeS2) in the black clay layers would be oxidized in the dry season because the groundwater level is lowered, then sulfuric acid water occurred there would be flew out in the wet season, concurrently the groundwater level would be risen over the black clay layers, then the zone of oxidation would be sealed again.

The content of iron ion decreases from April to June, and nitrogen or nitrate appears in May, however these contents are very little. These phenomena should be discussed in relation with other factors such as fluctuation of yield water volume during the measurement time.

2) Assay result

Three water samples from chemically characteristic springs and four groundwater samples from drilled wells have been assayed.

Sample No.		No.1	No.2	No.3	No.4	No.5	No.6	No.7
Date		4-Jun	11-May	30-May	Apr.18	9-May	23-May	
Whether		fine	fine	fine	fine	fine	fine	
1) Physical Exam.								
Appearance		clear	clear	clear	s turbid	clear	clear	clear
Temperature		23.0	25.4	19.1	--	24.0		
Conductivity	uS/cm	266.0	137.2	125.0	257.0	34.1	0.0	71.6
Turbidity mg/l		3	2	3	7	28	10	0
Color	degree	<5	<5	<5	<5	<5	<5	<5
Taste		normal	normal	normal	normal	normal	normal	normal
Odor	at 40C	none	none	none	none	none	none	slight
2) Chemical Exam.								
pH	mg/lasNaCl	7.23	6.53	7.60	6.96	7.35	7.47	7.00
T.D.S	mg/l	133.0	68.7	65.0	128.8	116.0	153.2	0.4
Alkalinity	mg/l	177.0	57.0	63.0	119.0	96.0	121.0	--
Hardness	mg/l	148.0	30.0	34.0	106.0	81.0	132.0	96.0
Chloride	mg/l	2	46	3	30	0	1	5
Sulfate	mg/l	<1	3	<1	0.5	<1	<1	nil
Phosphate	mg/l	0.10	0.30	0.20	0.10	0.45	0.20	N.A.
Nitrogen								
-Ammonium		nil	nil	nil	nil	nil	nil	nil
-Nitrite		nil	nil	nil	nil	nil	nil	<0.2
-Nitrate	mg/l	1.5	0.5	0.8	0.5	0.8	nil	nil
Dissolved Oxygen								
KMnO4	mg/l	5.0	4.7	4.8	2.2	5.5	2.3	nil
Residual Chlorine								
Iron	mg/l	nil	nil	0.3	0.45	0.75	0.3	nil
Manganese	mg/l	nil	nil	nil	nil	nil	nil	
Heavy Metal								
-Cu	mg/l	nil	nil	nil	nil	nil	nil	N.A.
-Cr	mg/l	nil	nil	nil	nil	nil	nil	nil

Note:

Sample	No.1	Upper Mitsina (spring)	No.5	CARD (TB-3, drill hole)
	No.2	Umtekha (spring)	No.6	Mitshina (TB-4, drill hole)
	No.3	Proper Phangyul (spring)	No.7	Lobeysa (TB-5, drill hole)
	No.4	Bajo (TB-2, drill hole)	N.A.: not assayed	

Chlorine in the samples from Umtekha and Bajo (TB-2) shows high values, and both are genetically related each other. This is discussed in the previous chapter.

Other geochemical characteristics are that a small amount of iron ion is commonly contained in all samples from the wells, and phosphate content in all samples is generally high, from 0.1 to 0.45 ppm.

D.3.4 Present status and future plan of utilization of spring water

Many farmers are living in the hilly areas or mountain slopes in the study area. The spring water in the area is only one water source for the villagers, and every villages have their own treatment plants such as simple desanding facility and conduits to their villages.

Many of those facilities have been made by the villagers getting UNICEF's aides including technical and financial assistance. Many of these facilities do not have storage tanks. Some tanks being held by villages are commonly less than 20 per cent of daily yield of the spring in its capacity, which is not sufficient even for urgent accidental demand. The water yielded in night time is run-out without any use, and sometimes triggers landslides in the farmland and down slopes.

Almost all springs are genetically associated with landslide blocks. Other types of the springs in the area are those very fluctuated yielding springs coming out from the boundary between the basement rocks and surface soil, specially in depressions or valleys, and those coming out from depressions in the mud flow deposits areas.

The springs utilized for drinking water are shown in the hydrogeological map.

The present yielding of each spring is shown in the hydrogeological map. In addition, potential yielding capacity in relevant geological unit, principally landslide block, is shown in the groundwater inventory map. If the water of the potential yielding is not used, then most of the yielding will be lost by evaportranspiration. Therefore, no ecological impact is expected in use of the potential yielding.

On the other hand, many villages do not have storage tanks, or even if they have those, the capacity of those are very small, say less than a quarter of daily yield of the spring. Wasted water is also making triggers for landslides or wet lands.

In conclusion, it is recommended, first to make plan for effective usage of the spring water applying adequate water management plan to utilize it, then to execute some proper development or treatment plans to increase yielding volume from the springs.

The water shortage problem in dry season in these villages will be eased by execution of these measurements.

D.3.5 Groundwater Development and its Environmental Impact

In this survey, water in the underground is classified into two sorts, subsurface water and groundwater.

Subsurface water presents in the low terraces, and its water table is about 2 meters from the surface. Its flow speed in some ancient river channels is significantly high.

The subsurface water is directly supplied from the rivers, and then exploitation may never affect to the physical and ecological environment.

The groundwater is hosted in the middle terraces and landslide areas. The middle terraces are utilized as cultivated ground or residential areas, and some irrigation water channels are constructed for rice fields. It is estimated that the groundwater in the middle terraces, being hosted below 25 to 30 meters from the surface, is supplied and recharged in a rate of about 2,000 liters per minute.

Accordingly, as far as less amount than above mentioned figure is pumped up, no environmental impact such as change of soil moisture in farmlands is expected on the surface in the terrace area.

