APPENDIX E
FIGURES

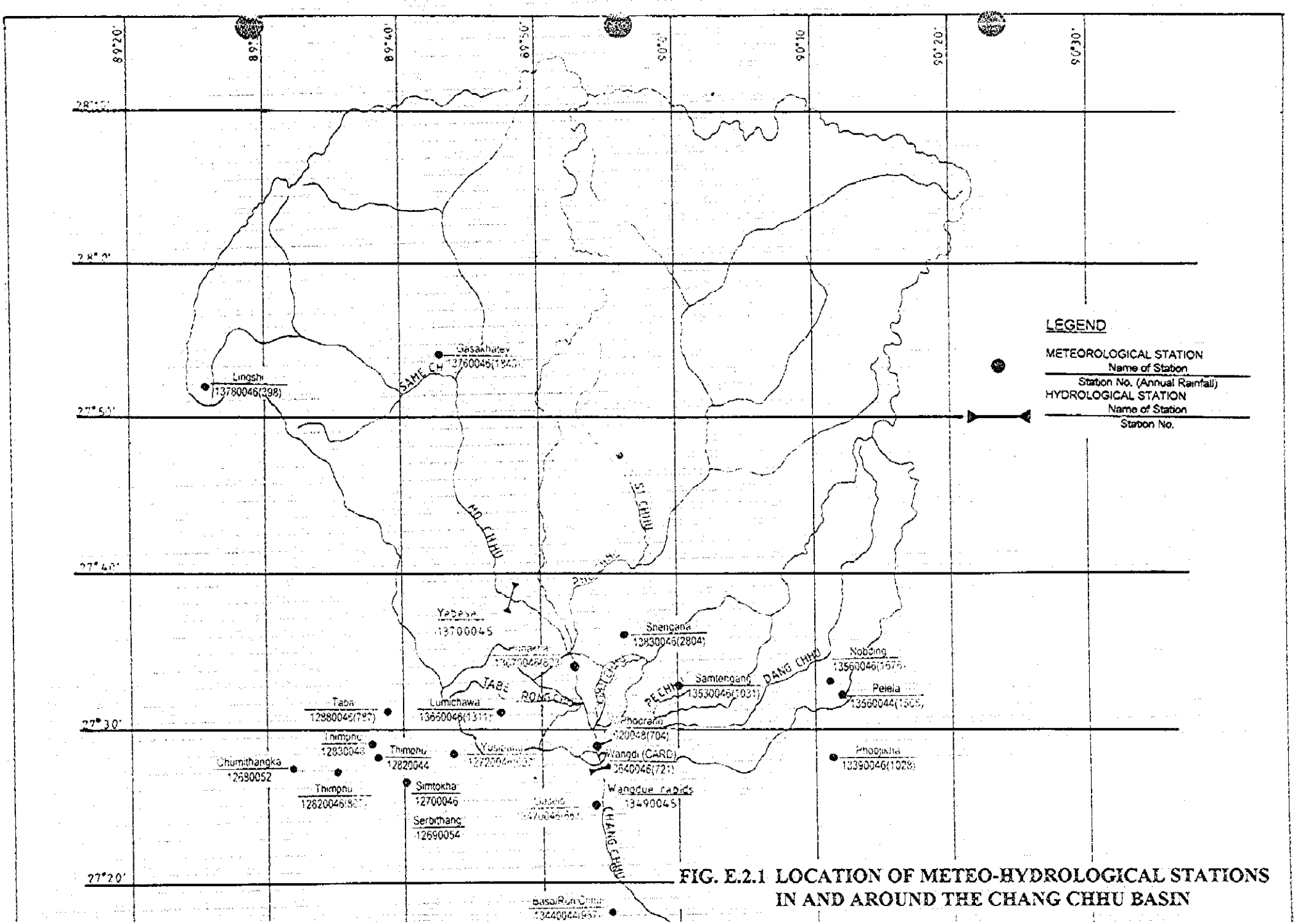


FIG. E.2.1 LOCATION OF METEO-HYDROLOGICAL STATIONS IN AND AROUND THE CHANG CHHU BASIN

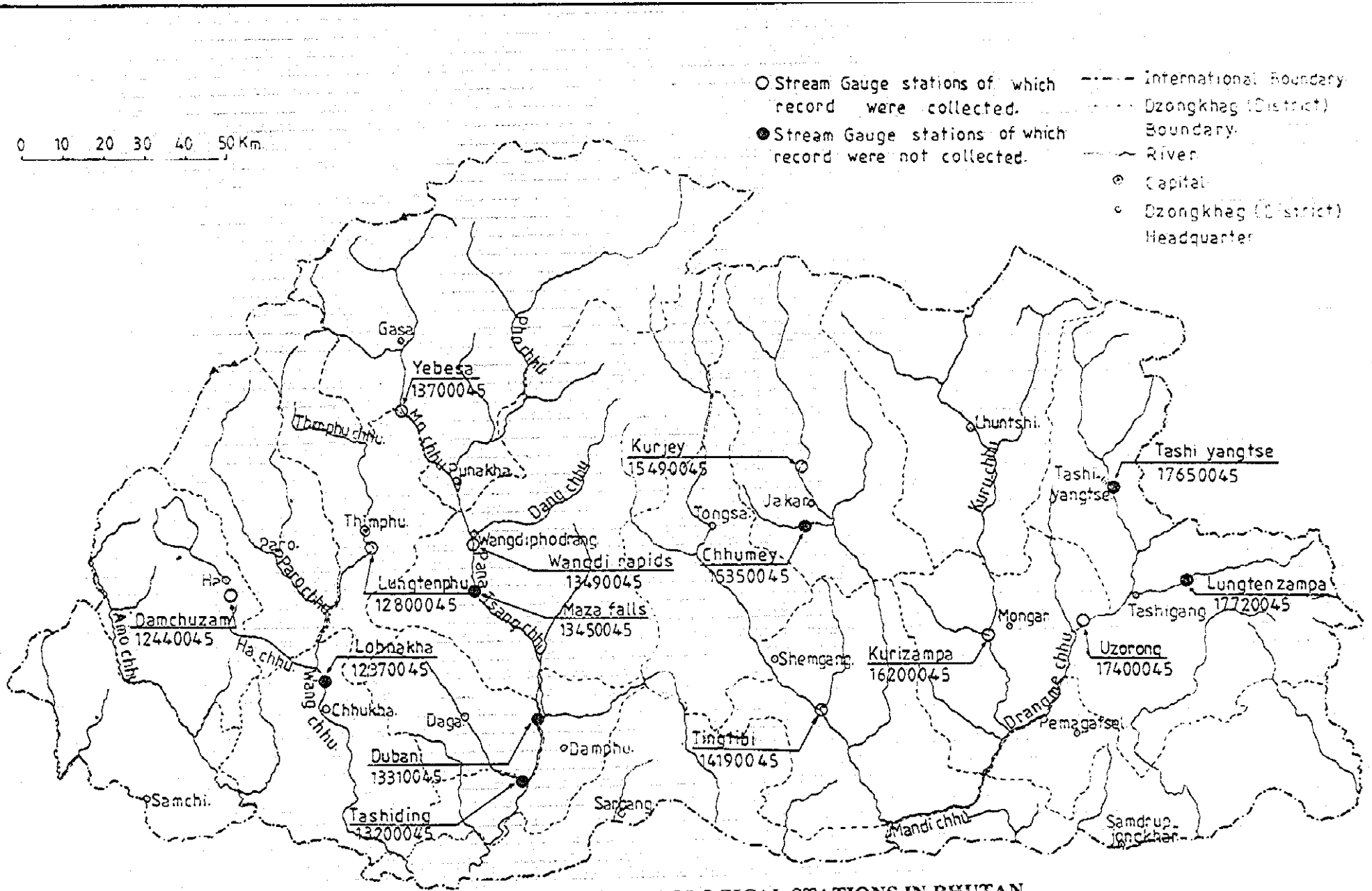


FIG. E.2.2 LOCATION OF HYDROLOGICAL STATIONS IN BHUTAN

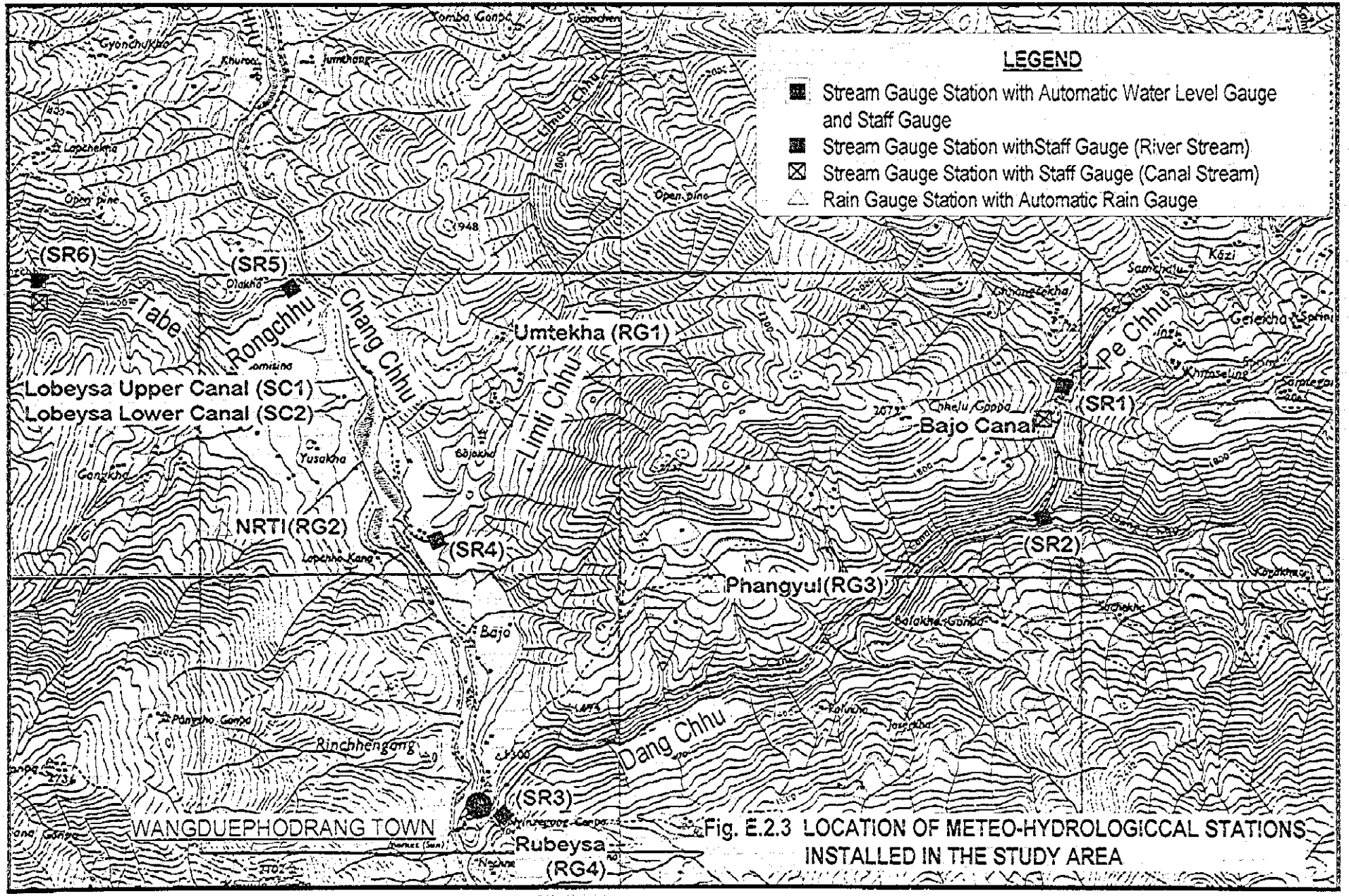


Fig. E.2.3 LOCATION OF METEO-HYDROLOGICCAL STATIONS INSTALLED IN THE STUDY AREA

(1) Rainfall Data

No.	Code	Name	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
1	12620046	Gidakom										
2	12720046	Yusipang										
3	12740044	Dochula										
4	12820046	Thimphu										
5	12860048	Thimphu'E'										
6	12880046	Taba										
7	13340046	Tasithang										
8	13390046	Phobjevkha										
9	13410046	Daga Uma										
10	13440044	Basochu										
11	13470046	Gaselo										
12	13530046	Samtangang										
13	13550046	Nobding										
14	13560044	Pele La										
15	13620048	W/phodrang										
16	13640046	Wangdue (CARD)										
17	13660044	Lumichawa										
18	13670046	Punakha										
19	13760046	Gasakhatey										
20	13780046	Lingishii										
21	13830046	Shegana										

Note ▽ : Data not available △ : Monthly data only available

■ : Data completed □ : Data not completed

Fig. E.3.1 BAR CHART OF DATA CONTINUITY (1/2)

(2) Temperature Data

No.	Code	Name of Station	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994
1	12620046	Gidakom	▽▽▽	▽▽▽▽	▽▽▽▽	▽■■■	■■■■	■■■□	■■■■	■■■■	■■■■	■■■■
2	12720046	Yusipang	□□▽	□■■■	■■■■	■■■■	□□□□	□□□□	□□□□	□□□□	□□□□	□□□□
3	12820046	Thimphu	□■□	□■□□	■■■□	■■■■	■■■□	■■■■	■■■□	▽■■■	□□□■	□□□□
4	12880046	Taba	□■□	□□□□	■■□□	□□ □	□■□	□■	□■▽▽	▽□■■	▽□	
5	13340046	Tasithang	▽▽▽	■■■□	■■■■	■■■■	■■■□	■■■■	■■■■	■■■□	▽▽▽▽	□■■□
6	13390046	Phobjevkha	□▽	□■	■□□	■■	■□□■	■■□	□■□□	□■□	■■■■	■□□■
7	13410046	Daga Uma	□■■	□■	□■■■	□□□□	□□□□	□□□	□□	■□		
8	13440044	Basochu						■□■■	■■■■	□■□■	□■□□	□■■□
9	13470046	Gaselo	□■■	■□■□	■■■■	□■■■	■■■■	■■□□	□□□□	□		
10	13530046	Samtangang	■■■	■■■■	■■■■	■■■■	■■■■	■■■□	■■■■	■■■■	□□▽▽	■■■■
11	13550046	Nobding	▽▽▽	▽▽▽▽	▽▽▽▽	□■■■	■■■■	■■■■	■■■■	□■■■	■■■■	■■■■
12	13640046	Wangdue (CARD)	□■■	■■■■	■■■■	■■■■	■□□□	■■■■	□□■■	□■■■	□■■■	□□■□
13	13660044	Lumichawa								■□■■	■□■■	□
14	13670046	Punakha	□■■	■■■■	□□□□	□	□□■	□□	■■■■	■■■■	■■■□	▽■■
15	13760046	Gasakhatev	□■■	■■■■	■■■■	▽▽▽▽	□□■□	□■■□	■□■□	□■□	□□□■	■■
16	13780046	Lingishii	□■□	■▽□	□□■□	□□□	□□□□	□□□□	▽▽▽▽	□		
17	13830046	Shegana	□■■	□□■■	■■■■	□■□□	□□□□	□□□□	■□■■	■■■■	■■□■	■■■■

Note □ : Data not Completed ▽ : Data not available
■ : Data Completed

(3) Hydrological Data

No.	Code	Name of Station	1991												1992												1993												1994											
			J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	Mi	A	M	J	J	A	S	O	N	D
1	12440045	Damchuzam on Haa Chhu								■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	□	■	■	□	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
2	12800045	Lungtenphu on Thimphu Chhu					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	□	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
3	13490045	Wangdue Rapids on Pho-Mo Chhu				□	□	□	□	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
4	13700045	Yebesa on Mo Chhu						□	□	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	□	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
5	14190045	Tinhtibi on Mangde Chhu					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
6	15490045	Kurjey on Chamkher Chhu					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
7	16200045	Kurizampa on Kuri Chhu					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
8	17400045	Uzorong on Gongri Chhu														■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Note ■ : Data Completed □ : Data not Completed

