Carrying Capacity Study of Teesta Basin in Sikkim

Volume-II

LAND ENVIRONMENT - GEOPHYSICAL ENVIRONMENT

Commissioned by :

Ministry of Environment & Forests, Government of India

Sponsored by :

National Hydroelectric Power Corporation Ltd., Faridabad

CENTRE FOR INTER-DISCIPLINARY STUDIES OF
MOUNTAIN & HILL ENVIRONMENT
CISMHE UNIVERSITY OF DELHI, DELHI

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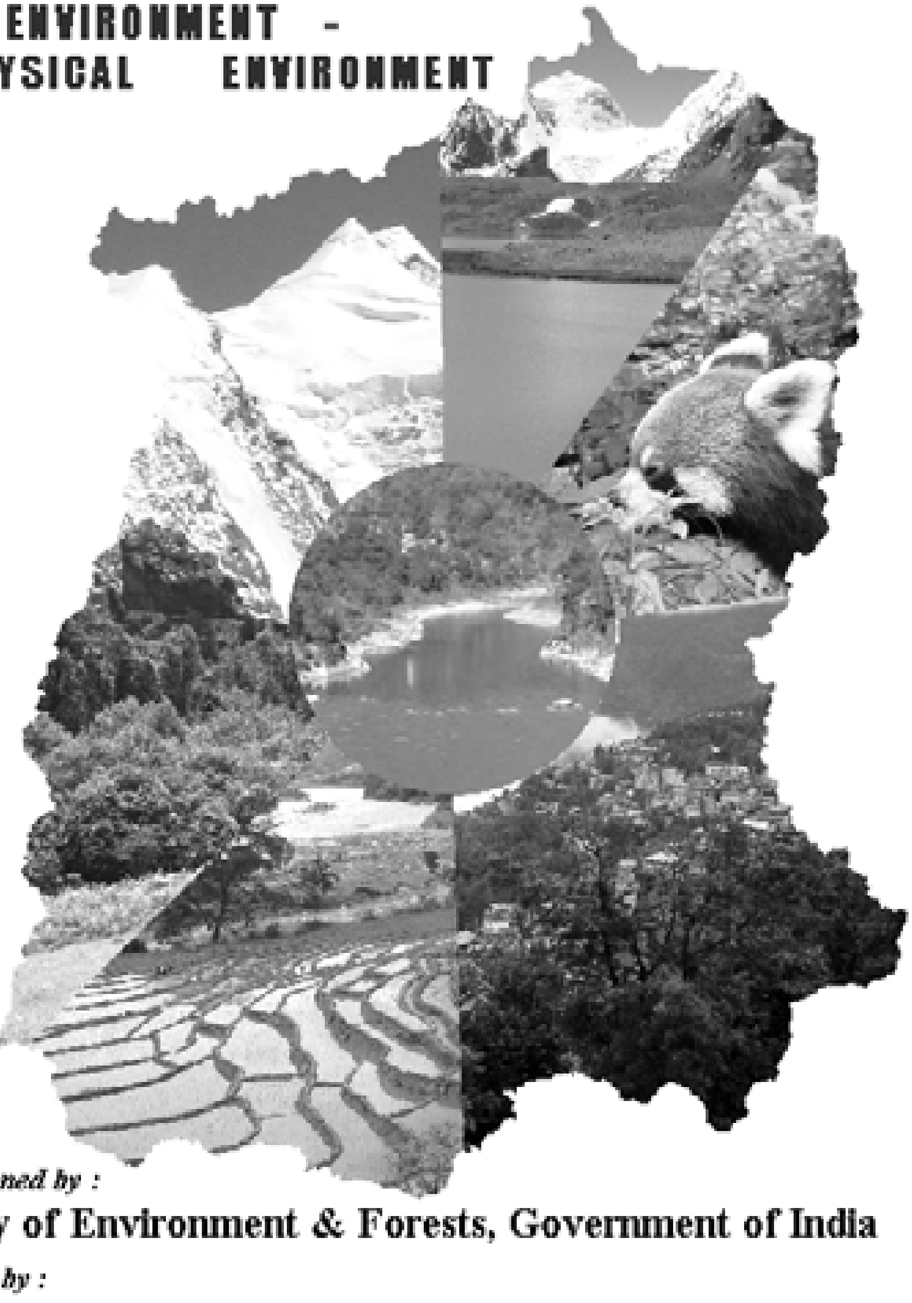

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VOLUMES INDEX*

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GEOLOGY AND SEISMICITY

1.1 GEOLOGICAL FRAMEWORK

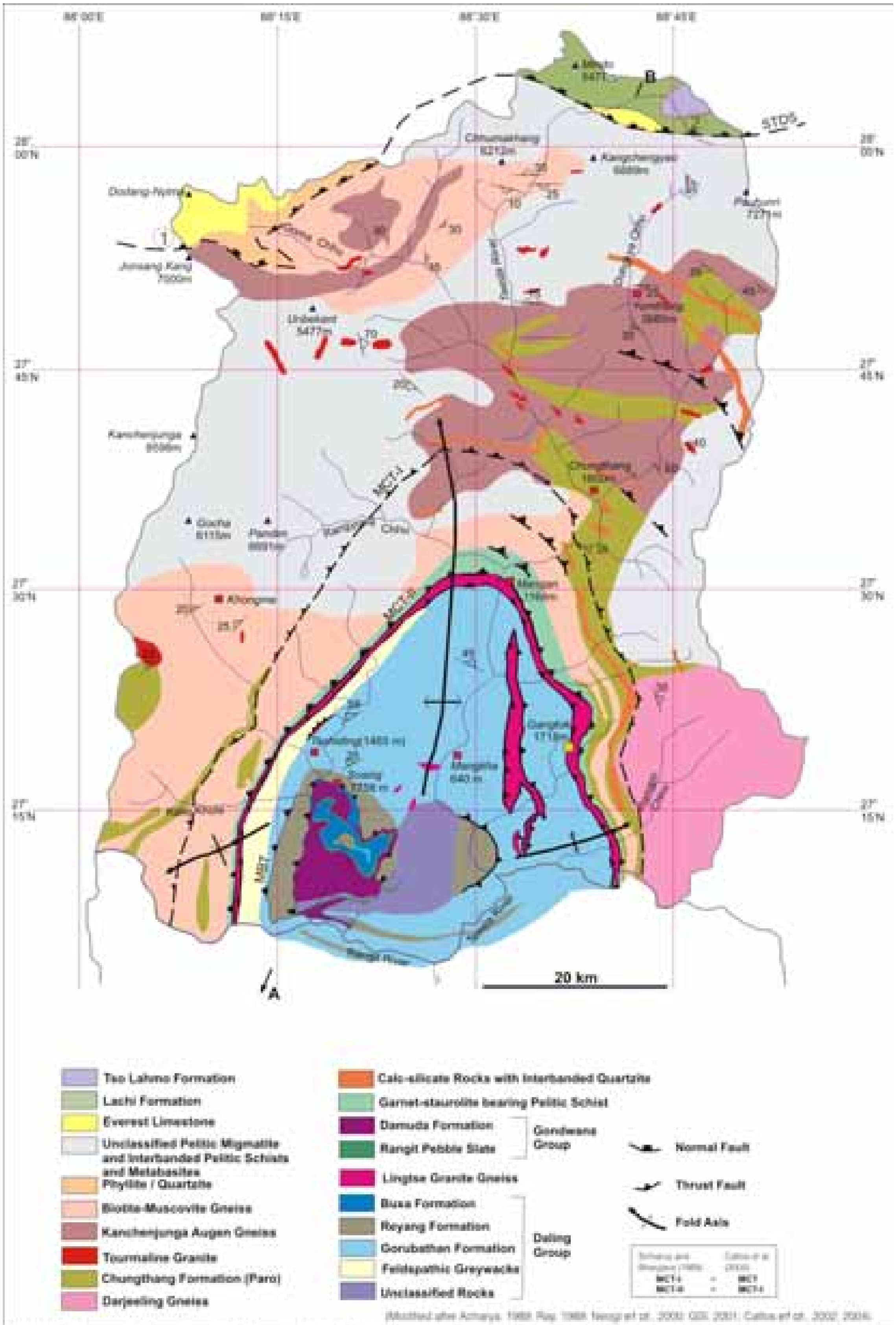
Since the work of Gansser (1964) in Darjeeling-Sikkim region, most workers have divided the Himalaya into a series of longitudinal tectonostratigraphic domains: i) Sub Himalaya, ii) Lesser Himalaya, iii) Higher Himalaya, and iv) Tethys Himalaya (Neogi *et al*., 1998). These domains are separated from each other by major dislocation zones.

Geology and geotectonics of Sikkim Himalaya have been studied recently by various workers from different perspectives *viz*. i) stratigraphy and structures (Ray, 1989; GSI, 2000), ii) metamorphism (Dasgupta *et al*., 2004), iii) out-of-sequence thrust movement (Catlos *et al*., 2004). Fig.1.1 shows details of lithology and structure of the region and Fig.1.2 shows the geological section from Darjeeling Hill to northern border of Sikkim along A-B marked on Fig.1.1. The core of the region is occupied by the Lesser Himalayan low-grade metapelites (Daling Group, Proterozoic to Mesozoic) and the distal parts by medium to high grade crystalline rocks of the Higher Himalayan Belt (Higher Himalayan Crystalline Complex, HHC, Proterozoic?). A prominent ductile shear zone (the Main Central Thrust, MCT) separates the two belts. In this region, the MCT is the southernmost of a number of northward-dipping ductile shear zones within the Higher Himalayan Crystalline Complex. Gondwana (Carboniferous-Permian) and molasse-type Siwalik (Miocene-Pliocene) sedimentary rocks of the Sub-Himalayan Zone occur in the southern part of the region. In the far north, a thick pile of

Cambrian to Eocene fossiliferrous sediments of the Tethyan Zone (Tethyan Sedimentary sequence) (see Fig.1.1) overlie the HHC on the hanging wall side of a series of north-dipping normal faults constituting the South Tibetan Detachment System (STDS; Burchfiel *et al*., 1992).

The HHC consists predominantly of high-grade pelitic migmatites with subordinate calc-silicate rocks, metabasites and granites. The pelitic migmatites are stromatic, with layer-parallel granitic leucosomes and biotite rich melanosomes (Neogi *et al*., 1998). Patchy leucosomes and discordant veins are also present. Banded, finely foliated augen gneisses show transitions from stretched leucosomes to composite crystal augens with porphyroblasts of K-feldspar. The augen gneisses display pervasive mylonitic fabrics, suggesting that augen development may reflect strain heterogeneities. Numerous layers of calc-silicate rocks and minor quartzite occur throughout the HHC. Small bodies of metabasic rocks are generally conformable to the gneissic and migmatitic layering. Intrusive bodies of biotite and tourmaline leucogranites, rarely exceeding a few tens of meters, occur in great profusion in the upper parts of the HHC.

Sikkim Himalaya has been subdivided into distinct geotectonic domains like other sectors, which are separated from one another by thrust faults (e.g. Acharya and Shastry, 1979; Ray, 1976; Sinha Roy, 1982; Catlos *et al*., 2004; Dasgupta *et al*., 2004). They are described as follows.



(Modified after Acharya, 1989; Ray, 1989; Neogi et al., 2000; GSI, 2001; Catlos et al., 2002, 2004)

Fig.1.1 Geology and Stratigraphy of Teesta basin in Sikkim

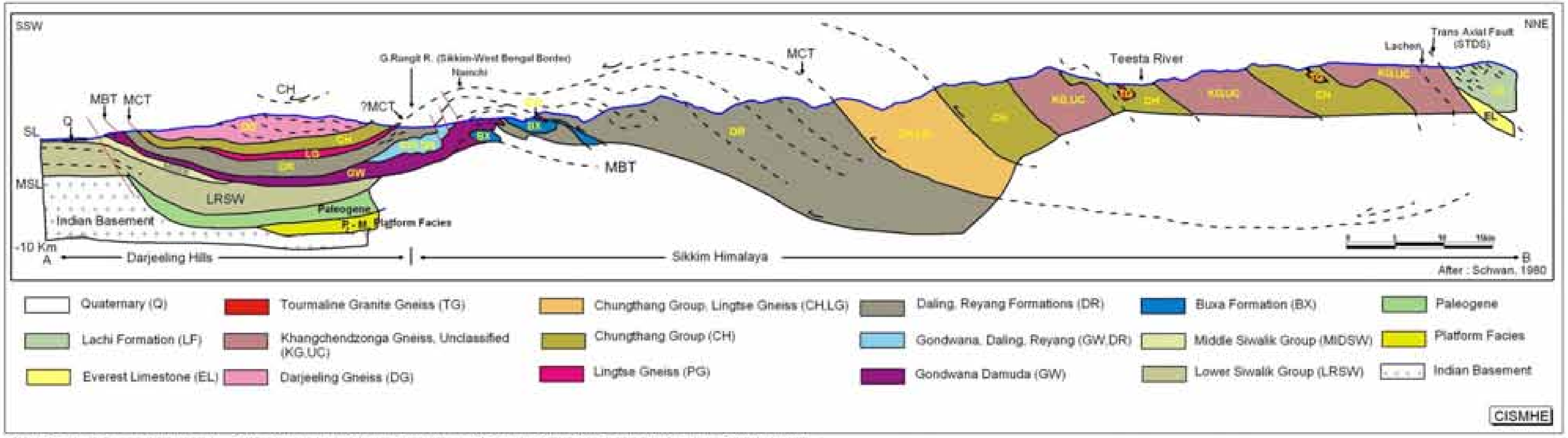


Fig.1.2 Geological section along A - B (see Fig.1.1) in Sikkim Himalaya. MBT: Main Boundary Thrust, MCT: Main Central Thrust

1.1.1 Sub-Himalayan Domain

This domain lies in the south and consists of mollase type deposits of the Siwaliks (Mio-Pliocene), and is separated from the lesser Himalayan domain (LHD) in the north by the Main Boundary Thrust (MBT).

1.1.2 The Lesser Himalayan Domain

The LHD consists of a thin strip of Gondwana rocks (Carboniferous-Permian), carbonate rocks (Buxa Formation) and a thick metasedimentary sequence of dominantly pelites with subordinate psammite and wacke (Daling Group).

1.1.3 Higher Himalayan Domain

The higher Himalayan domain (HHD) overlies the LHD and is composed of medium to high-grade crystalline rocks, commonly referred to as the higher Himalayan crystallines (HHC). These are dominantly of pelitic composition, with sporadic quartzites, calc-silicate rocks, metabasics and small bodies of granite. The HHC is separated from the lesser Himalayas by the Main Central Thrust (MCT). The exact location of this thrust has been controversial in many areas, including Sikkim (Lal *et al*., 1981; Sinha Roy, 1982).

1.1.4 The Tethyan Belt

A thick pile of fossiliferous Cambrian to Eocene sedimentary rocks belonging to the Tethyan Belt (Tethyan Sedimentary Sequence) overlie the HHC on the hanging wall side of a series of north-dipping normal faults constituting the South Tibetan Detachment System (STDS) in the extreme north of Sikkim.

1.2 STRATIGRAPHY

A comprehensive stratigraphic framework along a south-north traverse from the foothills of Darjeeling-Himalaya to the northernmost part of the Sikkim Himalaya is established by Ray (1989) and shown in Table 1.1. The repetitive nature of the three units, namely the Gorubathan, the Reyang and the Baxa of the Daling Group as also the two units, the Rangit Pebble Slate and the Damuda of the Gondwana Group, within a tectonic section has been shown from Darjeeling-Sikkim Himalaya (see Table 1.1).

Table 1.1 Tectonostratigraphic Succession along South-North Darjeeling-Sikkim Himalayan Section (after Ray, 1989, GSI, 2000)

North

⇧

TETHYAN GROUP	4. Tso Lhamo Formation
	3. Lachi Formation
	2. Mt. Everest Limestone
	1. Mt. Everest Pelitic Formation
TRANS AXIAL THRUST	
SIKKIM GROUP	Darjeeling Gneiss, Khangchendzonga Gneiss and Chungthang (=Paro) Subgroup

with Lachen Leucogranite (and its Equivalents)

SIKKIM (MAIN CENTRAL?) THRUST

DALING GROUP Gorubathan Subgroup
(with Lingtse Granite Sheets at different Structural Levels)
(Syngenetic Fe-Cu-Pb-Zn Mineralisation)

KALET CHHU-LEGSHIP THRUST

DALING GROUP

Reyang Subgroup
Buxa Subgroup Gondwana Group
Gorubathan Subgroup

PAJOK THRUST

A Zone of pile of thin scales of
Daling Group (Gorubathan-Reyang-Buxa Subgroups)
and Gondwana Group (Rangit Pebble Slate -
Damuda Formations)

NORTH TATAPANI THRUST

GONDWANA GROUP
2. Damuda Formation
1. Rangit Pebble Slate

DALING GROUP
3. Buxa Subgroup
2. Reyang Subgroup
1. Gorubathan Subgroup

NAYA BAZAR THRUST

A Zone of Pile of thin Scales of
Daling Group (Gorubathan-Reyang-Baxa Subgroups)

and Gondwana Group (Rangit Pebble Slate -
Damuda Formations)

___________ *KITAM-MANPUR KHOLA THRUST*_______________

DALING GROUP 2. Reyang Subgroup
1. Gorubathan Subgroup

________________ *SIM JHORA THRUST*_____________________

DALING GROUP Gorubathan Subgroup
(With Lingtse Granite Sheets)

_ *NORTH DARJEELING (BARNESBERG-BADAMTAM) THRUST* __

SIKKIM GROUP Chungthang Subgroup, Darjeeling Gneiss, Khangchendzonga Gneiss (? Middle Cenozoic Pegmatite Aplite Formation and small Granite Bodies)

___________*SOUTH DARJEELING THRUST* __________________

DALING GROUP Gorubathan Subgroup
(Intruded, Metasomatically Replaced and Technically Emplaced Lingtse Granite)
(Syngenetic Fe-Cu-Pb-Zn Mineralisation)

__________*DEORALI-RONGCHONGTHRUST* _________________

DALING GROUP 2. Reyang Subgroup
(with slices of Gorubathan Subgroup)
1. Gorubathan Subgroup
(with slices of Rangit Pebble Slate and Damuda Formation in Basal Portion)

_________________ *DALING THRUST* ______________________

GONDWANA GROUP 2. Damuda Formation

1. Rangit Pebble Slate
(Slices of Daling Group)

_______________ *TINDHARIA THRUST*_____________________

GONDWANA GROUP Damuda Formation

________ *MAIN BOUNDARY THRUST (SOLE OF NAPPE)*_______

SIWALIK GROUP 2. Geabdat Formation
1. Chunabhatti Formation

(Intermixed with Damuda Slices in Rangtong Thrust)

___________ *RANGTONG (IMBRICATE) THRUST* _____________

SIWALIK GROUP 3. Murti Boulder Bed
2. Parbu Grit
1. Geabdat Formation

______________ *UNCONFORMITY/FAULT* ___________________

QUATERNARY GROUP Alluvium
Terrace Boulder Beds

⇩

SOUTH

Further work has been carried out towards the north of MCT (GSI, Gangtok, 2000). The regional geologic map presented in Fig.1.1 is a compilation of observations contained in the works of Ray (1989), Acharya (1989), Neogi *et al*. (1998) and GSI, Gangtok (2000). In this figure excepting the unclassified region, pelitic migmatite (stromatic, patchy) and minor interbanded pelitic schist and metabasites of HHC (see Neogi *et al*., 1998), the rocks in the area covered by the political boundary of Sikkim towards the north of Main Central Thrust (MCT) are grouped into: Chungthang Formation, Biotite-Muscovite Gneiss, Darjeeling Gneiss, Khangchendzonga Augen Gneiss, Everest Limestone, Lachi Formation and Tso Lhamo Formation (See Fig. 1.1). Also observed in this region are isolated patches of tourmaline granite and calc-silicate rocks with interbanded quartzite.

1.3 STRUCTURE, TECTONICS AND METAMORPHISM

A number of discrete linear zones of ductile deformation (DDZ) are seen in many localities. The DDZ cut across lithological boundaries and the planar fabric S_2 commonly seen in the gneissic layering that is defined by the alignment of biotite and silimanite grains (Neogi *et al*., 1998). These zones are narrow, characterised by intense mylonitization, formed late in the deformation history, and are associated with mineral lineations and stretching lineations. The stretching lineations generally plunge to the north. Shear sense indicators consistently indicate a top-to-south sense of movement. S-C fabrics associated with the top-to-south transport are found within the gneisses in these zones (Neogi *et al*., 1998).

The MCT is generally regarded as a major intracrustal ductile thrust zone (Grujik *et al*., 1996). The MCT is few kilometers wide. In some parts of the Himalayan orogen, the upper bounding fault of the MCT zone marks a metamorphic discontinuity (Hodges and Silverberg, 1988; Metcalf, 1993), whereas in other parts no such break is recognized (Hubbard, 1989). In the Sikkim region of NE India, the Main

Central Thrust (MCT) juxtaposes high-grade gneisses of the High Himalayan Crystalline, the Darjeeling series, over lower-grade slates, phyllites and schists of the Lesser Himalaya, the Daling Series (Catlos *et al*., 2002). Inverted metamorphism characterises rocks that underlie the MCT, and is described in the Sikkim region as a gradual increase in metamorphic intensity in the Daling series at lower topographic levels to the Darjeeling series at higher levels with no apparent break across the fault (e.g. Mallet, 1875; Ray, 1947). Because both increasing (Metcalf, 1993) and decreasing (Thakur, 1986; Lombardo *et al*., 1993) grades of metamorphism towards higher structural levels have been observed the geological picture in the Higher Himalayas is rather confusing (Neogi *et al*., 1998). Numerous models have been proposed to account for the observed inverse metamorphic zonation in the Himalayas and a prominent role is assigned to the MCT in most of these models. The pressure gradient of 0.25 kbar/ km resembles a normal lithostatic gradient, which suggests that the HHC in Sikkim represents an inverted Barrovian sequence. This inverted zonation of the HHC is probably the result of large-scale structural inversion and/or tectonic juxtaposition because of ductile shearing (Neogi *et al*., 1998).

The Darjeeling rocks are largely gently N-dipping, but locally domed to fold west, east and north (Hooker, 1854). Structurally above these is the contact between the Darjeeling and Tethyan rocks, which in Sikkim has been reported from two places (Edwards *et al*., 2002, locations 1 and 2 in see Fig.1.1). In NW Sikkim on Jonsang Kang (~7000m – location 1 in see Fig.1.1) the northward dipping orthogranitic

Khangchendzonga gneisses (part of the Darjeeling series) are structurally in contact with limestones (Dyhrenfurth, 1931). From the Lachi Spur (location 2, see Fig. 1.1), Wager (1934) observed that the Permian Lachi series and a small sliver of the underlying Mt. Everest limestone are in 45°N dipping normal fault contact with “porphyroblastic feldspar” biotite gneiss (Wager, 1939). This appears to be the first accurate identification of the South Tibet Detachment System (STDS) (Catlos *et al*., 2002). The STDS and the trace of the Himalaya are monoclinally bent across the Chhumbi graben valley (the southern most part of the N-S Yadong-Gulu rift system) stepping north by ~40km to the east of this point (the Yadong Cross Structure) (Edwards *et al*., 2002).

The Dalings occupy large area of Teesta valley and form a dome below the Darjeeling gneiss. The Lingtse-granitoid gneiss occurs within the Daling Group of rocks. The contact between the Lingtse Granitoids with Dalings is controversial. The arcuate shape of the MCT in Sikkim is in conformity with the domal structure of the Higher Himalayan Crystalline. The MCT passes about 5 kms east of Gangtok and crosses the Teesta River near Manul. The E-W trending north dipping MBT crosses the Teesta river near Kalijhora township.

1.3.1 The Rangit Tectonic Window

The Daling Group of rocks was earlier considered as older than the Buxa Group. Later on Srikantia (1977) comparing the regional settings suggested that the Daling could be equivalent of the Simla and

Jaunsar Groups are probably younger than the Buxa. This suggests that Daling resting along a thrust over the Buxa in the Rangit Valley is a superficial nappe.

The lowermost structural belt in the Rangit Valley is the Precambrian Buxa Group with overlying Upper Carboniferous-Lower Permian Rangit Pebble Formation. The Buxa-Rangit Pebble on all side is framed by the Daling Thrust Sheet (see Fig. 1.2). Geology of the Rangit Window is summarised below.

Window	Rangit Valley
Thrust Sheet	Daling
Superficial nappe	
Thrust Sheet rocks	Dalings
Trace of Thrust	Dalings
Window Rocks	Rangit Pebble, Buxa

- - - - - - - - - - - - - - - - Unconformity -

1.3.2 The Main Central Thrust Zone

The deformation zone related to the MCT is often referred to as the Main Central Thrust Zone (MCTZ). Over the entire length of the Himalayas, the inverted Barrovian sequence is contained essentially within the MCTZ. The metamorphic facies distribution follows a pattern that is likely to have been controlled by tectonic development, particularly by the major dislocation zones such as the MCT which appears to be a deep crustal feature. The zonal boundaries are folded by NE-SW and NW-SE regional folds in the western Himalaya, and dominantly by N-S and E-W regional folds in the eastern Himalaya (Sinha Roy and Bhargava, 1989).

Himalayan metamorphism is essentially Barrovian with minor contact metamorphic signatures around major plutons. The foothill belt of the Siwaliks, and the Murrees are nonmetamorphic in character. The rocks of the Lesser Himalayan paraautochthonous belt, namely, the Gondwanas in the Eastern Himalaya and the Krol-Tal-Subathu sequences in the Western Himalaya, both of the frontal belt as well as of the Window zones (Eastern Himalaya), are either anchimetamorphic or in the lower greenschist facies. In the Eastern Himalaya the greenschist facies assemblages, represented by the Daling sequence, is delimited in the north by dislocation zone (MCT-I of Sinha Roy, 1988 □ MCT of Catlos *et al*., 2004) at the base of the tectonised slivers of the Lingtse Gneiss and in the south by a thrust (MCT-II of Sinha Roy, 1988 □ MCT of Catlos *et al*., 2004) at the contact of the Gondwana rocks (Fig. 1.3). At the lowest structural level of the Daling thrust sheet near MCT-II in the Sikkim Window zone, moderate-pressure and low-temperature metamorphism characterized by transitional glaucophanitic actinolite in metagraywacke has been reported by Sinha Roy (1975, 1977b). This metamorphism is considered to be due to thrusting deformation in low-temperature lower greenschist facies domain.

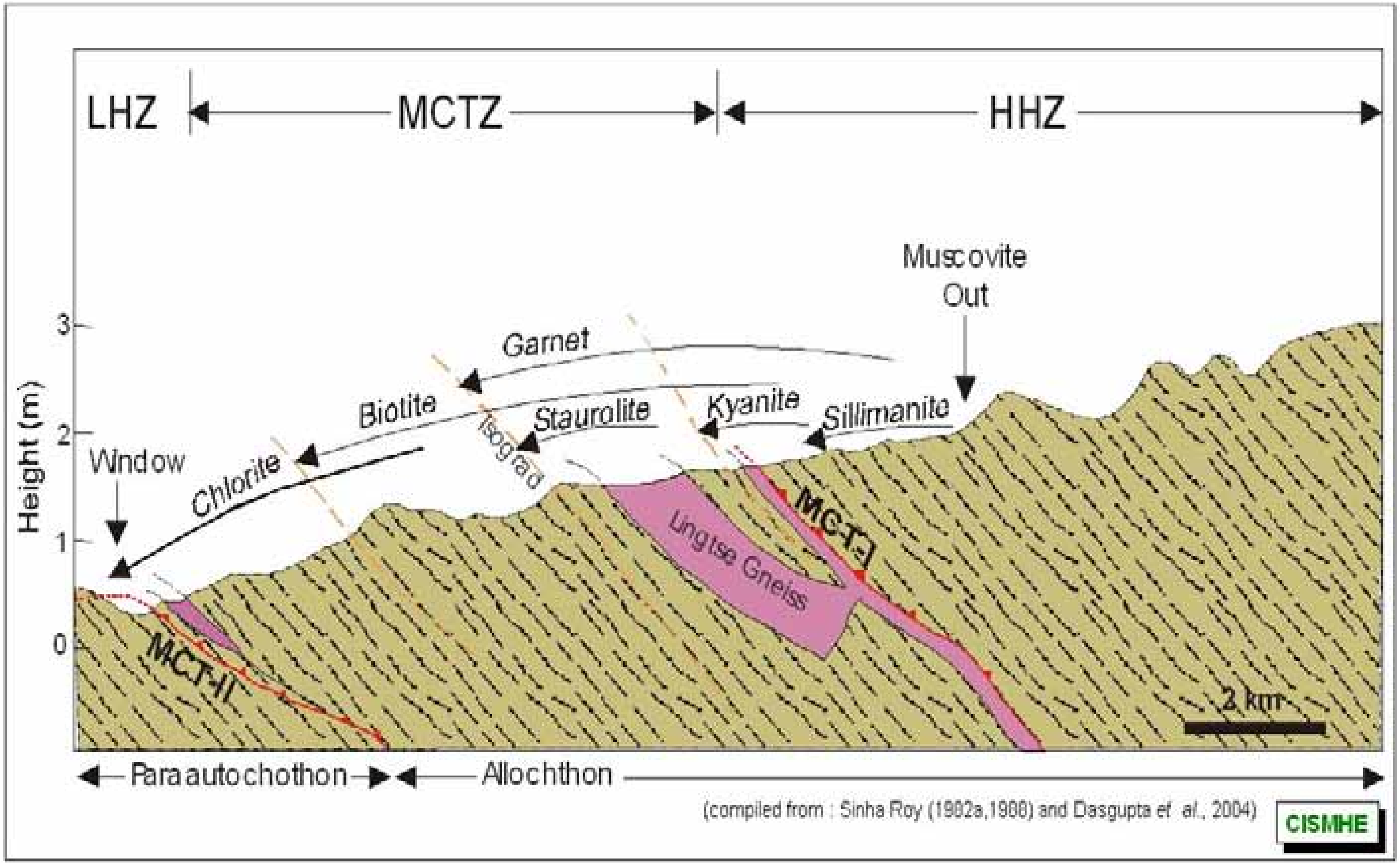
A sequence of all the Barrovian metamorphic zones along an SW-NE traverse (Fig. 1.3) is present within a short distance around Rongli Region (Sinha Roy and Bhargava, 1989; Dasgupta *et al*., 2004). In this region, metamorphism progressed in an easterly direction from chloritic, micaceous phyllite and quartzite to different varieties of micaschist, culminating in the appearance of migmatitic pelites. A dominant eastward dipping pervasive planar structure indicates that the whole section is an inverted metamorphic sequence. A well-foliated granodioritic augen gneiss, locally named as Lingtse Gneiss, is exposed in the middle of the sequence.

The MCTZ in the Rongli area is identified as a large-scale high-strain zone of disturbed deformation, as can be determined on the basis of detailed meso- and micro-structural analysis (Neogi *et al*., 1998; Dasgupta *et al*., 2004). This criterion of the MCTZ in the Sikkim Himalaya is similar to that proposed by Pecher (1989) in Nepal, Grujic *et al*. (1996) in Bhutan and Stephenson *et al*. (2000) from Zanskar. The MCTZ has variable exposed thickness in Sikkim, and along an E-W transect in Rongli is *ca*. 12 km wide, involving both the so-called lesser and higher Himalayan rocks, and extending from the biotite zone to beyond the muscovite-out isograd (Fig. 1.3). Rocks below the MCTZ are referred to as the LHD and those above it as the HHD.

Along an E-W cross-section Dasgupta *et al*. (2004) recognized three groups of major planar fabrics S_1, S_2 and $S_{3.}$ The S_1 is an incipient fabric, which is parallel to the compositional layering in the lesser Himalayas, and is commonly preserved as an included fabric in the porphyroblastic phases in the MCTZ. The S_2 is the most pervasive planar fabric in all domains, being a slaty cleavage in the chlorite and biotite zones, a schistosity in the garnet to sillimanite-muscovite zones and a gneissosity in the sillimanite + K-feldspar zone. The orientation of this planar fabric along the transect is roughly the same throughout, that is below, within and above MCTZ. The S_3 represents a crenulation cleavage or schistosity on S_2. In the higher grade rocks, S_3 is represented by a mylonitic foliation. Also, the metamorphic isograds are roughly parallel to the S_2 planar structures with the higher grade rocks appearing progressively northwards, eastwards, and westwards of what is known as the Teesta Dome. These observations suggest that a regional deformation folded the metamorphic isograds with approximately a northerly plunge.

In the Rongli location the determined kinematic shear sense is top to SW, whereas along the Teesta transect, it is top to S or SSW. The horse-shoe or mushroom shaped pattern of the Darjeeling-Sikkim region, which is attributed to the Teesta culmination zone, is due to the interference of E-W and N-S folds (Ray, 2000). Whereas the northerly plunging antiformal structures can be found in Sikkim, the E-W synformal structures are exposed in the Kalimpong and Darjeeling areas. The huge area of the Teesta culmination has exposed a vast expanse of the lesser Himalayan units in the core.

A qualitative model of sequential emplacement of thrust sheets progressively toward the south in Himalaya, and sequential metamorphism of the rocks under the increased overburden of the thrust has been proposed after detailed structural mapping in Nepal, (Robinson *et al*., 2003). This model proposes that the overburden decreases southward due to the gradual climb of the basal Himalayan



(compiled from : Sinha Roy (1982a,1988) and Dasgupta et al., 2004)

Fig.1.3 Barrovian zones in MCT zone along SW-NE

decollement in this direction and erosional denudation of the rocks. This model is also able to produce a close relationship between metamorphic crystallization and a dominant fabric and increase of both pressure and temperature in the up-section direction (Dasgupta *et al*., 2004).

1.3.3 Movement along the structural planes

The high Himalayan mountains are the result of collision of India with Asia that began ca. 60 million years ago (e.g. Le Fort, 1975; Yin & Harrison, 2000). High rates of seismicity and deformation are the characters of the range at present (Yeats *et al*., 1992). Widespread exposure of post-collisonal, high-grade metamorphic rocks in the Himalaya implies long-term, large-scale vertical transport (Catlos *et al*., 2004). The MCT has generally been regarded as an early Miocene structure (e.g. Hodges *et al*., 1996; Vannay and Hodges, 1996). However recent observations (e.g. Harrison *et al*., 1997a; Catlos *et al*., 2001, 2002a) have suggested that the rocks within broad MCTZ experienced metamorphism later than Miocene. For instance, the Th-Pb dating (Catlos *et al*., 2001) of small (c.15 micro m sized) monazite from rocks within the crystallized MCT shear zone in central Nepal yields ages as young as c.3 Ma.