As previously mentioned, two types of recharge patterns to the groundwater in landslide areas, penetration (infiltration) from the precipitation and infiltration from the fracture water in the background mountain.

The amount of infiltration from the precipitation, annually around 1,000 millimeters, is estimated as annually 200 millimeters, and that from the fracture water in the background mountain is around 240 millimeters. Therefore, the total quantity of annual recharge for each landslide block can be calculated as follows.

Area (square meters) × 0.44 (meter) = Annual recharge (cubic meters)

For an example, if the area is 300 × 300 meters, then the quantity of the recharge would be

$90{,}000\ m^2 \times 0.44\ m = 40{,}000\ m^3$/year (76 liters per minute)

At present, the yielding from the spring in such scale of landslides is about 10 liters per minutes, therefore no problem in the impact for the groundwater system might occur even if the yielding volume is increased up to three times by improvement of the existing facilities.

In conclusion, the groundwater in the landslide areas can be utilized as much as two or three times more than present usage amount, by improving existing intake facilities and/or storage tank, without any environmental and ecological impact. Also, the water in the middle level terraces can be utilized within the recharge volume of 2,000 liters per minute as estimated before.

APPENDIX D
FIGURES

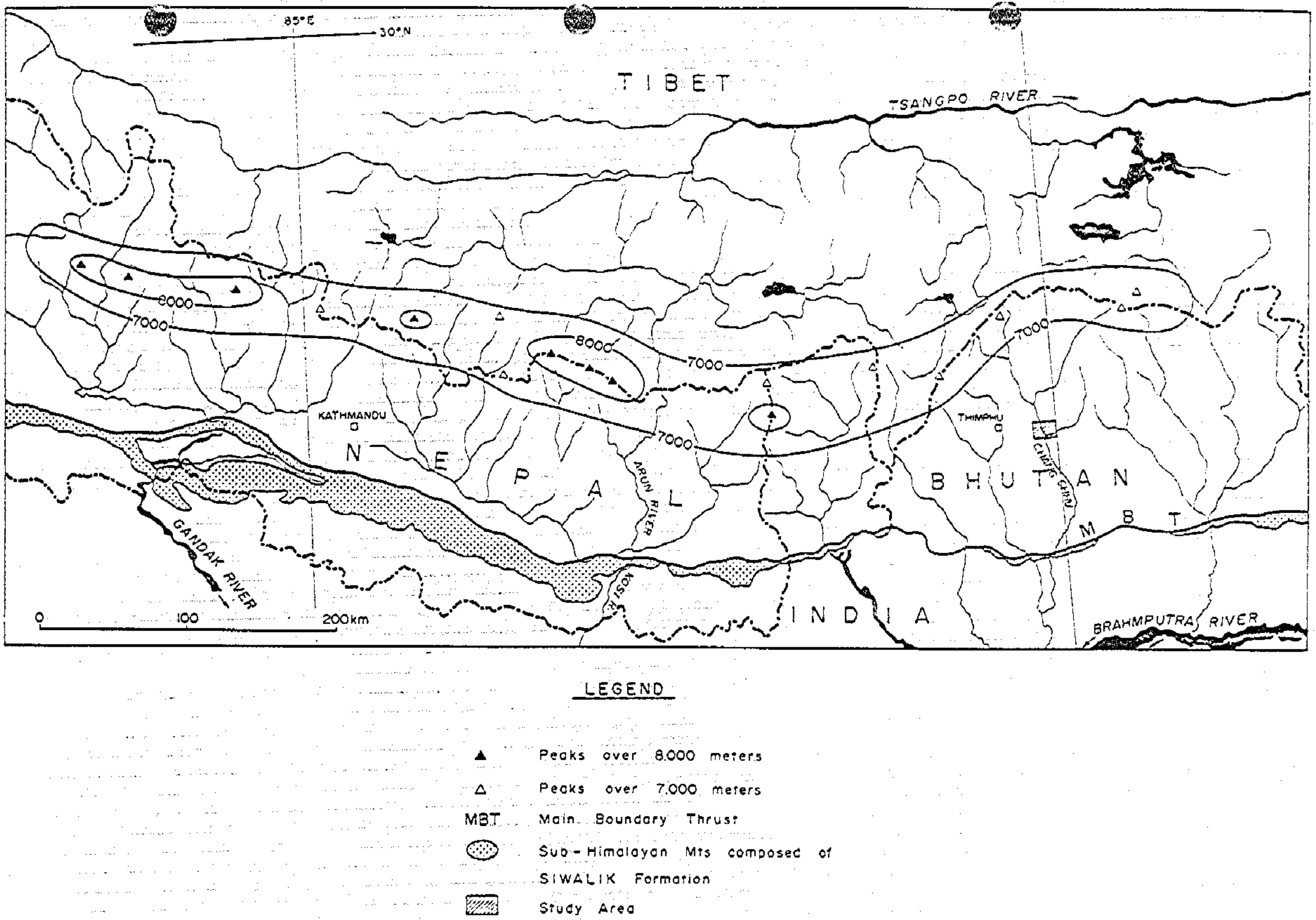


Fig. D.1.1 SUMMIT LEVEL AND DRAINAGE SYSTEM OF HIMALAYAN REGION

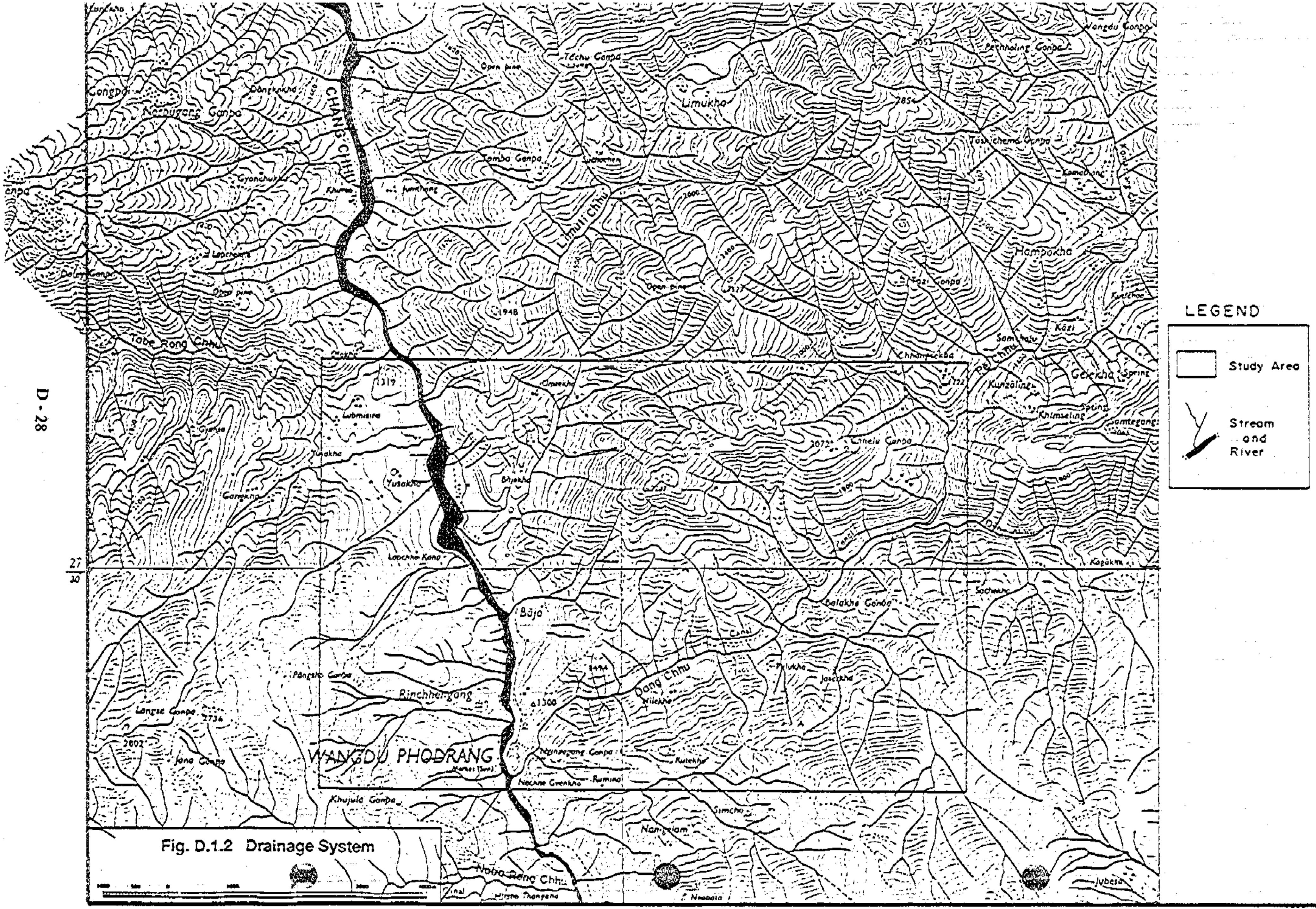


Fig. D.1.2 Drainage System

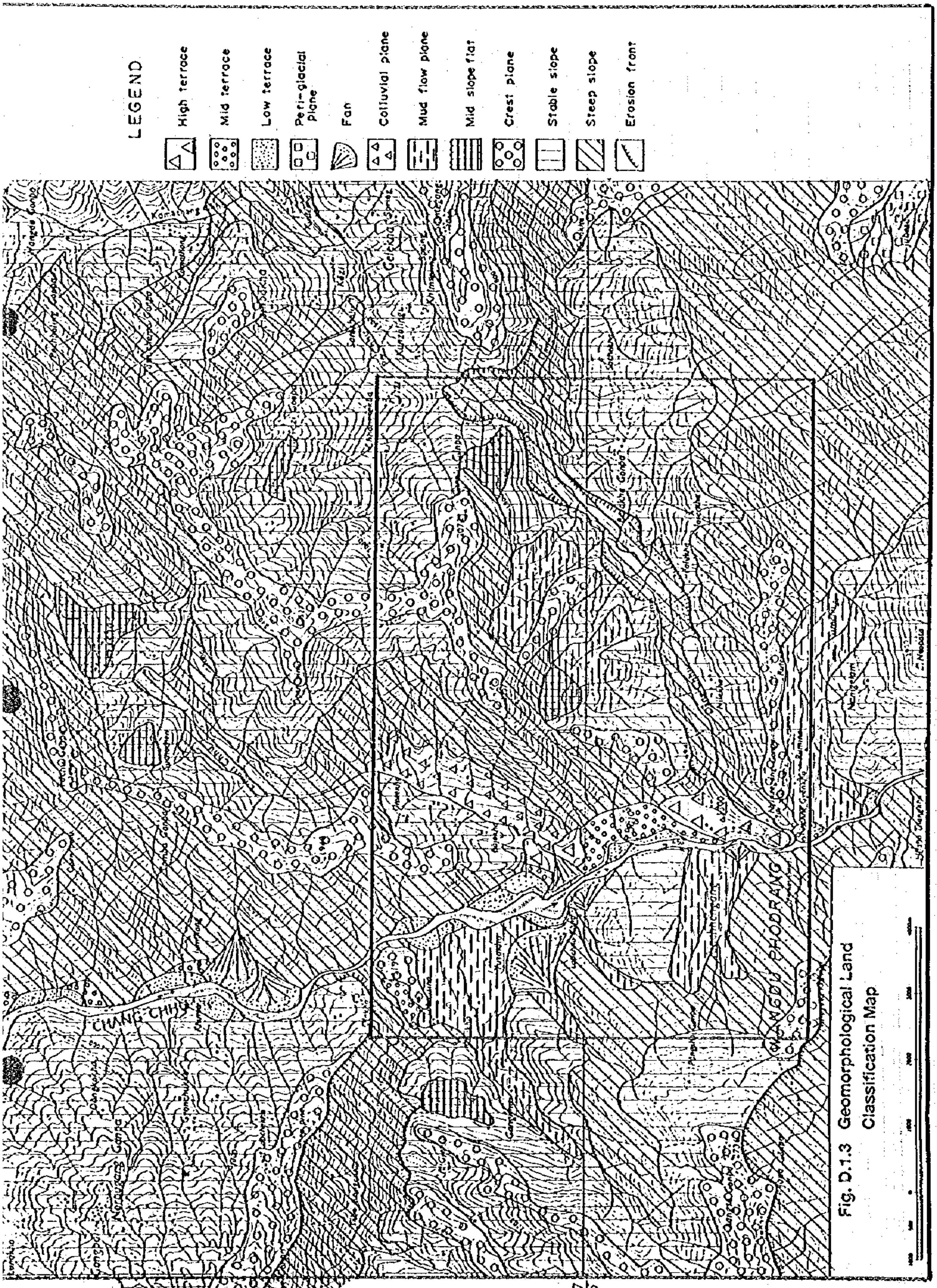
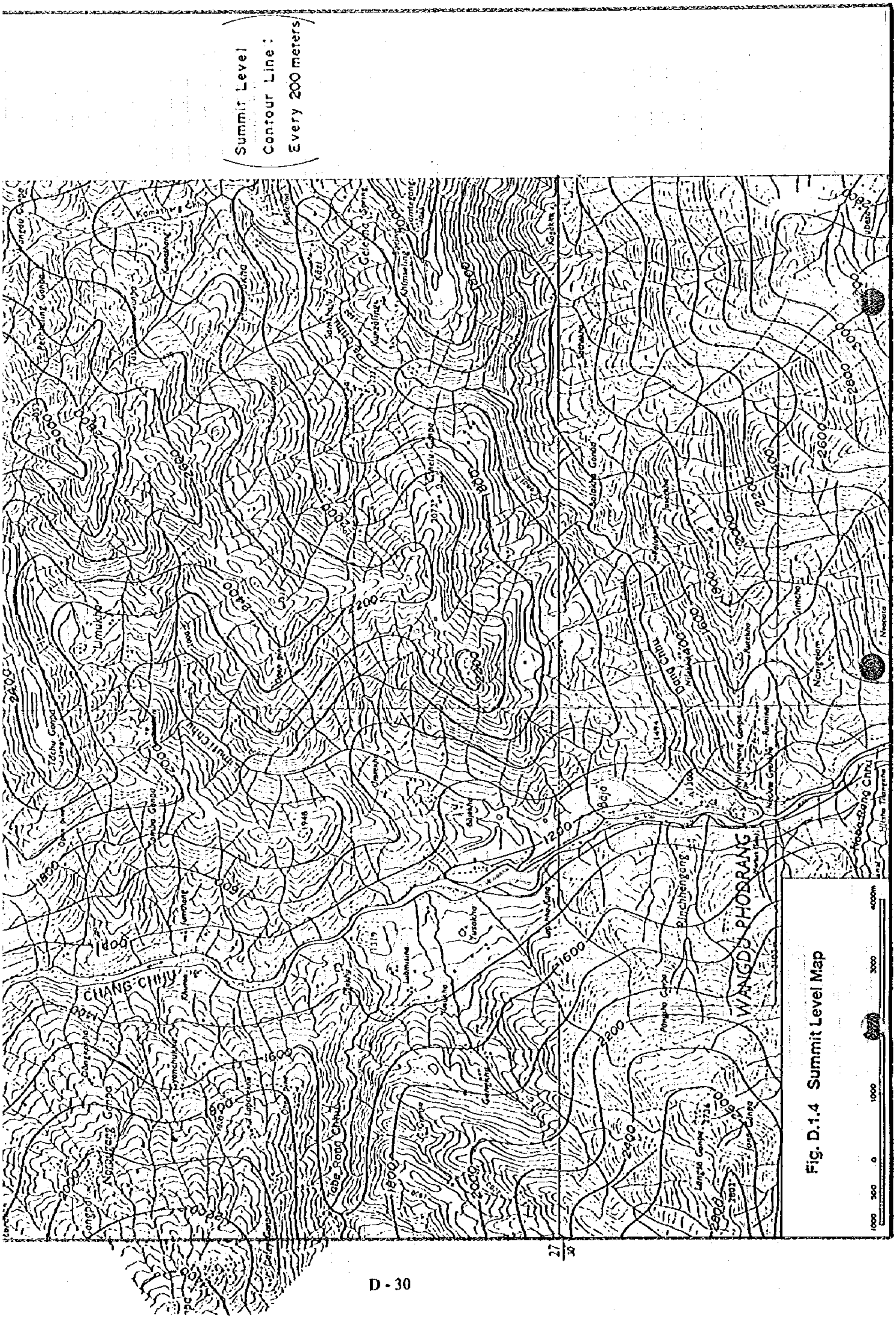