Fig. E.3.1 BAR CHART OF DATA CONTINUITY (2/2)

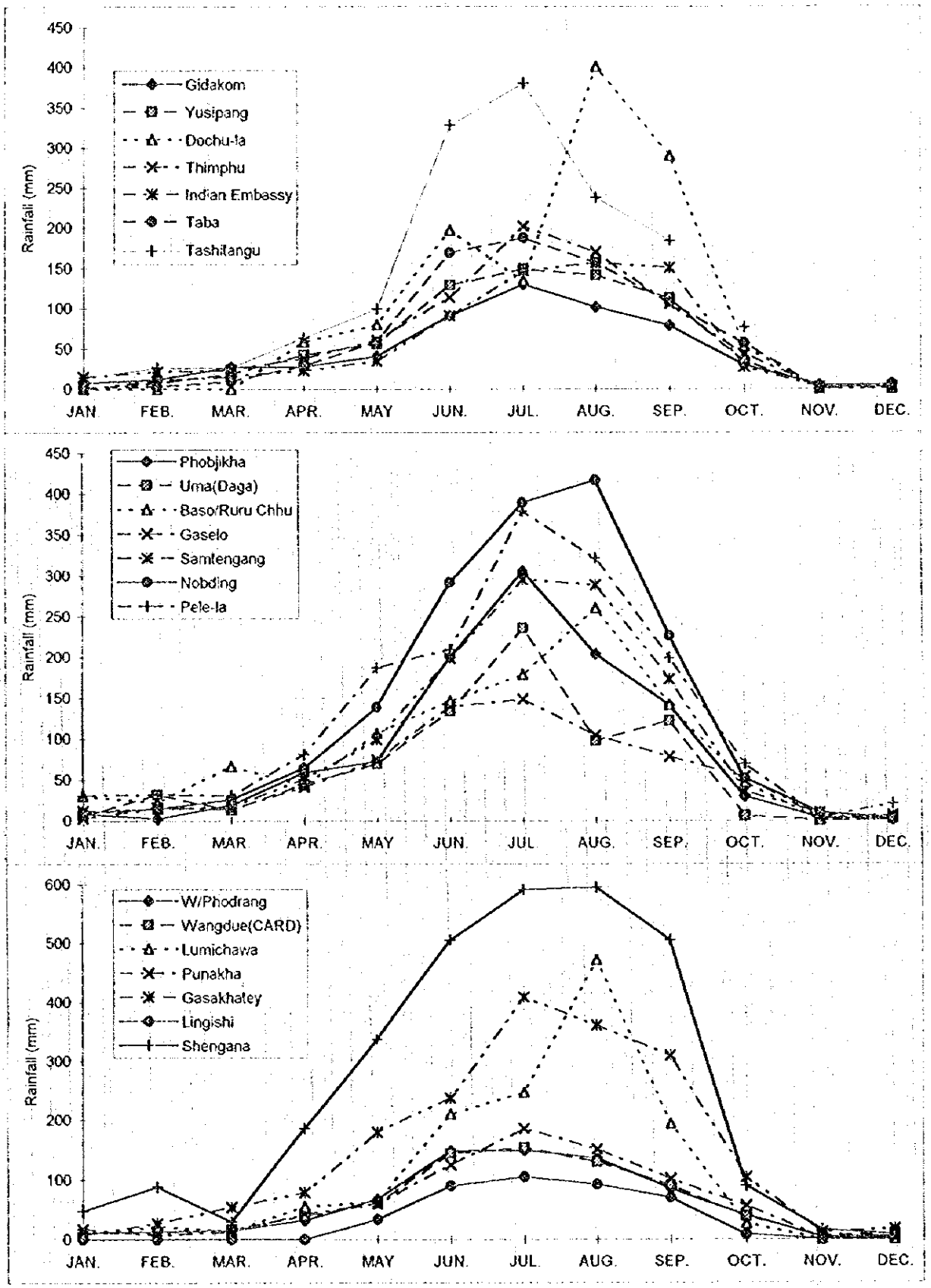


Fig. E.4.1 ANNUAL RAINFALL PATTERN

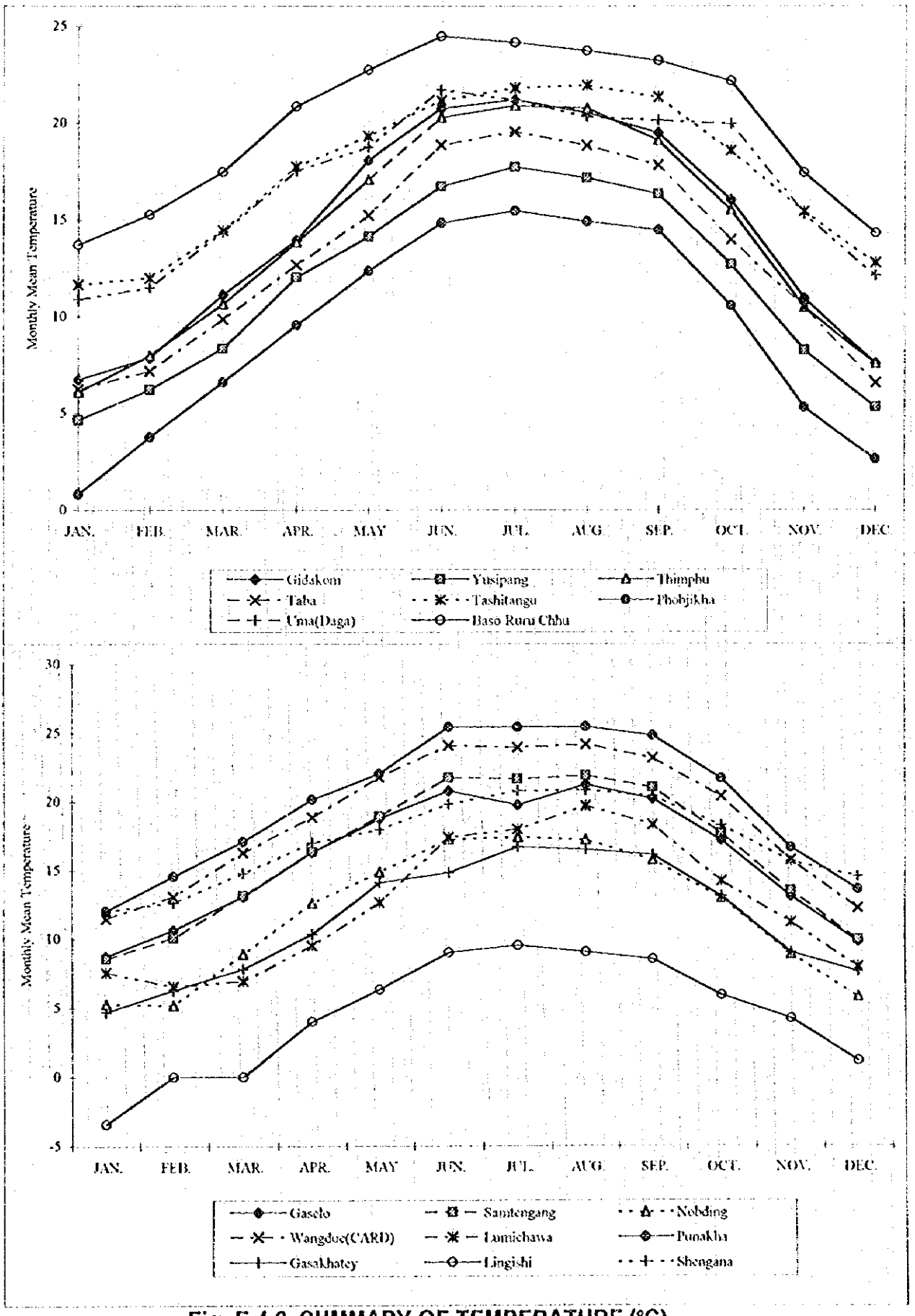


Fig. E.4.2 SUMMARY OF TEMPERATURE (°C)

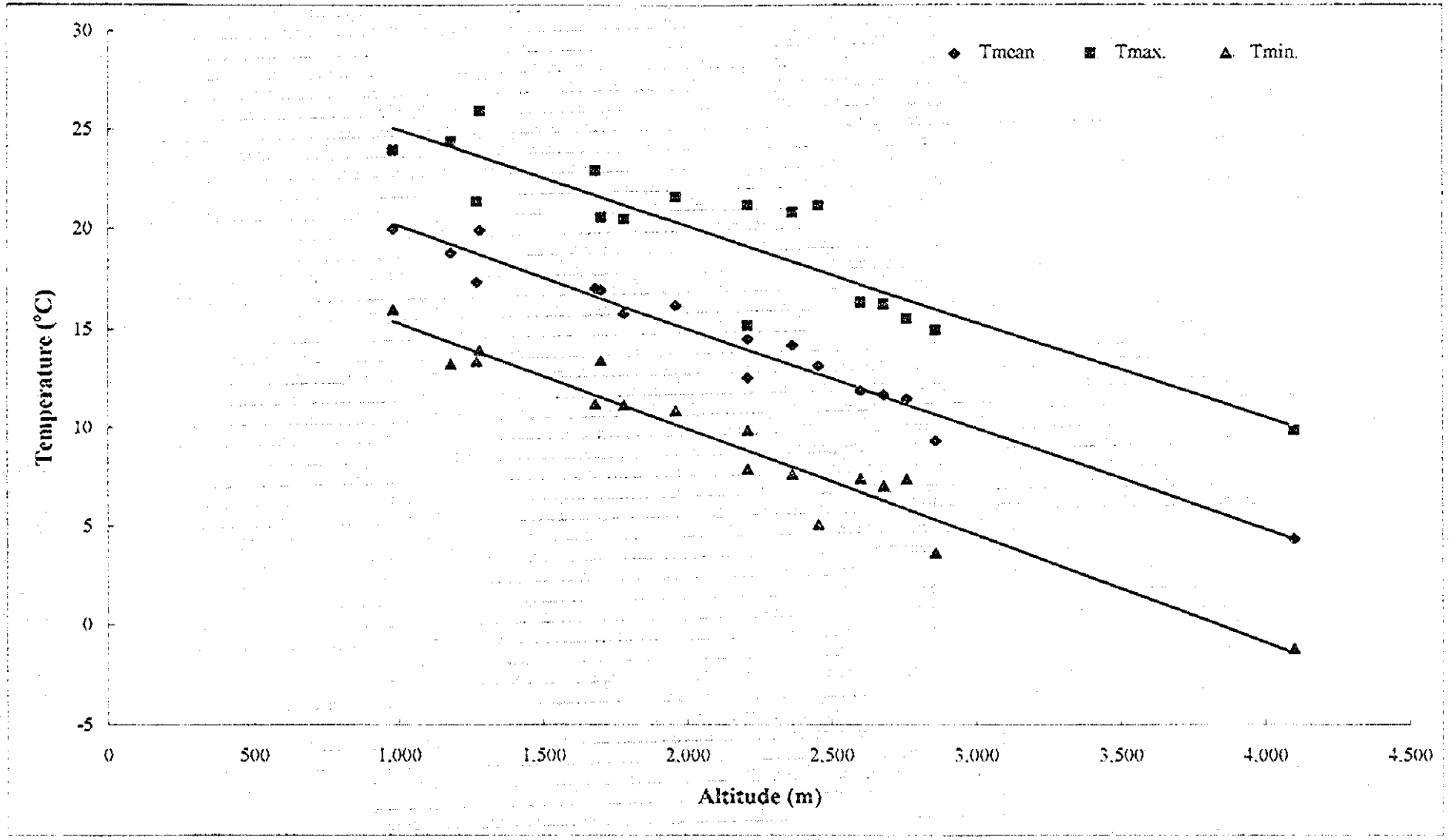
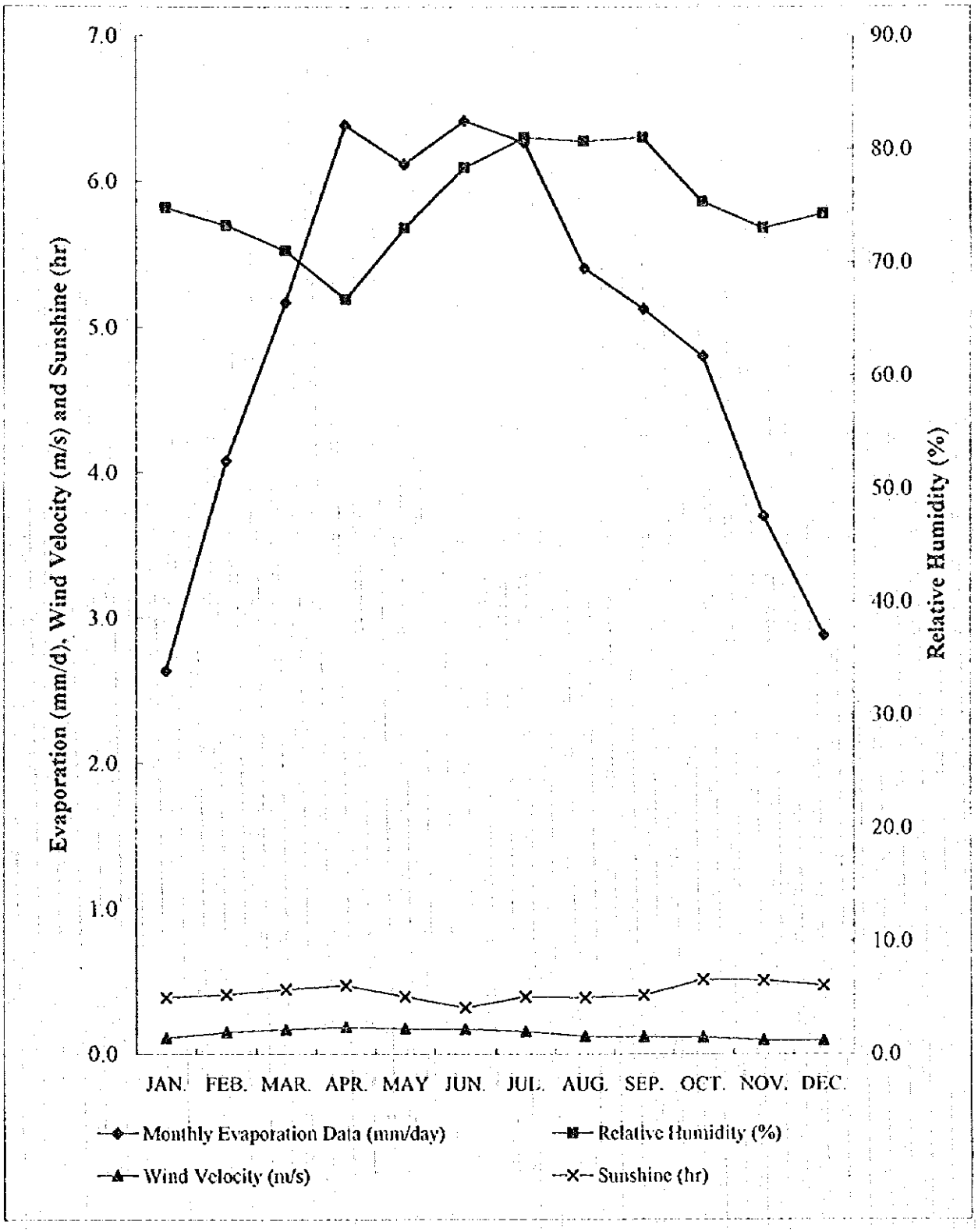


Fig. E.4.3 RELATIONSHIP BETWEEN ANNUAL MEAN TEMPERATURE AND ALTITUDE



Annual Mean Values			
Evaporation:	4.9 mm/d	Wind Velocity:	1.8 m/s
Sunshine:	5.5 hr	Relative Humid	75.2 %