It has also been thought that with the shift in deformation from Indus-Tsangpo suture towards foreland (e.g. the evolutionary model of Seeber and Gornitz, 1983) the MCT was formed subsequent to Late Cretaceous-Early Eocene Indo-Asia collision (e.g. Le Fort, 1975; Yin and Harrison, 2000). Although contraction appears to have broadly progressed towards the Himalayan foreland as activity shifted from the MCT during the Early Miocene (e.g. Hodges *et al*., 1996) to the Main Boundary Thrust (MBT) during the Late Miocene (e.g. Meigs *et al*., 1995), to the currently active Main Frontal Thrust (MFT, e.g. Yeats *et al*., 1992), monazite ages from the Lesser Himalaya in central Nepal and NW India (Harrison *et al*., 1997a; Catlos *et al*., 2001, 2002a) indicate that the hinterland thickened internally during the Late Miocene and Pliocene (Catlos *et al*., 2004). However, the post-Early Miocene MCT movement may be restricted to certain regions viz. central Nepal (Harrison *et al*., 1997a; Catlos *et al*., 2001), eastern Nepal and NW India (Catlos *et al*., 2002a). Thus, the generality of the out-of-sequence thickening along the strike of the Himalayan range remains unknown.

The temporarily distinct monazite ages from MCTZ and STDS in Sikkim suggest that the MCT was active at 22-20, 15-14 and 12-10 Ma, whereas the STDS may have been active at c.17 and 15-14 Ma supporting out-of-sequence thrusting in the region (Catlos *et al*., 2004). However the study of Dasgupta *et al*., (2004) reveals three key points: a) there is progressive increase of both temperature and pressure with increasing grade and structural height through the MCTZ and the lower part of the HHC, b) the growth of metamorphic minerals at all grades is closely related temporally to one dominant fabric, S_2, and c) there is nothing out-of-sequence in the Rongli section, in terms of not only increasing P and T, but also key mineral parageneses.

1.4 GEOMORPHOLOGY

The Teesta river originating in, and fed by the glaciers of the northernmost tracts of the Sikkim Himalaya, has formed an important river basin in the Eastern Himalaya. The Teesta valley is characterised by glacial and periglacial landforms in north and north-central Sikkim and by abundant fluvial terraces in the lower stretches. The geomorphic features observed in the region includes the terraces all along the courses of the higher order streams. Four-tier terrace system is observed in the central and lower stretches of the Teesta river in Sikkim-Darjeeling Himalaya. Their development is linked with regional uplifts and consequent incision and their dispositional irregularities with local tectonics and knick-points (Sinha Roy, 1980). Numerous active landslides are also present along the right and left banks of the major rivers in north, south, east and west districts of Sikkim. The glacial moraines predominates in the upper reaches of the Teesta river. Besides these features, alluvial fans and cones are present at several places in the basin.

1.5 MINERAL RESOURCES

The Geological map so far prepared by GSI serves as the base for mineral exploration and assessment of reserve in the state of Sikkim. It may be noted here that the completed geological mapping of Sikkim (area 7,325 km^2) by GSI does not cover the permafrost region (> 5,000 m) covering an area of 1,138 km^2 which mostly fall in the North Sikkim. Important Syngenetic Fe-Cu-Pb-Zn sulphide-oxide mineralized horizons occur in the Daling Group in Sikkim (see Table 1.1). Some of the important mineral deposits are listed in Table 1.2.

Table 1.2 Mineral deposits in Sikkim

Deposits	Locality
Copper ores	Western Sikkim: Changbong, Jugdum, Raothak, Sumbuk, Northern Sikkim: Dik Chhu
Iron Ore	Bhotang
Lead-Zinc	Rangpo, Dik Chhu and Jugdum
Dolomite	Ranguthang, Chinchi and Salebong
Limestone	Rinchingpong, Chhangu
Marble	Chungthang
Coal	Rangit valley: Rebong, Namchi and Rinchinpong hill, Put Khola, Roathak Khola, Baiguno Khola, Andhari Khola, Ranji Khola and Namrek Khola
Graphite	Bot village near Chungthang, Derhati, Kalijhar, Kuapani and north of the road from Tathing and Lachen
Garnet	Panchikhani (in small quantity)

The mineral deposits need to be evaluated not in terms of their importance as ‘resource availability’ and ‘uses in industry’ supporting the carrying capacity of the region but in terms of a) wastes likely to be resulted due to their exploitation, b) their chemical and physical effects on the land and water environments. Therefore, a detailed account of mineral and rock resources present in Sikkim (GSI, 2001) and their industrial usability is given below.

1.5.1 Mineral and Rock Resources

1.5.1.1 *North Sikkim*

The North Sikkim is situated in the rugged, inaccessible, high altitude region of the Himalaya. So far exploration programmes by GSI have been able to locate the calc-silicate/marble deposits in the north district of Sikkim and there is every likelihood that other deposits may be present in this district in substantial quantity.

i) *Calc-Silicate/Marble*

Calc-silicate/Marble bands occur within the high-grade gneissic sequence of Central Crystalline. There are three main occurrences of calc-silicate/marble rocks:

a) NE and NW of Chungthang. This deposit is situated mainly in the form of boulders at about 5.5 km NW of Chungthang on Chungthang-Lachen road. It has a length of about 300 m along the road up to the point where the highway crosses the Chubinbin Chhu.

b) The second deposit is located about 13.3 km NW of Chungthang-Lachen road and 700 m south of Tarum Chhu cutting across the highway. It has a length of about 450 m along the road and is represented by thinly interbanded calc-silicate, quartzite associated with calc-granulite and crystalline marble.

c) The third one is present near Malten Shiva temple, 6 km NE of Chungthang on the Chungthang-Lachen road. The deposit occurs in association with high-grade schist and gneiss and covers a stretch of about 50 m only along the vicinity of the Shiva temple. Other minor occurrences of calc-silicate/ marble are present along Singhik-Chungthang road near Myang village and near police check post at Tong. In many localities the carbonate being leached out in solution from the calc-silicate bodies and redeposited on the surface of quartzite, giving them a deceptive look by typical surfacial elephant skin weathering.

ii) *Building Stone*

The area comprises a variety of gneisses, some of which are compact and massive (weakly foliated varieties) and can be used as building stones. A few of these rocks could also find use as decorative slabs with suitable cutting and polishing. But the remoteness of such occurrences makes them non-viable for decorative and building stone industry.

1.5.1.2 *South Sikkim*

Several metallic and non-metallic mineral deposits are present in the South district of which the dolomite and coal are most important.

Sporadic occurrences of sulphide mineralisation have also been located in several parts of the district. Basemetal occurrences have been recorded in the Daling Group of rocks, dolomite within Buxas and coal in the Gondwana rocks.

iii) *Dolomite*

Dolomite occurring in this district are of two types :

a) *The high grade massive type*

The high grade massive dolomite occurs most extensively in the Rangit river valley region. Good quality dolomite belonging to the Buxa Formation are present near Rishi Khola at 27^{o},15’ N; 88^{o},18’ E. The dolomite is light grey in colour and fine grained in nature with high percentage of CaO and low insoluble content (insoluble 1.5-3%). A reserve of 1.10 million tonnes has been estimated by GSI down to a depth of 30 m from the surface. These dolomites are of both ‘Blast Furnace’ (less than 3% insoluble) and ‘Steel Melting shop’ (< 1.5% insoluble) grade.

b) *Low-grade flaggy type*

The low grade siliceous and flaggy dolomite occurs associated with Gondwana rocks between Namchi and Phong and between Namchi and Jorethang. Grey dolomite deposit occurs at Phalidanda, Tangji and Chamgaon areas near Namchi. The impure dolomite is suitable for crushing into powdery form for spreading on the cultivable lands for neutralization purpose.

c) *Coal*

Coal bearing horizons are exposed in and around Namchi (27°10’N; 88°24’E) area of South Sikkim. The total estimated reserve in this area is 1.4 lakh tonnes of coal. This is a bituminous to semi-anthracitic variety of coal, occasionally pulverized due to intensive folding and shearing movement. On analysis, this variety of coal indicates 40-60% fixed carbon, 22-40% ash, 3-8% V.M. and 3-6% moisture. This coal can be used for local consumption after proper benefaction and blending with the high volatile bituminous coal. This bands of coal are exposed near Jorethang on Jorethang-Namchi road section near Sikkip. Coal seams are also exposed in Namchi-Tinjir road section and in the areas on eastern slopes of the Rangit River along Rishi-Sagbari section. Due to tectonically disturbed nature it is very difficult to trace the continuity of the seams. Borehole data reveal that the coal seams are in association with band of clay stone, sandwiched between sandstone-shale sequences. The coal is normally overlain immediately by a carbonaceous shale and/or siltstone unit containing plant fossil fragments and is underlain by the carbonaceous shale unit. The quality of coal has deteriorated due to intense deformation, crushing and intimate mixing with associated sandstone and shale.

d) *Sulphide Mineralisation*

Stringers and disseminations of sulphide mineralisation in the form of chalcopyrite and pyrite occur sporadically within the phyllitic rocks of Daling Group in several localities of the district such as Damthang, Khani Khola, Subbuk, Pamphuk and Temi. In the bed of Khani Khola, a tributary of Manpur Khola, chalcopyrite and pyrite mineralization with few specks of galena is present. Analytical data reveals that sulphide mineralisation is rich in copper and contains traces of lead, zinc and silver. The mineralized zone is traceable in an old adit, located on the eastern bank of Khani Khola for about 30 m along strike. The sulphide-bearing horizon is associated with quartz vein and is found to be emplaced within the quartz-chlorite-sericite schist of Daling Group of rocks along the regional foliation plane. The host rock is trending E-W and has moderate dip towards north.

1.5.1.3 *East Sikkim*

The two producing Cu-Pb-Zn mines of Sikkim are located at Bhotang, Ramp and at Rorathang in the East Sikkim. Small occurrences of base metal prospects in East Sikkim had been known since long. Sizeable heaps of slags are found at several places like Pachekhani, Bhotangkhani, Tukkhani and Rattukhani.

Sikkim Mining Corporation is exploiting the polymetallic deposit at Rangpo and Rorathang. The prime mineralisation at Rangpo consists of chalcopyrite, pyrite, pyrrhotite and the total sulphide is less than 2%.

Associated country rocks are chlorite-phyllite, garnetiferous chlorite schist/sericite phyllite, quartzite and carbon phyllite. A total reserve of 0.6 m.t. of polymetallic ore at 1% cut off was estimated by IBM, most of which has already been mined out. Occurrences of sulphide mineralisation and an associated magnetite quartzite horizon around Kalej Khola (northwest of Rangpo), Andheri Khola (northeast of Rangpo) have also been reported. In Pachekhani-Rorathang block, sulphide mineralisation occurs as disseminations in gritty-quartz-biotite-phyllites, slaty carbonaceous phyllites and calcareous quartzites besides some post-tectonic hydrothermal quartz veins. At upper Pachekhani block, a total of 60,940 tonnes of copper ore of average grade 1.26% Cu has been estimated. In Dugalakha block, mineralisation mostly of galena and chalcopyrite are concentrated generally in hydrothermal vein quartz and rarely as disseminations.

Other significant base metal deposit, known as Dikchu Copper Zinc deposit, is situated at the confluence of the Dik Chhu and the Teesta River. Garnetiferous-muscovite-biotite schist is the main host rock in this zone. The sulphide mineralisation is chalcopyrite, pyrite, pyrrhotite, sphalerite and galena with magnetite as major oxide mineral. In Rungdu-Sodunglakha and Kerabari area falling in Pakyong and Rongli Sub-divisions of East Sikkim the copper mineralisation is associated with quartz-biotite-chlorite-chloritoid schist. Mineralisation is structurally controlled (?), concentrated at the closure of Rangpo Chhu antiform. This block may prove to be of economic importance.

1.5.1.4 *West Sikkim*

This district has great potential in terms of mineral resources and mineral based industries. The district has appreciable deposits of dolomite and limestone in a relatively undisturbed situation. There is scope for development of building stone/ polished shale (gneiss, marble, quartzite) industry, ceramics (clay horizons).

The major non-metallic mineral reported from west Sikkim are dolomite and graphite. Minor occurrences of soapstone or talc, magnesite and asbestos etc. have also been recorded but all, except talc, are till now of uneconomic quantity. Occurrences of sulphide mineralisation have been located in Chakum, Soreng, Chongbong, Roathak, Bum and Legship.

i) *Dolomite*

Both high-grade massive and low-grade flaggy type dolomites have been located in Rishi area, in the southeastern part of the district, west of Jorthang-Legship state highway. On either banks of Rishi Khola, adjacent to Rishi village (27^{o} 13’ N; 88^{o} 46’ E), four dolomite-bearing blocks have been delineated. Massive dolomites are light grey in colour, fine grained with high percentages of MgO (18-22%), CaO (ca. 30%) and insoluble (1.5-3 %). A total reserve of more than one million tonnes has been estimated down to a depth of 30 m.

ii) *Graphite*

Graphite both lumpy and flaky types, associated with graphite schist, marble and limonitised pegmatite of High Grade Gneiss, has been located at Chitre (27°16’20"N : 88°02’10"E) and Dareli (27°17’N: 88°03’E) of West Sikkim. The graphite bands occur even at depths of 2 to 3 m below the surface and the thickness varies from 30-80 cm. An estimated reserve of about 6,000 tonnes of graphite has been computed from Chitre sector. The IBM has conducted beneficiation test on this graphite, which indicated good liberation of graphite in finer fraction. However, impersistent and pocketry nature of graphite occurrences, their inaccessibility and location at high altitude (3,000-4,000 m) near India-Nepal border, have rendered these occurrences uneconomic in view of the high cost of exploration, mining and transportation of the materials.

iii) *Coal*

Thin coal seams occurring within the carbonaceous shale-sandstone sequence of Gondwana Group have been located around Put Khola, Roathak Khola and Rinchingpong area of the district. The coal is black to grayish black in colour, powdery in nature, semi-anthracitic with high ash, low volatile matter and high (?) moisture.

iv) *Asbestos*

Near Tashiding, bluish grey short matted, harsh fibre type of asbestos associated with acicular tremolite and actinolite crystals have been located within the Dalling Phyllites.

v) *Limestone*

Grey limestone interbanded with green phyllites is observed in Rishi Khola, south of Namgaon. An exposure of limestone, about 30 m thick is traceable over a strike length of 60 m near Rishi Khola. It contains CaO (42-46%), MgO (1.22-2.20%) and insoluble (12-14%). Pink limestone with shales is exposed at Nayabazar. Limestone is massive, hard and breaks with conchoidal to semi-conchoidal fracture. Selected portion of limestone horizon have 42-44% CaO, 1.22-1.6 % MgO and 11- 18% insoluble.

vi) *Talc*

Talc occurrences have been located in Rani Khola, Rishi Khola, and Roathak Khola within the metamorphic rocks of Daling Group. Talc is found as pockets within the phyllite and is intimately associated with an inrtrusive quartz vein in Rani Khola area.

vii) *Magnesite*

In the metasediments and metabasics of Rangit valley, magnesite occurrences have also been located.

viii) *Rock Phosphate*

Occurrences of rock phosphate in stromatolitic dolomite near Tatapani and Subuk area within the Daling Group have been reported in the eastern part of the district. The phosphate-bearing horizon are very thin and impersistent in nature.

ix) *Sillimanite*

Sillimanite along with kyanite occurs either as needles or as fibrous aggregates within the quartz cummingtonite-quartz schists forming a part of high-grade biotite gneiss. A few sillimanite enriched zones were located between Sardung and Dentam villages. The most promising occurrence is at Sardung area, which has a thickness of 50m and strike length of 250m prospected by trenching and sampling. Chemical analysis of five samples show very low Al_2O_3 (5-15 %) content. Therefore, this silimanite deposit does not seem to be of economic importance.

x) *Quartzite*

Occurrences of quartzite within the Daling Group of rocks has been reported from Mansari-Malbashe-Chakung and Bardang-Singrep-Jhum-Roathak areas. Extensive exposures of pure white/milky white massive and flaggy variety of quartzite at Mansari has some economic potential.

xi) *Sulphide Mineralisation*

Base metal occurrences containing chalcopyrite with pyrite, in the form of veins, stringers and disseminations have been located at Jugdum, Roathok, Sisni, Sirbong, Sontali, Chugbung, Legship and Bum.

a) Jugdum (27°11’ N : 88°14’48" E): The copper mineralisation is associated with quartz veins and occurs within the thick greenish chlorite phyllite of Daling Group over a length of 215 m. A few lenses of chlorite schist and phyllite containing mineralized quartz vein also occur in this area. There are three main mineralized quartz veins in the main zone. Copper mineralisation present between the vertical depths of 49 m and 57 m. Copper content of core sample was between 0.21 – 0.64%. At Jugdum, the Daling phyllites and schists have a NNE-SSW regional strike with foliation dipping towards WNW.

b) Roathak Khani (27°09’50" N : 88°15’18" E): The Roathak Khani occurrence is located at the confluence of Khani Khola and Roathak Khola and is about 1.6 km NE of Chakung village. Sulphide mineralisation containing chalcopyrite and pyrite is noted over a length of about 500 m on the right bank of Khani Khola. The copper mineralisation is mainly associated with quartz veins and slates of Daling Group.

c) Sisni (27°15’N : 88°14’23" E): Sisni deposit is located about 90 m upstream of the Sisni Khola from its confluence with Roathak Khola and about 2 km NW of Chakung village. The copper mineralisation with 0.15 to 0.35% Cu is associated with quartz veins in Daling slates. The main band has a thickness ranging from 0.8 m to about 2 m over an exposed length of about 44 m.

d) Shribong (27° 10’20" N : 88° 16’E): Chalcopyrite and pyrite is exposed in quartz veins associated with slaty phyllite of Daling Group. The quartz veins have widths ranging from 0.61 m to 1.83 m and are exposed on the bed of Shribong Khola, 1.6 km NNE of Roathak Khani.

e) Sontali: Copper mineralisation noticed in association with quartz veins within the sericitic phyllites, slates and chlorite schists of Daling Group. Three mineralized quartz veins were identified with widths ranging from 0.3 m to 0.6 m.

f) Chongbong (27°7’30" N : 88°15’ E): Chongbong occurrence is located on the southern slope of Chakung ridge at an elevation of about 900 m on steep scarp face and the left side of Chongbong Khola. Poorly mineralized quartz veins with total width of 1.3m occur within the slaty phyllite striking NE and dipping NW.

g) Legship (27°17’ N : 88°17’ E): In Legship area the basemetal mineralisation is observed in the northern bank of Bania nala, near its confluence with Rangit River. Sulphide minerals *viz*. pyrite, pyrrhotite, chalcopyrite, bornite and galena occur as disseminations and thin hairline fracture filling in quartz veins. The copper content ranges from 1200 ppm to <100 ppm.

h) Bum (27°13’ N : 88°15’ E): The mineral occurrences are observed both in phyllite and quartzite and are exposed on either banks of Rishi Khola near the Bum bridge. Pyrite, chalcopyrite, bornite, galena and pyrrhotite are seen in association with vein quartz stringers, varying in thickness from less than 1cm to 13cm. Sample from a 115 cm thick quartz vein from this area has yielded 3.41-4.50% copper, but it does not show persistent strike.

At present quartzite and talc are being mined from Mansari in West Sikkim. Previously dolomite was being mined from Rishi by private agencies. They used to crush the dolomite into powder and sale to the State Government of Sikkim for distribution to the farmers for spreading on cultivated lands for neutralizing the acidic soil. Only Dolomite may have some future potential for use in steel industry.

1.6 SEISMICITY

A detailed account on the seismotectonic environment of the Sikkim and its adjoining region is given in the recent syntheses of Narula *et al*. (2000) and Kayal (2001). Like other parts of the Himalaya, this area is also traversed by MCT and MBT (Fig. 1.4). The former separates the high grade Central Crystallines from the comparatively lower grade Lesser Himalayan packages, which are separated from the Siwalik belt by the MBT. At places, particularly towards east, several subsidiary thrusts are present between MCT and MBT. Besides these thrusts, several approximately N-S trending gravity faults are present particularly within the northern Tethyan belt and the southern Foothill belt (see pages 13-14 Narula *et al*., 2000). Within the Tethyan belt these N-S faults define some well known graben structures such as Pum Qu Graben and Yadong Gulu Graben. In the former, faults affecting the Quarternary glacial deposit are clearly evident. The latter graben is considered to be the longest one in the Tibetan Plateau. It is segmented into several N-S smaller grabens. The Rangpur Ridge is a prominent tectonic feature in the east which is bound on all sides by major faults, namely Malda-Kishanganj Fault, Jangipur-Gaibandha fault, Teesta fault and Katihar-Nailphamari fault. Several subsidiary faults, parallel to Teesta fault forming grabens are reported from this ridge (Narula *et al*., 2000). Many northeasterly and northwesterly trending lineaments also cut across the Himalayan belt in this region. Some of them are : i) the

Arun Lineament (NE-SW) believed to represent the northern extension of the East Patna Fault, ii) the Khangchendzonga Lineament (NW-SW) extends from the foredeep to well inside the Himalayan belt, iii) Teesta Lineament (NW-SE), and iv) Purnia-Everest Lineament (NW-SE).

The spatial distribution of seismic activity in the region during the period 1964-1992 suggests that the regional seismicity of Sikkim Himalaya is relatively high to the north of the Main Boundary Thrust (MBT) and the activity decreases progressively southward from the Lesser Himalaya to the foredeep region, under sediment cover (Nath *et*

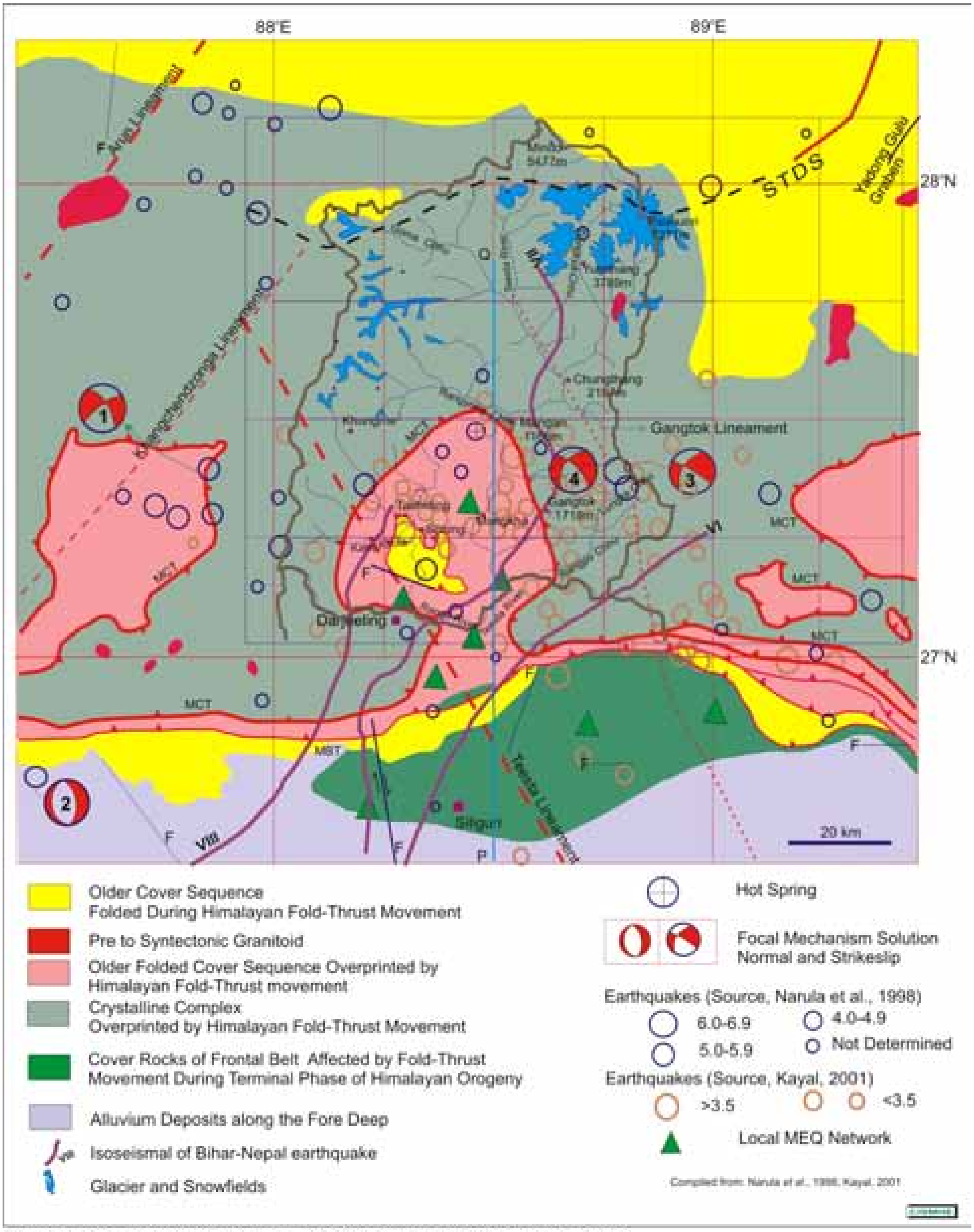


Fig.1.4 Seismotectonic map of Sikkim and adjacent regions

al., 2000). The central main Himalayan block with considerable seismicity separates the northern Tethyan block and southern foredeep block with subdued seismic activity (Narula *et al*., 2000). In this area most of the earthquakes are shallow focus (< 40 km) and are commonly of 4.5-5.5 magnitude range (Table 1.3).

Table 1.3 Chronological listing of some earthquakes of magnitude ≥4.5 for Sikkim (after Narula *et al*., 2000)

Sl.	Yr	Mo	Dt	Hr	Min	Sec	Lat	Long	Ms	Mb	Depth (km)
1.	1964	08	30	02	35	07.3	27.36	88.21	-	5.1	21
2.	1972	08	21	14	04	33.9	27.33	88.01	-	4.5	33
3.	1972	08	21	18	55	07.2	27.23	88.02	-	5.1	33
4.	1975	01	23	01	37	42.9	27.44	88.37	-	4.5	33
5.	1979	11	16	19	17	27.7	27.90	88.70	-	4.6	39
6.	1980	11	19	19	00	45.0	27.40	88.80	6.1	6.0	47
7.	1982	04	05	02	19	41.2	27.38	88.83	4.6	5.0	09
8.	1982	08	18	18	01	07.6	27.04	89.26	-	4.6	51
9.	1985	05	25	00	28	18.7	27.60	88.48	-	4.6	33
10.	1986	01	07	20	20	00.4	27.40	88.43	-	4.7	41
11.	1988	05	26	16	30	05.5	27.45	88.61	-	4.7	42
12.	1988	09	27	19	10	10.0	27.19	88.37	4.6	5.0	23

Source: International Seismological Centre (ISC)

1.6.1 Seismic Zoning

The revised Seismic zoning map of India (BIS:2000), encompasses four zones namely II, III, IV and V (Fig. 1.5). The Modified

Mercalli (MSK) scale intensity and horizontal force corresponding with seismic map zones of India are shown in Table 1.4. The area covered by Sikkim falls in zone-IV (see Fig. 1.5). The seismic zoning maps only serve as guide maps, and therefore, detailed study of any developmental site and its surrounding areas is essential to take safety measures against any future devastating tremors.

Sikkim region lies within the ambit of the Seismic Zone-IV of I.S. code 1893-1984/1998/2000. With reference to the MSK intensity scale used for all engineering design purposes the region lies in the high damages risk zone (VIII) corresponding to a magnitude of 6.7 in the Richter scale. Therefore, there is always a necessity to consider the factor of safety for highest earthquake intensity while designing an engineering construction.

Table 1.4 Seismic zones of India with corresponding MM (or MSK) scale intensity, Richter magnitude and horizontal force

Seismic Zones of India	**Hazard Intensity**	**MM (or MSK) Intensity**	**Richter Magnitude**	**Horizontal Force Coef.**
II	Low Damage Risk Zone	VI or less	5.2	0.02
III	Moderate Damage Risk Zone	VII	6.0	0.04
IV	High Damage Risk Zone	VIII	6.7	0.05
V	Very High Damage Zone	IX and above	□7.4	0.08

Force (H) = Coefficient of Horizontal force as fraction of building weight

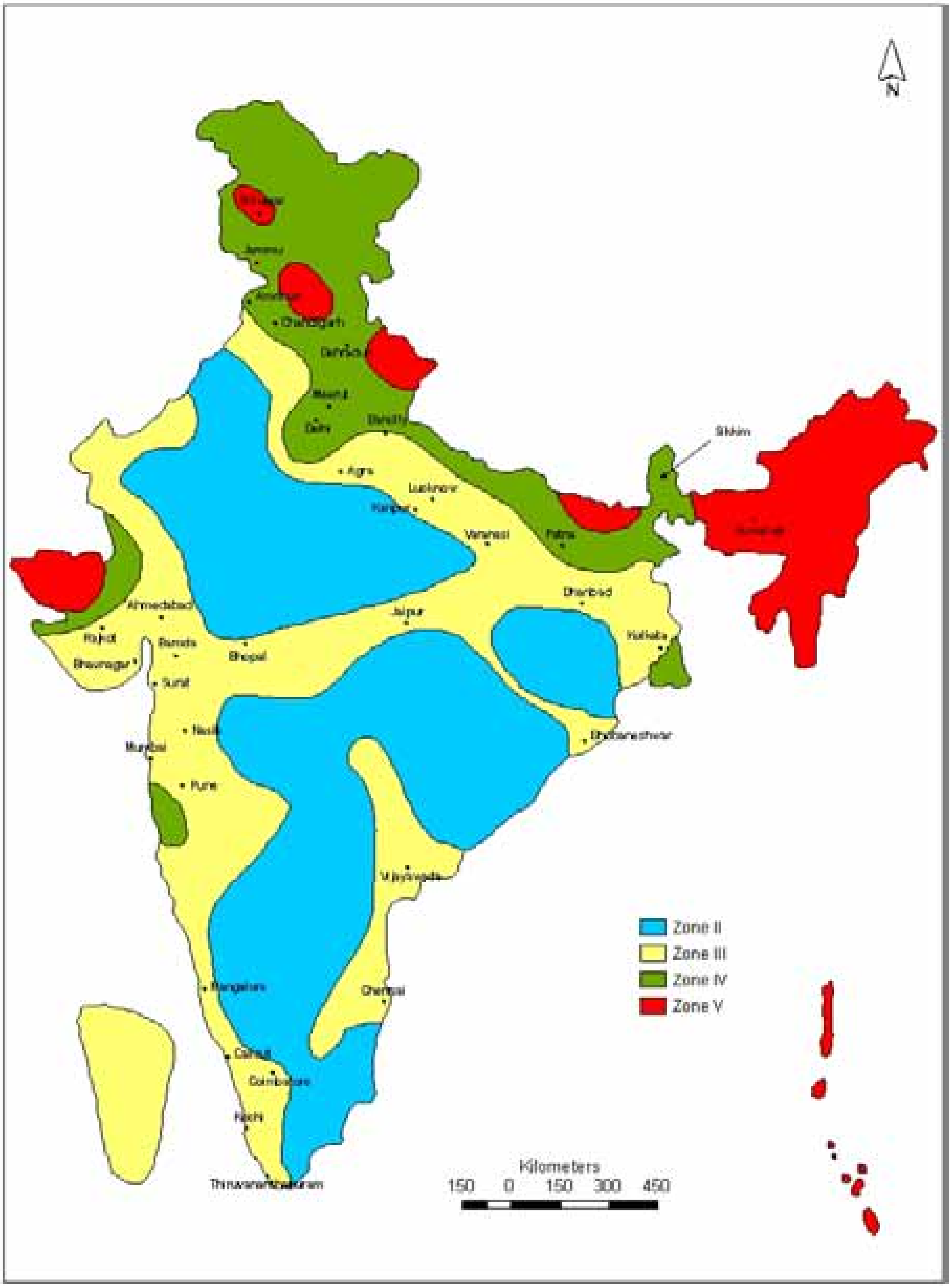


Fig.1.5 Seismic zoning map of India (Source : BIS, 2001, New Delhi)

1.6.2 Isoseismal Zones

Temporal variation of seismicity in the area shows that there is burst of earthquake for a year or two preceded by a quiet period of 3 to 4 years (Nath *et al*., 2000). The Bihar-Nepal earthquake of 1988 was distinctly felt in Sikkim. According to National Earthquake Information Centre, USGS report this earthquake of 20th August, 1988 occurred at 23:09:09.5 PM. The magnitude (Ms) was estimated to be 6.6. The epicenter was located at lat: 26.76º N and long: 86.62º E and the hypocentral depth estimated as 57km. The damages in the 3 distinct isoseismal zones (shown in Fig. 1.4) are outlined in the Table 1.5. The isoseismal VII passes through Gangtok town, in an approximately NE-SW direction (see Fig. 1.4). Several buildings in Gangtok were badly damaged and the death toll went up to 1003.

Table 1.5 Effects of Bihar-Nepal earthquake (1988) in Sikkim

Isoseismal Zone	Damage
VIII	Pass through Phulbazar and Chakum in a NNE-SSW direction. A triangular area west of this isoseismal VIII up to Nepal border experienced severe ground shaking where damages in buildings were extensive.
VII	South of Gangtok it passes in an approximate NE-SW direction. North of Gangtok it has a northerly trend up to Lachen. The impact of damages on power generation units, road alignments were

	mainly in the form of subsidence and landslides. The masonary walls of the buildings cracked and at places resulted in complete collapse.
VI	Lachung (1400 m a.s.l.) lie in this area. The area experienced strong vibration of the ground resulting in general damage to houses, subsidence of grounds and incipient cracks in the buildings. The ground movement was of shaking type and people reported to have felt tossing type of shock.