Fig. D.1.3 Geomorphological Land Classification Map



Summit Level
Contour Line :
Every 200 meters

Fig. D.1.4 Summit Level Map

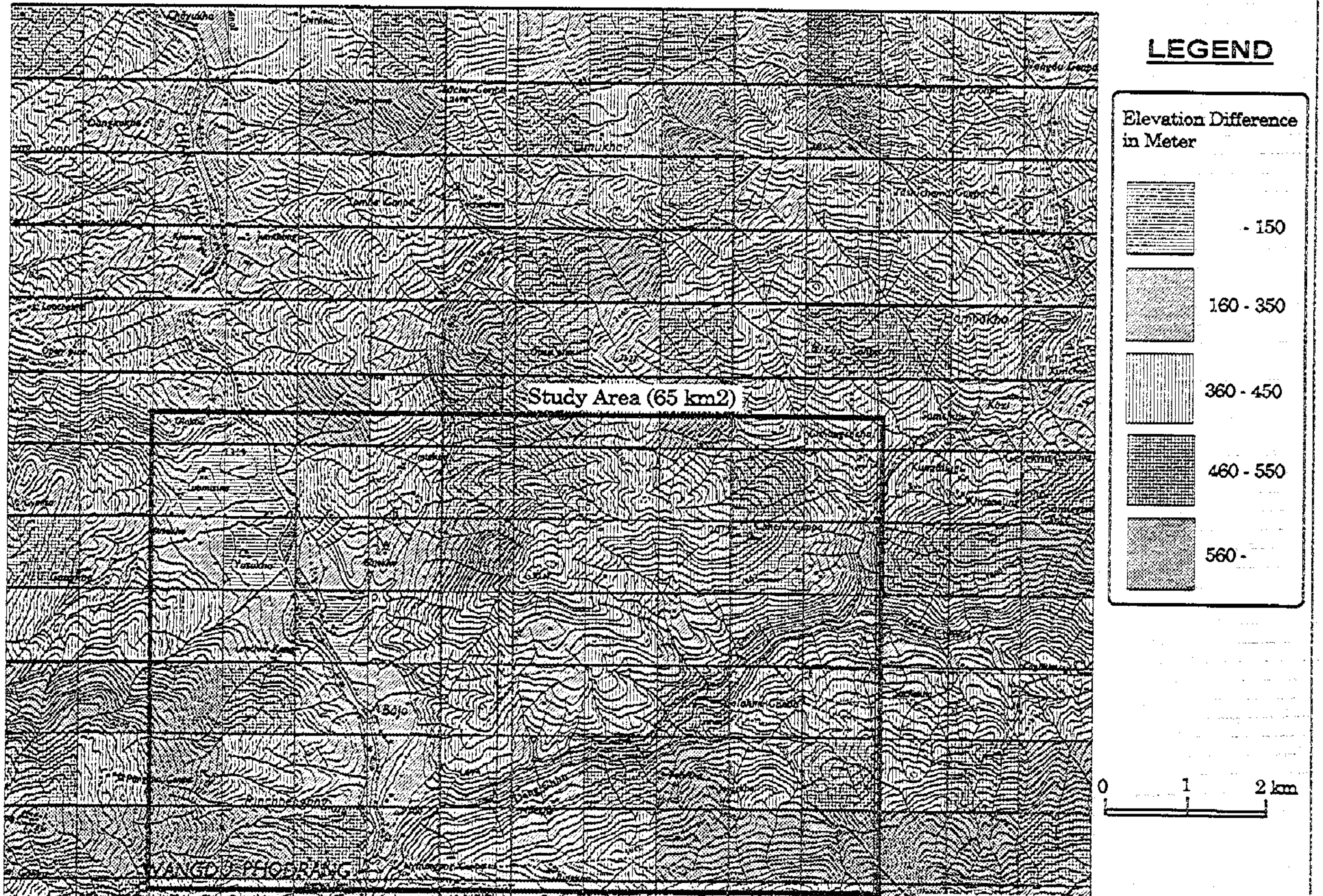