Fig. E.4.4 SUMMARY OF OTHER METEOROLOGICAL DATA

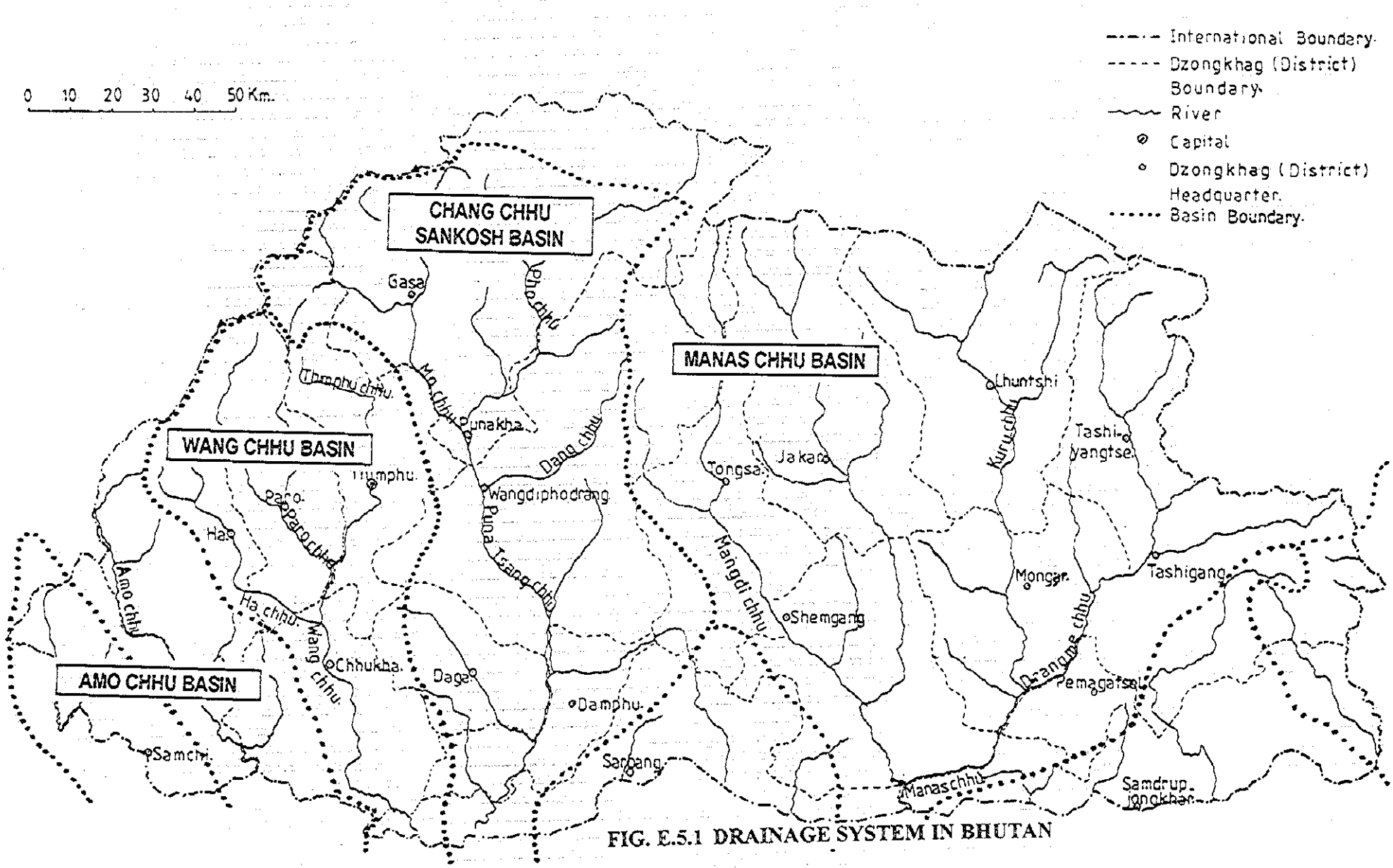


FIG. E.5.1 DRAINAGE SYSTEM IN BHUTAN

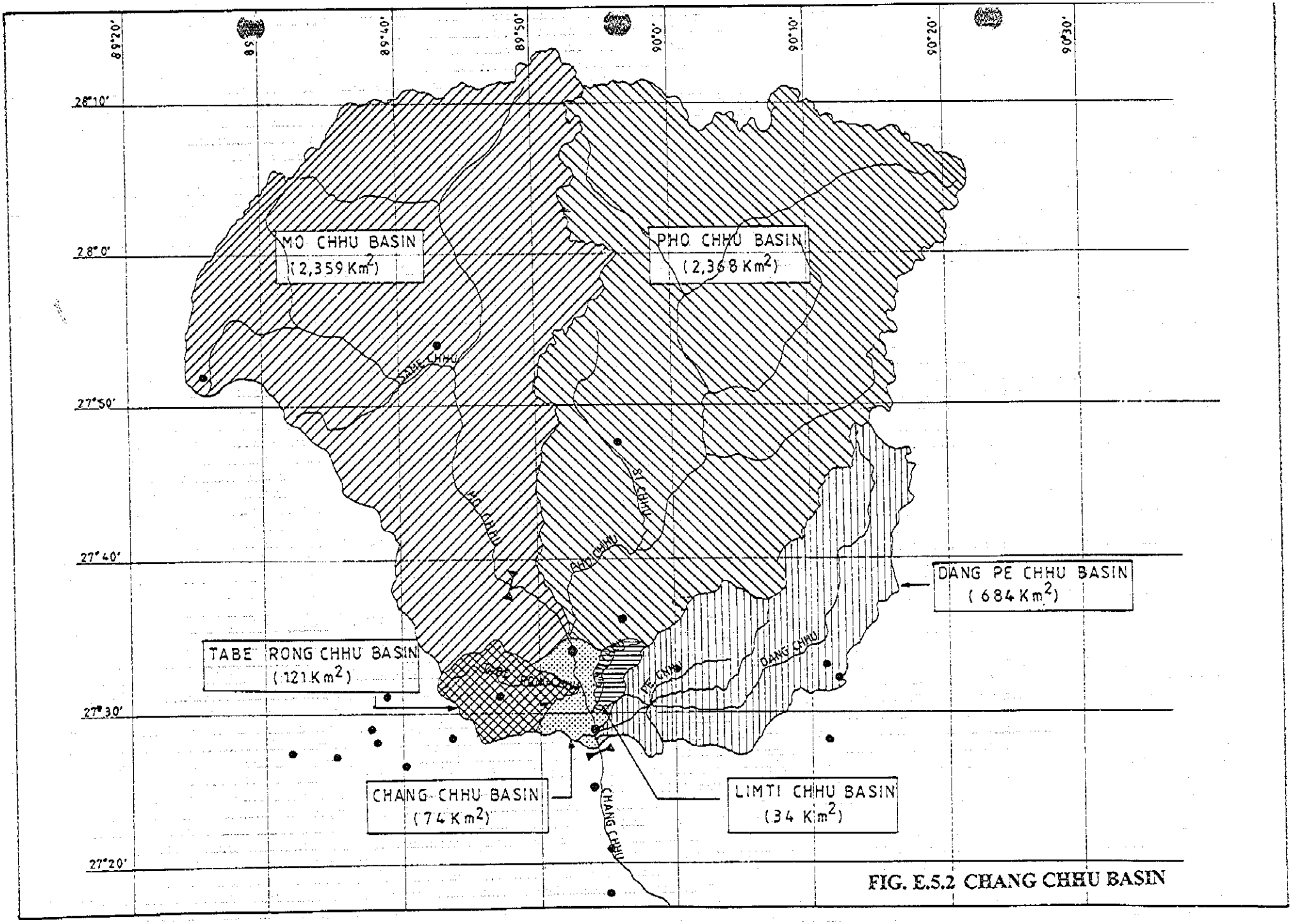


FIG. E.5.2 CHANG CHHU BASIN

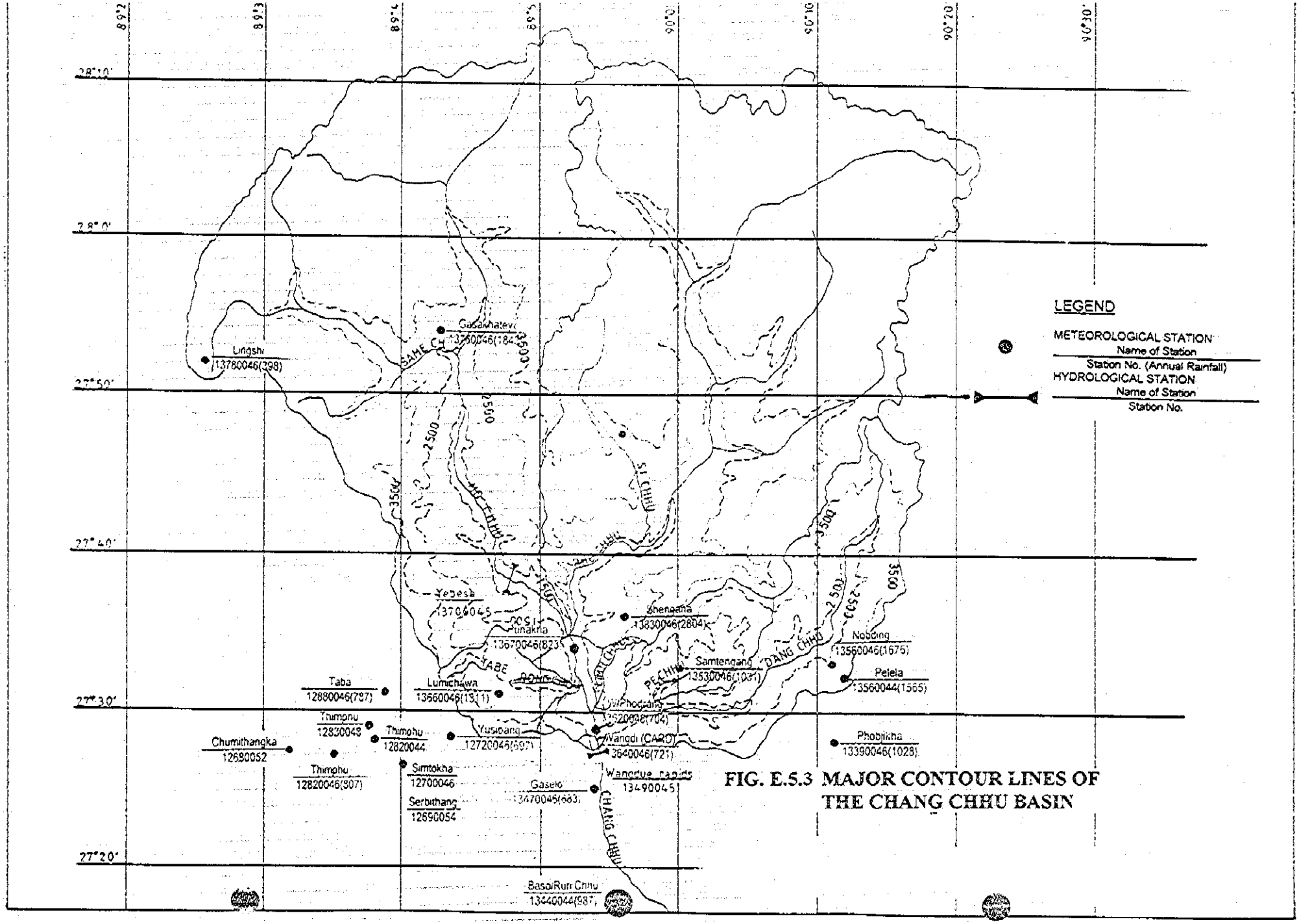


FIG. E.5.3 MAJOR CONTOUR LINES OF THE CHANG CHHU BASIN

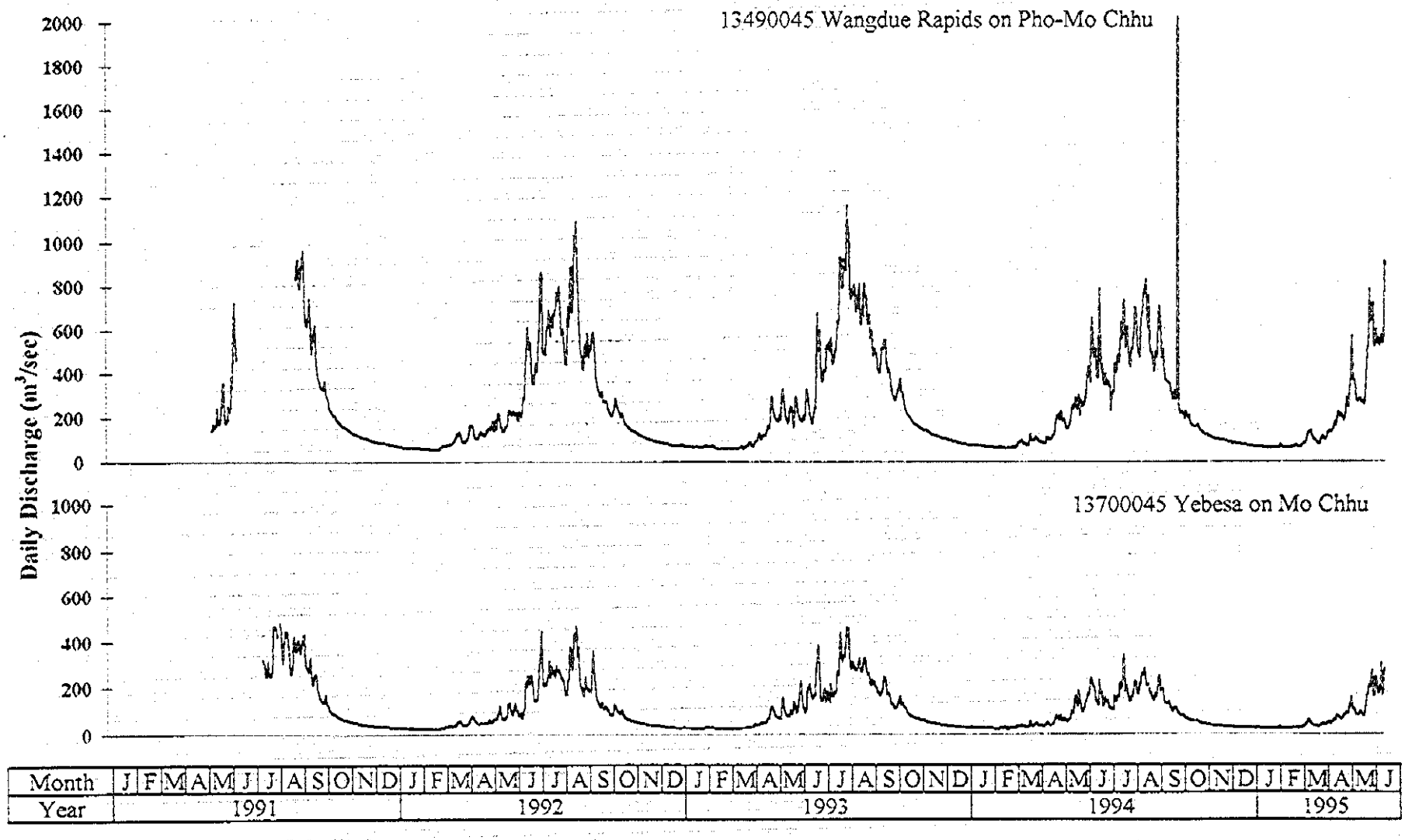


Fig. E.5.4 VARIATION OF DAILY DISCHARGE IN THE CHANG CHHU

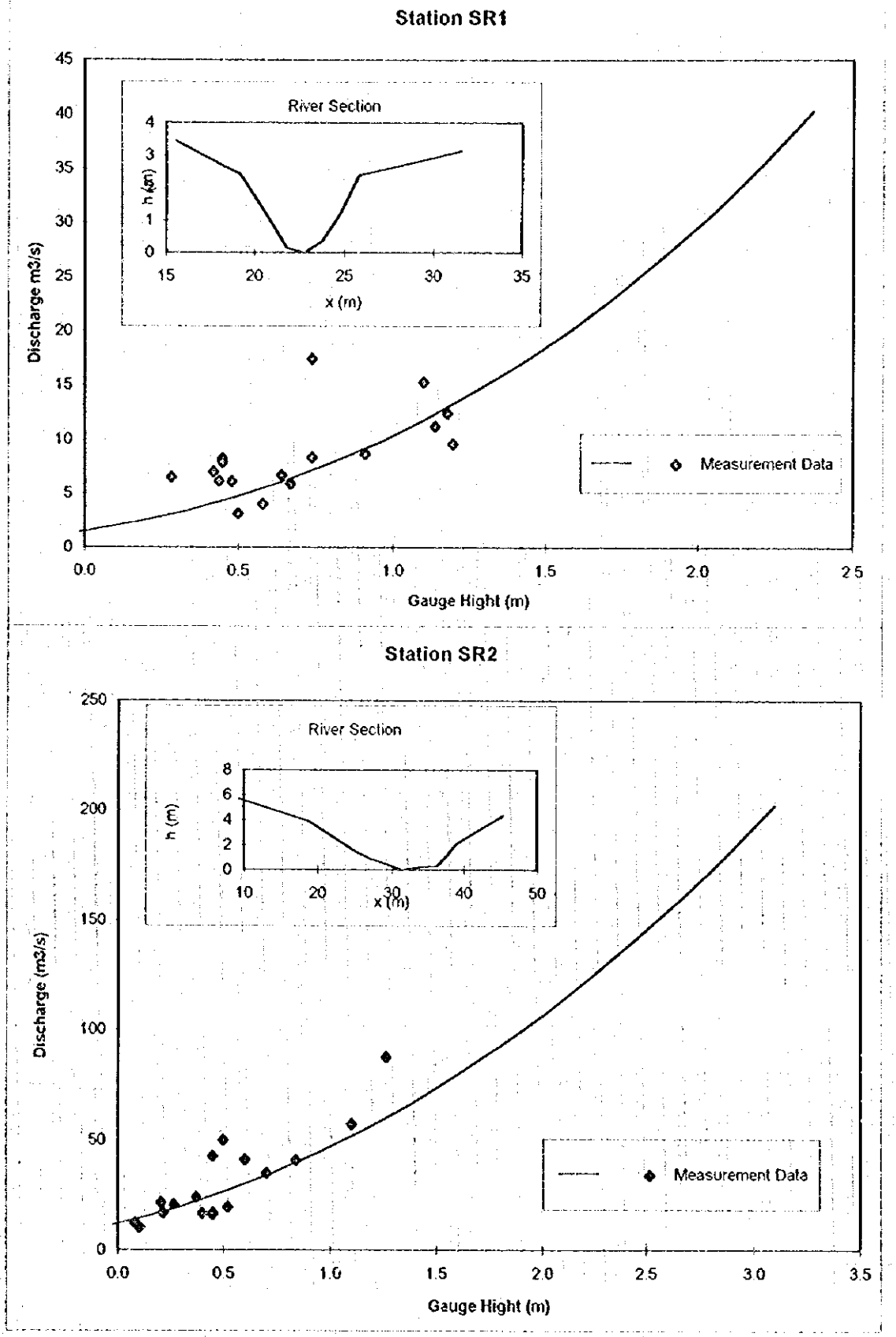