(Source: Sinha, 1993)

1.6.3 Recent Earthquake in Sikkim

An earthquake measuring 5.3 on the Richter scale jolted the region of Sikkim and adjacent states on 14th Feb, 2006 at 00 hr 55 min 26 sec (UTC) (6:25:25 AM local time). The epicentral region was located around Meekha between Peling and Rabangla at 27.3547 N latitude and 88.3552 E longitude with location uncertainity (±5.2 km) (USGS, 2006). This was a shallow focus earthquake the focal deptgh being 30.3 km.

The tremor was felt at Siliguri, Sikkim, Darjeeling, Guwahati, Itanagar, Jalpaiguri, Kooch Bihar, Karsiyang, Maldah, Shilong. It was also felt at i) Paro Chhu, Phuntsholing and Thimpu of Bhutan, ii) Dinapur, Naokhali Khad, Nilpahmari, Pabna, Rajshahi, Rangpur, Sylhet and Thakurgaon of Bangladesh, iii) Kathmandu in Nepal. About 60% of the houses got cracks in Gangtok and Rangpo. Cracks on roads observed at places. Water supply and telecommunication networks were disrupted. Two people killed by landslide at Sherathang and two were injured in East Sikkim.

1.6.4 Microearthquake Surveys

Detailed microearthquake surveys were carried out in the Darjeeling Himalaya (De, 1996) and in the Sikkim Himalaya (De, 2000). Kayal (2001) has provided a detailed interpretation of these studies. It is observed that the earthquakes are mostly clustered to the north of MBT, at a depth range of 10-40 km and majority of the earthquakes occurred below the plane of detachment (see Figs 1.4 and 1.6). A well-constrained composite fault-plane solution for a group of earthquakes (depth 10-40 km) shows thrust faulting with strike-slip component (see Fig.1.6). The north dipping E-W nodal plane is comparable with the MBT, and is the preferred fault-plane (De, 2000). The depth section and the fault plane solution suggest that the MBT is seismogenic up to the mantle in this part of the Himalaya; i.e. the MBT is a mantle reaching active fault (see Fig.1.6). Based on the gravity data, Choudhury and Dutta (1975) interpreted that the MBT is a mantle reaching thrust zone in the eastern Himalaya. Thus the microearthquake data as well as the gravity data do not support the steady state or evolutionary tectonic model in the eastern Himalaya, which postulates that the MBT converges at the plane of detachment and earthquakes occur above this plane.

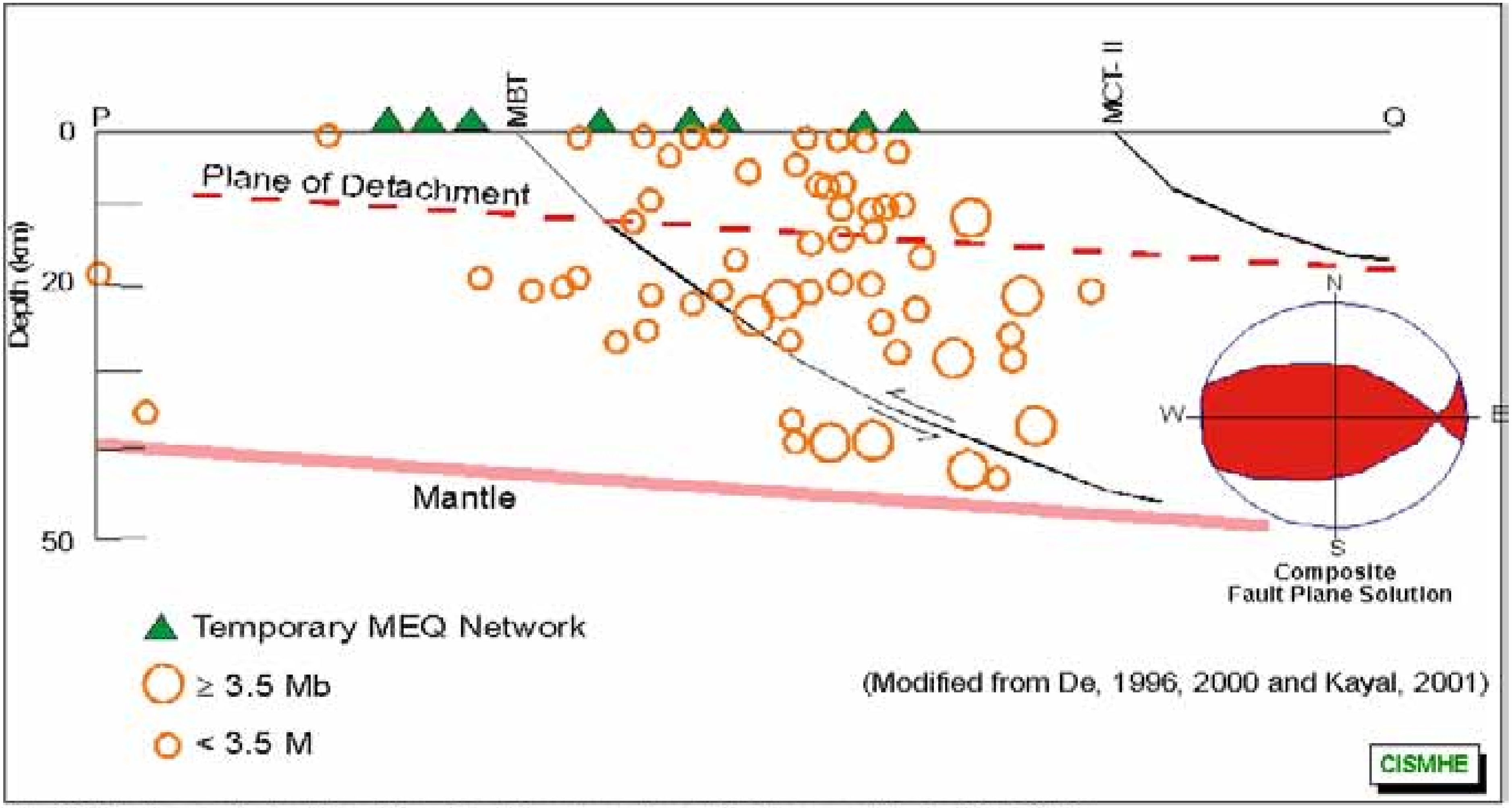
Three focal plane solutions from this domain suggest strike-slip mode of rupture along NW-SE or NE-SW trending faults (see Fig. 1.4, Table 1.6).

Table 1.6 Focal Mechanism Solutions

				NP1		**NP2**		**P-Axis**		**T-Axis**		**B-Axis**		
Plot	**Year**	**Mo**	**Dt**	**St**	**Dip**	**St**	**Dip**	**Pl**	**Az**	**Pl**	**Az**	**Pl**	**Az**	**Source**
1.	1965	01	12	233	76	326	72	23	192	03	281	66	14	Dg(a)
2.	1979	06	19	350	57	179	34	78	243	11	84	04	353	Dz
3.	1980	11	19	209	51	301	89	28	172	25	68	51	302	Dz
4.	1982	04	05	206	48	314	72	43	178	14	74	42	330	ND

From: Narula *et al*., 2000; Dg(a)- Dasgupta *et al*. (1987), Dz- Dziewonski *et al*.(1988),ND- Nandy and Dasgupta (1991)

Focal mechanism results suggest that the mosaic of active lineaments, forming conjugate shear planes, dominates the neo-tectonic deformation in the Nepal-Sikkim Himalaya and their foredeep (Dasgupta *et al*., 1987). The seismicity trend in the Sikkim Himalaya and its foredeep shows that the Teesta, Gangtok and Yamuna lineaments and the Goalpara wedge of the Shillong massif are seismically active. The devastating Monghyr earthquake of 1934 (Mb=8.4), which claimed 11,000 lives, had its epicentral location some 60 km south of the MBT under the East Patna Graben, where a set of splay faults of the East Patna basement fault connect northward with the Arun lineament.



(Modified from De, 1996, 2000 and Kayal, 2001)

Fig.1.6 North - south depth section of earthquakes along P-Q traverse (Fig.1.4) in Sikkim

1.7 GEOLOGICAL INVESTIGATIONS IN TEESTA BASIN IN SIKKIM

1.7.1 Bop Nala Region

In North Sikkim the right bank sections of Teesta valley at the Bop Nala and towards its south are landslide prone. For the past 5-7 years, erosion scrapped out sediments (clay to boulders size particles) from a steep slope have got deposited on a horizontal plane nearby the right bank. During heavy rain, these sediments are carried away from this horizon and showered on the road leading to impediment of traffic movement as well as loss of human life and property including domestic animals.

The rock units exposed in this region are mostly granitic gneisses and quartzites. The drainage pattern indicates the presence of conjugate folds associated with a shear zone. We observed along the right bank of Teesta that failure along two sets of joints, J1: N85°E-S85°W/85°→S and J2: E-W/45°→S as well as the foliation plane So: N20°W / 65°E in quartzites is leading to landslides whilst in most part of the North Sikkim the left bank of Teesta is stable where different levels of river terraces are overlain by landslide debris. Gradual deposition of the debris has resulted in gentle slope and reduced the landslide activity in most part of the left bank from south of Naga village to the north of Bop Nalla. Usually Granite gneisses are competent. But in most parts of the Sikkim, particularly in North Sikkim, they are well foliated and are rich in flaky mineral Biotite, which make them weak. In this region, at the right bank, the exposure provides clear evidence of a shear zone. The shear zone is marked by foliated Biotite granite gneiss (foliation has attitude 310°/50°→E) showing Boudinage structure. The distortion of the foliated gneiss is by the ductile deformation. Towards the north of this shear zone at the Bop Nala the quartzite beds dip 50° towards N20°E. The large special spread of the shear zone and fragility of the rocks present in this zone demand that more detailed investigation in this region is required in order to find out stable zones where developmental activities can be carried out with minimal level of fear for future natural destructions.

1.7.2 Chakung Chhu-Teesta Confluence Region

The pelitic migmatites (stromatic, patchy) and minor interbanded pelitic schists and metabasites of Higher Himalayan Crystallines (Darjeeling Gneiss Group ?) and the quartzites and dolomites/limestone of the Chungthang Formation are exposed in Chakung Chhu area. Isolated exposures of calc-silicate rocks with interbanded quartzites occur in the region. The regional foliation strikes E-W with 40°-60° dip towards the north/northeast. In this region, isoclinal folds with the axes plunging 15° and 20° towards west and east, respectively, are possibly superimposed by cross folds plunging at 30°-35° towards north. Two sets of discontinuous faults having attitudes NNW-SSE / 50°→E and E-W/vertical are observed in the competent quartzites and dolomites of the Chhungthang Formation. The Chakung Chhu river bed is covered with sand and boulders. The quartzites strike N15°E-S15°W/35° → W. Two sets of prominent joints with attitudes N45°E-S45°W/ vertical and E-W/40°→ N are observed in these rocks.

At the downstream side of the confluence of Teesta and Chankung Chhu rivers there exists a set of river terraces (Plate 1.1) containing rounded boulders and sands (Plate 1.2). Opposite to this location, at the right bank of Teesta river, a limb of the north plunging (fold axis plunges at 57º towards North) antiform is exposed where S-shaped folds are well developed (Plate 1.3) indicating counterclockwise rotation which reflects left-handed shear. This fold limb is intersected by two sets of joints (EW/45º→S; N85º E/ 85º→S) and the N-S trending bedding plane dips at 65º towards E. The intersection of these structural elements result in rhombohedral blocks (Plate 1.4) which appears to be separated out from the rock mass by plane failure mode. On the left bank of the Teesta river at the foot of the Tong hill the exposed rock types are quartzites trending N60°W-S60°E and dipping 55° towards E. Since the dip is towards the hill the slope is stable.

1.7.3 Ralang region within Rangit Window

Phyllite and quartzite rocks of the Gorubathang Formation belonging to the Daling Group are mainly exposed in the area. There is mantle upwarping near the Rangit window and the MBT surface is also folded. The strike of foliation of the rock is N40˚E to S40˚W with dips of 40˚ towards N60˚W. The strikes of the beds are sub-parallel to the river course. In the area upstream of the confluence of the Rangit river and

Chil Khola, wide-open joints, shear zones and widespread fracturing are observed. These fracture planes reveal that the region was subjected to high tectonic stresses in the past and are indicative of the possible presence of weak zones in the basement rocks. The presence of a) hot springs along a NNE-SSW alignment, more or less paralleling the Rangit river course, and b) a large landslide on the left bank also support the possible subsurface occurrence of weak zones in the region. The development of cracks in the single story dwellings at Polaut village high up in the hillside and hockey stick like configurations of some trees in the middle of the hill slope in the region between Pao Khola and Chil Khola possibly indicate creeping movement of the complete mass of talus, which in general appears as a stable slope.

The NW-SE and NE-SW alignments of drainage in the region indicate that two distinct sets of shear planes occur in the region. The slope of the right bank of Rangit river in this region is steep but the landslide is not active along this slope, whereas the left bank slope is less steep and covered with landslide debris. It appears that the region along the left bank experienced active landslide in the past because wedge failure along the north plunging lineation resulted due to intersection of two sets of shear planes (NW-SE/dipping towards NE; NE-SW / dipping towards NW). About 4 km downstream of this region the phylitic quartzite (So=N30ºE - S30ºW/ 32º → W) exposed at the right bank of Rangit river bears two sets of joints (N15º-20ºE-S15º-20ºW/62º-75º→W and N60ºW-S60ºE/65º→E). On the left bank of the Rangit river presence of boudinage structure indicates that this region represents a

Plate 1.1 River terraces at the confluence of Teesta river and Chakung Chhu

Plate 1.2 River terrace containing boulders and sand sized particles

Plate 1.3 S-shaped folds on the limb of north plunging antiform

[redacted]

Plate 1.4 Rhombohedral blocks separated out from the rock mass by plane failure mode

shear zone where distortion usually takes place by ductile deformation. In this region, the W and NW facing slopes are usually unstable because wedge failure seems to be taking place along the north trending lineation defined by the intersection of NW-SE and NE-SW shears. The topography, the joint patterns and shears in the region indicate that either a Duplex type structure or an Imbricate fan type structure (e.g. McClay, 1992) possibly occur in the region.

1.7.4 Geology around Rolep in East Sikkim

The Chungthang gneiss is exposed in the area. It shows distinct sets of well developed joints. The gneiss is foliated and at places thick mica (biotite) rich bands lead the rock to be weak and susceptible to erosion. Garnet porphyroblasts and feldspar augens are also observed in this gneiss. The gneissic foliation trends N30˚E-S30˚W and dips at 40˚ towards NW. The rock is intersected by two distinct sets of joints – a) E-W vertical and b) N25˚E-S25˚W joints dipping at 30˚ towards NW. The river bed is covered with large boulders of Biotite Gneiss.

There are mica rich zones in the gneiss. The weathering is more pronounced and deep along such zones. These zones may provide channel ways for the seepage of water during the tunneling. Furthermore, highly jointed nature of the gneiss with well-developed augens suggested the presence of shear and fracture zones under the debris cover. Near Lamaten village the foliation in garnetiferous biotite gneiss strikes N30˚E-S30˚W and dips 50˚ → NE. Three sets of joints *viz.*

a) E-W / 80° → S, b) N50°E-S50°W / 50° → SE and c) N30°E-S30°W / 70° → NW are present in this rock. Old and new landslide debris containing gravels, sand, silt and clay materials cover the hill slope.

Two topographic levels (benches) are observed at 955 m and 951 m near Lamaten village. The upper topographic level is mainly formed by landslide debris composed of large boulders, sand and silty soil whilst the sand and silty soil are only present in the lower topographic level. The Quartz-Biotite-Gneiss is exposed between the lower bench and the river bed for a height of 3-4 m and trends in N15°E-S15°W with a dip of 50° towards SE. This represents a shear zone as evident from the augen structures present in the gneiss. In this region the attitudes of the thick biotite rich zones with respect to the slopes of the river valley and major nalas are important because these zones may affect the stability of the tunnel.

1.7.5 Geology along Teesta between Tong to Mangan

The rocks exposed alongside the Teesta river channel between Tong in the North and Mangan in the south are Quartzite, Quartzitic Phyllites, Phyllitic Quartzites and Muscovite and Biotite bearing Granite gneisses. Bands of calc-silicate rocks are also present. There are a number of landslides *viz*. i) Ri Chhu slide (Biotite muscovite Granite), ii) Myang Khola (Biotite muscovite granite gneiss, Quartzite), iii) Lanta Khola (Biotite muscovite granite gneiss), iv) Manul-II (Biotite muscovite granite gneiss), v) Manul-I (Biotite muscovite granite gneiss, Quartzite;

show hockey stick like configuration of *Alnus* trees) in this sector. The terrace sequence covered by old landslide debris near Tong has recently resulted a landslide. The Lanta khola slide has been active for many years and interrupts the road. These landslides supply huge amount of sediments into the Teesta river channel. At places channel bars in the main river are resulted due to blokage by sediments supplied from tributary fans (Plate 1.5).

1.7.6 Geology along Teesta river between Mangan to Rangpo

The sedimentary deposits between Mangan to Tong lie at the confluences of many small and large tributaries with the Teesta river in the form of various fan lobes and alongside the main river channel as terrace deposits. These deposits are built up of sediments ranging in size from clay to large boulders. It appears that landslides have supplied huge amounts of sediments to the main channel in the past. The streams joining Teesta river on either banks also supply large volume of sediments to the main river channel. An important example is the Papung Khola Fan at Balutar, over which new settlement is developing (Plate1.6). Different modes of slope failure – plane failure, block failure and circular failure – along the banks of the streams are the major causes for the supply of large sediment load. These sediments were travelled as debris flows, hyperconcentrated flows and stream flows in the Teesta river channel (Plate1.7a-c).

1.7.6.1 *Debris Flows*

These are Coulomb Viscous flows and known as an efficient process for sediment transport and deposition in alluvial and slope settings. In debris flows, solid particles and water move together as a single viscoplastic body (yield strength > 400 dynes cm^{-2}). Solids may constitute 70-90% by weight (47-77% by volume) of the flow mass, and bulk densities generally are 1.80-2.30 g/cm^3 for typical poorly sorted sediments.

1.7.6.2 *Hyperconcentrated Flows*

These flows represent an intermediate state between debris flows and fluid flows where fluid turbulence remains an important dispersal mechanism of clastic particles. These are plastic, non-Newtonian flows (yield strength about 100-400 dynes cm^{-2}) which flow like fluids in which solids and water are separate phases and are characterized by sediment concentration 40 - 70% by weight (bulk densities 1.33-1.80 g/cm^3).

1.7.6.3 *Stream Flows*

These are Newtonian Fluids in which sediments are transported in fluvial channels mainly as suspended load and bed load. In this case there is a linear relationship between shear stress and rate of shear strain. The lack of strength (0-100 dynes cm^{-2}) dictates the low sediment concentration (1-40% by weight; bulk densities 1.01-1.33 g/cm^3).

Plate 1.5 Channel bars on Teesta resulted due to blockage by sediments supplied from tributary fans

Plate 1.6 Fan lobe the confluence of Papung Khola and Teesta river at Balutar

Plate 1.7a Terrace T3 at Mangalbare with stream flow deposits

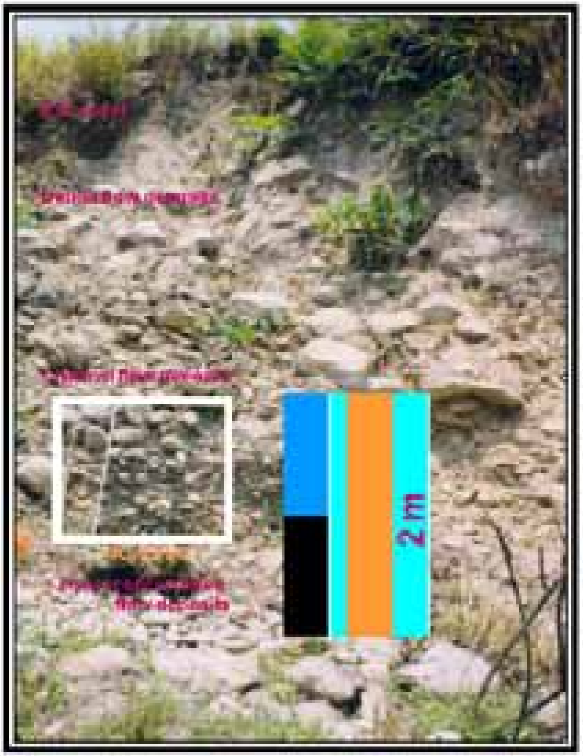


Plate 1.7b Terrace T2 at Mangalbare with debris flow, hyperconcentrated flow and stream flow deposits

Plate 1.7c Terrace near Ralap village with hyperconcentrated and stream flow deposits

1.7.6.4 *Debris and Hyperconcentrated Flows as Geohazards*

The debris and hyperconcentrated flows are highly destructive because of their high velocities, long run-out distances, and high sediment concentration. In the case of catastrophic floods or recurrent landslides and floods such flows are likely to result. If the slopes are tempered, laid barren by forest fires and indiscriminate human clearing of vegetation and isolated houses and some villages are built in hazardous areas, a strong rainfall may saturate the soils of the area, cause flood wave in the catchments and trigger landslides. These landslides will rapidly transfer downslope into cohesive debris flows. These debris flows will undergo further transformation in the main river channels, being progressively diluted into fast-moving hyperconcentrated flows. Such flows, if resulted, may lead to complete destruction of settlements, roads and forests situated below the maximum flood level. These flows would lead to intensive toe cutting of the terraces. Therefore, it is necessary that the stability of terraces against such possible events must be assessed before any settlement develops on these landforms.

1.8 SPATIAL DISPOSITION OF STUDIED REGIONS ON THE SEISMOTECTONIC MAP OF SIKKIM

Bop nala, Chakung Chhu catchment and Rolep regions fall between isoseismals VI and VII of the great Bihar-Nepal earthquake of 1988 (see Fig. 1.4). Usually, the zone at the north of MBT appears to be seismically active (see Fig. 1.4) and the seismicity decreases gradually towards the N, NW and NE of MCT. There exists a cluster of epicenters nearby Gangtok. Fault-plane solutions of two tremors that occurred in this region in 1980 and 1982 indicate strike-slip mode of rupture along NW-SE and NE-SW directions (see Fig. 1.4). The estimated depth for the 1980 earthquake was 47km (see Table 1.3 and Fig. 1.4, Focal-Plane Solution 3) and that for the 1982 earthquake was 9 km (see Table 1.1 and Fig.1.4, Focal-Plane Solution 4). A shear zone paralleling the Teesta river towards the northwest of Chhungthang extends towards south up to the region where this cluster of epicenters occurs (see Fig. 1.4). This region lies towards the south and southwest of the Chakung Chhu catchment and north and NW of the Rolep region and the shear zone passes through the Chakung Chhu river at the downstream side of the confluence of Glong Chhu and Sangchyo Chhu. Also, it is important to note that the trend of the Rangpo Chhu parallels the NE-SW shear dipping towards NW.

The region between Mangan to Rangpo along the Teesta river and Ralang region in Rangit catchment falls between isoseismals VII and VIII of the great Bihar-Nepal earthquake of 1988 (see Fig. 1.4). These regions lie within MBT and MCT (see Fig.1.4) and therefore, is seismically vulnerable. However, the recorded events are of low magnitude and appear to occur along NW-SE trending weak planes (see Fig. 1.4) dipping towards NE. It is important to note here that the trends of the tributaries of Rangit are subparallel to that of the weak planes.

1.9 GEOLOGICAL SENSITIVITY AND VULNERABILITY

The thick moraine deposits at several sites in North Sikkim provide weak substrates on which it seems very unsafe to establish any mega developmental project. Establishment of any small projects in this region would require detailed surface and subsurface investigations as well as proper engineering and seismic designing.

The landslides along the Teesta and Rangit supply huge amounts of sediments into the river channels. These sediments travel in the form of debris and hyperconcentrated flows and subsequently diluted into channel flows. The debris and hyperconcentrated flows for their high velocity and sediment concentration are important erosive agents because they may lead to toe cutting of terraces present alongside the river channel. Therefore, it is important to assess toe cutting of terraces which are situated along the channel because such events would destabilize the settlements developed on these terraces.

Heavy precipitation and glacial melt at times result flood in the river channel. These heavily sediment laden flood waters at times become so harzardous in the upper reaches of the Teesta basin that it destroys the forest (Plate 1.8), aggrades the river channel and changes the course of the channel (Plate 1.9). Such flows also erode the valley sides and result in the creep of the landforms, thereby affecting the settlements on it (Plate 1.10).

The repetition of different groups of rocks in Rangit valley region suggests two possibilities: i) a conceptual model of geo-ecosystem involving parameters related to the resurgence of varied lithologic, distributive, depositional basin and provenance, and ii) the piling up of a relatively limited number of units by tectonic diverticulations. However, the field characteristics of rocks suggests that the second possibility holds good (e.g. Ray, 1989) and therefore, the Rangit region represents a nappe.

Many transverse lineaments, subparallel to the outline of the subsurface ridges underlying the foredeep, displace not only the MCT and MBT, but even the surface trace of the Siwalik-Quarternary sedimentary contact well within the foredeep and appear to be seismically active. The neotectonic deformation in the Nepal-Sikkim Himalaya is mainly guided by the conjugate shear planes with attitudes NW-SE/dipping towards NE and NE-SW/dipping towards NW as indicated from the focal mechanism results (see Fig.1.4).

In Sikkim the confine of a cluster of epicenters in several regions and parallelism of the courses of major rivers and their tributaries either with the NE-SW or NW-SE shears (obtained through fault-plane solution results, see Fig. 1.4), and the seismogenic nature of MBT up to the mantle (see Fig. 1.6) do not rule out any future large magnitude tremor in such regions. Therefore there is always necessity of suitable seismic designing for any engineering structure in Sikkim. Necessary excavation and grouting of the geologically weak zones in such regions are important where developmental activities are aimed. Primary to this is the necessity for a constant vigil on the neotectonic activity in the region, such as active landslides and associated disturbances in the basin, during and after the construction operations.

Plate 1.8 Destruction of forest by flood in the Singba Sanctuary

Plate 1.9 Change in the course of Lachung river in Singba Sanctuary due to aggradation

Plate 1.10 Collapse of Terrace on the left bank of Lachung and Creeping of settlement on it

CHAPTER - 2

LANDSLIDES

2.1 INTRODUCTION

Landslides usually occur in the hilly terrain. The Himalaya, a young mountain chain in geological time scale, represents a geologically and ecologically fragile mountain ecosystem. It receives immense rain water, and is susceptible to earthquakes (in terms of frequency and intensity) and intensive soil erosion. Therefore, it is highly prone to landslides. Furthermore, the Himalaya has been the target of intense developmental activities over the past few decades. The planning, design and execution of development schemes, such as road building, construction and sitting up of hydro-electric projects are often carried out in an unplanned way due to financial, time and other constraints. Therefore, at times sufficient attention is not paid to the geological and geo-technical situations of a specific area/ region. Thus the resultant unstable slopes lead to increased incidence of landslides, and to a rapid rate of environmental degradation. The frequency of landslides in the last few years may be partially attributed to the negative impact of developmental activities on the geo-environmental setup of the region. Under this backdrop, where any developmental activity is planned in Himalaya it is necessary to investigate the region in terms of its landslide susceptibility.

Mass movement is a common geological process that is observed very commonly in the Himalayan terrain. The phenomenon of landsliding in the Himalayan region is controlled by a number of parameters *viz*. landforms, slope, geological and structural setting, landcover, ground water condition, amount of precipitation, geo-technical properties of the rock mass and tectonic setting, of the area, etc. High steep slopes in Himalayan ranges have attained, with time, an equilibrium with all the parameters. Whenever, any parameters in this equilibrium is disturbed, either by natural or anthropogenic cause, the slopes shed off the overburden (in the form of mass movements) to attain equilibrium. Mass wasting or mass movements refers to a variety of phenomena whereby geological materials are moved downward (mainly by gravity), commonly down slope, from one place to another (Montgomery, 1995). On a day-to-day basis the movement can be slow, subtle or almost undetectable. But the movement is cumulatively large over days and years. At times, the movement can be sudden, swift and devastating, as in rockslide or avalanche. Landslide is a term generally used for the rapid mass movements. Many landslides are directly related to natural processes which are operating inside or on the surface of the earth. On the contrary, certain unplanned human activities aggravate local landslide dangers, usually as a result of failure to take those hazards into account.

Based on the mass movement, landslides are divided into following major groups:

i) Slow Flowage: rock creep and soil creep,
ii) Rapid Flowage: earth movements, mudflows, debris avalanche,
iii) Sliding: slumps, rock slides, rock falls and landslips, and
iv) Subsidence: sinking of mass

The factors causing landslides are either, i) internal: such as the steeping of the slope, water content of the stratum and mineralogical composition and earth’s internal dynamics, which are tending to reduce the shearing strength of the rocks or ii) external: such as developmental activities, for instance the heavy traffic on hill roads causing the imbalance of the masses, or iii) triggered: such as internal weakness in substrate soil and rocks is accentuated by the human activities leading to slope failure.

2.2 STATUS OF LANDSLIDES IN TEESTA BASIN

The Sikkim Himalaya with rugged topography, ongoing seismic activity (by active tectonics) and heavy rainfall is subjected to intense landslide activities. The spurt of developmental activity in the region has lead to substantial growth in the area affected by landslide activity. At places old landslides have been stabilized while at others new landslides have developed. At few places old landslides have been reactivated. Figure 2.1 shows the spatial disposition of landslides in Sikkim. This figure contains landslide scars from 1977 SOI toposheets (1:50,000) as old landslides and those interpreted from satellite data of recent times i.e. merged LISS and PAN scenes of 2002 as new landslides. Some of the reactivated landslide areas have been considered as new landslides. These datasets have several limitations and therefore, may not give all the information related to landslide activity in Sikkim in spatial and temporal frameworks. However, these data provide a preliminary guideline on temporal change in landslide activity in Sikkim which has been discussed below.

Figure 2.2 shows the number of landslides (both old and new) in different watersheds. It is evident from the figure that the number of new landslides outrank that of old landslides in most of the watersheds in Teesta basin. Teesta (Lower Part) watershed contains maximum number of new landslides. There are also a large number of old landslide scars present in this watershed. In Prek Chhu, Rathang Chhu, Rangit river, Rangpo Chhu and Ramam Khola watersheds more than 100 new landslide scars have been recorded. It is to be noted here that the rate of developmental activity in Teesta (Lower Part), Rangit river and Rangpo Chhu watersheds is very high. In Rani Khola, watershed the number of new landslide scars are also higher compared to old landslide scars. Gangtok, the capital city of Sikkim, lies in this watershed. Over the years this city has grown on the hill slope towards its fringe.

Figure 2.3 shows the area covered by landslides (old, new and total) expressed as per cent of the watershed area. The planimetric area does not represent the exact area covered by a landslide because of topography. For instance, if there are two landslides of same base then the slide on the steeper slope covering a larger elevational range will have lesser planimetric area compared to that on a gentle slope. However, the Fig.2.3 provides some useful information to have a comparative study between two watersheds. As evident from this figure, Chhombo Chhu, Zemu Chhu, Rangyong Chhu watersheds have large geographic areas of which < 0.5% are covered with landslides; rest of the area covered with moraines. Lachen Chhu watershed covers a small area but 3% of this watershed is covered with old landslides. This watershed represents the right bank slope of Teesta river and is traversed by many streams. This slope is very steep and covered with dense vegetation.

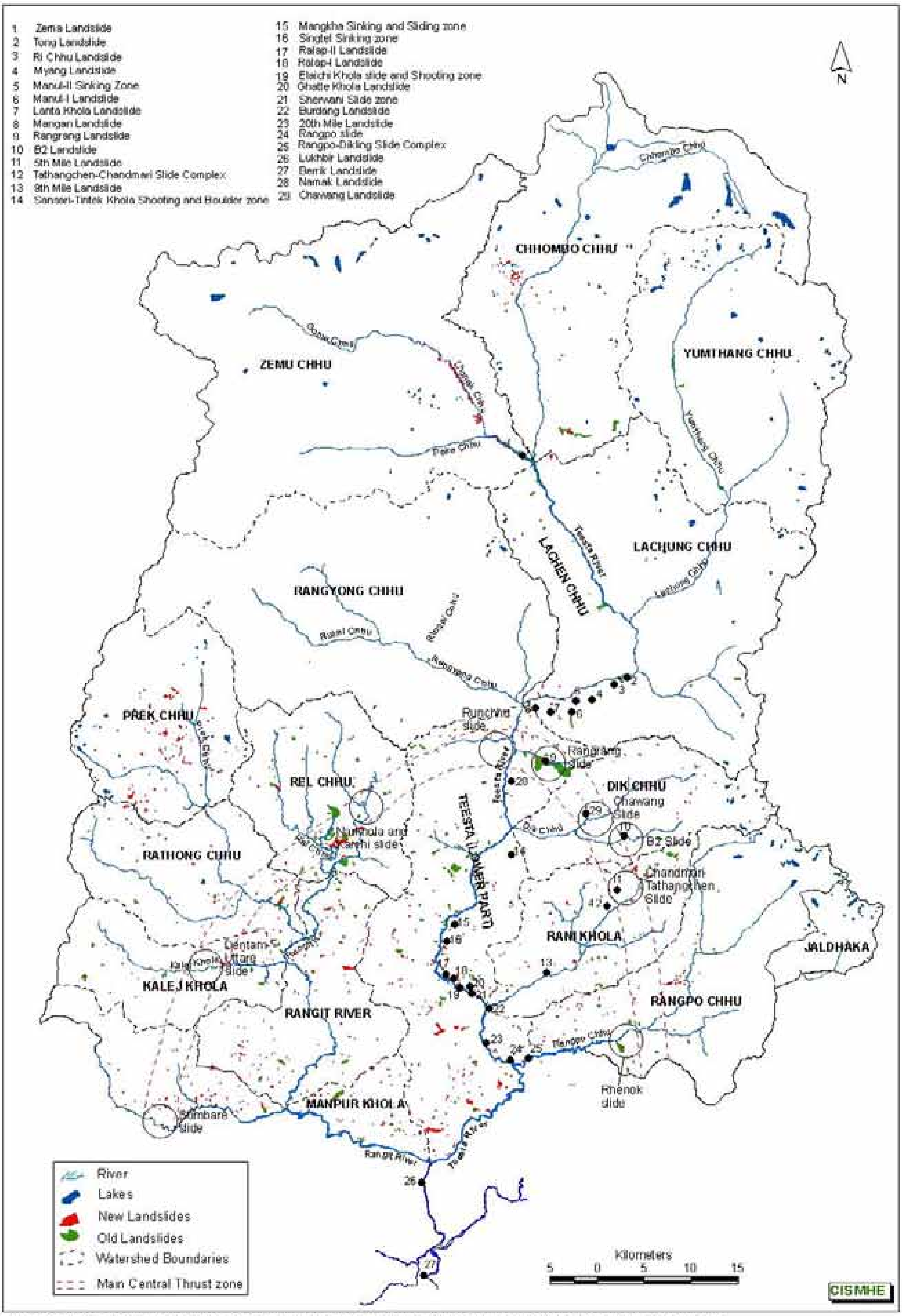


Fig.2.1 Old and new landslides in Sikkim Himalaya with locations of some of the important landslides

Settlements *vis-a-vis* deforestation have grown in the Manpur Khola watershed covering small area. About 1% of this watershed area is covered with landslides.