Fig. D.1.5 RELATIVE RELIEF MAP

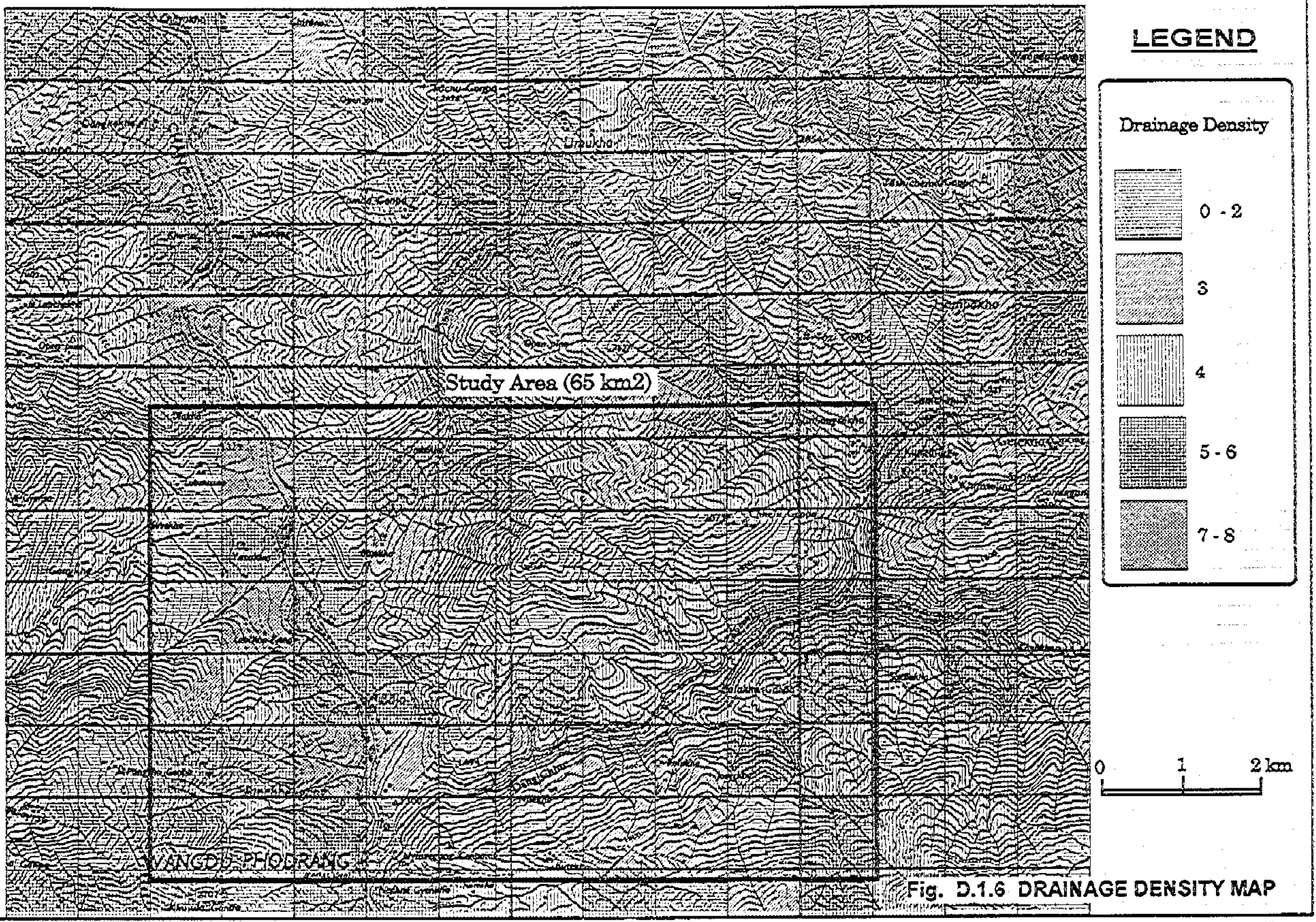


Fig. D.1.6 DRAINAGE DENSITY MAP

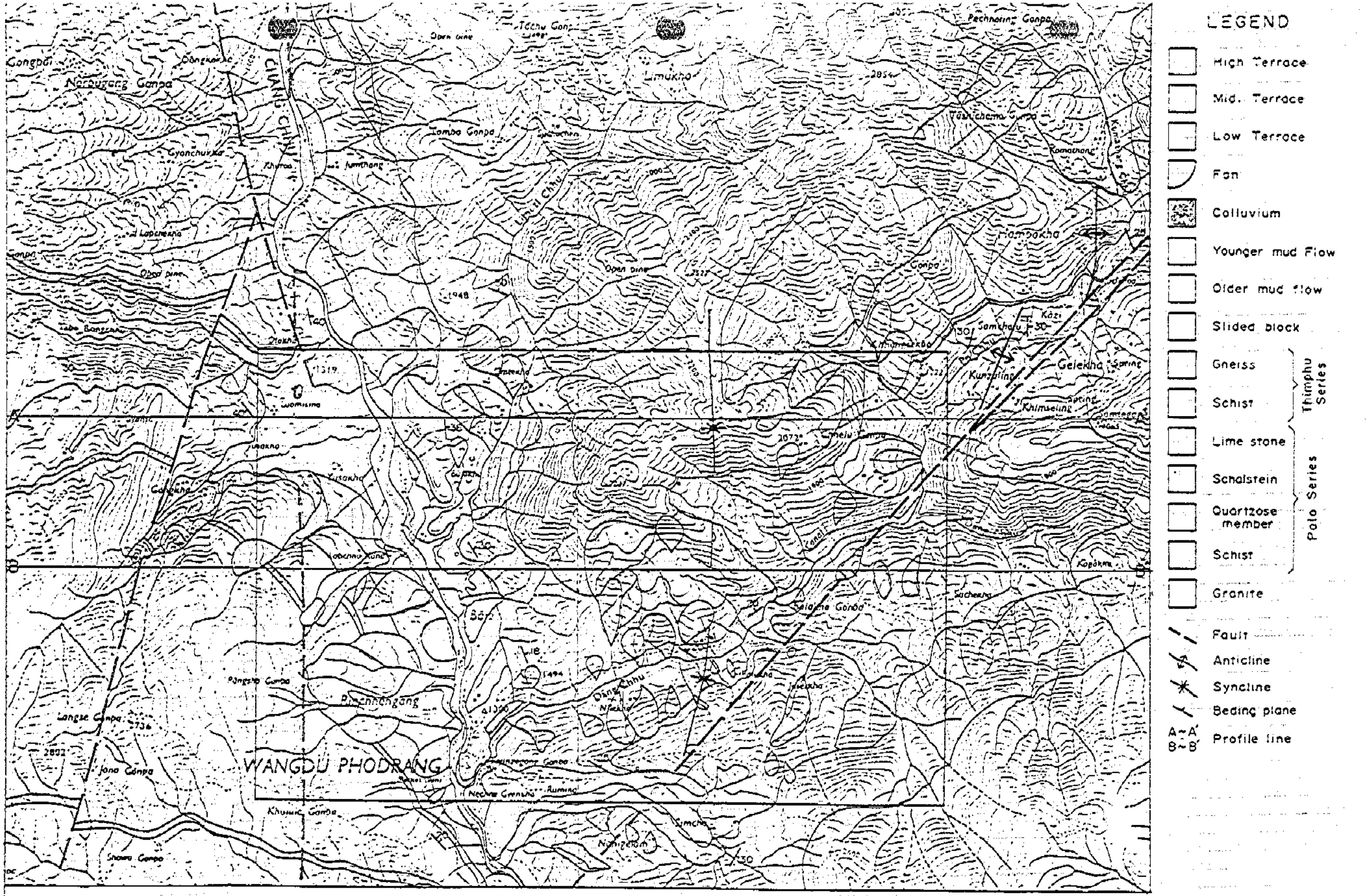