Fig. E.5.5 ESTIMATED H-Q RATING CURVE AT STREAM GAUGE STATION NEWLY INSTALLED (1/4)

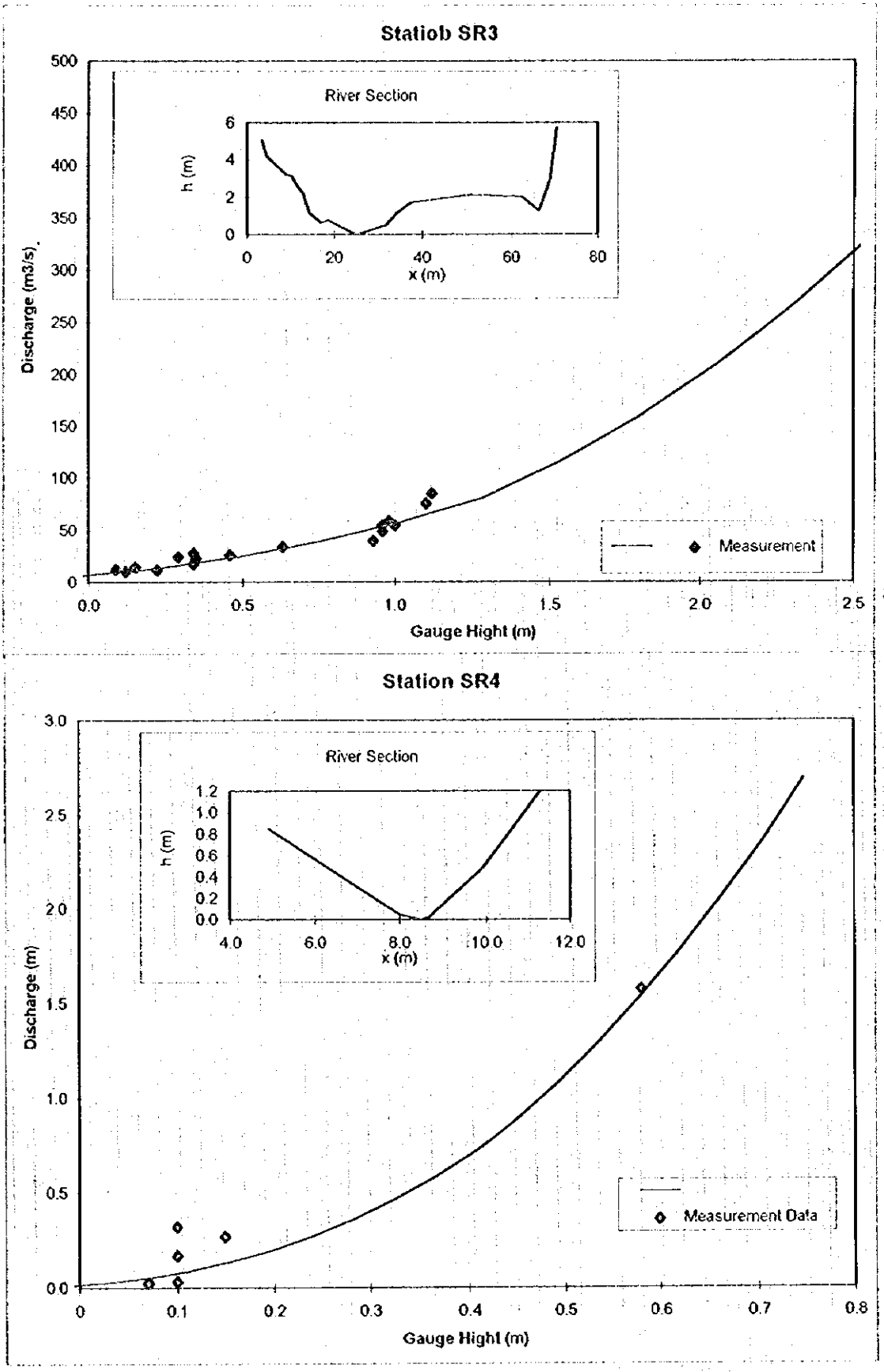


Fig. E.5.5 ESTIMATED H-Q RATING CURVE AT STREAM GAUGE STATION NEWLY INSTALLED (2/4)

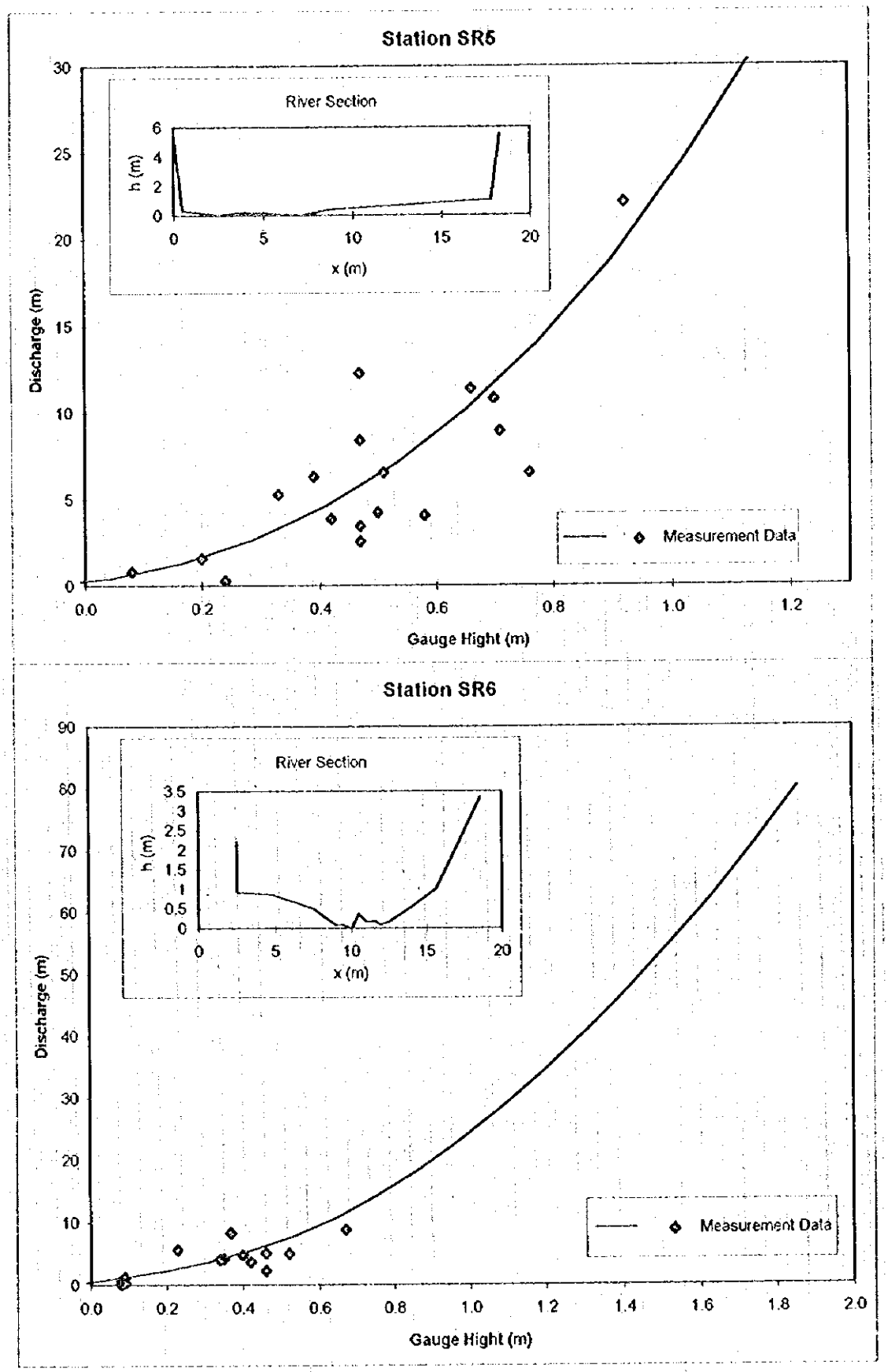


Fig. E.5.5 ESTIMATED H-Q RATING CURVE AT STREAM GAUGE STATION NEWLY INSTALLED (3/4)

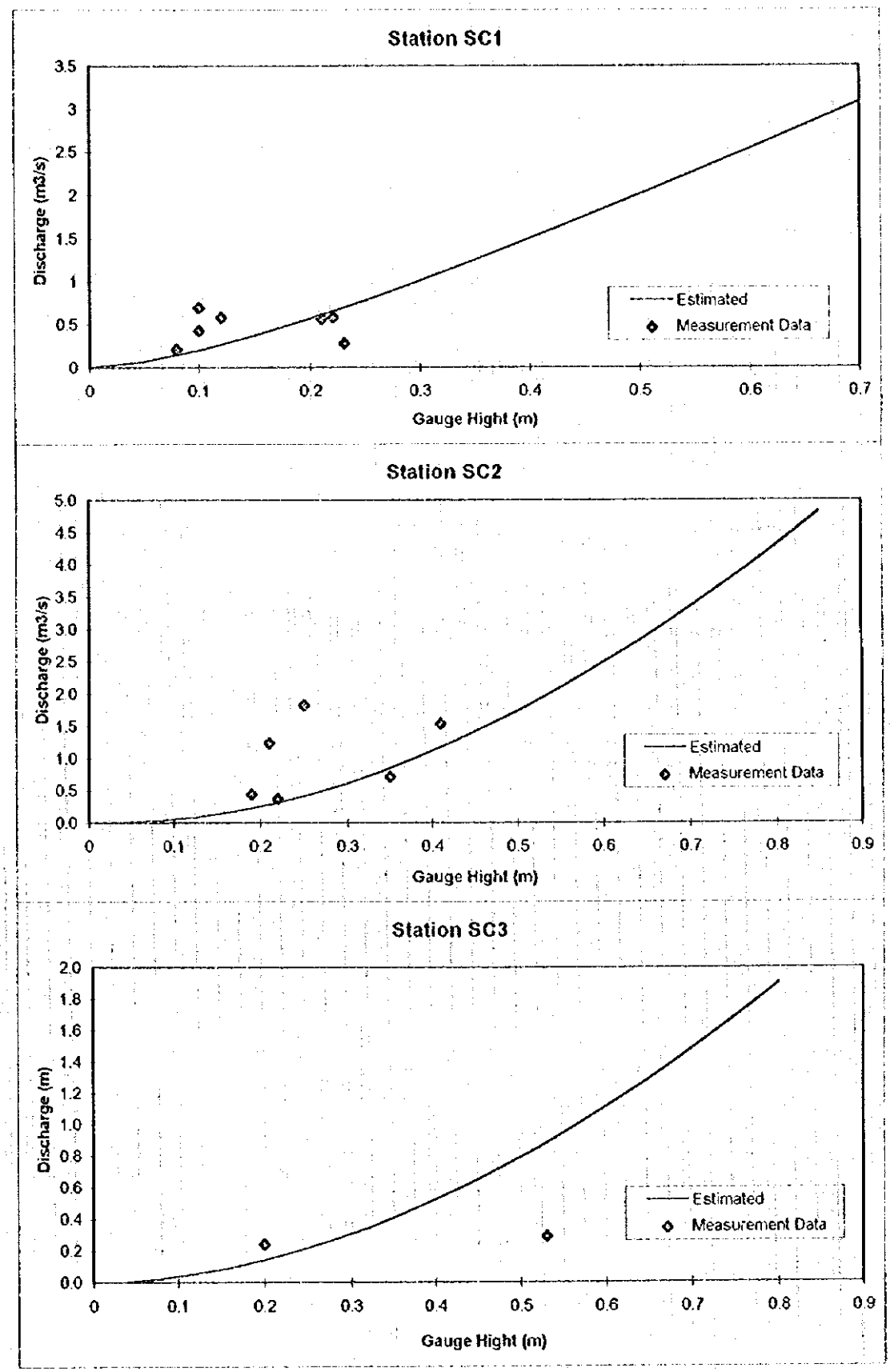


Fig. E.5.6 ESTIMATED H-Q RATING CURVE AT STREAM GAUGE STATION NEWLY INSTALLED (4/4)