Teesta (Lower Part) watershed has large area and the landslide covered area accounting for >1%. It is interesting to note that one of the largest old landslide scars in Teesta basin is present in the headwater region of Rangrang Chhu that flows in Teesta (Lower Part) watershed. This landslide has affected the forest vegetation also. Rangit river watershed has >0.5% area covered with landslides. In these two watersheds developmental activities are in progress. There are several new landslides in Rani Khola watershed (see Fig. 2.2) but the area covered by these landslides accounts to 0.4% of its total area (see Fig. 2.3).

The landslides in Sikkim have increased in number over time (see Fig.2.1) but the area covered by these new slides is much less compared to that of old landslides (see Fig. 2.2). This could perhaps be due to development of landslides on very steep slopes particularly along the roads.

2.3 SOME EXISTING LANDSLIDES IN SIKKIM

Some of the important landslides of Sikkim Himalaya are listed in Table 2.1 and their locations are shown in Fig. 2.1. Table 2.2 provides the data of landslides occurring alongside the major roads. Detailed description of some of these landslides is given below.

Table 2.1 Some of the important landslides in different districts of Sikkim

North Sikkim	South Sikkim	West Sikkim	East Sikkim
B-2 Slide: Slump associated with Mudflow *Rang Rang Slide:* Slump slide with mud-cum-debris flow movement at places *Myang Slide*: Rock fall on left bank and debris slide/ flow on right bank *Vong Slide*: Debris flow and debris avalanche *Lanta Khola Slide*: Rock-cum-debris slide/ flow *Manvi Slide*: Debris flow *Manul Slide*: Rock-cum-debris flow; caused by fault action *Zema Slide*: Rock-cum-debris flow, caused by heavy rainfall	*Between Melli to Rangpo along the right bank of Teesta*: Debris slide and rock fall. This zone is very active *Between Singtam and Yangyang*: Several old landslides; mostly rock fall	*Kyongsha (2000)*: Rock fall and debris slide; death of many people and damage to buildings *Areas between Dentam-Uttare; Kaluk-Dentam; Nayabazar-Sombarey; Legship-Gyalzing Nayabazar-Legship*: These are large deposits of soft materials composed of boulders, rock fragments and clayey soils.	*Rangpo Slide*: Rock fall and debris slide *Burdang Slide*: Rock-cum-debris slide; total slide zone extending 230 m in width and 350 m in height *Chandmari Slide*: It is a fossil slide, active for more than a decade. Debris Flow *5th Mile Slide*: At 12 km on North Sikkim highway, old slide reported to be active since 1960 situated in a bowl shaped depression between B-1 and B-2 nalas. Involves both rock fall and debris flow. *Sherwani Slide Zone*: Rock fall and debris flow. *Elaichi Slide*: Sliding shooting boulder zone. *Other Slide*: Singtel; 19th Mile Slide; 9th Mile Slide; Mangkha; Ralap-I; Ralap-II

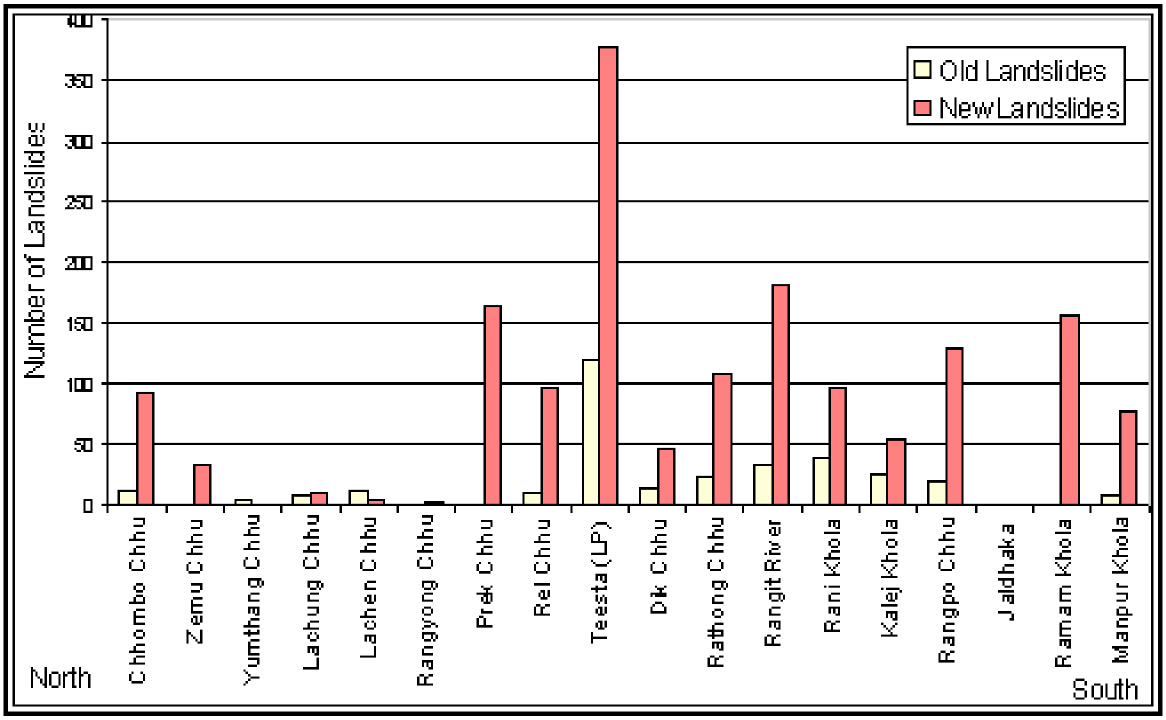


Fig. 2.2 Frequency of old and new landslides in various watersheds in Teesta basin in Sikkim

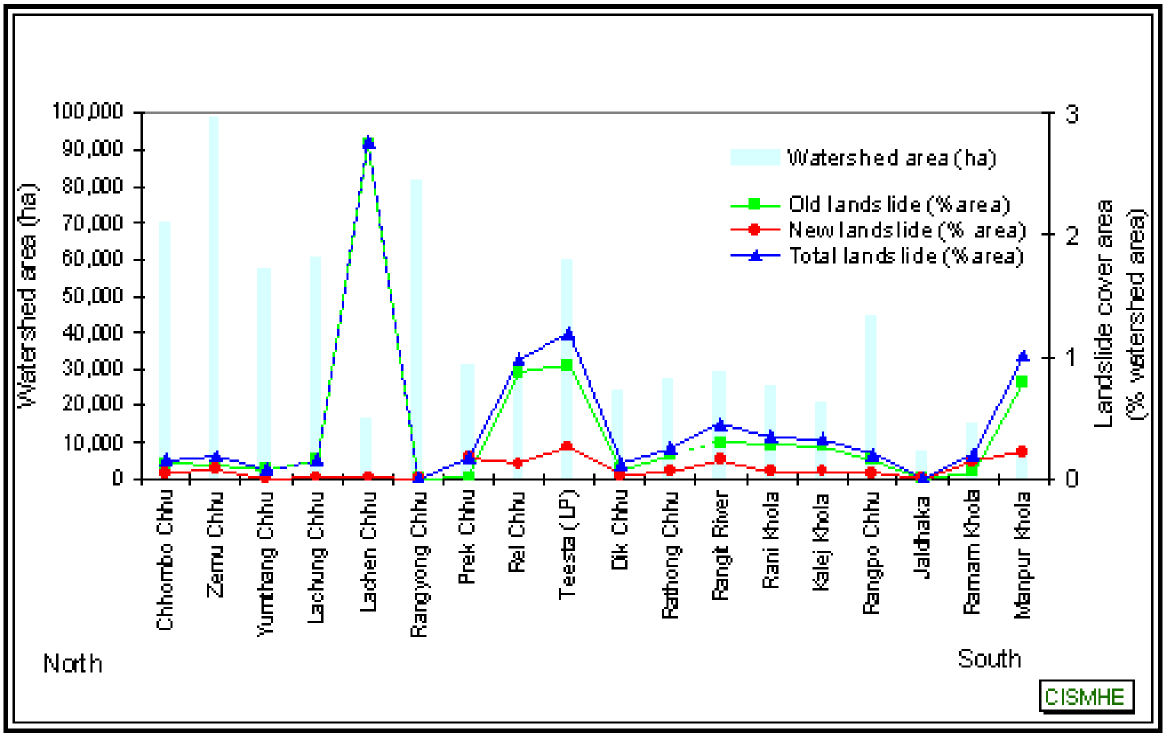


Fig. 2.3 Planimetric area of the watersheds (shown as bars) and the area covered by landslides (lines with dots) given in percent of the watershed area

Table 2.2 Landslides alongside the roads in Sikkim

Road	Slide
On National Highway 31A	Berrick Slide, Lukhbir Slide, Lepchajhora Slide, Km-40 Slide, Km-45 Slide, Rangpo Slide, Rangpo 19/6 Mile Slide (Burdang Slide), 9th Mile Slide 8.3 Km Slide, Mile-I Slide, Mile-II Slide
North Sikkim Highway	B-2 Slide, Rang Rang Slide, Myang SlideVong Slide, Lanta-Khola Slide, Manul Slide
Gangtok-Nathula Road	Chandmari Slide, 7th Mile Slide, 13th Mile Slide
Rishi-Rangli Road	Km 16.4 Slide, Sewakhola Slide
Rongli-Padamchen Road	Kue Khola Slide, Padamchen Slide
Singtam-Dikchu Road	Sherwani Slide, Ralap-I, II, Elaichi Khola, Singtel Sinking Zone, Mangkha Sinking Zone, Sansari-Tingtek Khola slide.

2.3.1 District-wise scenario

2.3.1.1 *North Sikkim*

Landslide and slope failures cause serious problem in the North Sikkim. Due to landslides the road communication in the district is disrupted every year, especially during the monsoon period. Slope failures and sinking of ground are also serious problems in many road and urban built up areas. The forests of the district are also affected by landslide and erosion. The hill slopes covered by softer rocks i.e. phyllite and schist of Daling Group and the areas surficially covered by thick deposit of glacial morainic material are most affected.

However, the areas where harder schist and even gneisses occur are also sometimes affected due to weak structural fabric, though to minor extent. There are a number of landslide zones on the North Sikkim Highway. Salient features of some of the important slides of North Sikkim are discussed below.

i) *B-2 Slide*

It is situated at 12 km milestone on North Sikkim Highway. The type of slide is slump associated with mudflow. Materials in the landslide are slope-wash material and debris. The granite gneiss is covered with silty and sandy soil with clay rich horizons. The causative factors are toe erosion in the initial stage and heavy precipitation, loss of shear strength caused by seepage.

ii) *Rang Rang Slide*

It is situated about 60 km from Gangtok. The type of slide is slump slide with mud-cum-debris flow movement at places. This slide contains fluvio-glacial material with clay pockets. Biotite-Muscovite schist, phyllite and garnetiferous biotite schist lie below thick overburden. Slumping/flow movement of clayey material results this slide.

iii) *Myang Slide*

It is located near Myang nala on North Sikkim Highway. The slide is characterized by rock fall on left bank and debris slide/flow on right bank of Myang Khola. The materials present in the landslide are quartzite blocks on left bank and rock fragments with clayey material on right bank. The cherty quartzite and granite gneiss are the basement rock. This slide is characterized by rock falls along sub-parallel joint planes and slides after heavy rainfall.

iv) *Vong Slide*

This slide lies between km 82 and km 84 on North Sikkim Highway. The slide is characterized by debris flow and debris avalanche. The rock types include fragments of gneissic rock mixed with sandy material with granite gneiss at patches. In this case valley widening and gully erosion are triggered by heavy rains/cloud bursts.

v) *Lanta Khola Slide*

This slide lies about 72 km from Gangtok and is characterized by rock-cum debris slide/flow. Thick fluvio-glacial non-cohesive material with large boulders present above schistose rocks at this site. Erosion of bank and bed material at high river discharge/ seepage above crown is the causative mechanism.

vi) *Manvi Slide*

This slide lies at km 75 on North Sikkim Highway. This is a debris flow containing pulverised slopewash material with sand and silt and granite boulders. The rock types are granite gneiss and cherty quartzite. The genesis of this slide is attributed to fault action, toe erosion and heavy rainfall.

vii) *Zema Slide*

This is a slide zone along the Zemu river, nearer to its confluence with Teesta river. The rock formations exposed in this region are quartzite and phyllites of Chungthang Formation, Khangchendzonga augen gneiss, Tourmalite granite, and calc-silicate rocks with interbanded quartzite. These rocks are well jointed and weathered and the foliation dip valley ward.

Therefore, during periods of heavy rain the slopes on either side of Zemu undergo failure.

2.3.1.2 *East Sikkim*

A number of slides and sinking zones have affected the NH-31A between Rangpo and Gangtok in East Sikkim. There are some landslides which have severely affected the Gangtok town. Salient features of some of the important slides of North Sikkim are discussed below.

i) *Rangpo Slide*

Occurred on July 23, 1993 about 1.5 km from Rangpo along Rangpo-Dikling road causing disruption of the road connection. This is triangular and elongated (length 800 m) in shape and characterized by debris slide and mud-rock flow. The slopeward dipping jointed and weathered phyllitic rocks are susceptible to failure in this region.

ii) *Burdang Slide*

It is commonly known as 20th Mile slide and is located about 2 km south of Singtam on NH-31A on the left bank of Teesta. It is a rock cum debris slide. The total slide zone extends 230 m in width and 350 m in height. The phyllitic rocks undergo block failure and the overburden undergo circular failure.

iii) *19th Mile Slide*

This slide is located at 60 km on NH-31A. The slide causes frequent blockade of the highway. This is a rock cum debris slide. The phyllite and quartzite rocks with soil overburden usually collapse during rainy season.

iv) *9th Mile Slide*

This is a very old slide located on NH-31A. The size of the landslide has grown with the passage of time. It has affected about 180 m long slope alongside the road. Dalings and granite gneiss are in thrusted contact in this region. It is suspected that a NE-SW trending fault passes along the right bank of Rangpo Chhu and the road runs through this fault zone.

v) *Chandmari Slide*

This slide is located at a distance of about 5 km from Gangtok on Nahu La-Chhangu road. It is a fossil slide, which has been active for more than a decade. This subsidence zone is between two thrusts and is composed of gneissic rock with thick overburden of soil.

vi) *Tathangchen Slides*

There are three slides. It is a fossil slide, which has been active for more than a decade. This subsidence zone is between two thrusts and is composed of gneissic rock with thick overburden of soil.

vii) *5th Mile Slide*

This is a complex slide located at 8 km from Gangtok. The rocks are banded/streaky granite gneiss (Darjeeling gneiss). The granite rock undergo planar and block failure. The over-burden undergo circular failure.

viii) *B-2 Slide*

Lies at 12 km on North Sikkim highway, old slide reported to be active since 1960. situated in a bowl shaped depression between B-1 and B-2 nalas. This landslides involves both rock fall and debris flow. The rock types exposed in the area are granite gneiss which are intensively sheared.

ix) *Chawang Slide*

It is an old landslide cone on the right bank of Dikchu, where settlements are developed. Due to heavy precipitation during 2005 this landslide cone undergone creep and circular failure. This destroyed some of the houses and the road as well as the agricultural fields developed on this slide

x) *Slopes along Singtam-Dikchu road section*

The Singtam-Dikchu road section on the left bank of Teesta river has been affected by a number of slides and sinking zones *viz*.

a) Sherwani Slide Zone : This slide is known as Sherwani slide zone, is situated about 1 km away from Singtam. This is a rock-debris slide whose crown portion extends 60 m above the road level and slide materials have descended down to Teesta river bed. The rocks are quartzitic phyllite or phyllitic quartzite. Rock-cum-debris fall and debris flow are the characteristics.

This is a slide complex with several active scars and old stabilised scars (Plate 2.1)

b) Ghatte Khola : This is a 250 m to 350 m long sinking zone on the left bank of Ghatte Khola. The slopewash materials composed of finer matrix (> 70%) and smaller clasts with occasional big boulder undergo circular failure.

The thaw imparted by the weight of landslide cone damage the retention wall (Plate 2.2). Human settlement is developed on this slowly creeping slope (see Plate 2.2).

c) Elaichi Khola sliding/shooting boulder zone (Rock-debris slide) : It is located about 6.5 km from Singtam. The rocks exposed in this region are phyllitic quartzite and phyllite steeply dipping (45^o - 60^o) towards north. They are well jointed. This Khola represents a shear zone. The pulverized rock flows down hill during the rainy season. Rectangular blocks also fall down along the valley.

Part of the old landslide cone is stabilized by vegetation growth on it and part of it suffer circular failure (Plate 2.3)

d) Ralap I and Ralap II : Near Ralap, two sliding/sinking zones named as Ralap I and II are found respectively at 8.6 km and 9.3 km from Singtam. Phyllitic quartzite, phyllite and quartzite are exposed in this area. They are well jointed and contain iron-oxide stains. Block failure of the rocks and circular failure of the loose materials are observed.

e) Singtel Sinking zone (200 m long) : Lies at 12.6 km from Singtam near the village Singtel. The phyllitic quartzite and quartzitic phyllite rocks are covered with boulders and soils. This area is sinking as marked by hockey stick like configuration of tree trunks (Plate 2.4).

f) Mangkha Sinking Sliding Zone : Mangkha sinking sliding zone affecting about 500 m long road sections is located at 13.3 km. This is a rock cum debris slide. The terrace at Mankha is also undergoing circular failure. The basement rocks are phyllitic quartzite. They are fractured and jointed. This is also characterized by fall of large boulders.

g) Sansari and Tintek Khola shooting boulder zones : These are located at 21.5 km and 28.7 km, respectively from Singtam. The rock types in this region are well jointed quartzitic phyllite and phyllitic quartzite (Plate 2.5). Here, rock fall and debris slide takes place during monsoon season.

2.3.1.3 *West Sikkim*

Landslide and slope failures cause serious problems in the West Sikkim. Every year, during the monsoon period, landslides disrupt the roads of the district. The areas between Dentam-Uttare, Kaluk-Dentam, Nayabazar-Sombarey, Legship-Gyalzing and Nayabazar-Legship are severely affected by landslides.

In August, 2000, a devastating landslide occurred in Kyongsa near Gyalzing. Heavy rain during this period lead to slope failure that caused loss of life and property.

Plate 2.1 Sherwani slide zone with active and old landslide scars

Plate 2.2 Ghate Khola landslide cone

Plate 2.3 Elaichi Khola sliding/shooting boulder zone

Plate 2.4 Singtel Sinking Zone

2.3.1.4 *South Sikkim*

South Sikkim has experienced intensive landslide activity in the past as the slopes are covered with large boulders. At present, slope failure is observed along some new road cuttings. Besides these, in some of the streams debris, through slope failure in the headwater regions, is put into the channel and are carried into the main Teesta channel. Some of the slides are slope failure near Payong, Kasur at the right bank of Teesta valley, and Brang and Sulpukh in Rangit valley.

2.4 CASE HISTORIES OF SOME IMPORTANT LANDSLIDES

2.4.1 The Rangpo-Dikling Landslide complex

A devastating landslide took place on the July 23, 1993, along the Rangpo-Dikling Road. This landslide resulted from the failure of hillslope (Fig. 2.4) at 1.5 km (27° 11’15’’ and 88° 33’E) from Rangpo and disrupted the traffic for a couple of days. Subsequently this slide has been well studied by Sarkar and Deb (1998). This region is characterized by several landslide scars and tongues.

The region extends from 350 m - 640 m. The slope dips at 42°-50° and Daling series of rock is exposed in this region (Gansser, 1964). The lithology includes slates, green quartzites, phyllites, chlorite sericite schists and chlorite quartz schists. These rocks are traversed by quartz and quartzo-feldspathic (5 cm thick and 5 m long) veins and are highly jointed. The rocks strike in NE-SW, NNE-SSW and EES-WWN directions with varying dips (30° to 50°). Scattered bushes, shrubs and bamboo cover the slope at places. Teak plantation is also found at some places. The slope is terraced for farming. During the rainy season, the soil covering the slope is partially saturated. The landslide is triangular and elongated in shape. The length of the scar is 800 m and its width varies from 25 m to 500 m. This is a debris slide and mud-rock flow. Total area affected is 20.8 ha.

2.4.1.1 *Factors responsible for this landslide*

The following factors were responsible for this landslide activity.

i) *Local geology* : The Rangpo landslide has precisely been identified to be on the phyllite, with occasional bands of slate and quartzite (see Fig.2.4). These rocks are highly jointed and weathered. Rainwater seeps through these rocks and chemical weathering forms kaolin, which acts as a lubricant for further sliding of slope materials. Rangpo river, with high discharge, causes toe erosion and thus the basal support of the slope is reduced.

ii) *The soil cover* : The soil cover is usually 30-50 cm thick. It is kaolinitic with high organic content, high water holding capacity and volume expansion.

iii) *Deforestation* : The hill slopes are deforested. They have been turned into cultivated terraces and settlements. Therefore, the

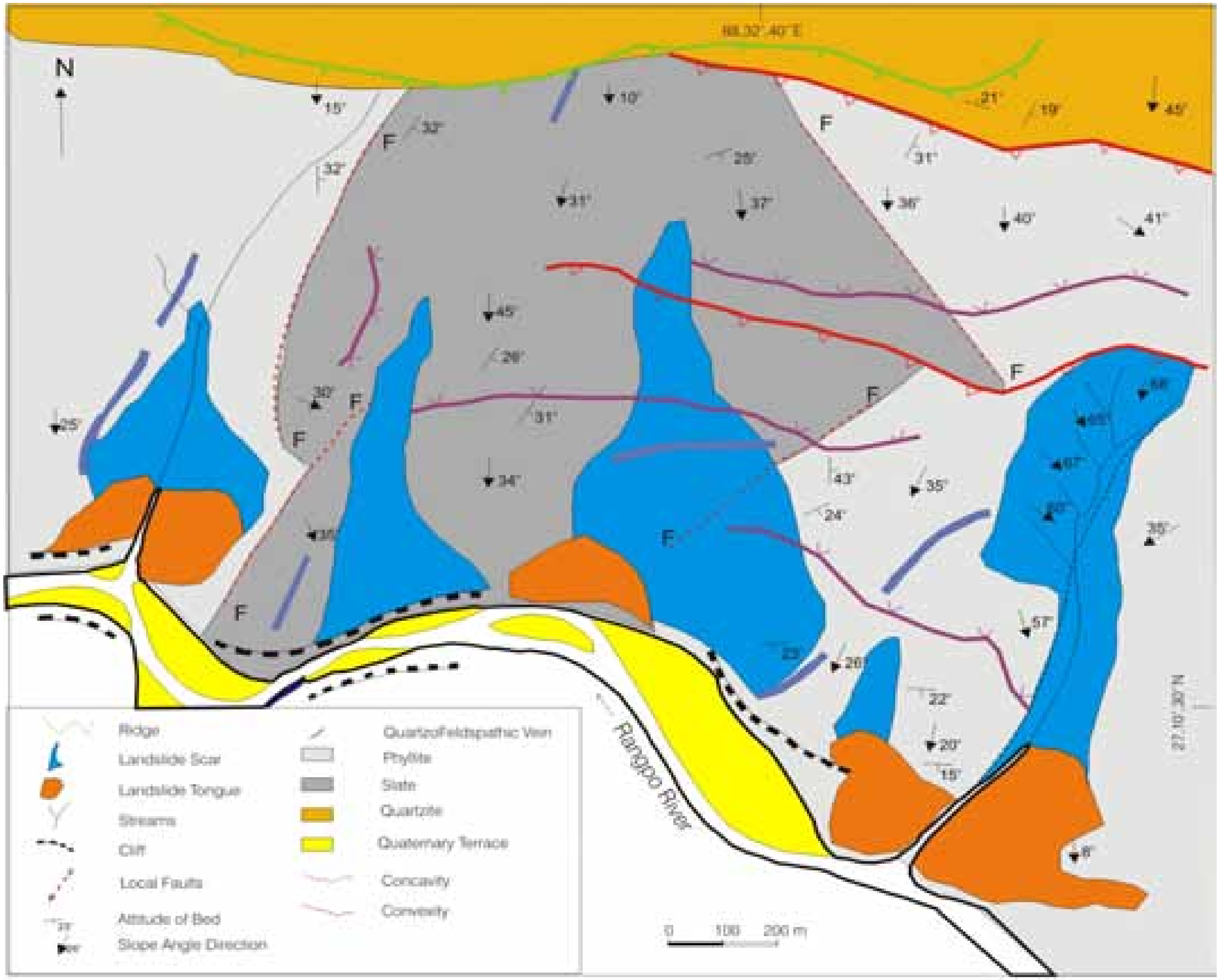


Fig.2.4 Geology around Rangpo-Dikling Landslide complex.

soil on this slope has lost cohesiveness and the slopes have become vulnerable to erosion.

iv) *Precipitation and Infiltration* : Percolation of rainwater through joints, cracks and fissures of bedrock and the pore-spaces of soil and regolith increases the pore-water pressure and changes the consistency and shear resistance of the slope materials (Sarkar and Deb, 1989 and references therein). The slope in the region being devoid of adequate vegetative cover, the material on the slope absorbs monsoon rain (>3000 mm) and leads to onset of rill cutting and gully erosion, thereby triggering slope failure.

v) *Effects of Human Interference* : Removal of basal support through cutting of slopes for construction of the road between Rangpo and Dikling during 1980s is an important anthropogenic factor that triggered massive Rangpo landslide. Deforestation has further aggravated the induced erosion of the slope materials.

2.4.2 Chandmari- Tathangchen landslide complex

In 1984 prominent slope failures occurred on the left and right banks of Chandmari jhora, Palace jhora, and Tathangchen jhora near Gangtok (Fig. 2.5). These slides affected the southeastern hill slope of the northeast-southwest trending Mintokang-Palace-Tashijing ridge. For this reason the southeastern slope of the hill, on which Gangtok city is situated, has a major stability problem, and has been a source of constant fear for the entire habitation on it.

Figure 2.6 shows the geology of the region. There is Daling Group of rocks between two thrusts trending NW-SE. Chandmari jhora flows along the eastern thrust. Therefore, the rocks on its left bank are banded gneiss/streaky gneiss (Darjeeling gneiss) and those on the right bank are Daling rocks. The foliation dips 43^o – 55^o eastward. The weathered and crushed rocks are overlained by thick soil cover. Large scale developmental activities *viz*. construction of roads and other super-structure *vis-a-vis* deforestation are also operative on this hill slope. Four different slides that occur in this complex (see Fig. 2.5) are :

i) *Chandmari Slide :* This slide was active during 1975-76 and thereafter, remained stable till 1984. During June, 1984 it was reactivated. In this subsidence zone highly crushed and weathered granite gneiss is overlained by thick soil cover. During the monsoon rain, the rock and the soil overburden collapsed. This landslide became an immediate concern because it damaged a number of houses, a school complex, a temple, a government vehicle workshop and a number of parked vehicles.

ii) *Palace Jhora slide* : This is an old slide which was caused by toe-erosion near the confluence of the Palace Jhora with Rora Chhu. With the passage of time the headward erosion increased and the crown of the slide reached near the base of the road at the east of the palace. Therefore, the road undergoes subsidence.

iii) *Tathangchen Minor Slide* : Tathangchen minor slide is present in a depressional area which is situated about 500 m northwest

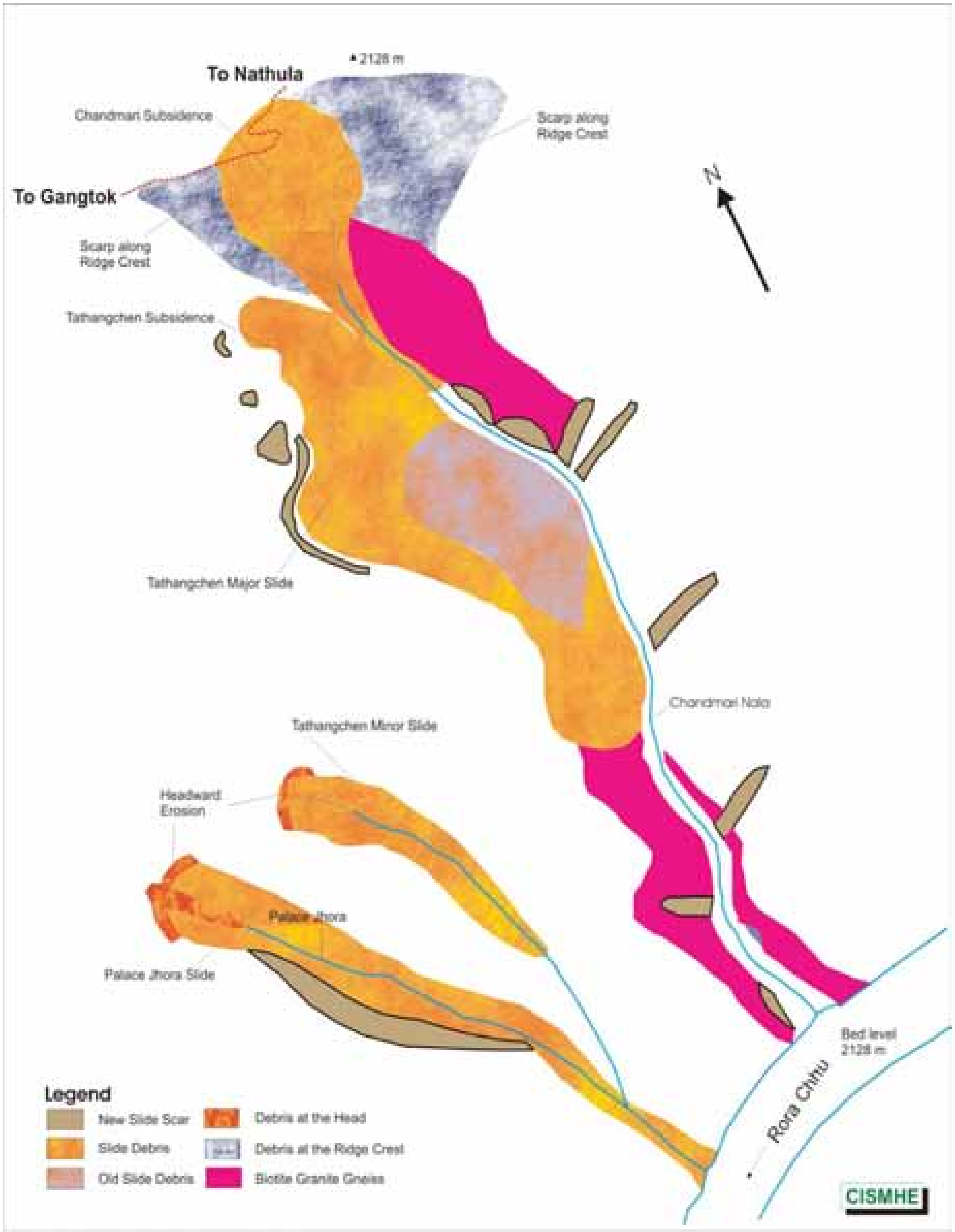


Fig.2.5. Chandmari-Tathangchen Landslide Complex

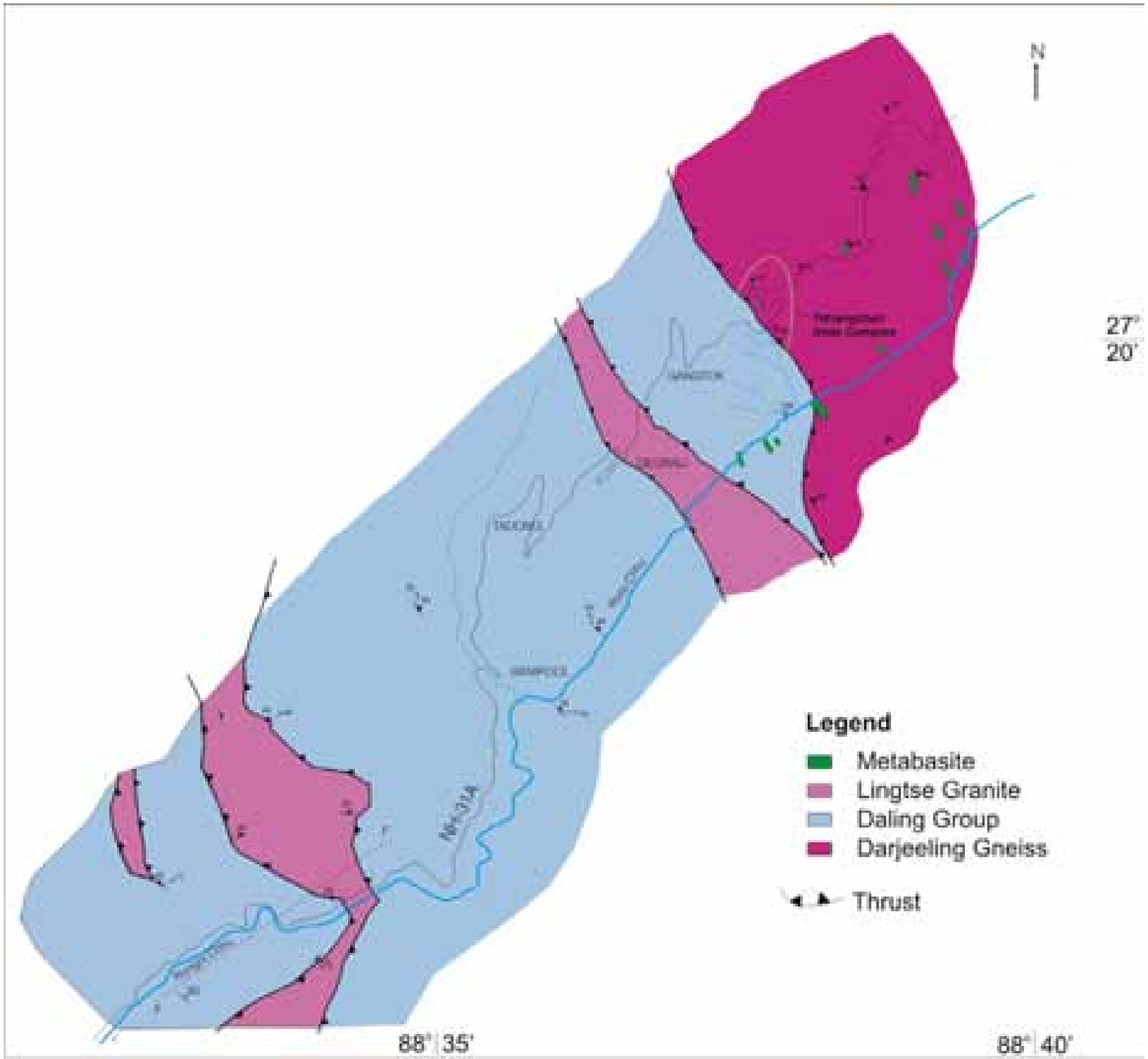


Fig.2.6 Geology of the area around Gangtok with locations of Chandmari-Tithangchen slide complex and 9th mile slide.

of Palace Jhora slide. Sericite-chlorite schist constitue the basement in this region. The rock units dip at 50^o – 55^o towards the east. They are intensively weathered and covered with regolithic soil. Planar failure along the foliation lead to valley-ward movement of over-burden material and with weathered bedrock during 1984 monsoon.

iv) *Tathangchen Major slide* : This landslide occurred in 1975. The reactivation of the slide during the 1984 monsoon lead to its lateral extension which ultimately affected areas further south. An area of about 800-1,000 m length and 200-250 m width was badly damaged. The debris from the active Chandmari slide, that is situated in the east of this slide, rolled down the Chandmari Jhora and caused toe erosion on the right bank. Due to intensive toe-cutting Tathangchen hill slope failed. The old landslide of 1975 was reactivated in 1984 and a new crack developed upslope of the old scar (see Fig. 2.5). The debris flown downstream and got deposited at the confluence with Rora Chhu. Part of the sediment flux was carried downstream by Rora Chhu.