Fig. D.2.1 GEOLOGICAL MAP

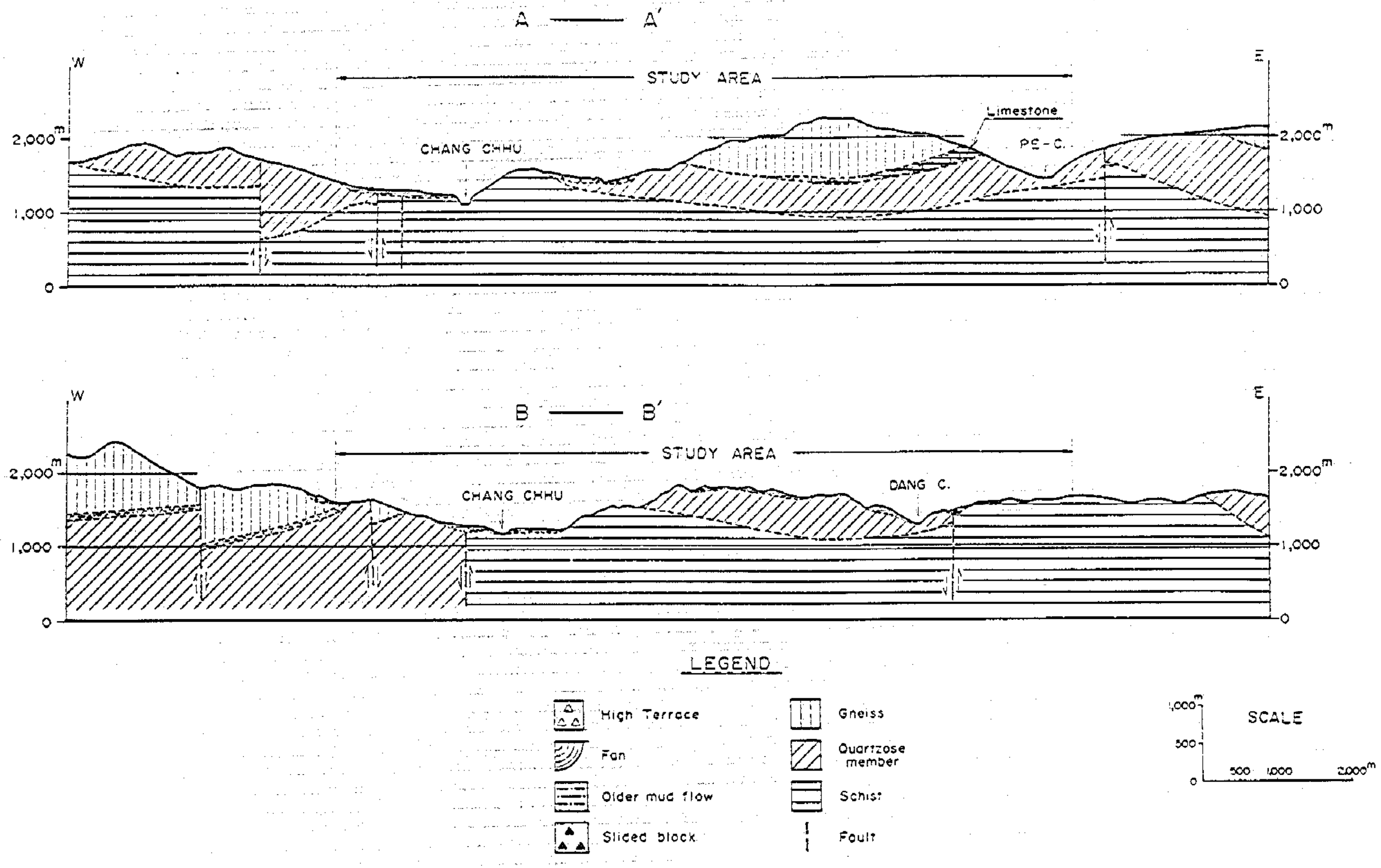


Fig. D.2.2 GEOLOGICAL PROFILE

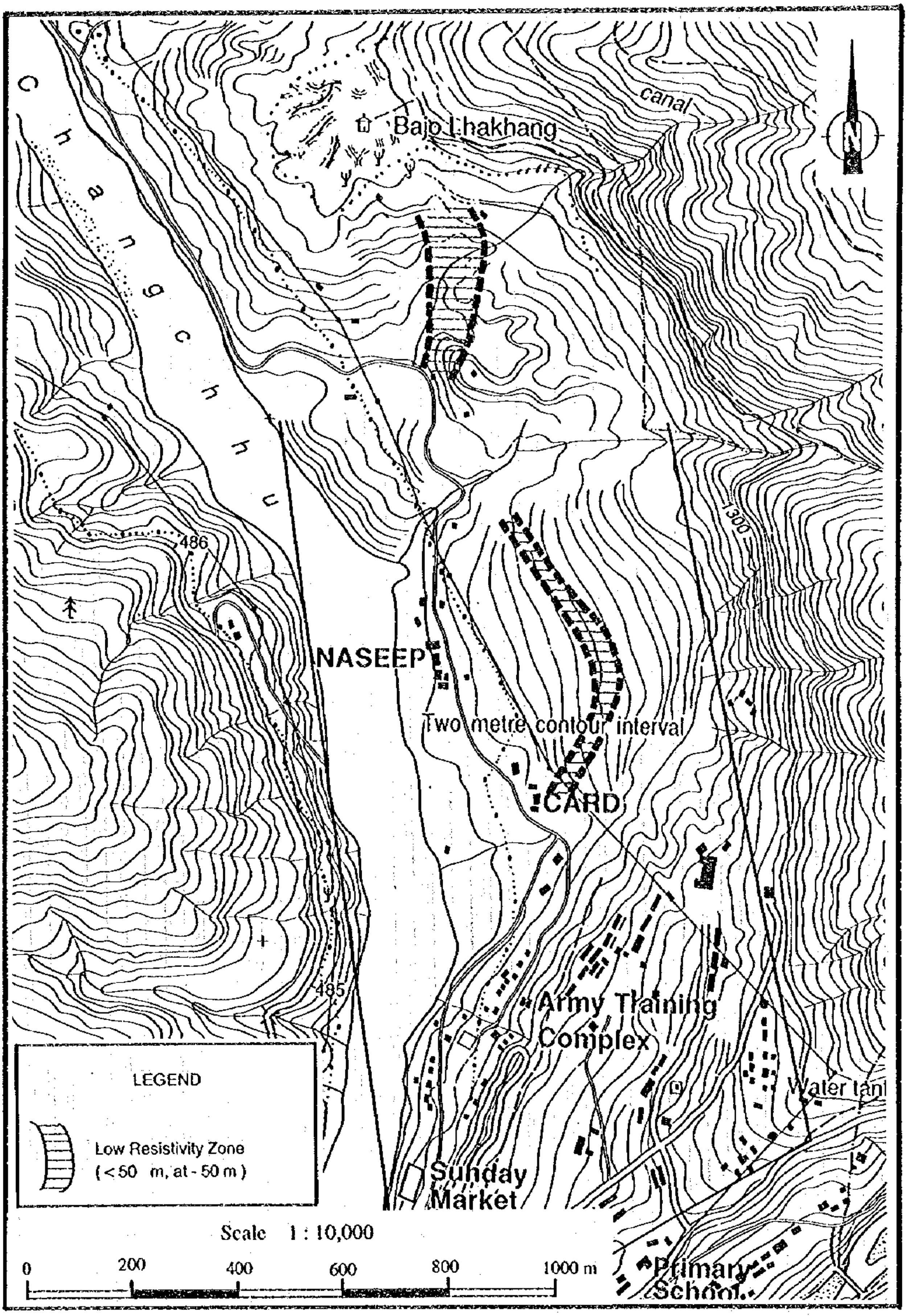