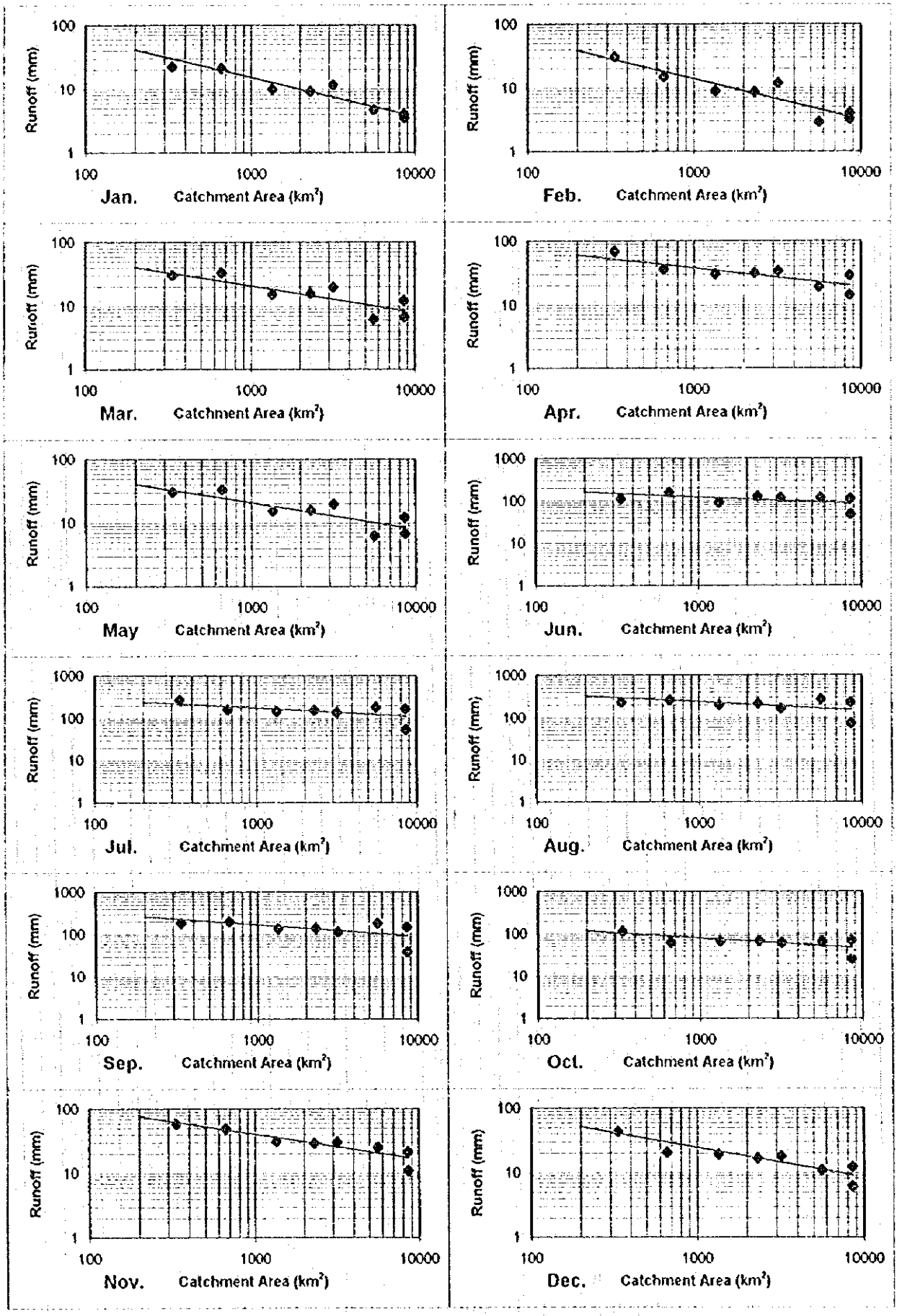
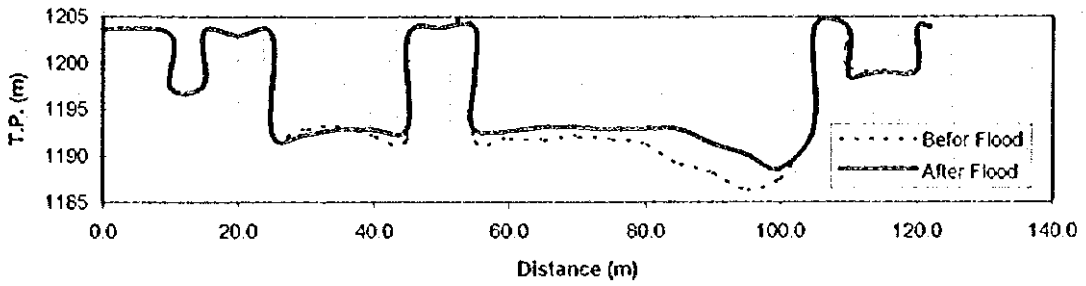
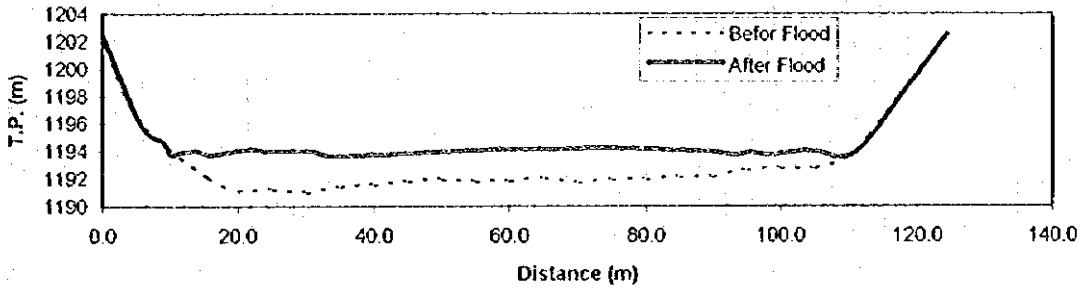


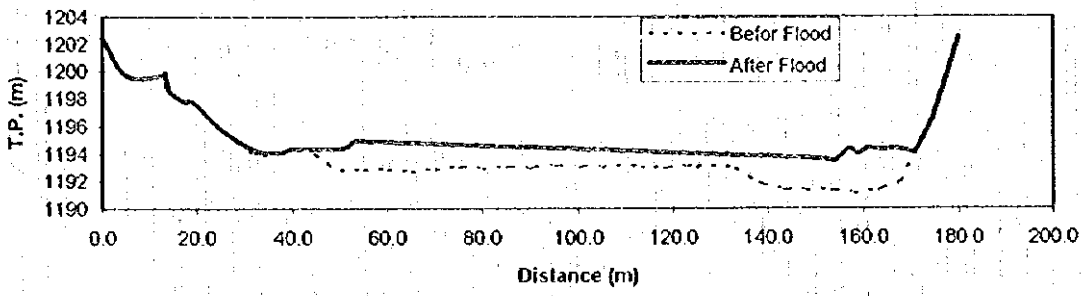
Fig. E.5.6 RELATIONSHIP BETWEEN CATCHMENT AREA AND RUNOFF



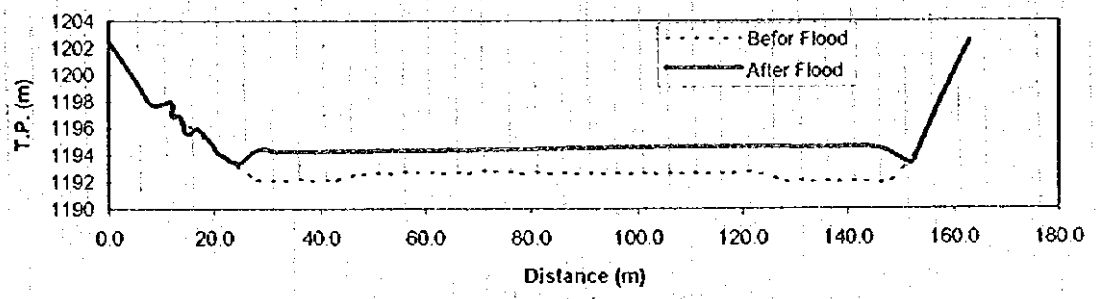
Wangdue Bridge (total length 0 m)



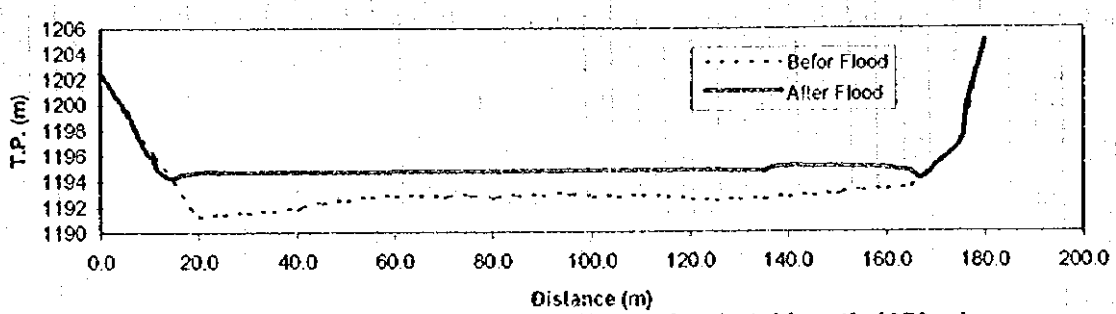
Market (total length 1220 m)



100 down stream from pumping station (total length 1470 m)



Pumping Station (total length 1570 m)



100 m upper stream from pumping station (total length 1670 m)

Fig. E.5.7 CROSS-SECTION PROFILE OF CHANG CHHU BEFORE AND AFTEER FLOOD

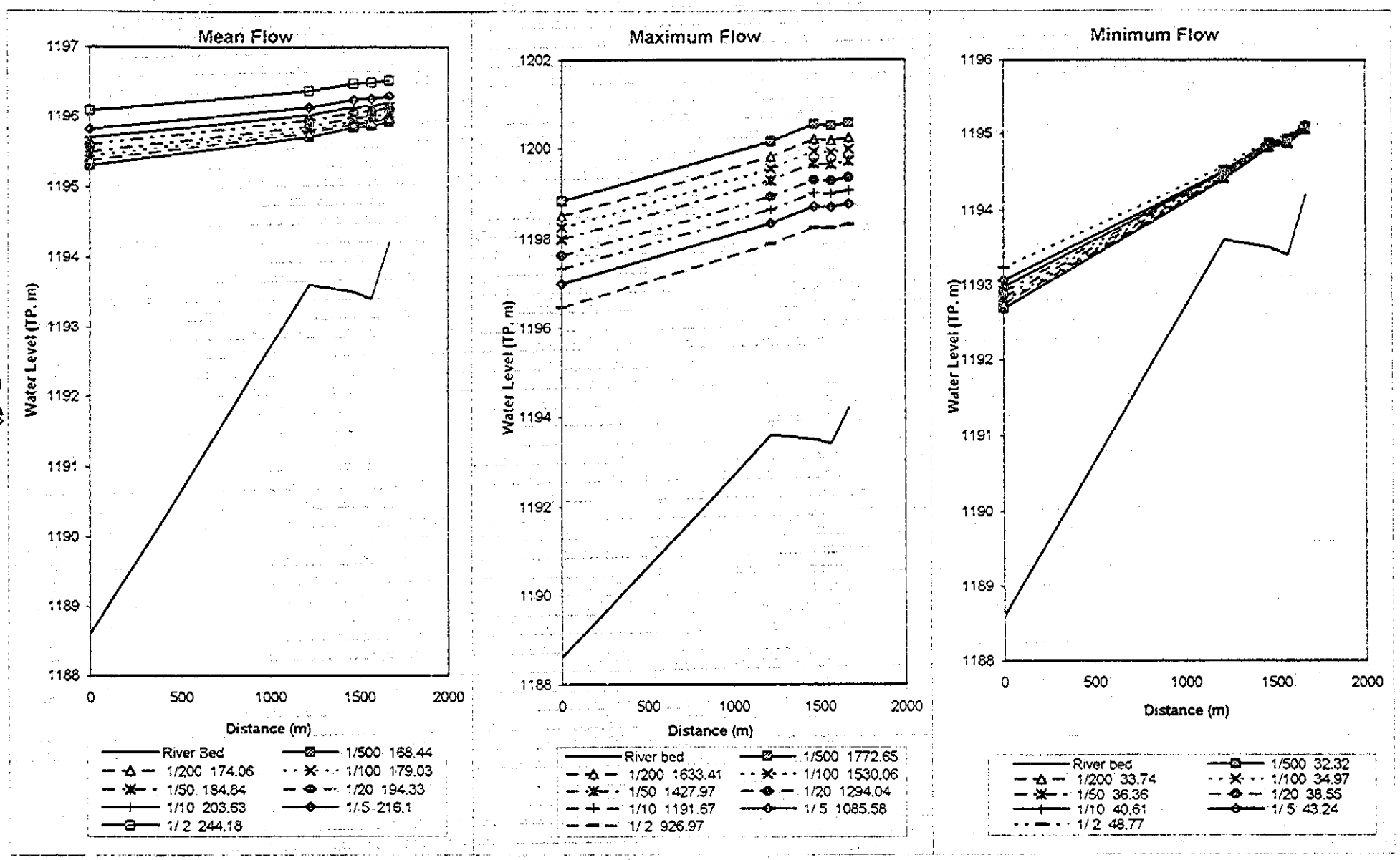


Fig. E.5.8 ESTIMATED RIVER FLOW AT CHANG CHHU

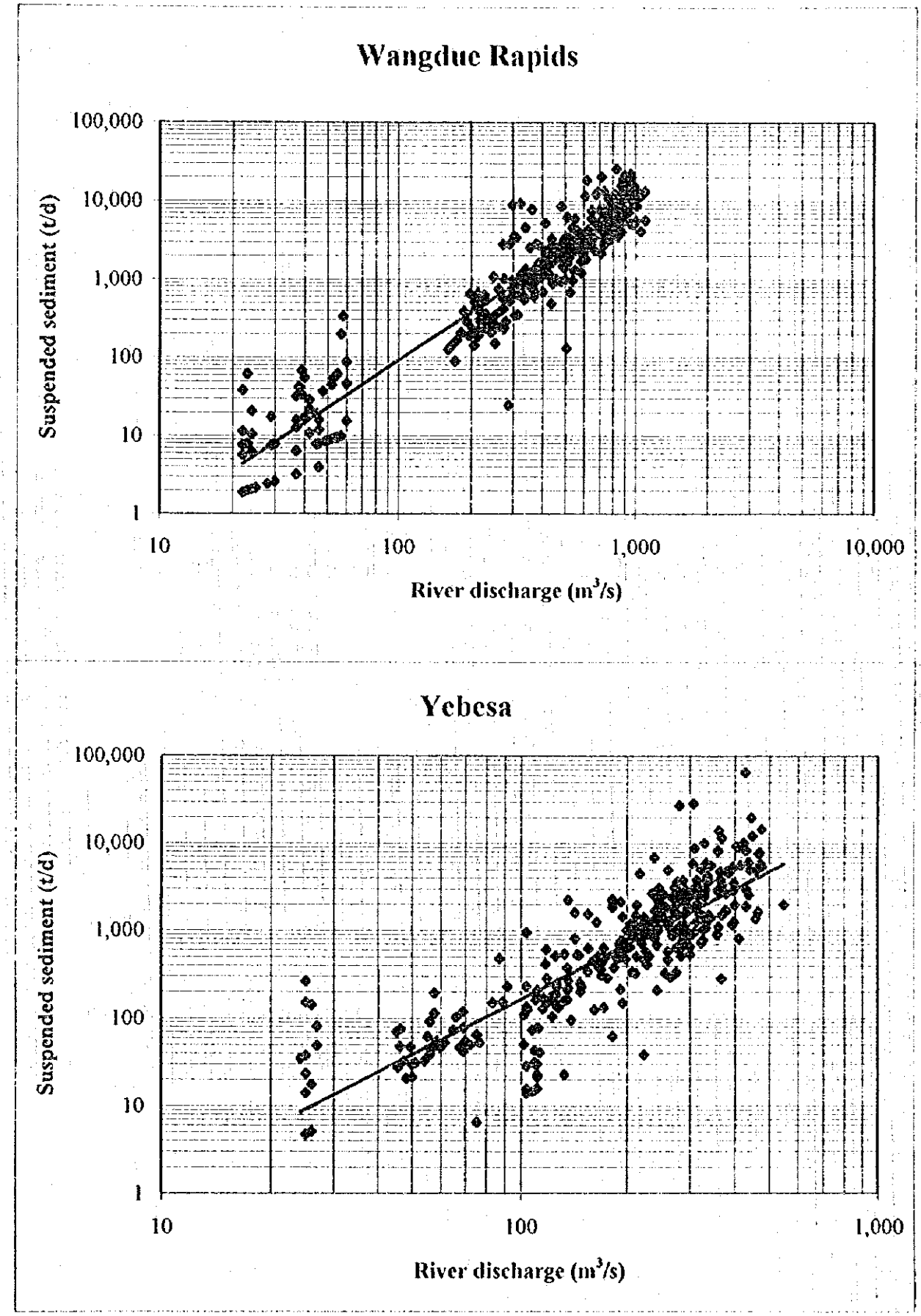


Fig. E.5.9 RELATIONSHIP BETWEEN RIVER DISCHARGE AND SUSPENDED SEDIMENT RUNOFF (1/2)