2.4.2.1 *Factors responsible for these landslides*

The Darjeeling gneiss is in thrusted contact with Dalings. The phyllites, schists and gneisses are well jointed and crushed in this thrust zone overlain by thick soil cover. This region receives intense monsoon rain which percolates through the soil and weathered rock. The region also experiences earthquake tremors (De and Kayal,

2004) which can trigger landslide activity. Beside these natural causes, the construction of building and roads in the region and deforestation are the anthropogenic factors responsible to reduce the stability of the hill slope.

2.4.3 Landslide Complex in the region between Mangan to Tong

Every year slope failures occur on the left bank of Teesta river between Mangan to Tong. These slides occur along the streams joining the Teesta river on its left bank. For this reason, North Sikkim Highway is blocked particularly during the rainy season and the left bank slope of Teesta along this highway is with major stability problem, and has been a fear for the entire habitation on it.

Figure 2.7 shows the geology of the region. Rocks of the Darjeeling Group are exposed in the region. Lithologically they are Biotite-Muscovite Gneiss and Chungthang Formation rocks *viz*. quartzite, calc-silicate-marble and graphite schist-gneiss. The foliation dips at 21^{o} – 35^{o} towards NE therefore, failure takes place along south bank of streams joining Teesta. At places, old terrace deposits are covered with landslide cones. They also get reactivated due to heavy precipitation in the region. The slides those occur in this complex are:

i) *Manul-I* : This slide is located at 74.1 km on the North Sikkim Highway. This is a 170 m long sliding and flood zone. The soil and rock materials constitute a thick zone above the Biotite granite overburden. This overburden material undergoes slow creep as

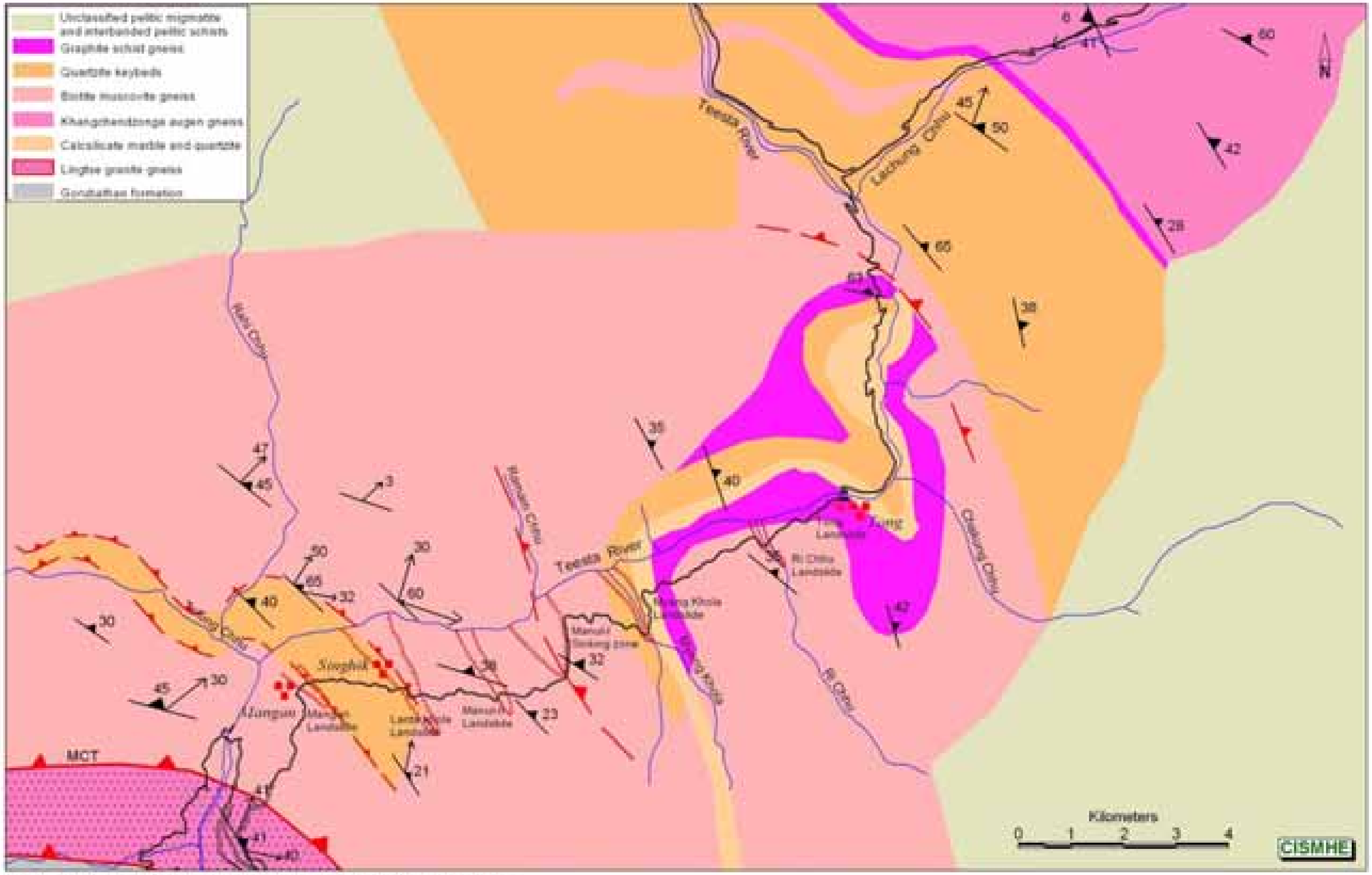


Fig.2.7 Geology around Mangan-Tong landslide complex

marked by hockey-stick like configuration of *Alnus* trees alongside the road. This slide is active since 1983.

ii) *Manul-II* : This slide is located between 75 and 75.6 km on the North Sikkim Highway. This is a 300 m long slide zone on the Biotite Muscovite Schist (Plate 2.6). Boulder and powdered rock material slide down along the stream gradient. This is a sliding and sinking zone since 1983.

iii) *Lanta Khola* : This slide is located between 71.6 and 72.4 km on the North Sikkim Highway. This is 800 m long and is characterized by rock-cum-debris slide/flow (Plate 2.7). Thick layer of fluvio-glacial non-cohesive material with large boulders is present above schistose rocks at this site. Thick biotite bands in the rocks lead to slippage and failure. Erosion of bank and bed material at high river discharge/seepage above the crown is the causative mechanism. This slide is active since 1978 and has been a major concern because every year it blocks the North Sikkim Highway.

iv) *Myang Khola* : The slide is characterized by rock fall on left bank and debris slide/flow on right bank of Myang Khola. The materials present in the landslide are quartzite blocks on left bank and rock fragments with clayey material on right bank. The cherty quartzite and granite gneiss are the basement rock. This slide is characterized by rock falls along sub-parallel joint planes and slides after heavy rainfall. The bed rock exposed along the left bank of the Myang Khola undergo slippage because it dips towards the valley. The rocks exposed at this site are Biotite muscovite granite and quartzite. The attitude of the quartzite beds is N20°E-S20°W, 48° → N70°E. This steam has high discharge; the water flowing over the road interrupts the traffic for some hours during the period of heavy rain (Plate 2.8).

v) *Ri Chhu* : Thick layer of fluvio-glacial non-cohesive material with large boulders present above Biotite muscovite granite, flows down the stream during the period of high discharge. Because of the high gradient of the stream the water rushes onto the road with high velocity (Plate 2.9). Therefore, the old bridge has collapsed and a new bridge has been built at a distance of only a few meters downstream. The materials carried down by the stream sometimes block the Teesta river as evidenced by a large bar with large angular boulders at its downstream side present at the confluence (Plate 2.10). Due to slow creep the protection wall of the road is deformed in the north bank of the stream (Plate 2.11).

vi) *Tong Slide* : This slide has developed only recently. An old landslide cone covers a terrace (Plate 2.12). Due to road cutting and seepage the slope has collapsed recently.

2.4.3.1 *Factors responsible for these landslides*

The biotite-muscovite bands in the granite gneiss are susceptible to chemical weathering. This region lies between MCT-I in the north and MCT-II in the south. Therefore, the rocks are sheared and crushed at places. In this region the left and right bank slopes of

Plate 2.5 Tintek Khola shooting boulder zone

Plate 2.6 Manul - II Landslide

Plate 2.7 Lanta Khola Landslide

Plate 2.8 Myang Khola Landslide

Plate 2.9 Water dashing at high velocity at Ri Chhu landslide site

Plate 2.10 Bar deposits in Teesta River at the confluence of Ri Chhu with large boulders at its head

Plate 2.11 Creeping and collapse of the protection wall near Ri Chhu

Plate 2.12 Collapse of old terrace and landslide cones at Tong

the Teesta river are very very steep. The precipitation is also very high during monsoon period. Thick glacio-fluvial deposits and the jointed and crushed bedrock provide channels for the percolation of water. Therefore, during the rainy season this region experiences immense landslide activity.

2.4.4 B2 Slide complex along Gangtok-Dikchu Road

It is situated at 12 km milestone on North Sikkim Highway. The type of slide is slump associated with mudflow (Plate 2.13). Materials in the landslide are slope-wash material and debris (Plate 2.14). The granite gneiss is covered with silty and sandy soil with clay rich horizons. The causative factors are toe erosion in the initial stage and heavy precipitation, loss of shear strength caused by seepage. Biotite rich bands undergo chemical weathering resulting clay minerals and slumping/flow movement of clayey material results failure of the slope. The B2 slide lies in the MCT zone (Fig. 2.8). It has three stages. The intermediate stage is stable. The top crown is active due to road cutting and heavy precipitation. The bottom stage is active where the tongue of the intermediate landslide cone is collapsed (see Plate 2.13 and 2.14).

2.4.5 Rangpo Slide

This slide is situated on the left bank of Teesta river on NH-31A upstream of the Rangpo-Teesta confluence. The phyllitic quartzite and slates at this site dip at 30^{o} – 40^{o} towards the river and are covered by a mantle of weathered materials (Plate 2.15). During rainy season, the percolating water removes the fine particles and increase the pore pressure. This leads to rock fall due to loss of cohesion.

2.4.6 Lukhbir and Berrik Slides in West Bengal

Lukhbir and Berrik landslides are in Darjeeling districts of West Bengal. They are very important because they interrupt NH-31, the only road route to Sikkim connecting Siliguri and Gangtok. At both the sites Quartzites and carbonaceous phyllites are exposed at both these sites. At the Berrik site there is a fault propagated fold (Plate 2.16). The carbonaceous phyllites undergo circular and block failure along the roadside at the right bank of Teesta river.

2.4.7 Landslides along the Lachung Axis

The rocks exposed in the Lachung axis are Kanchenjunga augen gneiss, quartzites of Chungthang Formation, politic migmatites and interbanded politic schists with metabasites, and tourmaline granite. There are some dislocation zones present in this region. Active landslide upstream of the Yumthang valley supplies sediment into the valley (Plate 2.17). The vegetation cover developed on the landslide cones provides stability to the slope. On the other hand, slope failure due to toe cutting leads to destruction of vegetation cover in the region. Glacier tongue on the right bank also supplies large volume of unconsolidated rock fragments into the valley (Plate 2.18). These material also destroys the forest in the region and at times lead to valley aggradation and change in river course. Downstream of Yumthang, near Lachung, thick periglacial deposits

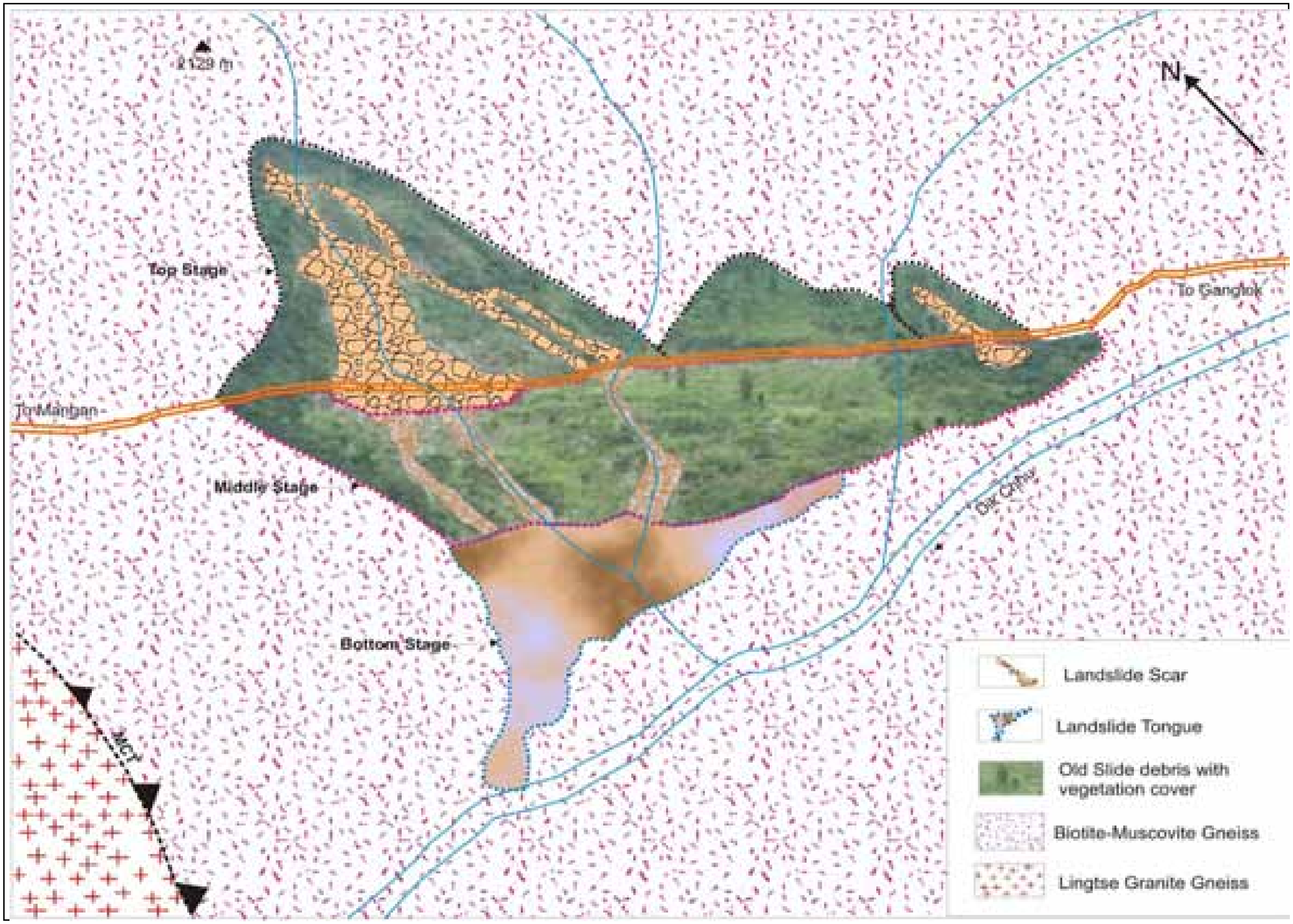


Fig. 2.8 B2 slide lies in the MCT zone

Plate 2.13 Mud flow at the base of the B2 landslide

Plate 2.14 B2 landslide

Plate 2.15 Rangpo landslide showing Rock fall and debris flow

Plate 2.16 Berrik landslide showing a fault propagated fold and the circular failure of carbonaceous phyllite

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Plate 2.17 Landslide upstream of Yumthang valley

1 8 [illegible]

Plate 2.18 Glacier tongue which supplies sediments into the Yumthang valley are preserved at several places (Plate 2.19). The collapse of these deposits due to toe cutting increases sediment load in the river. This may also lead to valley aggradation and subsequent outburst floods.

2.4.8 Landslides along Teesta upstream of Chungthang

The rock types exposed in this region are calc-silicate rocks with interbanded quartzite, Kanchenjunga augen gneiss, tourmaline granite, and politic migmatite and interbanded politic schists with metabasites. Most part of the area is covered with glacial moraine, periglacial deposits (terraces) and landslide cones.

Frost weathering upstream of Thangu has resulted in large quantity of debris. Debris delivered to the rock-wall foot accumulated initially as an extensive apron or series of talus cones (Plate 2.20). Seasonal melt is a major influence which affects the form of cones and their onward transfer processes. These unconsolidated angular rock fragments can be carriedout down stream in the event of heavy precipitation or glacial lake outburst. Immense landslide activity due to heavy precipitation in the Higher Himalaya leads to slope failure on eitherbank, thereby supplying huge sediment load into the main channel (Plate 2.21). Road building and frost action downstream of Thangu result in the collapse of old depositional landforms (Plate 2.22). This increases sediments in the Teesta channel and may lead to aggradation and subsequent lake outburst flood as well as change in river course.

2.5 ENVIRONMENTAL IMPACT OF THESE SLIDES

Most of the landslides along the NH-31A, such as Rangpo slide in East Sikkim, disrupts the traffic. Similarly, the landslide complex between Mangan to Tong also disrupts the traffic on North Sikkim Highway every year. Due to the dumping of material into the river the sediment flux in the rivers increases. Increase of sediment flux may have negative impacts on the aquatic ecosystem. Occasional blocking of the rivers may lead to flash floods. Some of the landslides affect the cultivable lands, thus leading to the wastage of productive soils. Some landsides in the city area, such as Tathangchen slide complex, damages the houses and leads to loss of life. At places, particularly at the south of MCT, rock falls are observed during the earthquakes (Plate 2.23).

Landslide debris, resulting from the developmental activities, accumulate as loose scree that kills vegetation, chokes streams, and creates new instabilities (Haigh *et al*., 1987; Haigh 2002). The absolute importance of human-triggered landslides in the total landslide budget of the Himalayan mountains is debated. Road construction and deforestation rank among the major triggers for landslide initiation (Bruijnzeel and Brenner, 1989). Each year, as much as 550 cubic meters of debris may fall on each kilometer of road bed (Valdiya, 1987). While human activities trigger many small superficial landslides, the bulk of the landslide sediments which reach mountain river channels come from large, deep seated, landslides created by river incision or tectonic uplift (Bruijnzeel and Brenner, 1989). The Himalaya are young and rapidly evolving mountain range

Plate 2.19 Periglacial terrace deposits at the left bank of Lachung near Lachung

Plate 2.20 Erosion due to frost action upstream of Thangu at the left bank of Teesta

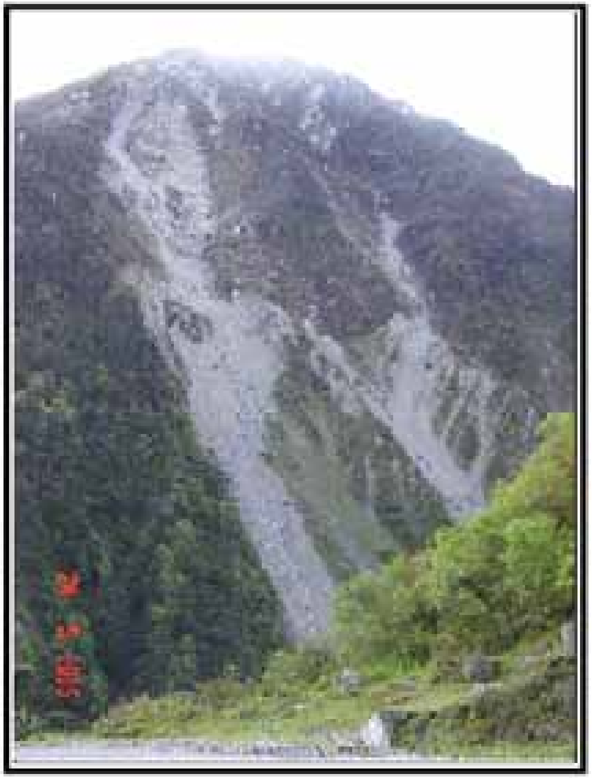


Plate 2.21 Landslide along the left bank of Teesta in Lachen axis

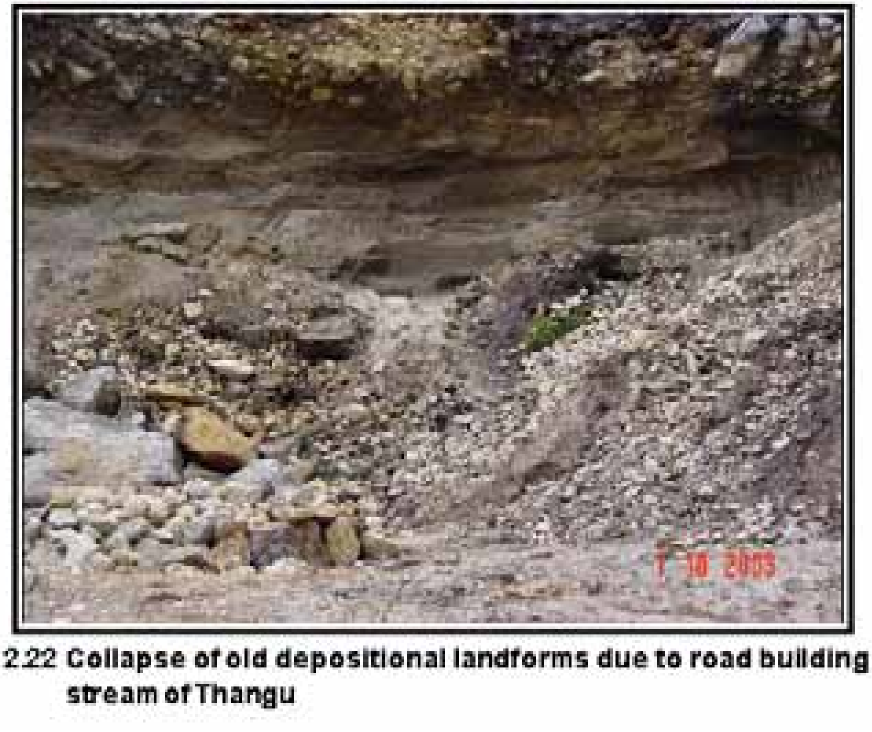


Plate 2.22 Collapse of old depositional landforms due to road building downstream of Thangu

(Valdiya, 1998) and these mountains undergo, in geological terms, very rapid tectonic uplift and this encourages equally rapid incision by river systems. The vast, steep slope of the mountains are the result. The very steepness of these slopes testifies to the fact that many lie close to the margins of their own stability. Even undisturbed, each monsoon brings down thousands of landslides from hillsides in a mountain landscape that has self-organised to a condition close to the limits of its own geomorphological stability.

Landslide is the pertinent natural problem, which is intensified manifold by human interferences particularly in active mountainous regions like Sikkim Himalaya. Softer and incompetent rock formation, rocks that are hard but incompetent due to fractures and joints, massive deforestation, inadequate drainage, cultivation on steeper slopes, toe erosion by stream, heavy loading/construction of massive structures on unstable ground and seismicity of the region are some of the factors responsible for landslide. Rainfall intensity in Sikkim Himalaya has been observed to trigger landslide activity. In Sikkim the roads are disrupted every year, especially during monsoon period, by landslides. The forests are also affected by landslide and erosion, which erode valuable forestland, destroy plantations and retards the growth of forest produce. The areas that are most affected are the areas covered by softer rocks viz. phyllites and schists of Daling Group. However, the areas where harder schist and even gneisses occur are also affected to a minor extent. In these regions the mica rich bands in the rocks lend the rock to massive failure.

It is also very important to note here that many of the major landslides of Sikkim *viz*. North Rhenok Slide, Tathangchen-Chandmari slide, B2 slide, Chowang slide, Rangrang slide, Runchu slide, Narkhola and Karchi slide, Dentam-Uttare slides, Sombre slides lie in the region of MCT (see Fig 2.1). The active landslides on the MCT are resulted due to the combined effects of i) road building, ii) heavy precipitation and iii) seismic activity between MBT and MCT.

In the planning and implementation of projects in the hilly areas sustainable development must be given due importance. One aspect of sustainable development in a mountainous region is proper examination of the existing instabilities of the terrain and consideration of appropriate development schemes so that the resultant geo-environmental hazards are minimized. Therefore, systematic investigations need to be carried out on regional to local scales. Due attention must be given to the relationship between the attitude of lithounits and road alignments. For instance, a valley ward dipping bedding plane/foliation can lead to slope failure on the road side, while the road on the stable slope where the bedding/foliation plane dip into the hill, is never affected by landslide and subsequent blockage of traffic or death toll (Plate 2.24). Landslide hazard zonation map is to be prepared with an objective to delineate zones with different damage potential. This will help in planning and implementation of projects under the milieu of sustainable development.

The remedial measures that are usually adopted are i) sealing of cracks with bitumen, ii) construction of good outlet of rain water in

Plate 2.23 Rock fall on the right bank of Rangpo Khola near Mangalbare

Plate 2.24 Relationship between road network, landslide and attitude of lithounits

the form of catch water drains, iii) rock bolting by wire mesh with boulders extending down to the river bed to check the toe erosion. These measures can be adopted at selective localities. However, where unstable geological structures (*viz*. highly jointed igneous and metamorphic rocks) are dipping towards the roads or river channels the roads must be diverted from such areas.

2.6 REMEDIAL MEASURES TO PREVENT LANDSLIDES

Landslides are problems that if not attended, grow with time. It is, therefore, important that they are tackled at the earliest opportunity and undue time is not lost. More often than not an immediate solution, even if partly correct or unconventional may prove more economical in the long run than the most perfect solution adopted after the problem has grown with time.

The corrective measures for a landslide can broadly be divided into four categories.

(a) Keeping the soil mass free of moisture
(b) Increasing shearing resistance of the soil
(c) Protection of toes of road embankments
(d) Training of streams to prevent damage.

2.6.1 Keeping soil free of moisture

The commonest way of doing this is to provide catchwater drains of a suitable section above the road formation. In case the terrain comprises of very steep slopes in such catchwater drains, it may be economical to line them with black polyethene sheeting, brick or stone.

Very often, when dealing with sand or silt mixed soils, the problem of moisture is not confined to only surface water, but sub-surface water also exists. In this case, open drains are dug. These are filled back with well designed porous fill of graded gravel- sand mixtures and they are closed at the top with polythene or a clay seal to prevent surface water going in. It may be indicated that in retaining walls or breast walls, little attention is often paid to back filling such walls after construction. If the back fill is too porous, which is often the case with rubble fills, the velocity of flow of water through such a fill is very high, which causes undermining in the soil retained. This undermining is easily repaired but the fine material lodges itself in the fill, thus making it impervious for any further movement of moisture. Excessive hydrostatic pressure is a common cause of failure of breast walls and retaining walls.

A technique which has not been tried extensively in India but which holds much promise is the provision of horizontal drains. For want of accessibility to mechanical equipment's at every site, this measure may have practical difficulties. Well point de-watering had been tried at some sites which consisted of jetting vertical pipes upto required depth into which an airlift pump could be lowered. By pumping compressed air into a series of such vertical pipes, occasional de-watering of the soil could be done and this flow could be discharged away from the site.

Bitumen mulching has also been tried at some locations and was found successful in keeping down surface percolation into the hill face, but it has exhibited that the face eventually cracks due to a rotational movement following toe erosion.

2.6.2 Increasing soil strength

Exclusion of moisture from the soil or rock mass prevents decrease in dry soil strengths. The techniques covered here improve its ability to withstand shear stresses. When soil is clayey or silty clay, seasonal variation in moisture gives rise to serious stresses. Expansive clays assume a much higher volume and exert swell pressures on retaining structures, or on pavement. Equally destructive forces come into play if the soil dries out and shrinks away. Injection of cement or hydrated lime slurry into the soil mass under pressure forces the grout through paths of least resistance moving along fractures, bedding planes, sand lenses, seams, roots and fractures created by jetting slurry. It may be added that the grout could be lime cement sodium silicate solution, bitumen emulsion or cut back depending on the type of material to be strengthened. Fractured rock sets well with bitumen and cement, plastic clays with lime or cement, sands and silts with bitumen and sodium silicate. The action consists in providing a curtain against percolation of moisture, and in case of clays, improving their plasticity properties due to base exchange with the calcium ion of lime or cement.

2.6.3 Toe protection works

Toe protection works consist of rendering the face of hill in contact with forces of erosion non-erodable. This is commonly done by erecting mass concrete, masonry or crated boulder walls. Slide is prevented from moving by a RCC mass concrete wall but at some locations, it has failed in overturning due to hydrostatic pressure owing to choking of drains on hill side . Mass concrete walls are also provided to prevent toe erosion. Dry stone walls in wire crate are suitable when placed on uncertain foundations. Unlike masonry wall which cracks due to differential settlement, these have a longer life. Masonry walls have failed due to rotational movement of slides. Selection and siting of toe protection works need care and experience.

2.6.4 River Training

River training works can be of several types.

(a) *Training of subsidiary nallas joining main rivers*.

These nallas should be provided with boulder check dams upstream. These will prevent large scale movement of silt by decreasing the slopes and the interference in the flow of main streams will decrease. It may often be necessary to check spillage of flood in the side streams by providing protective bunds.

(b) *Provision of groynes or guide bunds to prevent spilling of main streams and preventing toe erosion*.

Guide bunds have to be founded on firm soil-but it is uneconomical to place groynes or spurs at the scour depth. In such a case, it is often economical to site them suitably. However these are required to be rebuild after the floods.

2.7 TYPICAL LANDSLIDE PROBLEM

The landslide problems being encountered in Sikkim have been found to be mostly due to hydrological reasons. The case history of one of the typical landslides occuring at 7th Mile Slide on Gangtok-Kupup road describing its features, mechanism, treatment measures recommended by experts of various organizations and by the departmental authorities and those executed so far are outlined in the following paragraphs.

2.7.1 Features

(a) This slide, falling in the 12 km of the above road, has been posing subsidence problems since 1966. Ths length of the affected stretch is about 400 m (1300 ft) and the average up-hill and down hill slopes are 30^o and 40^o, respectively. The slope length from crown to road level is 152 m (500 ft) and from road level to toe is 700 m (2,300 ft). A big nallah (known as MS 8/7 nallah) also flows at the toe of this slide.

(b) The slide material involved consists of matrix of boulders of biotite gneisses in silty soil. Though sheet rock has been exposed on the Gangtok end of the slide, the depth of the moving mantle could not be assessed/ determined. The down hill slopes are full of springs and seepage. Heavy water flow has been noticed even a few feet below the road formation. During the monsoons of 1967 to 1969, the formation was completely damaged and fresh formation had to be cut every year.

2.7.2 Mechanism

(a) The annual rainfall in the area is about is about 5,000 mm (200 inches). During the monsoons the silty soil, in which the boulders are embedded, gets completely saturated when creep sets in. This also provides lubrication for the boulders to slide down due to gravity, with the result that the whole mass starts flowing resulting in subsidence.

(b) There are several small streams on the up-hill slopes of this slide. The discharge from these streams and also the surface run-off up hill of the shear line enter into the ground through the shear line, providing further lubrication for the sliding planes.

(c) On the down hill, the toe of this slide is being eroded by frequent floods in the MS 8/7 nallah. The hydrostatic and seepage's pressure developed have been further assisting the erosion of the toe.

2.7.3 Treatment Measures

The following works were executed in consultation with the Central Road Research Institute:

(a) A peripheral catch water drain above the crown of the slide was constructed.

(b) Treatment of up-hill and down-hill slopes by spraying two coats of cut back bitumen to prevent percolation of surface run off and to provide cohesion at the surface.

(c) Breast wall in combination with a 1.8 m (6') deep road side drain to trap the springs below the formation.

(d) Road retaining structures in sausage work (dry stone masonry filled crates in wire mesh).

The above work proved a success and the subsidence of formation during the monsoon of 1970 to 1973 were minor. In the monsoons of 1974, the road formation and catch water drains suffered extensive damages, which were repaired. The slide has shown sign of extension towards the Kupup end. One main reason for this was found to be the ingress of the discharge from a stream flowing on this end of the slide area which is being trapped and diverted away from the slide area.