Fig. D.3.1 ANCIENT RIVER CHANNELS FOUND BY ELECTRIC SURVEY

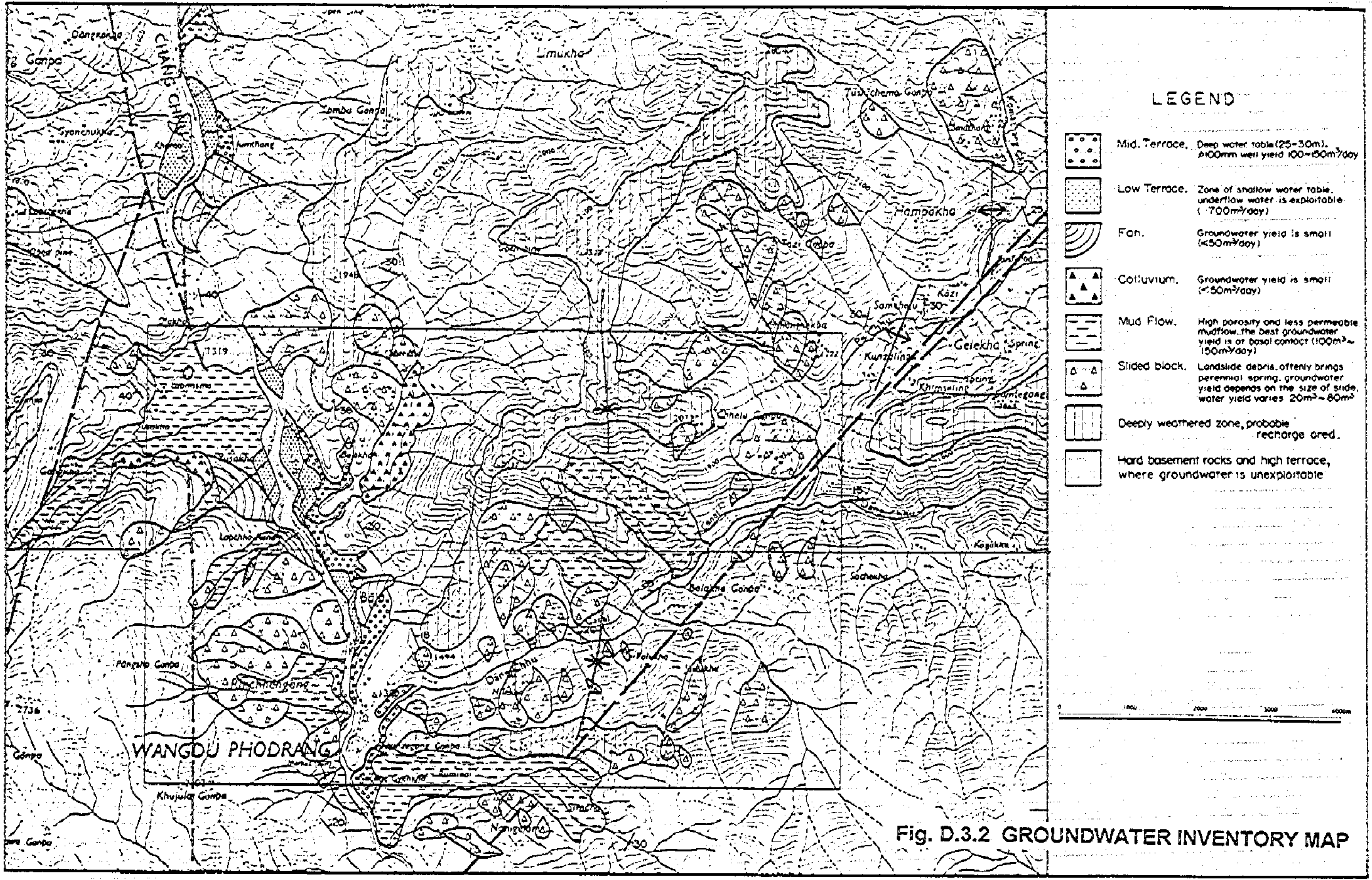


Fig. D.3.2 GROUNDWATER INVENTORY MAP