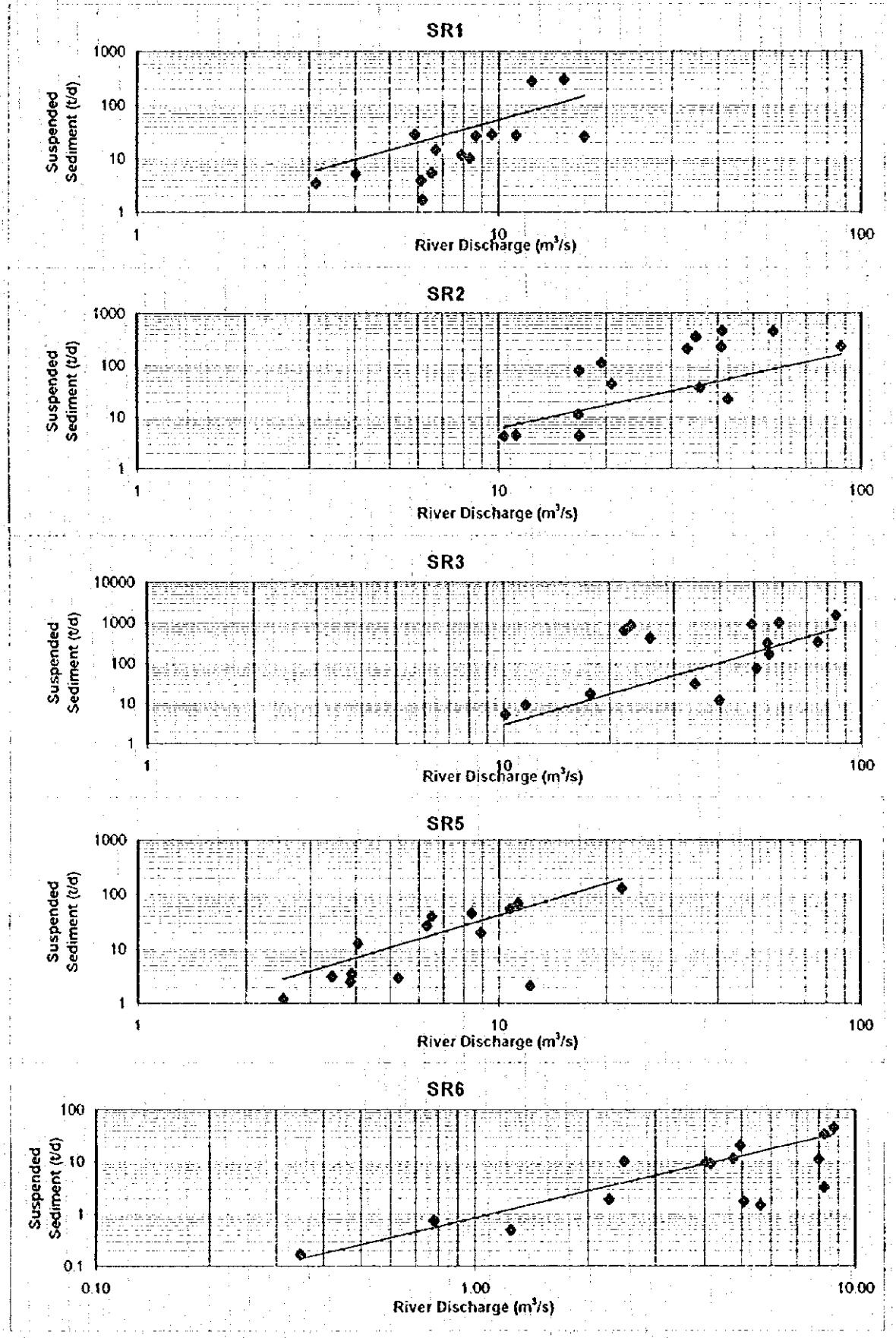


Fig. E.5.9 RELATION BETWEEN RIBER DISCHARGE AND SUSPENDED SEDIMENT RUNOFF (2/2)

APPENDIX F
GEOLOGICAL HAZARDS ASSESSMENT

THE STUDY
ON
GROUNDWATER DEVELOPMENT
IN
WANGDUEPHODRANG DISTRICT OF BHUTAN

FINAL REPORT

VOLUME III: SUPPORTING REPORT

APPENDIX-F GEOLOGICAL HAZARDS ASSESSMENT

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APPENDIX-F GEOLOGICAL HAZARDS ASSESSMENT

F.1 Introduction

The Himalayas are the youngest mountains in the world, still rising and under formation. Slopes will therefore generally be steep, and each infrastructure established is at a risk of washout and failure caused by erosion, gully intrusion, and landslide.

In Bhutan, glacial lake outburst, earthquake, flash-flood, and landslides constitute the main natural phenomena (geological hazards). These natural hazards are mainly due to natural causes but are accelerated in frequency and magnitude due to human interference with nature.

Man-made structures tend to disturb the equilibrium of the regime of nature and the nature in turn has damaging effects on such structures.

Needless to say, the development of land as infrastructure is necessary and inevitable to improve the security and welfare of the people. But the process of development has normally been followed by many negative and undesirable effects. Bhutan has been determined to ensure that the development process should be cautious and well-planned and that the balance of nature, as well as cultural and social values, are maintained.

The Study Area is physiographically situated in the zone of "mountain and valley belt" where nature has made deep gorges in the southern half and wide river valleys in the northern half of the zone.

The wide river valley is the main agricultural area in Bhutan and the major towns like Paro, Thimphu, Wangduephodrang etc., of elevation 1300 to 2500 meters are located in this northern half zone of the mountain and valley belt.

In the Study Area, with some exception, the geology of cultivated area is composed mainly of foliating phyllite and schist, and brittle quartzite. The massive and resistant rocks overlying the brittle and foliating sequence are the crystalline limestone and the Himalayan gneiss. These resistant rocks are distributed in places of high altitude forming crests of ridges surrounded by steep slope.

In short, the Study Area is composed mainly of weak geology. Because of weak geology, people have made terraces for cultivation on the slope or fossil landslide area. Sometimes these fossil slides become active by road cutting or canal cutting at the toe part of the slide.

Since, the Study Area is a highly developed agricultural area, man-induced hazards will intensify. Especially irrigation canals without lining may, due to percolation and water load, create landslides.

During the Phase II field study (1) a walk-over survey was carried out on the "rating of vulnerability", followed by (2) desk work on photogeological interpretation and slope analysis, and (3) geological hazards assessment.

F.2 Methodology (Rating of Vulnerability)

In some part of the Study Area, the natural process of mountain building and man induced physical impacts to topography are causing the mass movement of soil and rock. These mass movements often cause washout and/or failure of infrastructures such as irrigation canals and roads.

To assess the geological hazards along the canal, the study started with a "rating for state of nature".

Referring to the publications of the International Centre for Integrated Mountain Development (ICIMOD), a check-list is prepared for the field work on the rating for state of nature, which was later modified to the rating of vulnerability as shown on the following page.

Special consideration was paid for selecting the observation items along the linear infrastructure (canal in this study) which should be ranked in the field. For this reason the check list was simplified as much as possible.

After several times of trial rating along the same canals in the Study Area, a simplified check-list composed of eleven (11) items to be judged in the field was finalized for actual field use. (See Fig. F.2.1)

This simplified method, however inevitably relies on the experience based subjective judgement to a varying degree in rating. Furthermore, some logical discontinuities are intentionally employed to utilize the experience-based judgement, i.e., the old slide observed near by is allocated 5 points while new slide within 20 metes is given 8 points. Then the risk of new slide of 25 meters apart should be classified as equivalent to either old slide or slide nearly 20 meters apart.

Since the geological hazards are a multiple compound of natural process and man induced instability, many factors are genetically related to landslides or failures. Continuous and/or heavy rain, earthquake, snow melt, and groundwater seepage may be possible triggers in the Study Area.

The close relationship between rainfall and the number of slope failures is well known in China, Japan and other countries, but no observation is recorded in this country.

In general, the assessment of hazards in the linear infrastructure (canal) involves assessment of the state of nature and assessment of triggers.

The hazards may be defined as:

$$H = R \times P$$

while H=hazard
R=rating for state of nature
P=possibility of trigger occurrence

To clarify the possibility of trigger occurrence, several years of continuous observation on those triggers and intensive data collection is essential. Due to constraints on the study on the triggers, this study treats the rating point as a vulnerability index instead.

F.3 Field Survey

F.3.1 General

Walk-over field survey was carried out along the main canals in the study area. Those canals surveyed are as follows:

Name	Length (km)	No. of Observed Segment
Upper Lobeysa canal	7.1	29
Lower Lobeysa canal	8.1	15
Bajo canal	15.0	47
Phangyul canal	16.0	57
Genikha canal	3.5	11
Nalakha canal	3.9	13
Rotekha canal	2.2	13
Maphekha canal	2.2	10
Naykoyuwa	1.7	8
Rumina	1.1	7
Total	60.8	210

In the field, each geomorphological unit was taken as a segment for the rating. Observation and judgement on each item of the check-list, are converted to the point as shown on the list and the total points are treated as the vulnerability index.

During the field survey;

- Geological observation was supplementarily done together with the rating.
- Critical section of danger was shown on the map by arrows and the length of possible damage is noted beside the arrow.
- Other phenomena observed carefully in the field are;
  - age of trees in the fossil slide zones;
    to estimate the age of the slide
  - bending of tree trunks or leaning of the trees on slopes;
    to estimate the movement of soil
  - exposed roots of trees;
    to estimate the depth of soil erosion

After the field works, aero-photos of the area have been observed using a stereoscope, concentrating study on areas around hazard areas as judged in the field survey. Scales of landslides and status of gully intrusion from lower parts of slopes have carefully been observed, and the appropriateness of its vulnerability rating in the field has been checked. In addition, scales of possible hazards have been estimated, and these have been shown on maps.

As a whole except some segments of the Bajo canal and Phangyul canal, most of the canals are constructed in stable areas and no major damage is likely in the near future.

F.3.2 Vulnerability Rating of Canal

(1) Upper Lobeysa Canal (C1) [Fig. F.3.3 (1) ~ (3)]

The intake is situated in the middle-stream of the Tabe Rong Chhu river, about 1,430 meters above sea level. The total length of the canal is 7.1 kilometers.

1) Segment 1 and 2

The segment is in a small-scale river terrace, and its topographic relief is gentle. The main part of the segment is occupied by cultivated land, but some scrubs are scattered in places. Some deformation and damages, which have been caused by river flood, are seen in the river side canal. Other areas are stable. The arithmetic average of the vulnerability indexes in the segment is 31 points.

2) Segment 3 to 8

The segment is underlain by highly foliated biotite schist, and its schistosity inclines to the mountain side. Accordingly, despite that the slopes in the area are quite steep, no large-scale failure is seen there. The vegetation in the segment is of secondary forest mainly consisting of broad leaf trees, but with pine trees in the upper part of the slope. More significant soil erosion is recognized in the pine tree forest than broad leaf tree forest. No canal deformation is seen in the section. The arithmetic average of the vulnerability indexes in the segment is 38 points.

3) Segment 9

The segment is underlain by highly foliated biotite schist. Some slope failures are seen on the steep slopes. The vegetation in the segment is heavy except some failure parts. The arithmetic average of the vulnerability indexes in the segment is 46.

4) Segment 10 to 14

The segment is underlain by highly foliated biotite schist, and its schistosity gently inclines to the mountain side. The vegetation in the segment is of thick secondary forest consisting of broad leaf trees, which well prevent soil erosion. Some damages are locally seen along the canal, especially at places crossing small streams, but the land is generally stable. The arithmetic average of the vulnerability indexes in the segment is 37 points.

5) Segment 15 and 16

The segment is underlain by biotite schist, and overlying biotite quartzite and quartzose gneiss. Landslides occurred in the boundary of both facies, and many gully intrusions are seen in this section. The vegetation in the segment is of mainly low shrubs, and some places are naked due to gully intrusion. The canal is partly repaired by masonry, but the slopes underneath the canal are poor in vegetation,

and not stable. The arithmetic average of the vulnerability indexes in the segment is 53 points.

6) Segment 17 to 20

The segment is underlain by brittle quartzite, quartzose gneiss, and calc-silicate rocks, and its foliation inclines to the mountain side. Areas distributed by these rocks, generally, are rich in thick reddish-brown soil, and this situation applies to this segment as well. The vegetation in the segment is of pine scarce forest, and many tree-roots are exposed due to soil erosion. No special deformation is seen in the canal. The arithmetic average of the vulnerability indexes in the segment is 42.5 points.

7) Segment 21

The segment is underlain by mud flow deposits, which form gently sloped cultivated lands and residential areas. The land is quite stable. The arithmetic average of the vulnerability indexes in the segment is 36 points.

8) Segment 22 to 29

The segment is underlain by quartzite and overlying colluvium, and gneiss and overlying mudflow deposits. The quartzite and gneiss are in fault contact, and significant fracturing in the basement rocks is recognized nearby the fault. Many gully intrusions exist around the fault, and the canal has been damaged over a length of 5 to 6 meters. It is necessary to repair this point. The area is stable except this fault zone. Because the surface reddish soil is very thick, it is anticipated that the area is susceptible to gully intrusion. The vegetation in the area is poor, consisting of pine scarce forest. The soil erosion in the area is significant because of poor vegetation, and tree roots are commonly exposed. The canal is situated nearby a road, and no special deformation or damage is seen. The arithmetic average of the vulnerability indexes in the segment is 41 points.

(2) Lower Lobeysa Canal (C2) [Fig. F.3.3 (1)~(3)]

The intake of the canal is situated about 550 meters down stream of the Upper Lobeysa Canal, around 1,380 meters above sea level. The canal was constructed simultaneously with the Upper Canal.

1) Segment 1 to 3

The segment is situated on a narrow river terrace, and its geological condition is quite stable. The vegetation in the segment is of scarce shrubs, and some parts of the segment are cultivated. No deformation is seen in the canal. The arithmetic average of the vulnerability indexes in the segment is 33 points.

2) Segment 4 to 6

The segment is underlain by strongly foliated biotite schist, and the foliation is almost horizontal or gently inclines to the mountain side. The topographic relief of the area is quite steep, and the rocks are fragile, accordingly, many small-scale slope failures exist in the area. The places of slope failures are the same as the section in the upper canal. The vegetation in the segment is of secondary forest of broad leaf trees, however there is no purpose in structural land protection because of thin soil layers on the surface. The arithmetic average of the vulnerability indexes in the segment is 44 points.

3) Segment 7 to 12

The segment is underlain by biotite schist and brittle quartzite, and a landslide has occurred on the boundary between these different rocks. Many deep gully intrusions are seen in the landslide zones, and this suggests that these landslide blocks are still moving. Thick reddish soil stably overlies the quartzite. The vegetation in the segment is mainly of secondary forest of broad leaf trees, although scarce pine tree forest is present in the quartzite area. Some places along the canal have been temporarily repaired. The arithmetic average of the vulnerability indexes in the segment is 53 points.

4) Segment 13 to 21

The segment is underlain by mud flow deposits, the surface of the land is gentle, and cultivated for rice farming. No other risks than flash flood of the river is expected. The arithmetic average of the vulnerability indexes in the segment is 37 points.

(3) Bajo canal (C9) [Fig. F.3.4 (1) ~ (3)]

The intake is situated in the down-stream area of the mineral spring in the Pe Chhu river, about 1,380 meters above sea level. The length of the canal is 15.0 kilometers, and a part of the canal water is used as the water supply for Wangdue Phodrang town.