Therefore, in addition to the above measures, it was proposed to provide toe walls so that the toe erosion problem is cut down. To reduce the pressure on the toe walls it was also proposed to provide trench drains on the down hill slopes to trap and lead the subsoil water. Site Plan of the slide is given is given at Fig. 2.9.

2.7.4 Various forces to be considered

Relevant data in respect of geology, hydrology and seisomology of the area is essential to determine the design parameaters and to asses the forces acting on the structure subjected to land slide. Some of the mainload / forces acting on the structures are described below.

2.7.4.1 *Weight of Structure*

Weight of structure and imposed vertical loads act vertically downwards though its centre of gravity.

2.7.4.2 *Lateral earth pressure*

(i) When retaining soil surface is horizontal, pressure intensity (p) at any depth ‘h’ is given by

$$p \ \frac{1-\sin\phi}{1+\sin\phi} = wh$$

Lateral pressure ‘P’ therefore, per unit length of wall for dry and ideal soil is given by :

$$P \quad = \quad wh^2 \frac{1-\sin\phi}{1+\sin\phi} \text{ acting at h/3 from base}$$

(ii) When retaining surface is horizontal and wall carried super load ‘q’ per unit area, equivalent height of wall , he = q/w and

$$p \quad = \quad w \frac{1-\sin\phi}{1+\sin\phi} (h + he)$$

(iii) When structure is to carry superimposed load inclined at an angle to the horizontal and direction of p is parallel to surcharge.

$$p = wh.\ \cos\ \alpha \qquad \frac{\cos\alpha - \sqrt{\cos^2\alpha - \cos^2\phi}}{\cos\alpha + \sqrt{\cos^2\phi\alpha - \cos^2\phi}}$$

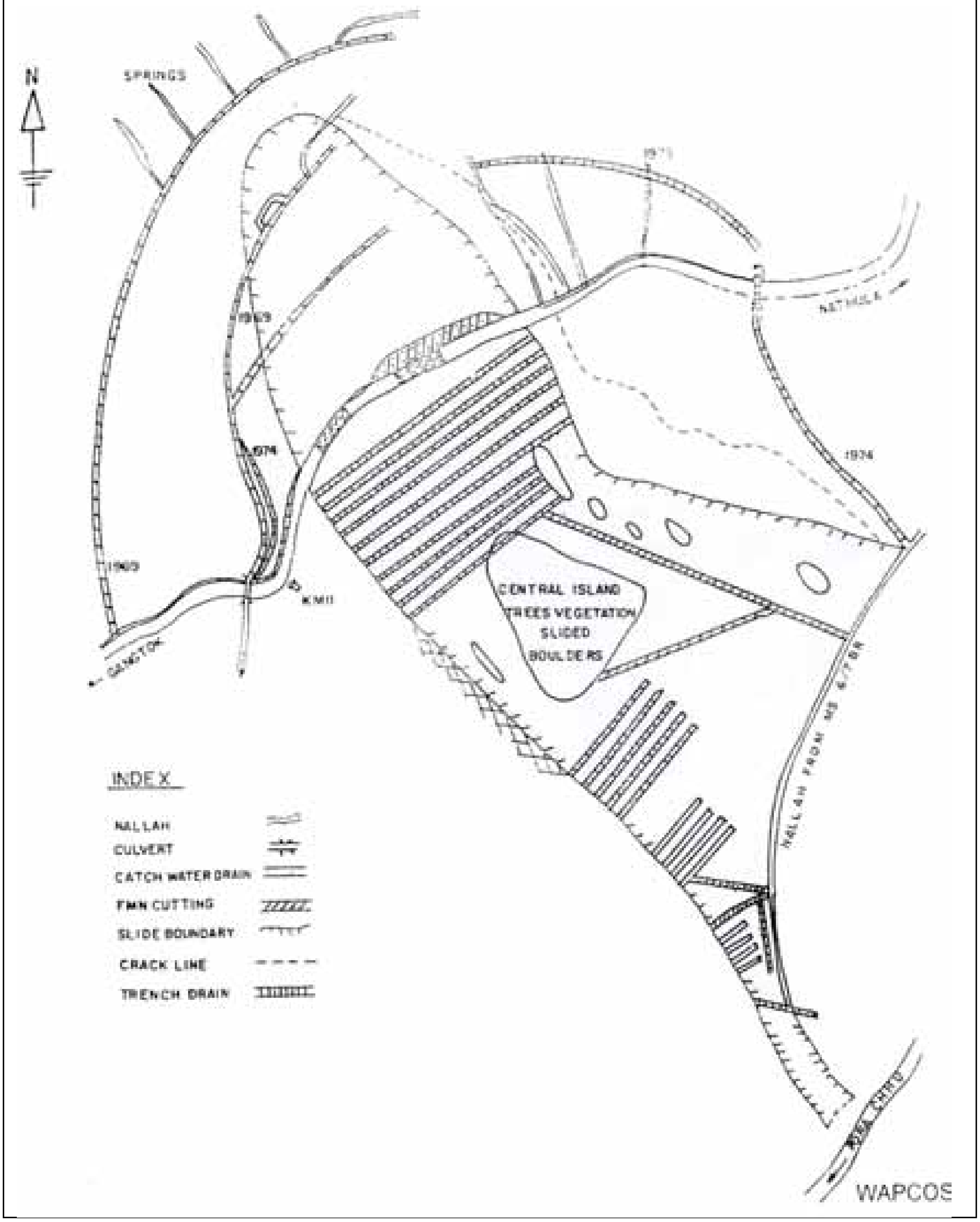


Fig.2.9 Site plan of 7th mile slide on Gangtok-Kupup road

Above formulae presuppose that moisture content has optimum value, materials on the back are granular, non- cohesive and ideal, but soils in actual practice do not behave in this manner. In order to make correct assessment of lateral earth pressure, pressure diagrams should be constructed from actual data. By plotting results of various observations on graphs and interpolation of data, suitable values of ‘p’ in terms of variable parameter ‘h’ can be obtained for design calculations.

2.7.4.3 *Wind pressure*

Wind load may be assumed as 150 kg/ m^2 acting horizontally at h/2 from bottom of the superstructure on theoretical consideration for the State of Sikkim

2.7.4.4 *Hydrostatic pressure of water*

If the back fill happens to be cohesive and the structure is impinged by large quantity of water, structure will experience Hydrostatic pressure of intensity,’ P’ given by

$$P = wA\bar{x}$$

Where w is the specific weight of water, A is the surface area on which pressure acts, and $\bar{x}$ is the distance of Centre of Gravity (CG) vertically below such soil level.

In case of structures which have already been constructed for ideal soils, and above conditions are encountered, suitable net work of subsoil drains should be provided.

2.7.4.5 *Hydrostatic uplift*

If the structure is wholly or partly submerged in liquid, it will experience upward force exerted by the liquid and its magnitude will be equal to the weight of displaced liquid. This force acts at the point known as center of buoyancy which coincides with CG of the immersed portion of the structure.

Stilling basin and aprons designed for all relevant conditions and loads at times fail due to this upward force known as buoyancy.

2.7.4.6 *Seepage force*

Seepage force ‘F’ is given by

$$F = wiza$$

Where, w is the density of water,

i is the hydraulic gradient

z is the thickness of soil mass through which water percolates and

a is the total cross sectional area through which seepage pressure acts.

Amount of seepage is determined by discharge measurements. These measurements have to be made with great precision and repeated on numerous occasions at various stages. Geological location of gauging sections at suitable intervals can render evaluation of effects of under flow channels, faults or other discontinuities that may intersect streams and *kholas* between gauging stations.

2.7.4.7 *Ice pressure*

Any structure subjected to slow or freezing rain is normally designed for snow load of at least 45 kg/m^2. The amount of snow fall is usually expressed in terms of its water equivalent, i.e. the depth of water that would result from its melting. Forces exerted by snow are based either on experience or empirical formulae because of complexities of density, conversion to water, flowage and evaporation etc. The areas where the soil freezes between 1.5 to 2 m alternate expansion and contraction of the upper layer of the soil produces ice pressure due to freezing and thawing of water in it. This poses serious problems for roads and allied structures due to the freezing soil expansion because of the formation of ice. When this expanded soil thaws, cavities are formed. The solution of this problem partly lies in provision of adequate drainage system.

2.7.4.8 *Seismic forces*

Seismic forces act at the CG of the body or at the CG of the section of the body above any horizontal plane passing through the structure. Both horizontal and vertical seismic forces must be considered.

Horizontal seismic force ‘H’ is given by

$$H = (a / g) W = cW$$

Where, a is the ground or seismic acceleration such as the acceleration of the earthquake wave
g is the acceleration due to gravity
W is the weight of structure or its components and
c is the seismic factor

2.7.4.9 *Dynamic impact*

An accurate evaluation of the impact on the roads and allied structures is a complex process as it depends on wheel loads, speed and surface conditions. When structures are subjected to moving or rolling loads, impact effect are based on empirical formulae : e.g. for bridges it is generally taken as 4.5 / (6+l) where 'l' the span in meters. Structures on which it is expected that load "W" of slides is expected, the structure should be designed for an intensity of 2 W/A and not W/A. This is based on strain – energy relation. Design of retaining walls, breast walls, and toe walls is based on various earth pressure theories.

2.8 FLOOD PROBLEM

Flood problems in the predominantly hilly terrain of Sikkim are mainly that of inundation of marginal lands on low river terraces and erosion of land by rivers and hill streams. While the flooding due to over bank spills is not serious and is confined to isolated patches affecting a total area of 10,000 ha, land erosion poses a serious threat to rural and urban population, strategic lines of communication, public utilities, agricultural lands, plantations, forests and mineral resources. Erosion of land has even more adverse effects on environment and ecology not only in the affected areas but also in the plains lower down where the heavy loads of debris are deposited in the river beds and flood plains aggravating the intensity of flood and disturbing the river regime.

The loss of land and the process of environmental degradation are irreversible and therefore preventive and protective measures have to be taken in right earnest. The cost of inaction can be enormous in terms of loss of human lives and natural resources besides set back to developmental programmes and economic activity. These aspects have been considered in the context of very limited availability of utilizable land in hilly areas and even more limited range of options for development.

The average annual damages due to floods in the state are as follows:

Area affected = 0.01 mha (max 0.02 mha)
Population affected = 0.005 million (max 0.1million)
Damage to Crops
  Area = 0.001 mha (max 0.02)
  Value = Rs. 0.415 crore (max Rs. 7.63 crore)
Damage to houses
  No. = 427 (max 9746)
  Value = Rs.0.054 crore (max Rs. 1.83 crore)
  Cattle Lost = 91 (max 3260)
Human lives lost = 6 (max 107)
Damage to Public Utilities = Rs.1.94 Crore (max Rs. 28.15 crore)

The above data does not include the damage to roads maintained by the Border Roads Organisation (BRO). The enormity of the problem can be appreciated from the fact that they have to remove about 650 cum of debris every year per kilometre of road under their jurisdiction.

2.9 SOCIO-ECONOMIC IMPLICATIONS OF FLOODS AND LAND EROSION/ SLIDES

While the flooding due to over bank spills is not very serious and is confined to isolated patches affecting a total area of 10,000 ha, land erosion poses a serious threat to rural and urban population, strategic lines of communication, public utilities, agricultural lands, plantations, forests and mineral resources. The erosion of land has even more adverse effect on environment and ecology not only in the affected areas but also in the plains lower down where the heavy loads of debris are deposited in the river beds and floods plains aggravating the intensity of flood and disturbing the river regime.

2.9.1 Flood Management works in Vogue

2.9.1.1 *Sausage walls*

The inundation of marginal lands by rivers and streams in the state is limited to low river terraces, but the main problem is that of bank erosion either due to direct river attack or due to sloughing of saturated bank material. The protection works in such cases are usually in the form of sausage walls with concrete lining in one or more steps.

Where, a varies from 0.6 m to 0.9 m

h = as per site condition

h_1 = 1/3 of c

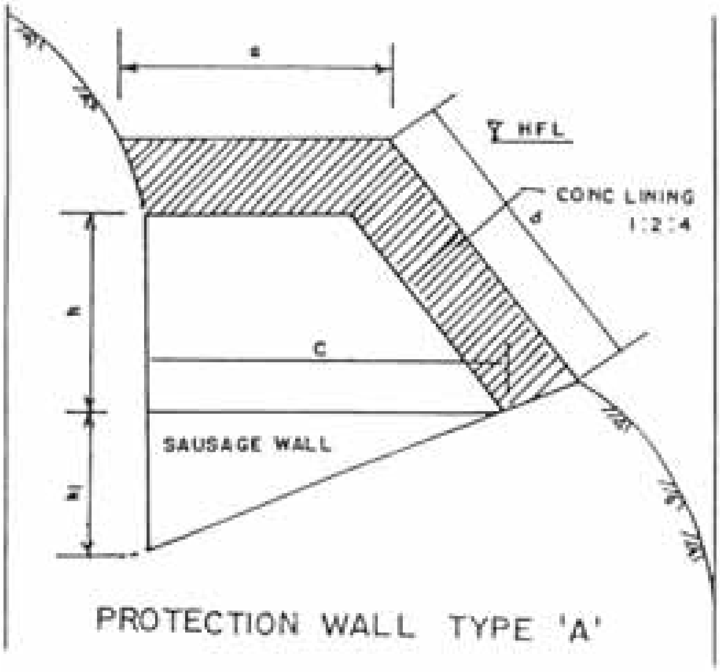
c = a + h/3

Where the banks are high, slope protection works are often necessary above the concrete lined walls. These are in the form of sausage walls with out concrete lining.

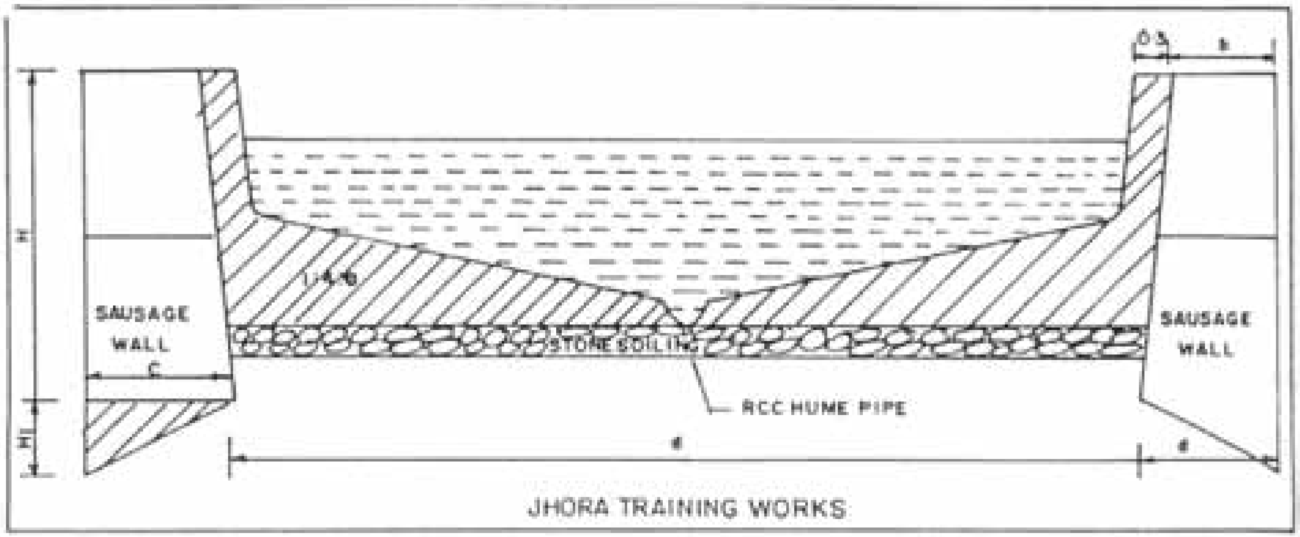
2.9.1.2 *Stream (Jhora) training works*

Many hill streams erode the toe of their banks causing land slides on either side. Training of such streams is done by providing standard protection works along both the banks and in the bed.

While the bank protection in done by sausage work with 0.3m thick concrete lining, bed protection is done by 1:2:4 concrete lining over 1:4:8 concrete base laid over boulder soling. In order to take care of low discharges, a semi circular pre cast RCC cunnet section is provided in the middle of the bed. There are standards designs, depending upon the channel size and discharge of the stream. One of the typical design is as follows:



Sausage Walls



Jhora Training Works

Where, a varies from 1.0m to 7.0m

b =b + H/3

c =1.3 to 3.2 m

d = 0.9m

H = as per site condition

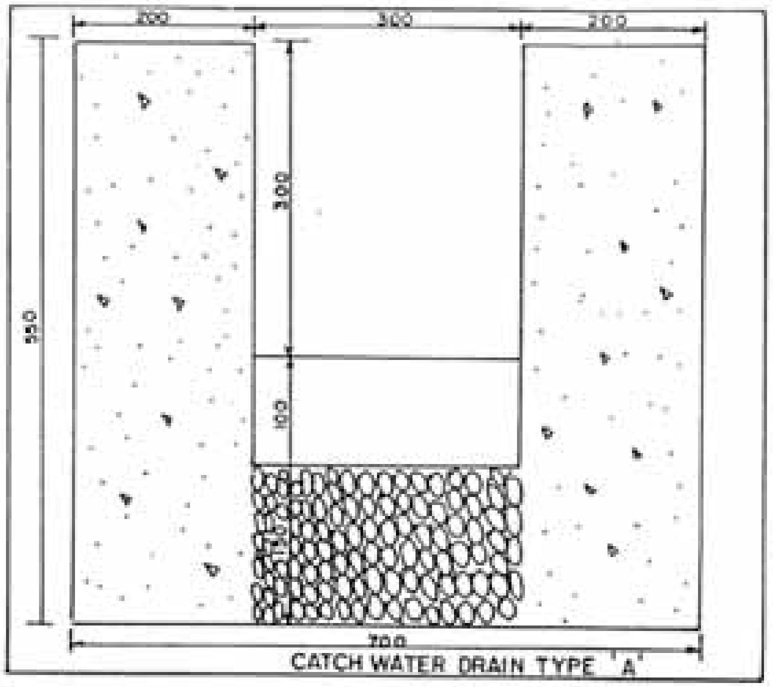
H_1 = 1/3 of c

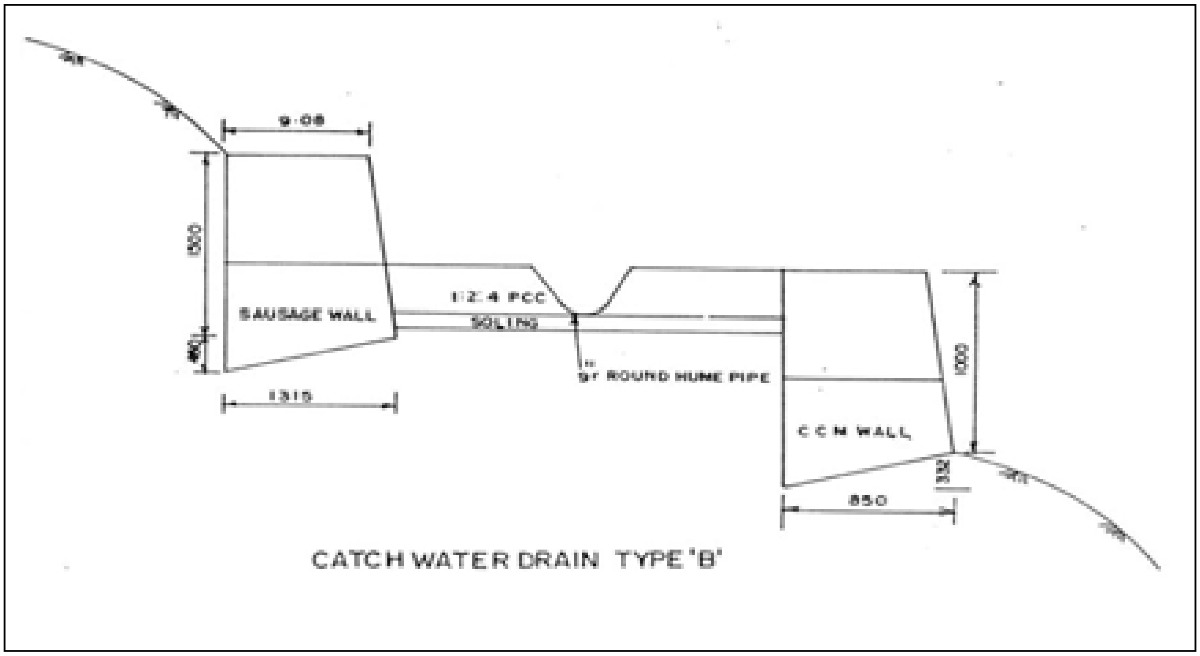
2.9.1.3 *Catch water drain*

The erosion of hill slopes and land slides are often caused due to inadequate drainage. Such cases are conspicuous due to the presence of numerous rills and gullies and signs of land sinking and slides. Excessive flow of storm water and consequent expansion of gullies down the hill slope causes damage to habitations, lines of communication and public utilities. Preventive measures therefore have to be taken in the form of catch water drains across the hill face to safely discharge the monsoon run off into the nearest drainage channel. Typical section of a catch water drain is as follows.

2.9.2 Performance of Flood Management Works

By and large stream (Jhora) training works, and catch water drain perform well and meet the objective. Stream training works, however, often suffer damage to the concrete lining in the bed due to settlement of the stone soling or due to rolling of heavy boulders or both. The side walls are rarely affected.





Catch Water Drain

Anti-erosion works to protect river banks also perform well since the main ‘pucca’ wall is usually protected by sausage work near the water edge.

The works which are most frequently damaged are the sausage walls due to settlement of hand packed boulders. Damage is also caused due to excessive active pressure from the sliding slope material. Maximum damage to protection works, therefore, occurs in active land slide zones. The hill slopes with thick over burden of clayey soils or morainal material usually have slides in the form of mud-cum-debris flows. Protection works in such cases are relatively more susceptible than those in rock slide areas. In the latter case, damages occur in the intial stages but get reduced over time as the slide zone gradually gets stabilized. The works taken up by I&FC Department are mostly in the potential land slide areas and relatively few in active land slide areas. The works, therefore, perform better than those of General Reserve Engineering Force (GREF) who have to provide protection to the strategic road communication network mostly in active land slide zones.

2.9.3 Formulation and Implementation of Schemes

Sikkim has active Panchayti Raj institutions. The panchayats take active part in formulation and implementation of all rural developmental schemes including flood management schemes. The Government of Sikkim has laid down procedures which require, *inter-alia*, all schemes to be formulated in consultation with the Panchayats. For small schemes costing upto Rs.10.00 lakhs, the

Panchayats are also involved in the tendering process and award of work to the contractors. Since the works are intended to protect the life and property of the villagers, rural development works, valuable lands under crops and plantations, the local people take keen interest in the supervision during construction.

2.9.4 Evaluation of Flood Management Works

The Rashtriya Barh Ayog (RBA) has recommended that anti-erosion works should not be taken up to protect agricultural land and should only be taken up to protect towns, village *abadies*, public utilities and strategic lines of communication. They have gone into the problem of landslides in the context of heavy sediment loads in some rivers, and the related problems of flooding and erratic behavior of rivers. In this connection they have recommended certain regulatory measures to minimise inflow of sediment load into the rivers. No specific recommendations have been made for anti-erosion works in hilly areas. There are, however, certain precedents to go by. These provide a clear insight into the general approach of the Government of India in this regard.

Various central teams, which visited the state from time to time to assess the damages due to floods and to recommend Central assistance for relief and restoration measures, have taken the following aspects into consideration:

- Damage to houses, roads, bridges, irrigation canals/works, power and telephone lines, drinking water pipelines, plantations and crops.

- Damage to rural development works
- Loss of humans lives
- Loss of cattle and poultry
- Damage to existing hydro-electric projects
- Land use and environment

Since most of the schemes are of minor nature and are scattered over a vast hilly area their performance has been assessed in general qualitative terms taking into consideration the following main aspects:

i) Broad assessment of the extent of problem in qualitative terms in respect of each scheme,
ii) The nature of works taken up under each scheme with estimated cost and year of construction,
iii) Condition of the various structural components. Damage, if any suffered during previous floods and apparent causes thereof, and
iv) Weather or not the works have been effective in providing the desired protection.

The evaluation studies in terms of above aspects for a few important schemes in each district as undertaken by WAPCOS under a separate project are given below.

2.9.4.1 *South Sikkim*

(i) Jhora Training Work, Catch Water Drain and Anti-Erosion works at Goshkhan Jhora at Namchi- Estimated Cost Rs. 55.43 lakhs

Goshkhan Jhora drains the western side of Namchi town. All the surface run-off from the Namchi-Namthang and Namchi-Nayabazar roads and the Bazar area drains into the Jhora. The Jhora has a wide valley and steep bed slopes. The banks are friable due to highly sheared weak rocks at the base and the overlying clayey material. There are many scars of previous land slides and active gully formation on both banks. The Jhora carries a normal flood discharge of the order of about 4 cumec. The upper parts of the Jhora slopes have considerable urban habitations and a stretch of the Namchi-Wok road. There are a few houses in the lower part of the slope which are even more susceptible to slide.

The I&FC Department had earlier carried out training of the Jhora in a length of about 400 metres. In view of the continued threat to the urban and sub-urban population of Namchi Bazar and the lines of communication the Department carried out further training of the Jhora in a length of 550 metres. The works under this scheme under reference are in the form of guide walls to protect the Jhora banks and drop walls to minimise the impact of high monsoon flows on the bed. In order to stablise the hill slopes against sliding breast walls have also been built.

The immediate objectives of the protection works are :

a) Protection of urban and rural habitation of Namchi Bazar.
b) Protection of Namchi-Wok Road.
c) Prevention of gully information on steep hill slopes.

The training works have apparently performed well during the monsoons of 2000 and 2001 since these are no signs of any damage to any of the three components. These are also no signs of any fresh erosion or sinking/sliding of the hill slopes in the protected area.

(ii) River Training Works on river Teesta at Melli- Estimated Cost Rs. 51.9 lakhs

Melli Bazar township is situated on two natural terraces on the right bank of the Teesta river. The upper bank is relatively stable due to the presence of rock out crops at its base. The lower terrace is prone to erosion due to toe-cutting by the river. The terraces and the river bank are composed of morainal deposits of boulders and silty clay. The bank slopes are steep being 0.5: 1 to 1:1.

The riverbed has a huge deposit of large boulders on the right bank, which protects part of the bank against erosion during low and medium floods. However, during high floods the bank is prone to erosion. Remaining part of the bank extending beyond this boulder deposit is exposed to river erosion even during low floods. During high floods, the old retaining wall protecting the school playground also comes under river attack.

The objective of the protection works is to prevent toe cutting and slope protection. The works constructed are as follows:

i) Apron along the water edge in boulder sausages 1.5 m high and 2.5 m wide at the top.

ii) Plum concrete wall 3.08 m high and 0.9 m wide at the top. This wall is protected upto 1.5-m height by the apron.

iii) 2 m high sausage wall at higher elevation to protect the hill slope against sliding.

iv) Plum concrete filling 0.3 m thick between the plum concrete wall and sausage wall.

The works have faced two floods and are in good condition except for some minor damage to the apron due to the impact of rolling boulders. The damage to the apron is to be excepted since it is meant to protect the main wall.

2.9.4.2 West Sikkim

(i) Jhora Training Work and Catch Water Drain and Anti-Erosion Works below 16th km Sombarey Hilley Road-Estimated Cost Rs. 51.49 lakhs

The works taken up during 1999-2000 had following main components besides a large number of small components.

a) Protection works at Bhalu Jhora at Bharang.

b) Training works at Basbotey Jhora at Rumbuk.

c) Jhora Training works at Maley Dunga, Siktam Tikapur.

d) Jhora training works at lower Siktam.

It is understood from the Panchayat members that the schemes had been formulated to protect the worst affected areas in consultation with them. Since, the area under this slip is large being of the order of 20 ha and required comprehensive protection measures, the various components of the scheme were planned as per the priorities decided by the Panchayat in consultation with the affected people taking into consideration the limited availability of funds. The Panchayat and local people were fully involved in the implementation of the scheme. More importantly, they participated in the process of tendering and award of work to the contractors and construction supervision.

The works at Bhalu Jhroa (Bharang) and Basbotey Jhora, which were inspected, are as per the standard design of the state government. These are in the form of sausage walls in a total length of 300 m. The objective of the schemes is to protect the village *abadi*, road, plantations and agricultural crops. The works were taken up in December, 1999 and completed in October, 2000. These have stood two flood seasons and are in good condition. The works have provided the desired protection.

(ii) River Training Works at Kalej Khola, Dentam – Estimated cost Rs. 20.00 lakhs

Kalej Khola has a wide channel with rocky outcrops and boulders in the bed and the banks. Above the rocks and boulders, the hill slope is steep with an angle of about 60°. The hill slope is composed of friable material which is mainly a matrix of silty clay, boulders and rock fragments.

During low floods, the Khola banks are well protected by the armour of rock and boulders, but during medium and high floods the toe of the hill gets eroded leading to land slides. The problem is further aggravated due to erosion of the hill slopes by two Jhoras which outfall into Kalej Khola. One of the Jhoras has since been channelised and trained by the Forest Department and the other by the Irrigation & Flood Control (I&FC) Department under funding from NABARD. However, due to toe erosion by the Khola, the hill slope was slowly sinking in an area of about 20ha. As a result, the Dentam-Uttaray and Pelling-Dentam roads were under serious threat. Besides, the cash crops of cardamom on the hill slopes was also getting damaged. The protection works in the form of plum concrete walls and sausage walls have effectively arrested the land slides/sinking.

2.9.4.3 *North Sikkim*

(i) Jhora Training Works at Bojoghari- Estimated Cost Rs. 24.40 lakhs

The Jhora passes through the rural habitation of Bojoghari. In recent years, the Jhora has eroded its banks causing damage to the local habitations and Indira Byepass road. The threat to the road is serious since it is also used by the army. The total length of the sliding area is about 300 m. The Jhora has, therefore, been trained in a length of 300 m above the road.

The works constructed under the schemes are PCC wall on the sides and cement concrete lining in the bed. The structure has stood the floods of 2000 and 2001 except for some damage to the concrete lining in the bed. The works are generally in good condition and have arrested the landslide/sinking of the hill slope.

(ii) AEW/JTW/CWD at Kabi Tingda - Estimated Cost Rs. 14.00 lakhs

The area of Rongdong- Tumlong village is under threat of landslide/sinking due to toe erosion of hill slope by a local stream. The hill slope has a large number of habitations of the village. The erosion is posing threat to some houses, lines of communication, cardamom plantations and agricultural fields. The length of the sliding zone is about 200 m.

To protect the village habitation, the I&FC department has constructed the works under seven different estimates as follows:

i) Catch Water drain and anti-erosion works at Phodong- Rs. 2.18 lakhs
ii) Catch Water drain and anti-erosion works at Kyonghu, Phodong- Rs. 0.54 lakhs
iii) Catch Water drain and anti-erosion works at Phodong- Rs. 0.99 lakhs

iv) Catch Water drain and anti-erosion works at Yongyong- Rs. 1.42 lakhs

v) Renovation of Fauji Jhora- Rs. 2.50 lakhs

vi) Protection Works and catch water drain at Lapsi Dara- Rs.2.49 lakhs

vii) River training works at Longbu in Kabi- Rs. 3.51 lakhs

These works are said to be scattered over a large area and are said to have been taken up on the specific request of the Panchayats. The work mentioned at S. No. (vi) was randomly chosen for evaluation.

The hill slopes in the vicinity to Kabi Tingda village have poor drainage. Because of meager vegetative cover, the monsoon runoff has carved out numerous rills and gullies. A local Jhora is also eroding its banks. As a result, the village habitations including the development works done by the Rural Development Department are under serious threat of damage. In order to provide immediate protection, the I&FC Department has built a catch water drain and Jhora training works. These works costing Rs. 2.5 lakhs have afforded benefits to a population of about 450.

(iii) Jhora Training Works of Rafong Khola at Mangan- Estimated Cost Rs. 73.00 lakhs

Rafong Khola is a large hill stream which passes through the marketing centre of Mangan town. The Khola has high banks on either side with large number of residential and commercial building on them. The Khola has a zig zag course with large out crops of rock in the bed. As a result, the high monsoon flow gets deflected from one bank to the other causing severe erosion. In recent years the erosion has been particularly severe and is threatening the township, especially the strategic lines of communications and various public utilities like the water, pipes and sewer lines.

The I&FC Department has taken up the training of the Jhora. The works are in the nature of sausage work in bed and bank with concrete lining. The works were completed only after the flood season of 2001.

2.9.4.4 *East Sikkim*

(i) Jhora Training Works and Catch Water Drain Near Rumtek School - Estimated Cost Rs.40.50 lakhs

There are two prominent Jhoras one each on either side of the school at Ramtek. The two Jhoras join below the school. In recent years, the Jhoras have eroded their banks causing damage to some of the school buildings. The primary school building located at a lower level has been badly damaged and is presently not in use.

In order to protect the school, the I&FC Department has trained the Jhoras. The works are in the nature of sausages in the bed and banks with 10 cm thick cement concrete lining. Besides, hill slope protection work has been done with sausage walls in one or two steps depending upon the height of the slope considered prone to sliding.

The Jhora training and slope protection works have prevented the erosion and sinking of the hill slope and thereby prevented further damage to the school buildings. Stabilisation of the hill slope has facilitated construction of an irrigation channel. The school authorities and the villagers have expressed satisfaction as to the utility and benefits of the scheme.

(ii) Jhora Training Works at Lower Sichey - Estimated Cost Rs.19.63 lakhs

The works under this estimate have the following three main components.

1. JTW below tri-junction of Sichey Ranka at km 13 (Namgay Jhora).
2. Catch Water drain and protective works below IBP at lower Sichey (Near Mandir)
3. Anti erosion works below IBP at lower Sichey.

First of the above three components was randomly chosen for evaluation study.

The Namgay Jhora crosses the Ranka Sichey road at 4 places. The scheme in question is located between the second and third loops of the road (km 12 and km 13). Due to the fast pace of urbanisation on both sides of the Jhora and extensive drainage improvement works taken up in the town, the Jhora discharge is said to have increased many fold in recent years. As a result, the Jhora is threatening the urban habitations on either side especially the road and other public utilities.

In 1999-2000, the I&FC Department carried out the training of the Jhora between 12 km and 13 km of the road. The works are in the form of 265 m of PCC wall and 380 m of sausage wall. The works have stood the floods of 2001 and are in good condition.

CHAPTER - 3

GLACIERS

3.1 HIMALAYA AND GLACIERS

Himalayan snow and glaciers are apex natural water resource reservoirs and release large quantity of freshwater year round. In Himalaya, it is roughly estimated that the 10-20% of the area is covered by glacier ice while an additional area ranging from 30-40% by seasonal snow cover. Himalayan glaciers (including Tibet) cover around 100,000 km^2 of geographical area. These fields store about 12000 km^3 of fresh water. These enormous snow and ice fields have a significant cooling affect on their immediate neighbourhood and the region as a whole. Some studies indicate that their cooling extends globally. The icy conditions in the Himalaya rival those existing in polar regions and therefore, it is sometimes referred as a 'third pole'. Thus, the extensive Himalayan snow and ice fields act as a great refrigerator, cooling the earth's environment.

The account of glaciers and glacial lakes given in this report is based upon inputs from a number of similar studies done by other institutes like ICIMOD, GSI, RRSSC (Nagpur) and work of Bahadur (2004). In addition to these studies, an attempt was made at CISMHE separately to study glacial hazards which was supplemented with extensive field work.

3.1.1 Glaciers

Glaciers are rivers of ice and are dynamic systems sensitive to their surroundings and constantly change their shape and form. Glaciers are classified based on various criteria e.g. morphological (area-altitude), thermal (polar, temperate and sub-polar) and dynamic (active – maritime) environment at low latitudes and passive - high latitude or in continental environment.

3.1.2 Glacial Movement

A glacier is a huge flowing ices mass. The flow is an essential property in defining a glacier. Usually a glacier develops under conditions of low temperature caused by the cold climate, which in itself is not sufficient to create a glacier. There are regions in which the amount of the total depositing mass of snow exceeds the total mass of snow melting during a year in both the polar and high mountain regions. A stretch of such an area is defined as an accumulation area. Thus, snow layers are piled up year after year in the accumulation area because of the fact that the annual net mass balance is positive. As a result of the overburden pressure due to their own weight, compression occurs in the deeper snow layers. As a consequence, the density of the snow layers increases whereby snow finally changes to ice below a certain depth. At the critical density of approximately 0.83g cm^{-3}, snow becomes impermeable to air. The impermeable snow is called ice. Its density ranges from 0.83 to a pure ice density of 0.917g cm^{-3}. Snow has a density range from 0.01g cm^{-3} for fresh snow layers just after snowfall to ice at a density of 0.83g cm^{-3}. Perennial snow with high density is called firn. When the thickness of ice exceeds a certain critical depth, the ice mass starts to flow down along the slope by a plastic deformation and slides along the ground driven by its own weight. Lower the altitude, the warmer the climate. Below a critical altitude, the annual mass of deposited snow melts completely. Snow disappears during the hot season and may not accumulate year after year. Such an area in terms of negative annual mass balance is defined as an ablation area.

A glacier is divided into two such areas, the accumulation area in the upper apart of the glacier and the ablation area in the lower part. The boundary line between them is defined as the **equilibrium line** where the deposited snow mass is equal to the melting mass in a year. Ice mass in the accumulation area flows down into the ablation area and melts away. Such a dynamic mass circulation system is defined as a glacier. A glacier sometimes changes in size and shape due to the influence of climatic change. A glacier advances when the climate changes to a cool summer and a heavy snowfall in winter and the monsoon season. As the glacier advances, it expands and the terminus shifts down to a lower altitude. On the contrary, a glacier retreats when the climate changes to a warm summer and less snowfall. As the glacier retreats, it shrinks and the terminus climbs up to a higher altitude. Thus, climatic change results in a glacier shifting to another equilibrium size and shape.

The movement of glaciers is due to internal flow of ice and its slippage over its bedrock. Normally they move a few centimeters per day. Warm glaciers move more rapidly as compared to cold glaciers. Increase in velocity results in extending flow and the glacier advances and thins while a decrease in velocity leads to compressive flow and glacier shrinks and thickens. Some glaciers surge due to a large and rapid increase is basal slip.

Glacial mass balance is mainly controlled by changes in a relatively thin ice layer (zone of accumulation and ablation). A positive mass balance results in glacier advance while negative mass balance results in glacier retreat. The glacier advance and retreat modify landscape. It is controlled by pressure, temperature and other micro-meteorological elements e.g. radiation, relative humidity, evaporation and wind direction. Observations on mass balance are required for several years for a representative value for any engineering venture.

3.1.3 Glacial Erosion

Glacier erosion takes place due to abrasion and bodily moving rock fragments in the glacier mass. Direct evidence of erosion on bedrock is in the form of striae, grooves, smoothing, rounding and sharp truncation of internal rock structure. Large scenic features e.g. U-shaped and hanging valleys, glaciers steps, excavated lakes, etc. Undercutting of steep slopes takes place by glacier sapping and glacier milling takes place by circulation of melt-water in the glacier crevasses and depressions.

Glaciers have enormous capacity to transport rock debris. Generally sediments move slowly with speed of 1m/d in ice mass but transport over glacier margin, debris flow, running water and wind operate at much faster speed.

Depositional features, moraines, erratics outwash plains and trains, ground moraine sheets, drumlin and various ice content features e.g. Kettle holes, kames and esker. Glacio-aeolian deposits include sand dune sheets and mantle of loess (dust). Glacial lake deposits are used for dating palaeo-environment. Glacier lake outburst floods occur due to breaking of moraine or glacier dammed lakes.

3.1.4 Classification of Glaciers

Himalayan glaciers are generally classified as longitudinal or transverse glaciers. Longitudinal glaciers occupy structural valleys, along low gradient slopes (6:1 or less) while the transverse glaciers originate from small depressions and flow along steep slopes (gradient 2:1).

Glaciers in Western Himalaya receive more winter accumulations due to westerly disturbances while those in Eastern Himalaya receive more nourishment from the summer monsoon. In the Western

Himalayan region, the average annual winter precipitation is about 80% and 20% in summer season creating arid to semi-arid conditions. The situation reverse in Eastern and North-Eastern region where the average precipitation is 20% in winter and 80% in summer, resulting in humid and per-humid conditions. The annual glacier melt is about 50 percent in the west, which decreases to about 10 percent in the northeast region.

Rivers with large glaciers areas are less susceptible to the effects of drought or excessive flooding due to the self regulating mechanism of glacier systems as the glaciers release more water during dry-hot year as compared to a wet-cold year due to more incident solar radiation.

3.2 RECESSION OF GLACIERS

The recession of glaciers is linked up with the warming of the earth's climate. During Pleistocene (about 2 million years ago), the glaciers occupied about 30% of the total area of the earth as against 10% at the present. The data on Himalayan glaciers is not sufficient to produce a maximum ice surface reconstruction or to resolve the Pleistocene glaciation. It is now well known that the climatic changes lead to repeated glaciations. The most recent glaciation reached its maximum advance about 20,000 years ago when the Himalayan snow line was depressed from 600 to 1,000 meters lower than the present elevation due to fall of temperatures by 5 to 8°C. Global warming has already caused a significant glacier ice loss since the Little Ice Age (AD

1,550-1,850) resulting in both glacier retreat and thinning (loss of ice volume). Catastrophic natural processes triggered by these glacier changes were responsible for considerable death and destruction throughout the mountains. These processes included ice avalanches, landslides and debris flows, outbursts from moraine-dammed lakes and also outbursts from glacier dammed lakes. Glacier avalanches have occurred where glaciers have retreated up steep rock slopes. Landslides caused by debutressing due to glacier thinning lead to rapid, mobile rock avalanches and non-catastrophic slope deformation. Sources of debris flows are frequently moraine complexes exposed during glacier retreat, which also may be ice-cored. Outbursts from moraine dammed lakes result from the catastrophic breaching of the moraine dam - a process which is commonly initiated by glacier avalanches - generated waves that overtop the moraine. Himalayan and Trans-Himalayan glaciers are in general state of retreat since AD 1,850. The average rate of retreat ranges from less than 4 m/yr to more than 40 m/yr depending upon location and the type of the glacier.

Glaciers are always active and their activity generates a lot of fresh water and sediments. Over a period of time their erosional and depositional landforms generate spots of great scenic beauty and attraction to mankind. At times they generate huge natural hazards, scaring and distressing all life forms. As the infrastructural facilities increase in the mountain settlements, the mountain hazards damages also increase. Therefore, there is need to monitor high altitude glaciated region to understand the natural processes and the magnitude of natural hazards, for mitigation measures. Suitable blends of traditional and modern concepts are needed, so that loss could be minimised and more harmonious environmental conditions are created in the mountains. This becomes even more important when global warming due to greenhouse effect is knocking our doors and our present scientific knowledge of glacier - climate relationship is insufficient to address the effect and consequences of these climate changes on the high terrain.

3.3 GLACIAL STUDIES IN SIKKIM

Sikkim is a fully mountainous state of India, where the entire land is in the form of rugged terrain including mountains and hills. The central and northern mountain sectors are steeper than the southern sector. The state is vulnerable to landslides and river erosion due to great elevation differences, steeply sloping terrain, and fragile geological conditions. In addition, the watersheds of the state are covered by some major glaciers and glacial lakes, which are quite susceptible to disastrous hazards due to Glacial Lake Outburst Floods (GLOFs). The glaciers, some of which consist of a huge amount of perpetual snow and ice, are found to create many glacial lakes. These glaciers as well as glacial lakes are the sources of the headwaters of two main rivers in the region, e.g. the Teesta and the Rangit rivers. The glaciers and glacial lakes of in Sikkim Himalaya are nature's renewable storehouse of fresh water that benefits hundreds of millions of people downstream. Lakes at elevations higher than 4,000 m are considered as glacial lakes. Most of these lakes are located in the down valleys close to the glaciers. They are formed by the accumulation of vast amounts of water from the melting of snow and ice cover and by blockage of end moraines. The sudden break of a moraine dam may generate the discharge of large volumes of water and debris causing disastrous floods downstream.

For the inventory of glaciers and glacial lakes, the methodology used as per adopted by Mool *et al*. (2001a, b), and also based on the research study carried out by the Temporary Technical Secretary (TTS) for the World Glacier Inventory (WGI) of the Swiss Federal Institute of Technology (ETH), Zurich (Muller *et al.* 1977 and the World Glacier Monitoring Service [WGMS] 1989) and ICIMOD (2004).

3.4 OBJECTIVE OF THE STUDY

The main objective of the current study was to establish an inventory of database on glaciers/glacial lakes and change due to global warming affecting potential glacial lake outburst floods (GLOFs) and associated hazards. The database would be very useful for planning and also to establish GLOF hazard monitoring and early warning systems for environmental risk mitigation.

3.5 GLACIERS

The glaciers are concentrated in the northwest and northeast extremes of the state. The perpetual snow line is found above 5,300 m. A number of glaciers descend from the northeastern slopes of Mt.

Khangchendzonga into the Sikkim Himalaya in North and West Sikkim. The glaciers in the northwest section are mostly valley glaciers and have long dimensions, whereas the glaciers in the northeastern section are small and isolated in the form of mountain glaciers. The longest one is Zemu glacier, which covers 133 sq km which accounts for more than 30% of the glaciers of the state and extends down to 4,000 m from Mt. Khangchendzonga. On the basis of satellite images of 1987 to 1989, Kulkarni and Narain (1990) reported that the glacier cover an area of about 426 sq km in the Sikkim Himalaya.

3.6 GLACIAL LAKES

As Sikkim Himalaya is characterized by of rugged terrain and steep sloping high mountains without flat plains, the occurrence of lakes on such a rugged terrain is least expected. However, the Sikkim Himalaya harbours a number of lakes even though their sizes are not very large. These lakes are fed by spring, river, as well as glacial melt water. There are altogether 180 perennial lakes reported in different altitudes. Some of them are of glacial origin. The details of the lake origin are still unknown. Among the lakes, some of the lakes are important from the view of tourist and recreational value. On the Gangtok – Nathu La highway, 34 km from Gangtok, lies the Chhangu (Tsomgo) Lake at an altitude of about 3,660 m in East Sikkim, Khecheopalri lake is another well known lake that lies on a bifurcation of the route between Gyalzing and Yuksom in West Sikkim. Menmoi Chho, Green lake, and Samiti lake are some of the other beautiful lakes.

3.7 DATA USED AND METHODOLOGY

The basic materials required for the compilation of an inventory of glaciers and glacial lakes are Survey of India topographic maps at 1:50,000 scale and satellite images of different dates. In the present study, mainly, the satellite images of the land observation satellites (Landsat-4, 5 & 7), thematic mapper (TM) and enhanced thematic mapper (ETM+), and the Indian Remote Sensing satellite series 1D (IRS-1D) and Linear Imaging and Self-scanning Sensor (LISS-3) and panchromatic sensor (PAN) of different dates were used to study the activity of glaciers and for the identification of potentially dangerous glacial lakes (Table 3.1). The combination of digital satellite data and the Digital Elevation Model (DEM) of the area created from the digitized contours from topographic maps of 1:50,000 were used for better and more accurate results for the inventory of glaciers and glacial lakes.

Table 3.1 Database used for landuse/ landcover mapping of Teesta basin

Satellite	Sensor	Path/Row	Date	Data type & Bands
IRS-1C	LISS-II	107/051	Nov., 1990	Digital (1,2,3,4)
IRS-1D	LISS-III	107/051	19.01.2000	Digital (2,3,4,5)
IRS-1D	PAN	107/052	30.11.1999	Digital (A0)
IRS-1D	PAN	107/052	13.01.2002	Digital (B0)
IRS-1D	PAN	107/052	30.11.1999	Digital (C0)
IRS-1D	PAN	107/051	13.01.2002	Digital (D0)
LANDSAT	TM	139/41	10.11.1989	Digital (1,2,3,4)
LANDSAT 7	ETM+	139/41	26.12.2000	Digital (1,2,3,4,5,7)
LANDSAT 7	PAN	139/41	26.12.2000	Digital

3.7.1 Topographic Maps

The entire state of Sikkim is covered by the 20 topographic maps published by the Survey of India. The index numbers and location of the topographic maps of the period from 1950s to 1970s are given in the Table 3.2.

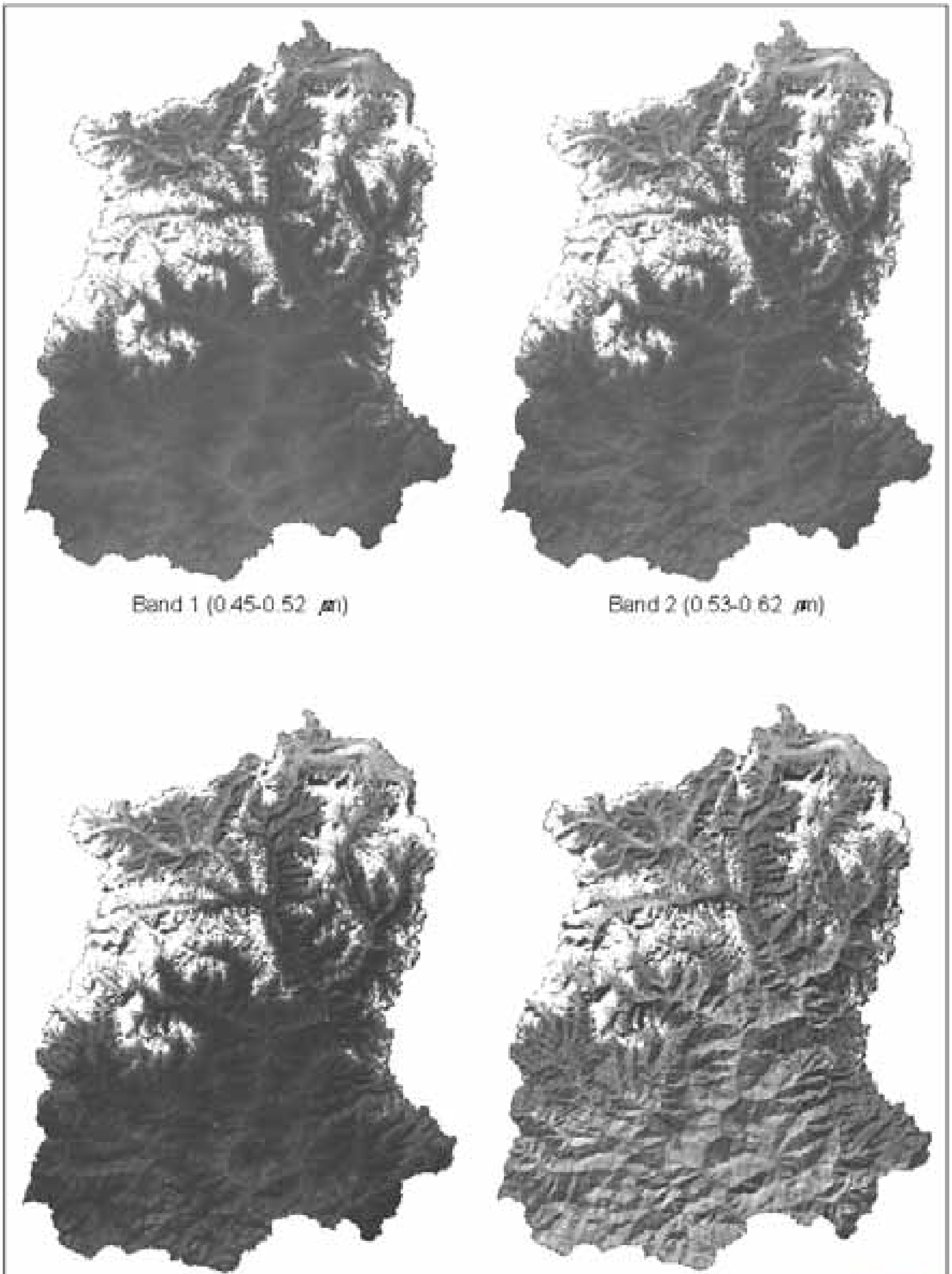
Table 3.2 List of used topographic maps published by the Survey of India

Grid number	Sheet No. (total 20 sheets)
77D	4, 8, 12 and 16
78A	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16

The topographic maps mentioned in the Table 3.2 were used as a base maps to georeference the satellite images.

3.7.2 Satellite Images

The whole of Sikkim State is covered by a single image of Landsat-7 ETM+ of Path 139 and Row 041. The Landsat- 7 ETM+ image scene has the facilities of 7 bands and one panchromatic scene. The scene were viewed individually or in a combination of 3 bands at one time for the identification of clean glacier, debris glacier, lakes, etc. Sikkim state is covered in Path 107 and Row 51 and 52 of IRS-1D LISS-III one full scene and four PAN full scenes (A-D). The digital format resample, in 5.6 m-pixel size, IRS-1D PAN data have been used for the study after merging PAN scene with LISS-3 scene. Different bands (1-7) of Landsat-7 (ETM+) of December, 2000 are given in Figs. 3.1-3.3. Subsets and colour composites of different band combinations of



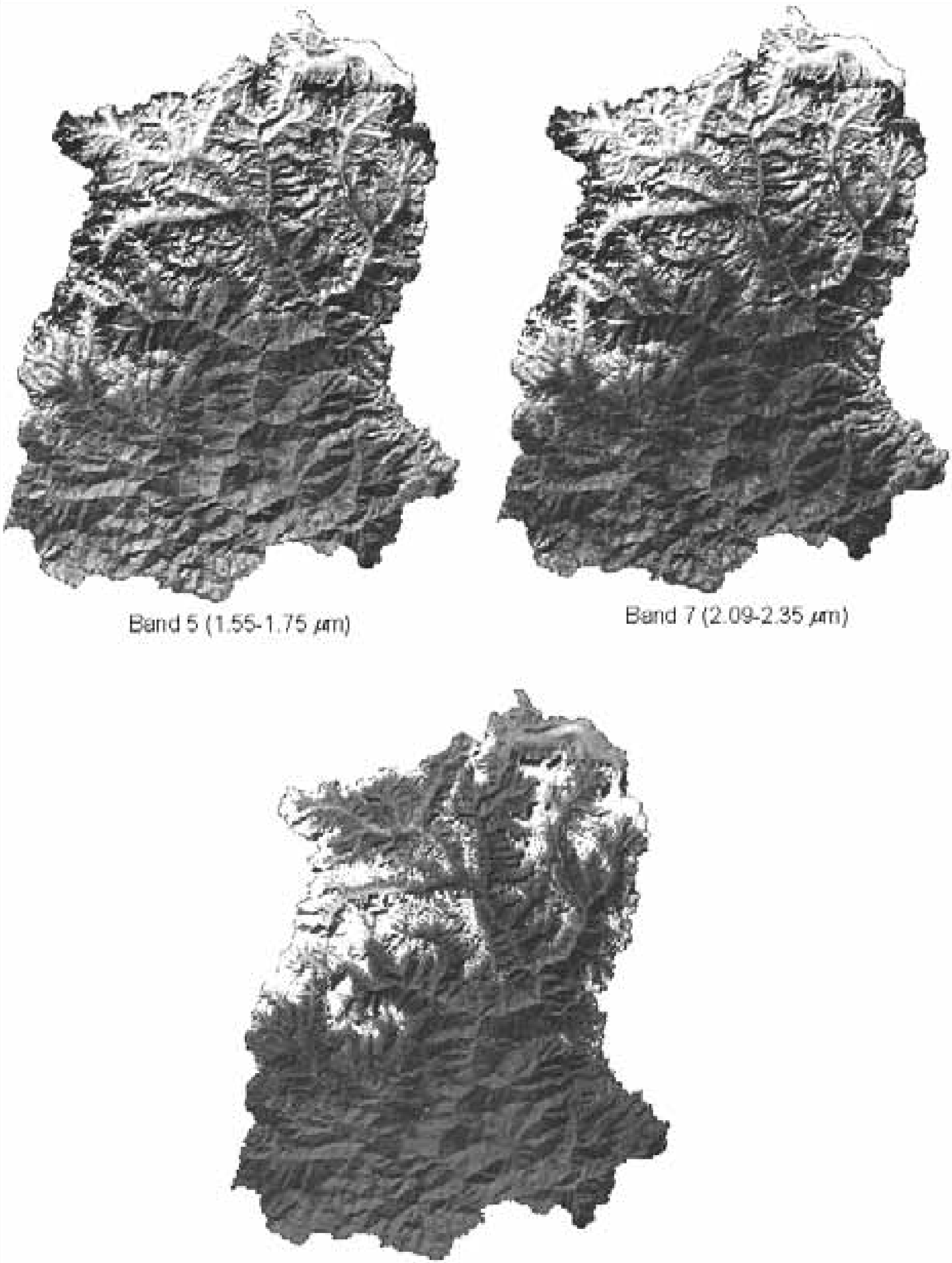
Band 1 (0.45-0.52 µm)

Band 2 (0.53-0.62 µm)

Band 3 (0.63-0.69 µm)

Band 4 (0.78-0.92 µm)

Fig. 3.1 Different bands of Landsat-7 (ETM+) of December, 2000



Band 5 (1.55-1.75 μm)

Band 7 (2.09-2.35 μm)

Band 8 (0.52-0.90 μm)

Fig. 3.2 Bands 5, 7 and 8 of Landsat-7 (ETM+)

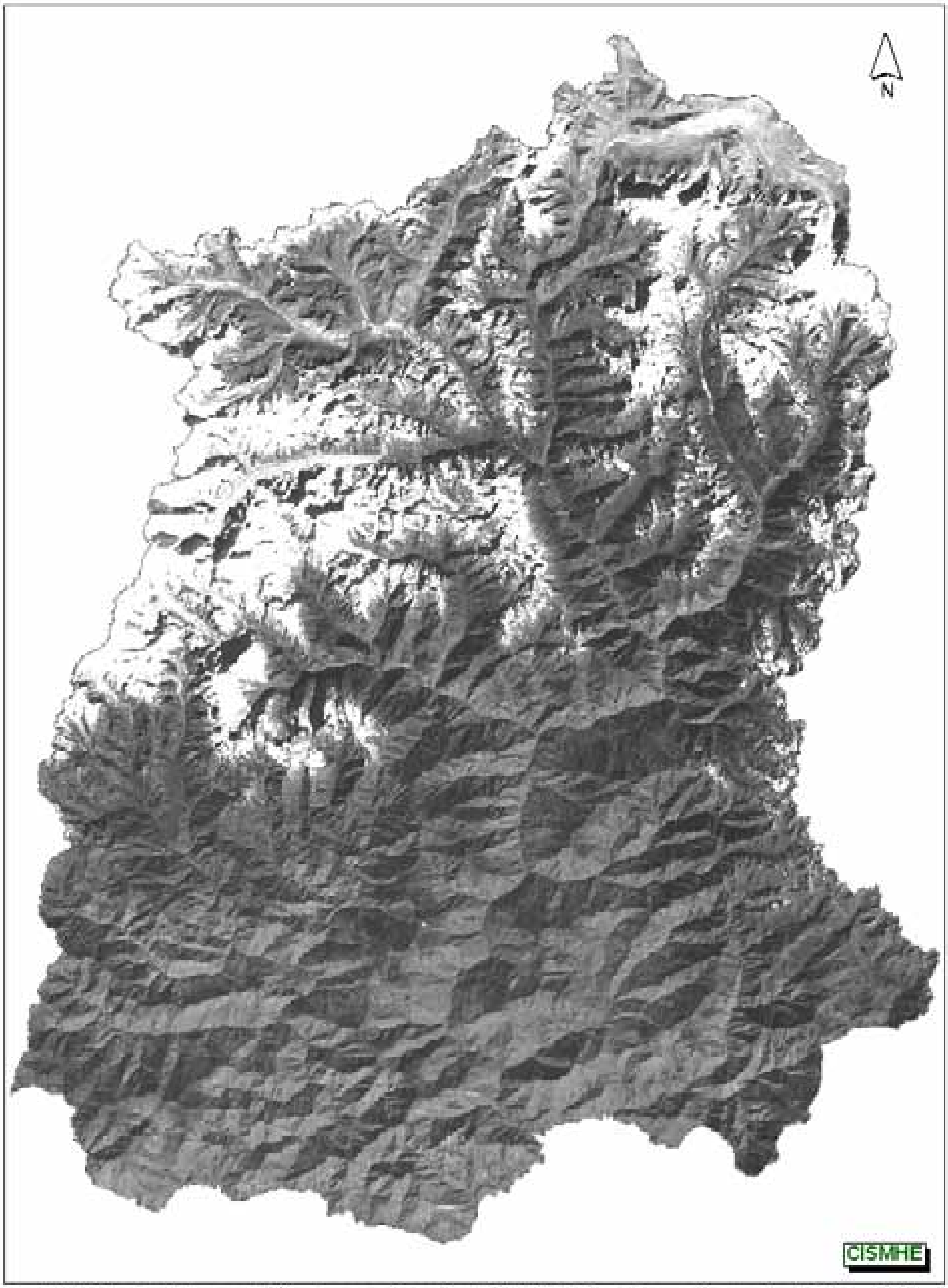


Fig. 3.3 Subset of the satellite image of landsat -7 ETM + Panchromatic mode of Dec., 2000 covering Teesta basin in Sikkim for the mapping of glaciers and glacial lakes

Landsat-7 ETM+ to identify the ice cover, debris and clear glacier, and glacial lakes are given in Figs 3.4 to 3.10.

3.8 INVENTORY OF GLACIERS

The glacier margins were delineated in the geo-referenced Landsat-7 ETM+ and IRS-1D PAN – LISS-3 merged scenes of IRS-1D and compared with other individual bands as well as in different color composite bands, and the exact boundaries between glaciers and seasonal snow cover were determined. No defined coding system was adopted, however, the later further studies would be based on the subordinate relation and direction of river progression according to the World Glacier Inventory. The descriptions of attributes for the inventory of glaciers are given below.

i) *Registration of snow and ice masses*

All perennial snow and ice masses above 5,300 m were registered in the inventory. Measurements of glacier dimensions are made with respect to the carefully delineated drainage area of different watersheds. Marginal and terminal moraines were also included if they contained ice. The ‘inactive’ ice apron, which is frequently found above the head of the valley glacier, was regarded as part of the valley glacier. Perennial snow patches of large enough size were also included in the inventory. Rock glaciers were included if there is evidence of large ice content.

3.8.1 Area of the glacier

The area of the glacier is divided into accumulation area and ablation area (the area below the firn line). The area was recorded in square kilometres. The delineated glacier area was digitized in the 'GeoMedia Professional 5.2 and the database was used to calculate the total area.

i) *Length of the glacier*

The length of the glacier was divided into three columns: **total length**, **length of ablation,** and the **mean length**. The total (maximum) length refers to the longest distance of the glacier along the centreline. The mean value of maximum lengths of glacier tributaries (or firn basins) is the mean length.

ii) *Mean width*

The mean width was calculated by dividing the total area (sq km) by the mean length (km).

iii) *Orientation of the glacier*

The orientation of accumulation and ablation areas is represented in eight cardinal directions (N, NE, E, SE, S, SW, W, and NW). Some of the glaciers are capping just in the form of an apron on the peak, which is inert and sloping in all directions, and is represented as 'open'. The orientations of both the areas (accumulation and ablation) are the same for most of the glaciers.

iv) *Elevation of the glacier*

Glacier elevation was divided into **highest elevation** (the highest elevation of the crown of the glacier), **mean elevation** (the arithmetic mean value of the highest glacier elevation and the lowest glacier elevation), and **lowest elevation**.