1) Segment 1 to 5

The segment is underlain by brittle quartzite and quartzose gneiss. The foliation of the rocks inclines to the mountain side, and the rock blocks are generally stable. Some parts of the area are steep in topography, and risky for rock falls. Some marshes exist in the landslide blocks. The vegetation in the segment is poor, because of its rugged topography and poor permeability of the rocks. The arithmetic average of the vulnerability indexes in the segment is 36 points.

2) Segment 6 and 7

The segment is underlain by quartzite and quartzose gneiss, cut by a fault striking northeast to southwest, and many fractures exist in the rock bodies. Some slope failure, recently occurred, is seen in some places in the area, and steel launders are

set for those areas. The vegetation in the area is moderate, except some steep cliff areas. The arithmetic average of the vulnerability indexes in the segment is 67 points.

3) Segment 8 to 15

The segment is underlain by quartzose gneiss and calc-silicate rocks, and the gneissosity of the gneiss gently inclines to the mountain side. Accordingly, the area is generally stable, however, small-scale landslides, 10 meters in width, and failure are seen in some places. The vegetation in the segment is generally poor, consisting of scarce pine forest, which is used for pasturing. The arithmetic average of the vulnerability indexes in the segment is 49 points.

4) Segment 16 and 17

The segment is underlain by mud flow deposits consisting of various sizes of fragments within the muddy matrix. The deposits are massive and compact, and stable as a body. The vegetation in the segment is moderate. The arithmetic average of the vulnerability indexes in the segment is 34.5 points.

5) Segment 18 to 21

The segment is underlain mainly by biotite schist showing strong foliation and partly by mud flow deposits. The schistosity of the schist gently inclines to the mountain side, so that the rock blocks are stable in the segment. The vegetation in the segment is generally poor, consisting of scarce pine forest. The arithmetic average of the vulnerability indexes in the segment is 49 points.

6) Segment 22 and 33

The segment is underlain by significantly foliated biotite schist. The schistosity gently inclines to the mountain side. The segment should, therefore, geo-structurally be stable, but actually many slope failures such as landslides and gully intrusion exist in the area. The reason why is that the Dang Chhu river joins and falls down into the Chang Chhu river near the area, and the Dang Chhu river has been rapidly deepened and has formed steep cliffs on both banks of the river. The vegetation in the area is moderate to scarce, and no root anchoring to prevent soil erosion is not anticipated. This longest section in the survey area is one of the most dangerous sections. The arithmetic average of the vulnerability indexes in the segment is 62 points.

7) Segment 34 to 43

The segment is underlain by mainly highly-foliated schist and partly overlain by thick soil layers; however, normally the soil layers are thin. The schistosity inclines to the mountain side, so that the area is structurally stable, and almost no failure is seen in the area in spite of its steep slopes. The vegetation in the segment is generally poor due to poor soil, and partly scarce pine forest can be seen. The arithmetic average of the vulnerability indexes in the segment is 43 points.

8) Segment 44 to 47

The segment is underlain by fine sediments in the terraces and biotite schist. The terraces are used as farmlands, and have artificially been stabilized. The places underlain by biotite schist have formed stable slopes due to inclination of the foliation toward the mountain side, and the steep slopes are commonly grass lands. The vegetation in the area is generally poor. The arithmetic average of the vulnerability indexes in the segment is 36 points.

(4) Phangyul Canal (C10) [Fig. F.3.5 (1)~(3)]

This is the longest canal in the area, with a total length of 16.0 kilometers. The intake of the canal is located at the upper-stream of the Kamathang Chhu river, 2,300 meters above the sea level. The water from two streams toward the upper-stream is diverted into the canal.

1) Segment 1 to 5

The intake area is underlain by hard biotite schists, schistosity of which incline about 40 degrees to the mountain side. The vegetation in the segment area is of heavy forest of huge trees, and the roots of the trees form so called "root anchoring", preventing the erosion of the weathered zones. Even a small-scale rill erosion is seen around the canal, however the area is quite stable in general. The arithmetic average of the vulnerability indexes in the area is 34 points.

2) Segment 6 to 11

The segment is underlain by granitic gneiss and intruded coarse grained diorite. Sometimes gneissosity is recognized in the granitic gneiss. The gneissosity of the gneiss inclines toward the mountain side, so that little chance is expected for large-scale slope failure or slide. The vegetation in the segment is of dense secondary forest, and no soil erosion is seen except in parts of the cultivated land. The arithmetic average of the vulnerability indexes in the segment is 38 points.

3) Segment 12 to 17

The segment is underlain by slightly weathered coarse-grained biotite granite. Steep cliffs, some times slope failure, are seen in some places in the area. The vegetation in the segment is of virgin forest of huge trees, and those trees form the root anchoring. The arithmetic average of the vulnerability indexes in the segment is 40 points.

4) Segment 18 to 22

The segment is underlain by highly weathered and decomposed granite, which is brittle and sandy in appearance. It is presumed that the decomposed rocks reach 15 meters in depth in some highly weathered sections. The vegetation in the segment is of moderate forest. Some places of the segment are causing landslides with the

scale of 400 meters wide, and swelling and mounding cause tilt of trees, and gully intrusion causes fall of trees. The segment is one of the most risky segment in the area, and the arithmetic average of the vulnerability indexes is 59 points.

5) Segment 23 to 28

The segment is underlain by weathered granite, and is a large-scale fossil landslide area consisting of three main slide blocks. These slide blocks are already stabilized, and trees are over 30 years old , Quercus species, are growing in the blocks. In other words, no recent movement occurs in the blocks. The vegetation in the segment is moderate forest, and some cultivated areas are seen in the gently sloped ancient slide areas. The arithmetic average of the vulnerability indexes in the segment is 50 points.

6) Segment 30 to 38

The segment is underlain by weathered granite, which is not strongly decomposed. Steep cliffs and many spots of small-scale slope failure are seen in the segment. The vegetation in the segment is of modest secondary forest. The arithmetic average of the vulnerability indexes in the segment is 43 points.

7) Segment 39 to 42

The segment is underlain by weathered granite, which is situated in the place close to the boundary between the granite and gneiss terrain. Decomposition of the rocks is significant. Progressive down warping is occurring in a part of the canal. The vegetation in the segment is poor, and parts of land are of marshes with flags and other wet-land flora. The arithmetic average of the vulnerability indexes in the segment is 49 points.

8) Segment 43 to 46

The segment is underlain by gneiss, but its surface is covered by thick brown soils. The general landscape of the area is of gently sloped hill. This topographic relief has been well preserved by the fact that the down-slope areas underlain by massive limestone act to prevent land erosion of the higher areas. The vegetation in the segment is of secondary shrubbery forest, and some cultivated land spots are scattered in the area. The arithmetic average of the vulnerability indexes in the segment is 37 points.

9) Segment 47 to 49

The segment is underlain by gneiss, and the gneissosity of the rock gently inclines to the mountain side. The gneiss in the segment is hard, so that the topographic relief in the segment is very steep. The vegetation in the segment is of virgin forest consisting of huge and old trees. No special risk factor is recognized in the segment. The arithmetic average of the vulnerability indexes in the segment is 27 points.

10) Segment 50

The segment is underlain by gneiss, and its position corresponds to that of the synform axis. Deformation of the canal and ancient landslide topographic relics, as a result, are not recognized in the segment. The arithmetic average of the vulnerability indexes in the segment is 52 points.

11) Segment 51 to 57

The segment is underlain by gneiss, and its gneissosity inclines to the mountain side. The mountain slopes, accordingly, are stable. The vegetation in the segment is poor in general, and parts of the land are used as cultivated farmlands. The canal is mainly situated on stable slope, but parts of it are in small-scale landslide areas or risky areas for rock falling. The arithmetic average of the vulnerability indexes in the segment is 40 points.

(5) Gemkha Canal (C15) [Fig. F.3.6 (1) ~ (3)]

The canal is 3.5 kilometers in length, and its intake facility is situated in granitic terrain, about 1,800 meters above sea level.

1) Segment 1 to 3

The segment is mainly underlain by granite, and weathered crust is thin in the area. The vegetation in the segment is of pine forest, 20 to 30 years old. A wooden launder is seen along a cliff, but no risky place is seen in the area. The arithmetic average of the vulnerability indexes in the segment is 39 points.

2) Segment 4 to 6

Many landslide blocks exist in this segment. The terminal of these slide blocks have became mud flows, and formed flat planes in their down- flow areas. The vegetation in the segment is of moderate forest. Parts of these trees unevenly incline, and some marshes exist in the depressions in the area. The arithmetic average of the vulnerability in the segment is 52 points.

3) Segment 7 and 8

The segment is underlain by massive limestone, which is thinly banded impure limestone in its upper horizon and massive crystalline limestone in the lower horizon. The limestone is resistant to weathering, so that the rock bodies are quite solid and stable, and form steep slopes on the surface. On the mountain slopes, some springs are seen on the surface of the limestone layers, due to poor permeability of the limestone layers. The vegetation in the segment is rich because of sufficient water on the surface, and some surface soil zones have crept due to such spring waters. The arithmetic average of the vulnerability in the segment is 45 points.

4) Segment 9 to 12

The segment is underlain by quartzite and calc-silicate rocks, which are overlain by limestone formation in other areas observed in the former segment. This segment is in an old landslide block, and it shows a gently sloped landscape. Major parts of the land are used for cultivated land and housing. The landslide itself is almost stabilized at present, however, some fresh gully intrusions are seen in the lower parts of the slide block, indicating possible reactivation of the land in recent times. The arithmetic average of the vulnerability indexes is 42 points.

(6) Nalakha Canal (C18) [Fig. F.3.7 (1) ~ (3)]

The canal was constructed on the left bank slope of the Dang Chhu river, about 1,450 meters above sea level, and is 3.9 kilometers in length.

1) Segment 1 to 3

The segment is underlain by foliated schist. The strike of the schistosity of the schist is perpendicular to the contour lines of the slopes, and gently dips toward the upper stream. Accordingly, in spite of the fact that mountain slopes are very steep, because water seeps out through the schistosity, and this environment has given rise to heavy forests consisting of huge trees. These trees have generally formed root anchoring, which prevents slope failure on the slopes. Landslide and marsh accompanied by black slippery clay exists along the canal and parts of the canal are at risk for slope failure. The arithmetic average of the vulnerability indexes in the segment is 54 points.

2) Segment 4 to 10

The segment is underlain by quartzose gneiss and highly foliated schist. A synform axis exists in the segment, so that the schistosity of the schist is nearly flat. Almost all the area is cultivated land. Some landslides are locally seen in the area, but the segment is generally well managed and stable. The arithmetic average of the vulnerability indexes of the segment is 47 points, however, if one landslide block is excluded, it is 44 points.

3) Segment 11 to 13

The segment is underlain by significantly foliated schist. Many landslides exist in the area, resulting in the rice fields at the top of the landslides being abandoned in large areas. Gully intrusion is recognized in the toes of the landslides, forming deep depressions in the soil. The vegetation in areas other than farmland is poor, consisting of small shrubs in grass land. No deformation of the canal is recognized at present, however, some attention to this possibility is recommended. The arithmetic average of the vulnerability indexes in the segment is 51 points.

4) Segment 14

The geology of the segment is just the same as the previously mentioned segment, and many landslides are seen here. The canal of this segment is not in use at present, and it is said that it has been in this state for the past several years. No gully intrusion is seen in the segment because of no water flow. The arithmetic average of the vulnerability indexes in the segment is 37 points.

(7) Rutekha Canal (C19) [Fig. F.3.8 (1) ~ (3)]

The canal is situated on the eastern slope of the Rubesa sub-area, and its total length is 2.2 kilometers. The elevation of the intake is about 1,800 meters.

1) Segment 1 to 10

The segment is underlain by garnet bearing schist intercalated by quartzite bands. The schist is partly overlain by mud flow deposits. The schistosity is perpendicular to the contour lines of the mountain slopes or inclines to the mountain side, and the slopes are generally stable. The vegetation in the segment is of secondary forest of broad leaf trees, except some cultivated lands. Because the segment is geologically stable, no deformation of the canal is recognized. The arithmetic average of the vulnerability indexes in the segment is 36 points.

2) Segment 11 to 13

The segment is underlain by quartzose gneiss and calc-silicate rocks, which are commonly overlain by thick reddish brown soil layers. The vegetation in the segment is of scarce shrub forest and grass. Because of thick soil, the canal has deeply incised in the soil layer. No damage of the canal function is anticipated. The arithmetic average of the vulnerability indexes in the segment is 39 points.

(8) Maphekha Canal (C20) [Fig. F.3.8 (1) ~ (3)]

The canal is situated in the southern slope of the Rubesa sub-area, and its intake is at about 1,770 meters above sea level.

1) Segment 1 to 5

The segment is underlain by garnet bearing biotite schist, and the strike of the schistosity is almost perpendicular to the contour lines of the slopes and gently inclines to the east, toward the upper stream. Along the canal, many springs seep out trough the schistosity of the rocks. The vegetation in the segment is of heavy secondary forest of broad leaf trees, and no soil erosion is seen in the area. Some sections nearby the intake, which is situated in a risky position for flood, was reconstructed by a concrete launder, therefore no deformation or damage is seen in the canal. The arithmetic average of the vulnerability indexes in the segment is 38 points.

2) Segment 6 to 9

The segment is underlain by biotite schist as well as previous sections, however some landslides are seen in the slopes above and underneath of the canal. The lower parts of the slopes are cultivated for rice fields. The vegetation in the segment is of secondary forest of broad leaf trees. Only a small-scale down warping is seen in the canal; however, in general, the land is stable. The arithmetic average of the vulnerability indexes in the segment is 39 points.

3) Segment 10

The segment is underlain by biotite schist, which is the same geological situation in the previous segment. The strike of the schistosity is parallel to the contour lines of the slope, and dipping to the mountain side. Accordingly the land is geologically quite stable in the segment. The vegetation in the segment is of scarce pine forest, but some shrubs and grass lands are seen in the area. The land is quite stable in spite of its steep slope. The arithmetic average of the vulnerability indexes in the segment is 37 points.

(9) Naykoyuwa Canal (C21) [Fig. F.3.8 (1) ~ (3)]

The canal is situated on the north facing slope at the south of the Rubesa sub-area, and is at the highest position among the canals in the sub-area. The intake is at an elevation of 1,900 meters, and no farmland exists in the higher elevation of the slope. The length of the canal is 1.7 kilometers.

1) Segment 1 to 5

The segment is underlain by garnet bearing biotite schist, intercalated by quartzite beds. The schistosity of the rocks is oblique to the contour lines of the slope, and gently inclines to the mountain side. The slope above the canal is steep, but underneath the canal is gentle, forming thick talus deposits. The vegetation in the segment is of heavy forest of broad leaf trees, and the soil in the section is well preserved. The arithmetic average of the vulnerability indexes in the segment is 30 points.

2) Segment 6 and 7

The segment is in the same geological situation, and the land is quite gentle. Some float boulders are scattered there, but no exposed rock is seen. There is a possibility that the land is a landslide block. Almost all land is used as rice fields. The arithmetic average of the vulnerability indexes in the segment is 35 points.

3) Segment 8

The segment is in the same geological situation of the segments 1 to 7, but the land is quite steep. The schistosity of the rocks inclines to the mountain side, and as a result the land is stable. The vegetation in the segment is of scarce pine forest. The

soil is thick there, and rock outcrops are very scarce. The arithmetic average of the vulnerability indexes in the segment is 32 points.

(10) Rumina Canal (C22) [Fig. F.3.8 (1) ~ (3)]

The canal intakes water from the Tagarong Chhu river running through the central part of the Rubesa sub-area. The intake is situated at the elevation of 1,550 meters, and the end of the canal reaches the watershed of the Dang Chhu river. The canal is 1.1 kilometers in length.

1) Segment 1 to 3

The segment is underlain by mud flow deposits, and some boulders, over one meter in diameter, are scattered in the area. The land is gentle, and used as rice field. The arithmetic average of the vulnerability indexes in the segment is 37 points.

2) Segment 4 to 6

The segment is underlain by biotite schist. Because the section is in a ridge of mountain, a gentle crest flat (crest plane) being a relict of peneplain extends widely. A 10 meters thick soil layer covers the crest flat, and the canal has incised to the depth of 2 to 3 meters in the soil. The vegetation in the segment is of scarce shrubs, and soil is exposed on the surface, which is scarce in humus soil. The canal is set in the deep part of the soil, and there is no risk for damage. The arithmetic average of the vulnerability indexes in the segment is 37.

3) Segment 7

The segment is underlain by biotite schist, and the strike of this is oblique to the contour lines of the slope, and gently inclines to the valley side. The segment is on steep slope, facing north, in the watershed of the Dang Chhu river. A landslide block exists just under the end of the canal. The vegetation in the segment is of scarce shrubs and grass, and a minor-scale failure is seen nearby the canal. The arithmetic average of the vulnerability indexes in the segment is 47 points.

F.4 Geological Hazards Map and Hazards Assessment

The results of field work on the rating for vulnerability of canals are compiled on the map of 1:10,000. Meanwhile photogeological interpretation on the aero-photographs as well as slope analysis around the canals were carried out on the desk and complied on the maps. The series of the geological hazards map is composed of several maps, i.e. geological map, slope analysis map, and vulnerability index map.

Each map has independently its own complete information, however the causes of geological hazards can be read by referring all other maps to the vulnerability map. In addition, it is possible to know sizes of geological phenomenon such as landslides, understand the background of geological hazards, and estimate outlines for grades of future risks. As discussed before, the concept of hazards includes the possibility of occurrence of triggers. The area shown by arrows in this map indicates the highly

hazardous zone, which is selected based on observations in the field. The figures of the vulnerability index also indicate the hazardous degree of the segment estimated by experience based judgement.

As mentioned in a National Environmental Commission's report, slope failures due to canals are very common in Bhutan. The examples in the survey area suggests that some countermeasures for the stabilization of the slopes underneath the canals are necessary at the time of construction.

Although some modification may be necessary when applied to other areas or infrastructures such as roads, the proposed check list for the vulnerability may provide a reasonable standard for hazard assessment when it is utilized by the experienced geologists or civil engineers. The hazard assessment on linear infrastructures in mountainous area may have a good starting point with the simplified check list on the vulnerability.

APPENDIX F
TABLES

Table F.3.1 Summary of Hazard Assesment

Group A				Group B		Group C		Group D		Group E		Group F							
Code C1		Code C2		Code C9		Code C10		Code C15		Code C18		Code C19		Code C20		Code C21		Code C22	
Upper Lobeyna Command Area 61 ha Total Length 7.1 km		Lower Lobeyna Command Area 300 ha Total Length 8.1 km		Bajo Command Area 143 ha Total Length 15.0 km		Phangyul Command Area 91 ha Total Length 16.0 km		Genikha Command Area 15 ha Total Length 3.5 km		Nalaikha Command Area 29 ha Total Length 3.9 km		Rutekha Command Area 40 ha Total Length 2.2 km		Maphekha Command Area 27 ha Total Length 2.2 km		Naykoyuwa Command Area 24 ha Total Length 1.7 km		Rumma Command Area 28 ha Total Length 1.1 km	
Index	Distance (m)	Index	Distance (m)	Index	Distance (m)	Index	Distance (m)	Index	Distance (m)	Index	Distance (m)	Index	Distance (m)	Index	Distance (m)	Index	Distance (m)	Index	Distance (m)
28	210	32	400	21	110	37	270	41	210	56	230	38	340	35	170	30	450	37	240
34	280	35	250	38	130	31	480	39	250	61	270	29	90	39	240	26	300	37	240
43	240	39	350	43	270	27	340	38	320	44	240	34	290	40	120	24	150	34	230
32	200	47	360	40	250	42	220	49	280	44	260	36	270	31	190	39	180	39	140
42	140	40	500	36	330	31	690	49	190	41	190	46	100	33	130	31	190	32	270
34	100	44	280	65	200	43	270	59	170	39	200	38	280	47	210	31	340	43	220
37	190	61	130	68	160	40	390	47	580	56	270	34	120	40	220	39	150		
41	140	52	200	44	150	34	250	42	280	47	290	35	380	29	290				
50	100	51	220	41	130	36	300	34	260	49	160	30	120	41	260				
39	70	59	240	50	230	34	460	49	300	46	240	37	50	31	310				
39	220	52	230	42	510	40	260	49	440	58	250	37	170						
37	270	43	240	56	450	39	530	37	220	48	440	45	50						
31	270	36	410	44	180	36	460			46	380								
39	290	36	360	57	130	34	410			37	280								
52	170	36	400	56	130	38	360												
54	260	40	430	34	280	50	210												
49	170	40	370	35	370	42	290												
40	510	39	330	53	260	60	180												
39	320	36	510	42	310	50	450												
42	310	36	550	58	190	65	360												
36	520	40	240	38	610	62	330												
51	170	34	660	55	370	57	220												
37	380			62	110	47	320												
42	130			66	190	43	380												
39	150			64	300	56	350												
42	370			61	310	46	250												
39	690			53	220	58	180												
45	230			62	200	46	170												
				67	460	55	110												
				64	200	39	270												
				64	210	45	470												
				57	310	52	310												
				59	350	55	160												
				69	310	40	400												
				59	190	36	270												
				41	210	34	320												
				44	310	46	200												
				40	280	40	530												
				44	180	54	220												
				37	310	51	430												
				50	260	39	650												
				41	560	52	320												
				39	320	39	320												
				52	360	35	290												
				43	260	37	570												
				34	860	37	140												
				40	370	24	300												
				40	540	29	360												
				31	1020	27	220												
Mean Index	39.83	Mean Index	39.90	Mean Index	46.76	Mean Index	41.45	Mean Index	44.53	Mean Index	48.12	Mean Index	36.16	Mean Index	36.28	Mean Index	30.80	Mean Index	36.60

APPENDIX F
FIGURES

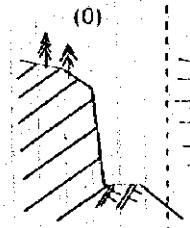
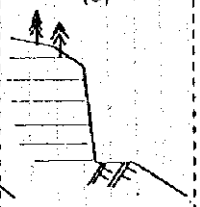
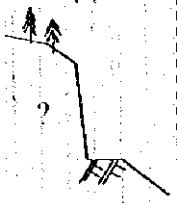
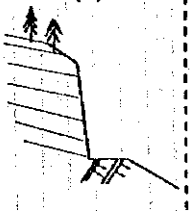
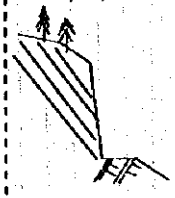
Attribute	Description/ measurement				
Vegetation		tough root anchoring (-3)	thick (0)	moderate (3)	sparce, barren cultivated (5)
Slope Angle (degrees) up		< 5 (0)	6 ~ 20 (3)	21 ~ 45 (5)	> 45 (3)
Slope Angle (degrees) down		< 5 (0)	6 ~ 20 (5)	21 ~ 30 (8)	> 31 (10)
Nearby drainage	none (0)	simple  (3)	under cutting or rill swarm  (5)	gully  (8)	active gully  (10)
Slope surface		smooth (0)	un-even (3)	mound scattered (4)	irregular with mid-slope flat (5)
Surface cover thickness		< 3 m (0)	3 ~ 5 m (3)	5 ~ 10 m (5)	> 10 m (3)
Surface cover material		massive debris, soil (3)	colluvium, debris with < 1 m block (5)	debris w/ wet mud or 3 m block (8)	loose debris, rock debris (10)
Bed rock	massive resistant (0)	jointed hard R massive soft R (3)	not observed & others (5)	Weatherd R open-cracked, foliated (8)	crushed, decomposed, argillized (10)
Orientation of discontinuity	(0) 	nearly flat (3) 	not clear (5) 	5 ° ~ 20 ° (8) 	> 20 ° (10) 
Cutting + banking height		< 3 m (0)		3 ~ 6 m (3)	> 6 m (5)
Deformation of structure	none (0)	minor < 3 m (3)	med., deform. 3 ~ 6 m (5)	med. ~ major deform. repaired temporarily (8)	down warp seems active (10)
Possible wash out/ rock fall		not likely (0)	possible (3)	probable (4)	in danger (5)
Existing slide, creep failure (w < 6 m)	none (0)	rill erosion (3)	old slide near-by (< 10 years) (5)	new slide within 20 m (8)	zone of major or active slide (10)

Fig. F.2.1 SCORE FOR RATING VULNERABILITY

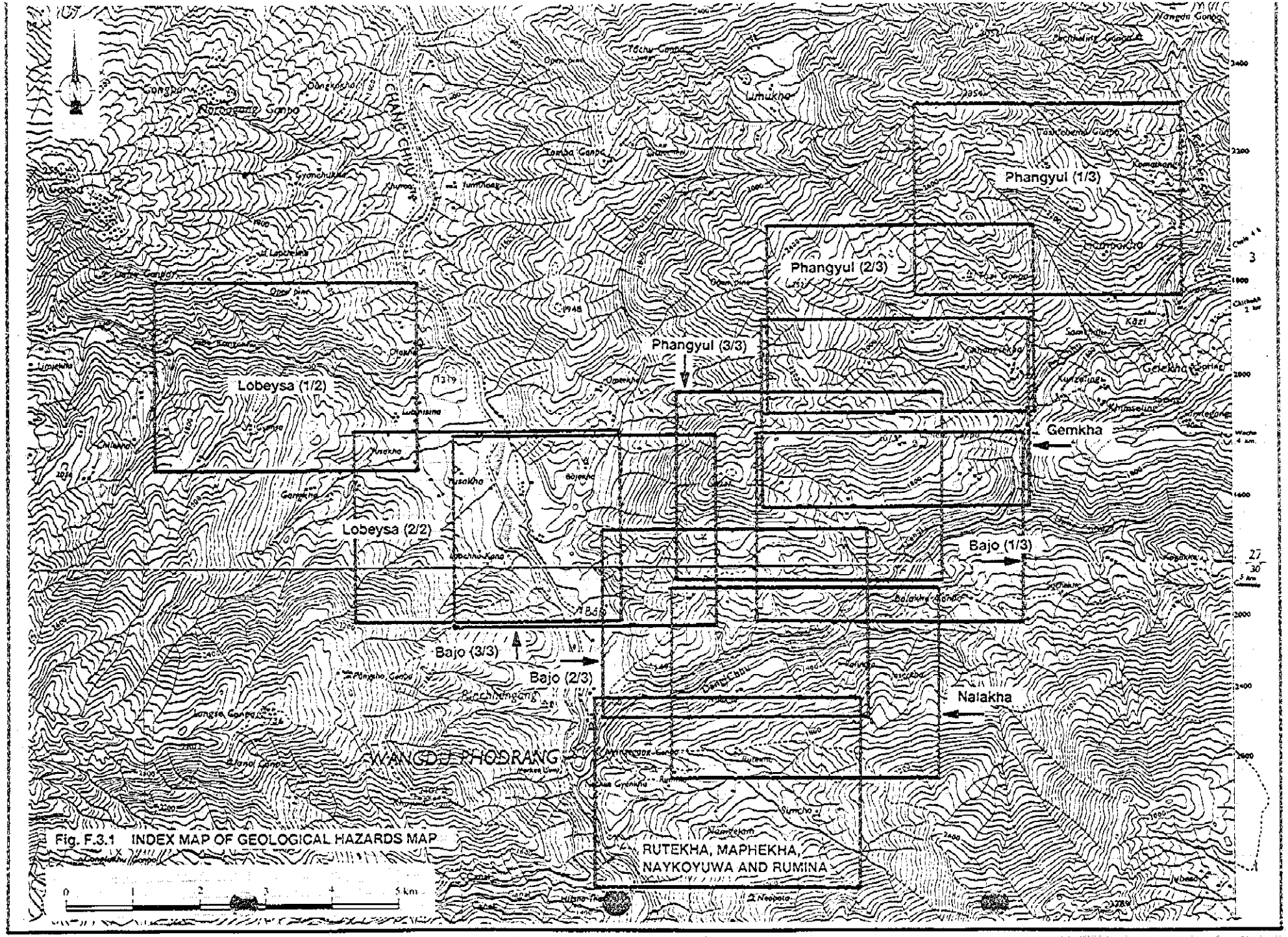


Fig. F.3.1 INDEX MAP OF GEOLOGICAL HAZARDS MAP

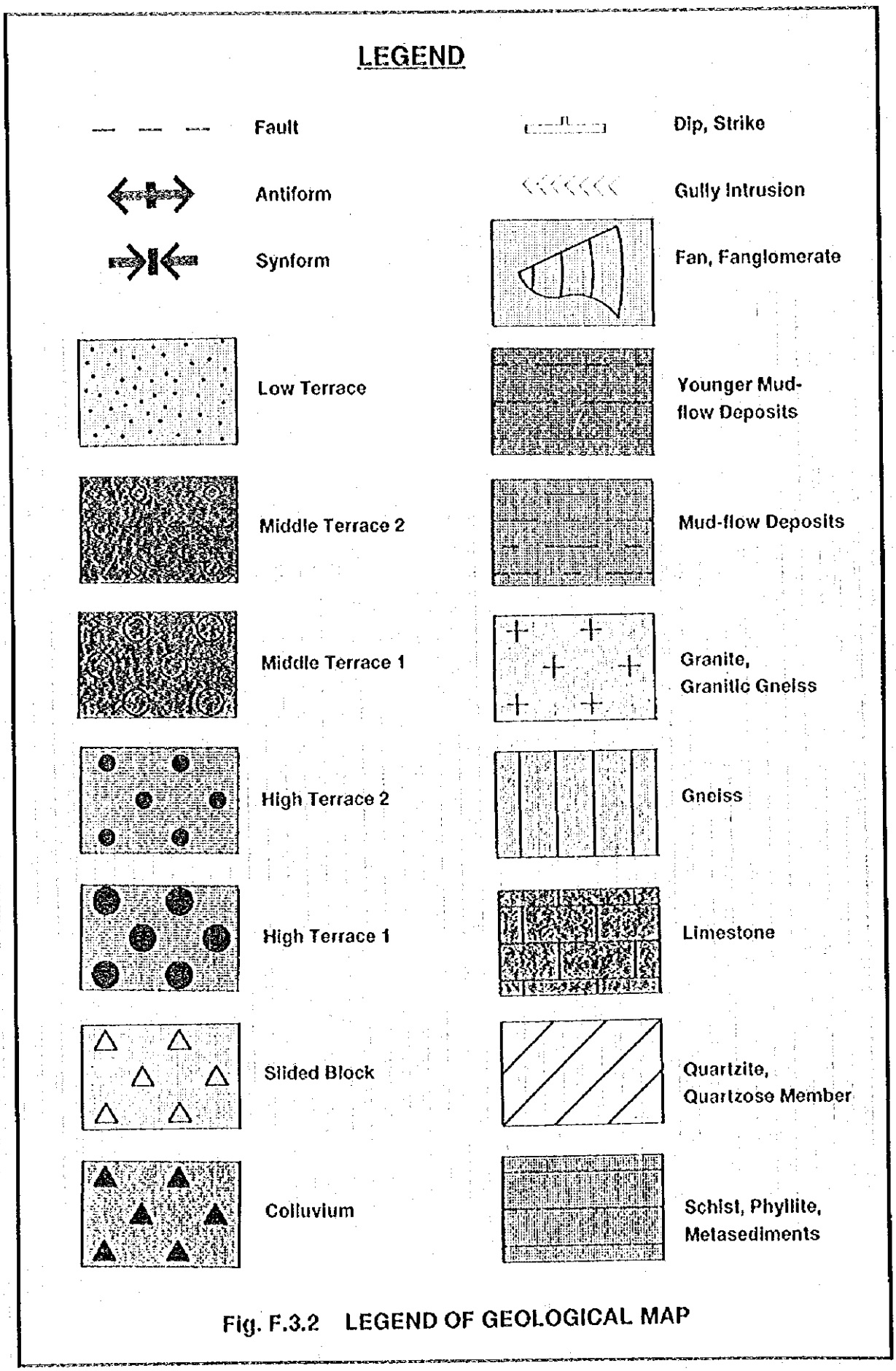


Fig. F.3.2 LEGEND OF GEOLOGICAL MAP