Fig. 3.4 Subset and colour composite bands 9(R), 3(G) and 2(B) of Landsat-7 ETM+ of 26 Dec 2000 to show the ice cover in the Zemu glacier

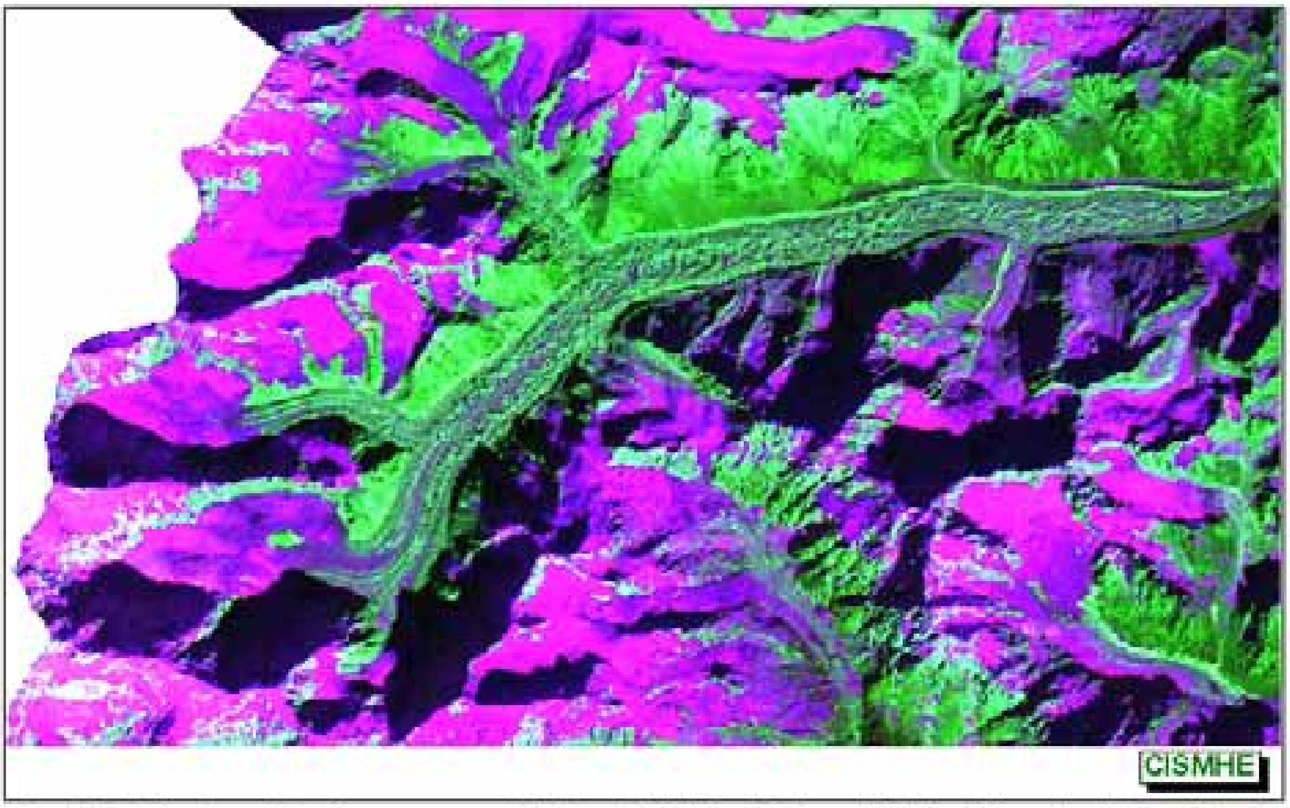


Fig. 3.5 Subset and colour composite bands 9(R), 8(G) and 2(B) of Landsat-7 ETM+ of 26 Dec. 2000 to show the debris and clean glacier including the supraglacial lakes in the Zemu glacier

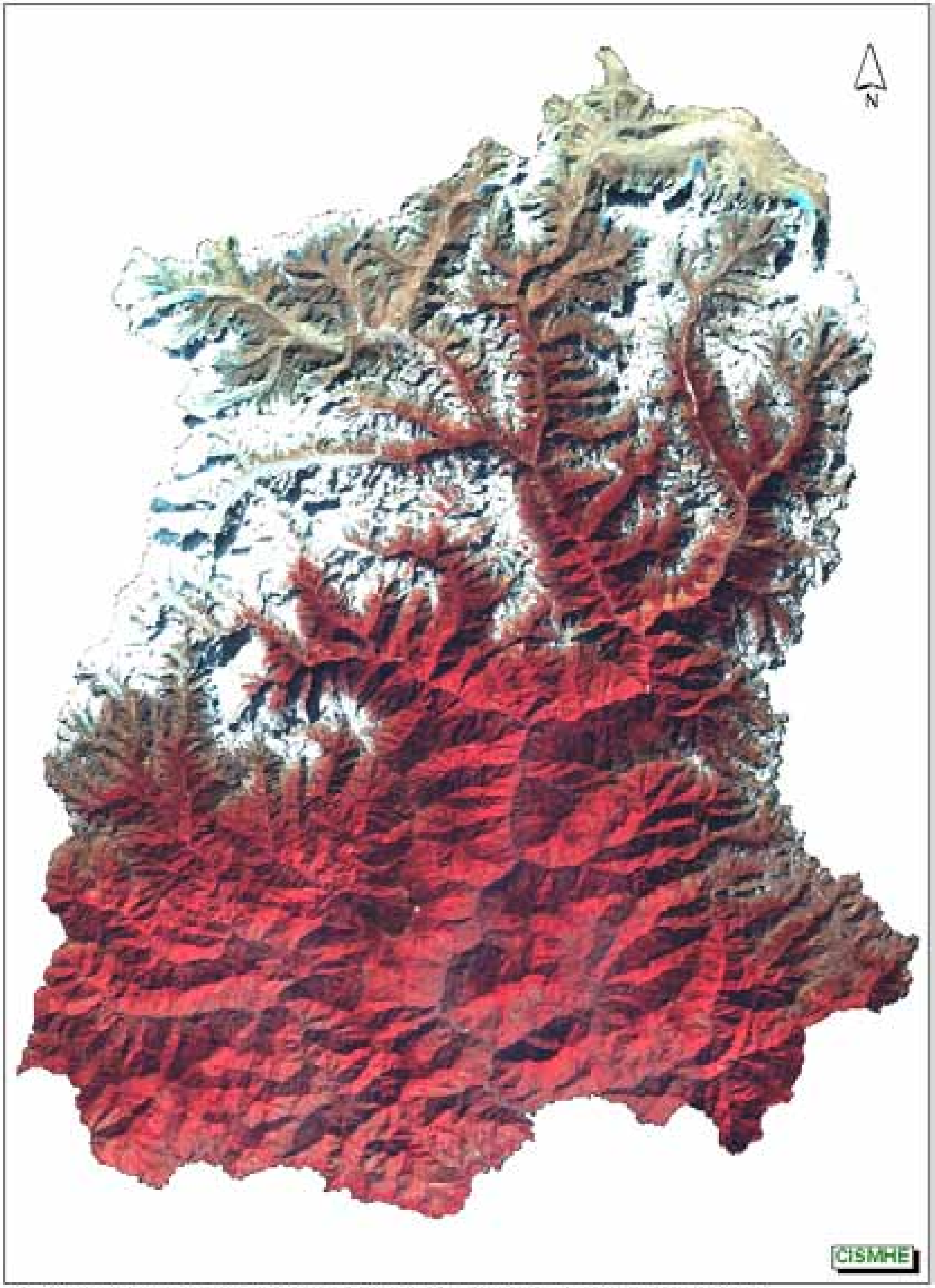


Fig. 3.6 False colour composite (bands 4, 3 and 2 of the Landsat-7 ETM +) of Teesta river basin in Sikkim

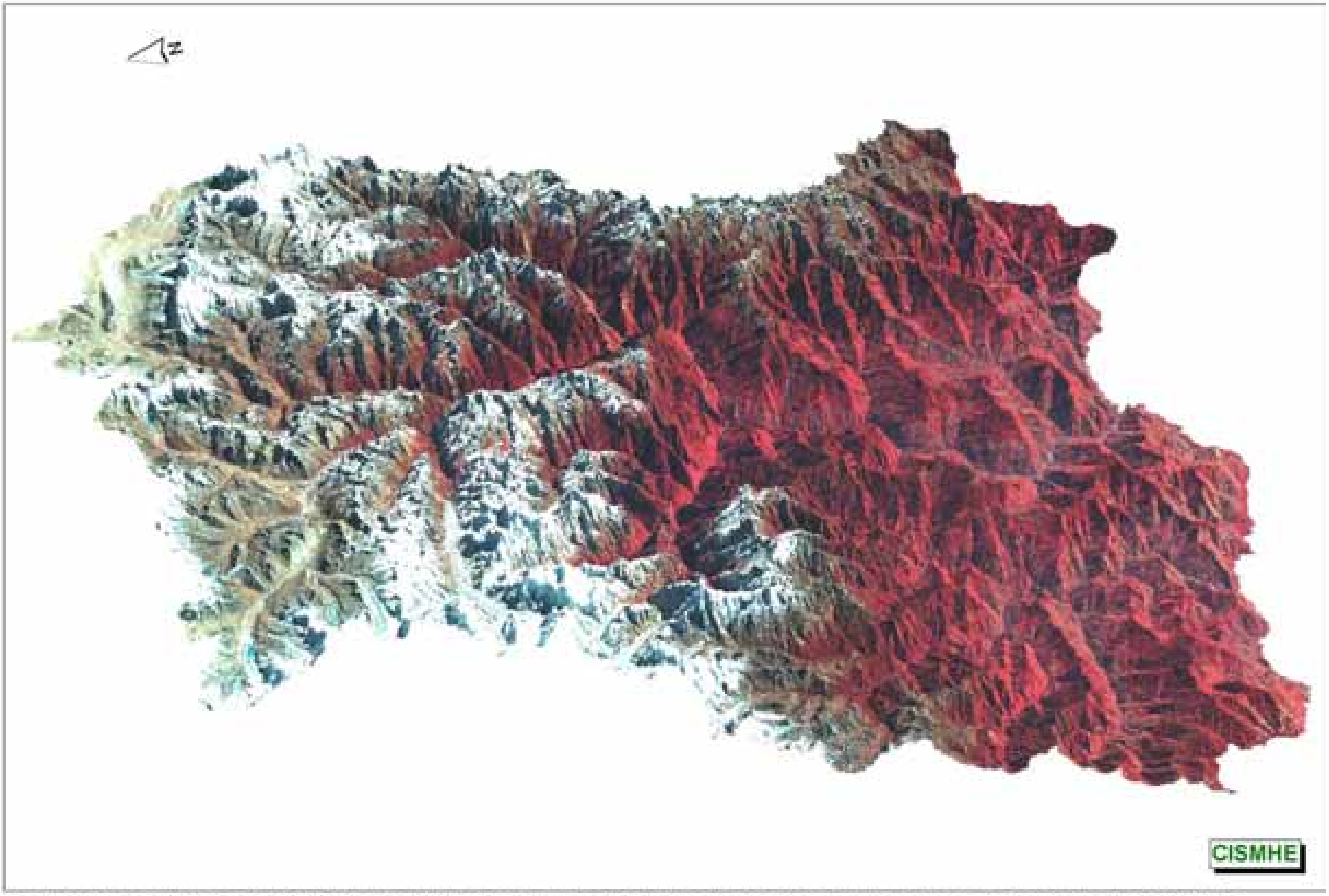


Fig. 3.7 Three-dimensional (3D) view, digital elevation model draped over the satellite image of Teesta basin in Sikkim

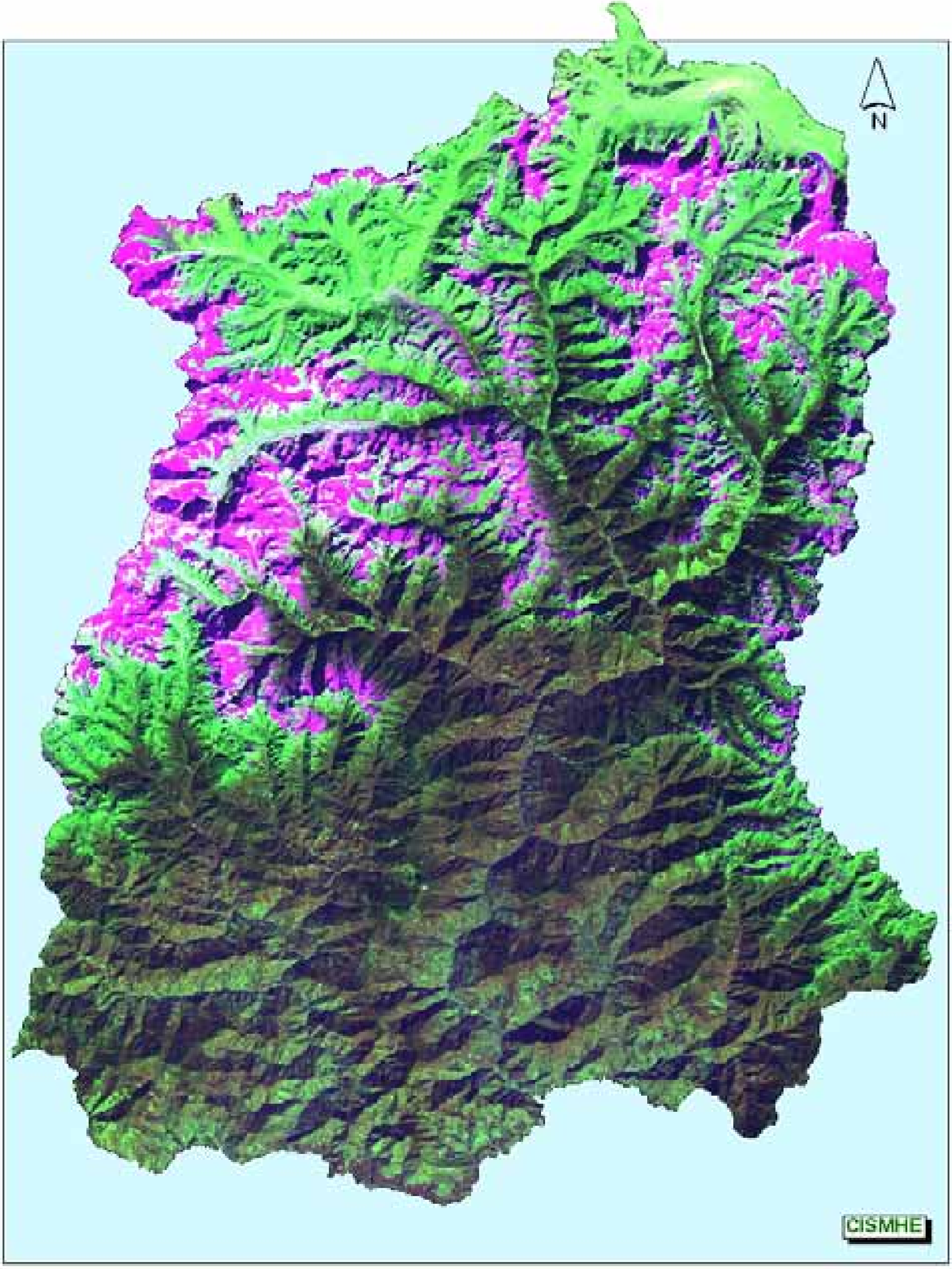


Fig. 3.8 Subset and colour composite bands 9(R), 8(G) and 2(B) of Landsat-7 ETM+ of 26 December, 2000 of the Sikkim

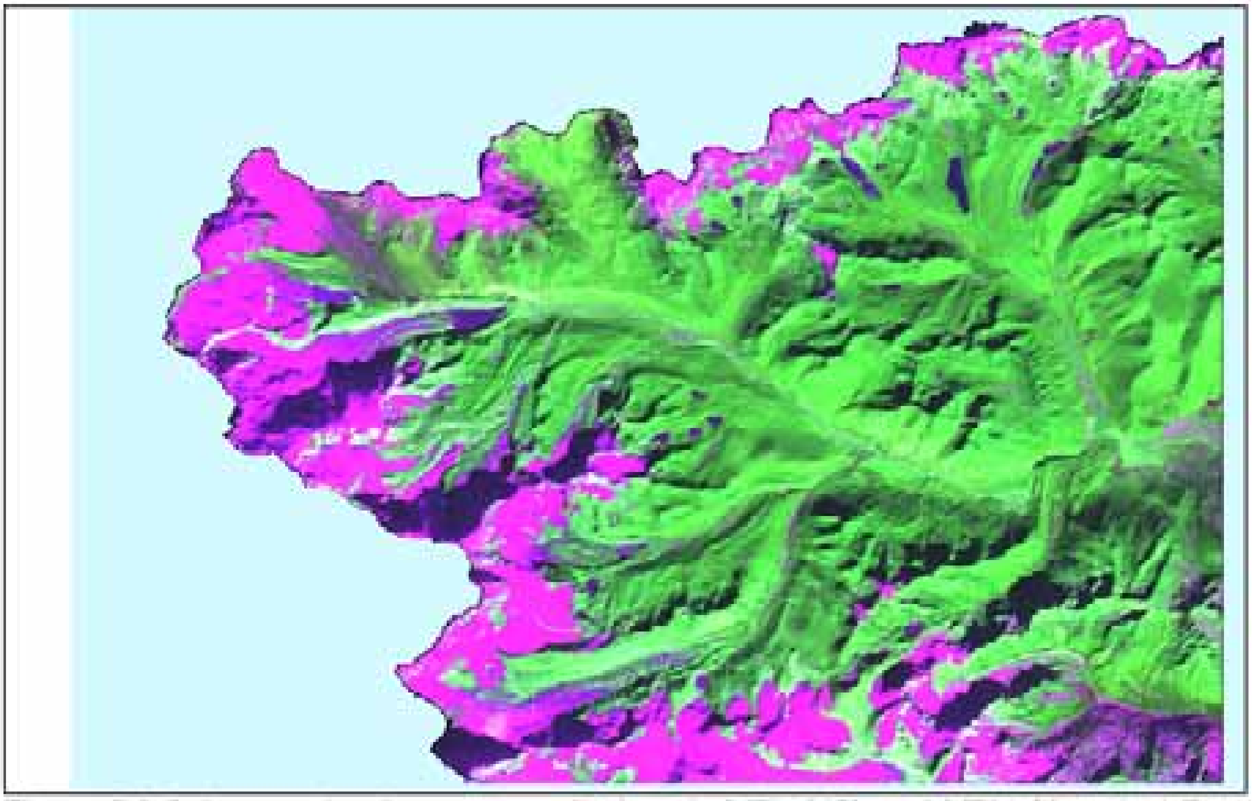


Figure 3.9 Subset and colour composite bands 9(R), 8(G) and 2(B) of Landsat-7 ETM+ of 26 Dec 2000 for the identification of glacial lake of the north-western part of the Sikkim

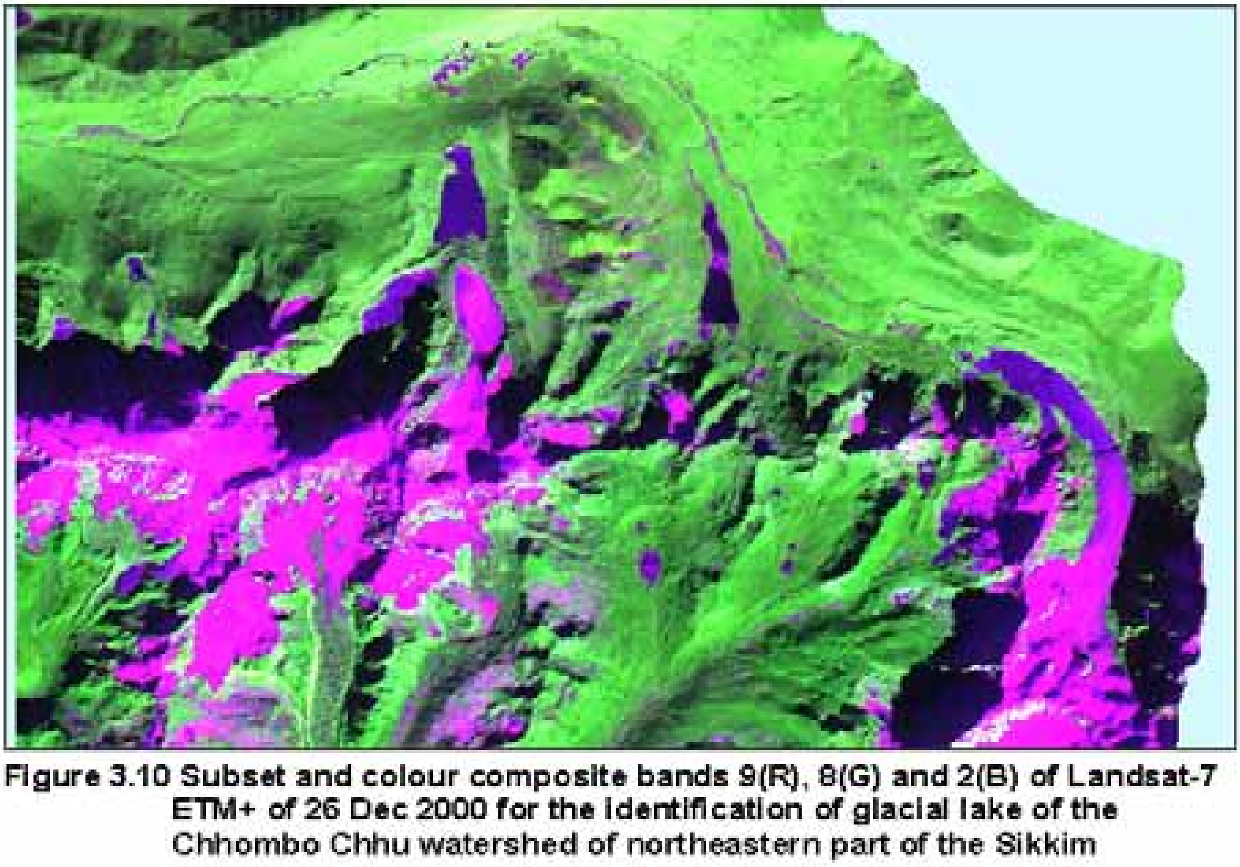


Figure 3.10 Subset and colour composite bands 9(R), 8(G) and 2(B) of Landsat-7 ETM+ of 26 Dec 2000 for the identification of glacial lake of the Chhombo Chhu watershed of northeastern part of the Sikkim

3.9 INVENTORY OF GLACIAL LAKES

The glacial lakes on satellite image of IRS-1D PAN scenes, Landsat-7 ETM+ of panchromatic mode and other individual bands of both IRS-1D and Landsat-7 ETM+ and different colour combinations were delineated and compared with other satellite images. All the glacial lake boundaries are demarcated by screen digitizing in the georeferenced satellite images of IRS-1D PAN scenes as well as Landsat-7 ETM+ PAN image.

Rapid melting of big glaciers due to global climate changes in the first half of 20th century has given rise to a number glacial lakes. In recent times, due to the faster rate of ice and snow melting, the accumulation of water in these lakes has been increasing rapidly. Therefore, the isolated lakes above 3,500m are assumed to be the remnants of the glacial lakes left due to the retreat of the glaciers.

The following characteristics of glacial lakes were recorded.

i) *Longitude and latitude*

Reference longitude and latitude are designated for the approximate centre of the glacial lake by creating a digital point map over the screen digitized glacial lakes.

ii) *Area*

The area of the glacial lake was determined from the digital database of the lake.

iii) *Length*

The length was measured along the long axis of the lake, and represented in metre units.

iv) *Width*

The width was calculated by dividing the area by the length of the lake, down to two decimal place in hectare units.

v) *Orientation*

The drainage direction of the glacial lake was specified as one of eight cardinal directions (N, NE, E, SE, S, SW, W, and NW). For a closed glacial lake, the orientation was specified according to the direction of its longer axis.

vi) *Altitude*

The altitude is registered by the water surface level of the lake in metre.

3.9.1 Classification of lakes

Genetically glacial lakes can be divided into the following.

i) **Glacial erosion lakes**, including cirque lakes, trough valley lakes, and erosion lakes

ii) **Moraine-dammed lakes** (also divided into neo end moraine and paleo end moraine lakes), including end moraine lakes and lateral moraine lakes

iii) **Blocking lakes** formed through glaciers and other factors, including the main glacier blocking the branch valley, the glacier branch blocking the main valley, and the lakes formed through snow avalanche, collapse, and debris flow blockade

iv) Ice surface and sub-glacial lakes

3.9.2 Stability Analysis

According to their stability, the glacial lakes are divided into three types: stable, potential danger, and outburst (when there have been previous bursts).

Glacial lakes are divided i.e. types of water drainage into drained lakes and closed lakes according to the drainage condition. The former refers to lakes from which water flows to the river and joins the river system. In the latter, water does not flow into the river.

One important index for evaluating the stability of a glacial lake is its contact relation with the glacier. So an item of distance from the upper edge of the lake to the terminus of the glacier has been added and the code of the corresponding glacier registered. Since an end moraine-dammed lake is related to its originating glacier, this index is only referred to end moraine-dammed lakes. As not enough field data exist, the average depth of glacial lakes is difficult to establish in most cases.

3.9.3 Types of Glaciers

Generally, six types of glacier were observed in the Sikkim Himalaya—mountain glaciers, valley glaciers, cirque glaciers, niche glaciers, ice caps, and ice aprons. The glaciers of uncertain or miscellaneous compound basins, compound basin, or simple basin in the form of a hanging glacier are considered as mountain glacier. The major source of nourishment is snow and/or drift snow. Mountain glaciers were dominant in distribution and the profile shows a hanging nature. Other glaciers, except the valley glaciers are also a mountain glacier, but differentiate as ice cap, cirque, niche, and ice apron. But the thickness of ice of these glaciers is comparatively low. The number of valley glaciers is comparatively low but the corresponding areas and ice reserves are higher than those of mountain glaciers. If a valley glacier continues up to a mountain glacier and is represented as a single unit, then this part of the mountain glacier is also considered a valley glacier. The area and ice reserves of the valley glaciers are generally large owing to the fact that the ice thickness increases with increase in the area of the glacier. Ice caps, cirque glaciers, niche glaciers, and ice aprons are other types of hanging mountain glaciers, but they are considered to be a different type due to their significance in size, shape, form, and ice thickness. The most significant valley type glaciers are fewer in number and characterized by compound basins, compound basin, and simple basin. They are mainly nourished by snow and drift snow at the headwaters and by snow and ice avalanches in the lower valley. The adjoining part of the valley glacier at the headwater is characteristically a mountain glacier, but due to its continuation into a valley glacier, the whole ice mass will be considered to be a valley glacier. Hence, the area of the valley glacier is higher than the mountain glaciers. The longitudinal profile of the valley glacier from crown to toe shows an even or regular shape. As the headwater is steeper and has a gentle slope in the lower reaches, the profile makes the curve concave upwards. Due to the gentle slope at the lower reaches and the accumulation of debris derived from the headwater, glacial lakes develop in a supra- glacial and moraine-dammed lake. The stability of such supra-glacial and moraine dammed glacial lakes is poor and there is always chances of avalanches from mountain glaciers, which may break the damming material and cause GLOFs.

3.10 GLACIERS OF SIKKIM HIMALAYA

The present inventory work is based on the IRS-1D LISS-3 scene, PAN A-D scenes and Landsat-7 ETM+ scenes (see Fig. 3.4 – 3.10). The glaciers of Sikkim Himalaya are distributed only in the upper reaches of the Teesta basin. The glaciers of the Sikkim Himalaya extend from the latitude of 27° 30’ to 28° 03’ 56” and the longitude of 88° 03’ 25” to 88° 53’ 26”. In all 271 glaciers could be delineated in the present study covering an area of 518.97 sq km with an approximate ice reserve of more than 60 km^3 (Table 3.3, Fig. 3.11). However, as per the studies of ICIMOD, there are 285 glaciers altogether covering an area of 576.433 sq km with an ice reserve of approximately 65 km^3 (Table 3.4). Similar on the basis satellite images of 1987-1989, Kulkarni and Narain (1990) reported that glaciers, cover an area of 426 sq km in Sikkim Himalaya, whereas GSI studies (1999) reported the presence of 449 glaciers covering an area of 705.54 sq km.

The glaciers of the Sikkim Himalaya are classified into Ice cap, Valley glacier and Mounatin glacier. The mountain glaciers are further classified into cirque, niche, and ice apron.

The number of mountain glaciers as per the recent studies of ICIMOD, is highest (170) and other types of glaciers are less in number as shown in the Table 3.3. For the classification of valley glaciers, the headwater region of the valley glacier is a mountain glacier, while the adjoining mountain glacier with a valley glacier is considered to be a valley glacier. Hence the aerial extension of the valley glacier is very high compared to other type of the glaciers as shown in the Table 3.3. The ice caps, ice aprons, cirque glaciers, and niche glaciers have small aerial extension with a thin ice sheet or ice thickness. The aerial extension of these mountain glaciers are around 1% and the ice reserve contributed by these glaciers are less than 1%. The glaciers on the mountain slopes with the forms of miscellaneous, simple basin, compound basin, and compound basins are higher in number and cover 161.67 sq. km of around 28%. The ice reserves contributed by these glaciers are almost 14% in the Sikkim Himalaya (see Table 3.4).

The area occupied by the mountain glacier is generally high in comparison to the other forms of mountain glacier. Again the area

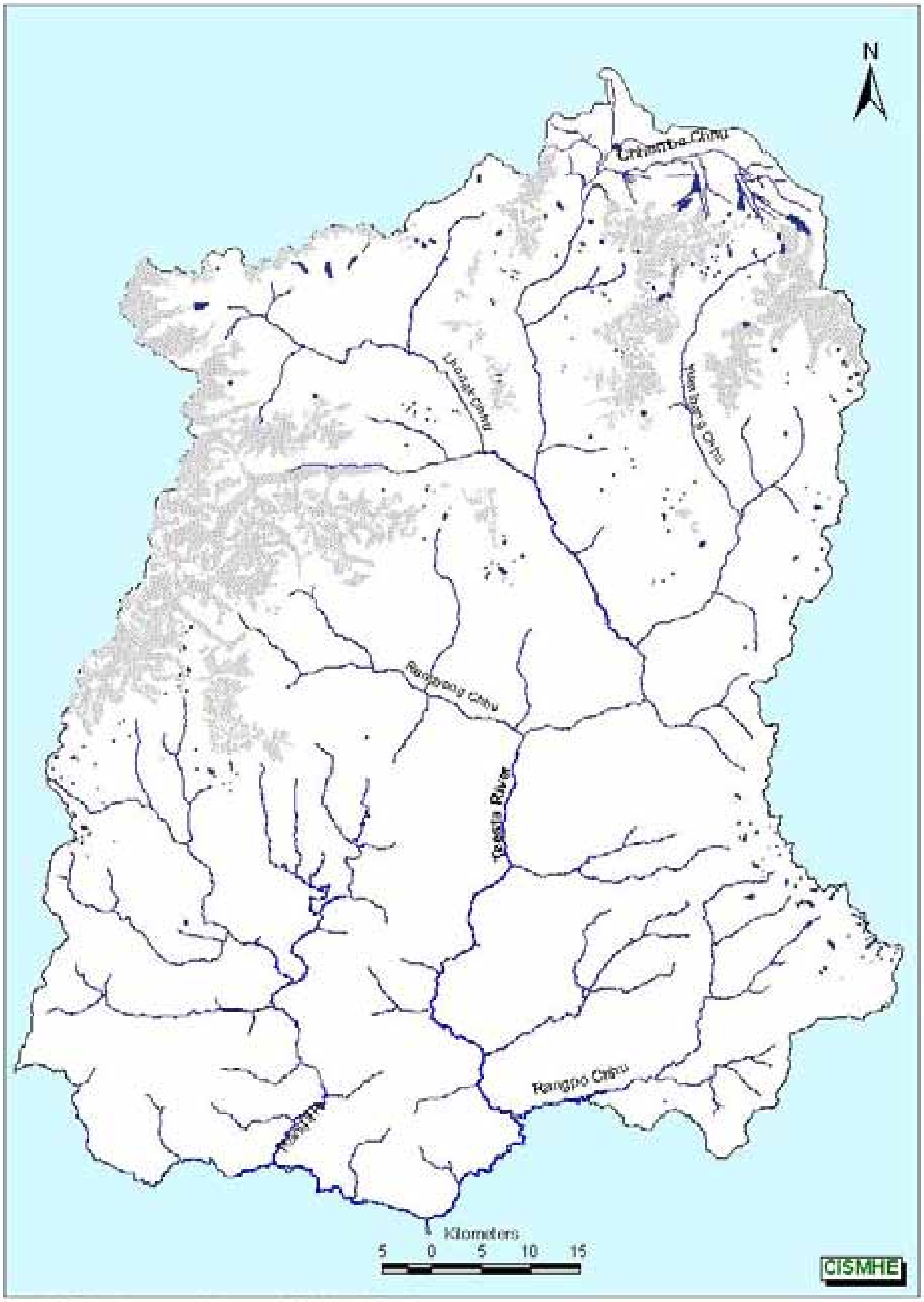


Fig.10 Glaciers and lakes of Sikkim Himalaya

occupied by valley glaciers (68.65%) is quite high due to the addition of the adjoining parts of the mountain glaciers. The valley glaciers cover about 395.8 sq km with 68.65% of the ice reserve. Mountain glaciers cover about 28% of the area and have 13.63% of the ice reserve. Other types of glaciers cumulatively occupy 4% of the area and have less than 1% of the ice reserve.

Table 3.3 Glacier cover area inventory in Sikkim Himalaya

Organisation	Glacier cover (sq km)	No. of glaciers
CISMHE (2000-2002)	518.97	270*
CISMHE (SOI Toposheets – 1970s)	661.50	N.A.
GSI (1970s)	705.54	449
ICIMOD (2000)	576.43	285
RRSSC, Nagpur (1998)	667.18	N.A.
SRSAC, 2001	691.00	281*

*This includes glaciers as well as permanent snow fields

Table 3.4 Types of Glacier in the Sikkim Himalaya

Types of Glacier	Number		Area		Longest (km)	Shortest (km)	Ice reserve	
	Count	(%)	(sq km)	(%)			(km^3)	(%)
Mountain glaciers	170	59.65	161.67	28.04	8.57	0.02	8.8275	13.63
Niche glaciers	33	11.58	4.7	0.83	1.08	0.02	0.1168	0.18
Ice caps	25	8.77	6.27	1.09	1.18	0.04	0.1885	0.29
Valley glaciers	22	7.72	395.80	68.65	107.31	3.47	55.4176	85.55
Cirque glaciers	18	6.32	3.15	0.55	0.72	0.03	0.0766	0.12
Ice aprons	17	5.96	4.85	0.84	1.02	0.03	0.1525	0.24
Total	**285**		**576.51**				**64.7795**	

Source: ICIMOD

The Geological Survey of India - 1999 studied the glaciers of the Sikkim Himalaya and divided the region into four glaciated basins on the basis of topographic maps published in the 1970s complemented by field work. The study reported 449 glaciers with the area coverage of 705.54 sq km. The glaciers mapping was done basin-wise (Table 3.5).

Table 3.5 Number and area of glaciers in the Sikkim Himalaya as published by the Geological Survey of India, 1999.

Basins	Number of glaciers	Area of glaciers (sq km)
East Rathong	36	58.44
Talung	61	142.90
Changme Khangpu	102	144.35
Zemu	250	359.85
Total	449	705.54

The State Remote Sensing Application Centre (SAC) of the State Council of Science and Technology for Sikkim in collaboration with the State Remote Sensing Application Centre (SRSAC), Department of Space, Government of India, using the IRS-1C data provided the inventory of glaciers from the topographic map of scale 1:50,000 (Glacier Atlas of the Teesta basin, 2001) reported 84 glaciers and 197 permanent snowfields covering an area of 440 sq km and 251 sq km respectively (SAC and SRSAC 2001).

There are considerable differences in the total glacier cover area as well as number of glaciers in Sikkim Himalaya reported by different organization at different periods of time. One reason for this is the difference in the year of satellite data used as the satellite data of earlier years i.e. between 1970 and 1990 is of low resolution of about 76 m x 76m pixel size (Fig. 3.12), whereas the satellite data of later years is of much better resolution i.e. with pixel resolution of up to 5.6 m. Therefore, the decrease in glacier cover is partially due to data quality and also may be due to glacial melting. Generally low resolution satellite images of 1980s and early 1999s, has resulted in reporting or more area under glacier cover because due to lower resolution, it is difficult to differentiate glaciers from the adjacent landcover with accuracy, thereby resulting in more glacier cover. Moreover, the data set of November-December months only, gives the realistic picture of the glacier spread. However, for better understanding of the glacier cover over the years, had to be undertaken by these agencies/ organizations together after pooling their resources and adopting the common and universal methodologies.

On the basis of satellite data of IRS-1B LISS-II of 1990, Jeyaram *et al*. (1998) at RRSSC, Nagpur reported 65 glaciers covering an area of 667.18 sq km of Sikkim Himalaya and divided the glaciers of Teesta basin in Sikkim in to seven glacier complexes *viz*. Chhombo, Yumthang, Lambgo, Zemu, Talong, Rathong and Rel glacier complexes.

3.10.1 Zemu Glacier

The Zemu glacier is the largest and longest glacier in the Sikkim Himalaya, which occupies an area of around 107 sq km. The mean length of the glacier is around 25.7 km with an ice reserve of 22 km^3. The crown and toe of the glacier ranges from 7,790 m to 4,070 m. The glacier flows from the eastern aspect of the Mt Khangchendzonga ridge, which separates it from Nepal. The Zemu glacier flows as a valley glacier flows from west to east with many minor glaciers from other directions (Fig. 3.13). The major tributaries of the Zemu glacier are some parts of the Hidden glacier, Tent peak glacier, Nepal gap glacier, Twin glacier, Passaram glacier and Simvo glacier.

The glacier extends from 8,000 m to 4,000 m with an elevation difference of 4,000 m along a distance of about 55 km. The elevation rises abruptly within the distance of 10 km from the crown of the Zemu glacier. The equilibrium line lies at round 6,000 m. As the glacier is valley type, the length of the ablation is less than 8 km, whereas the length of the accumulation is around 50 km. The profile of Zemu glacier shows that the ablation part is very steep whereas the accumulation part is gentler. The equilibrium line area shows an upward curve convex whereas the overall curve shows upward concave indicating the maturity of the profile.

3.10.2 Glacial Lakes of Sikkim Himalaya

The inventory of glacial lakes is based on the satellite images of Landsat-7 ETM+ and IRS-1D LISS-3 & PAN. The identified glacial lakes are delineated and inventorised mainly from the merged satellite LISS-3 and PAN scenes of IRS-1D. Some of the important glacial lakes could not be mapped from the topographic maps (see Figs 3.9 and 3.11), so instead of mapping from the SOI topographic maps the glacial lakes were mapped from the satellite data and were verified and confirmed

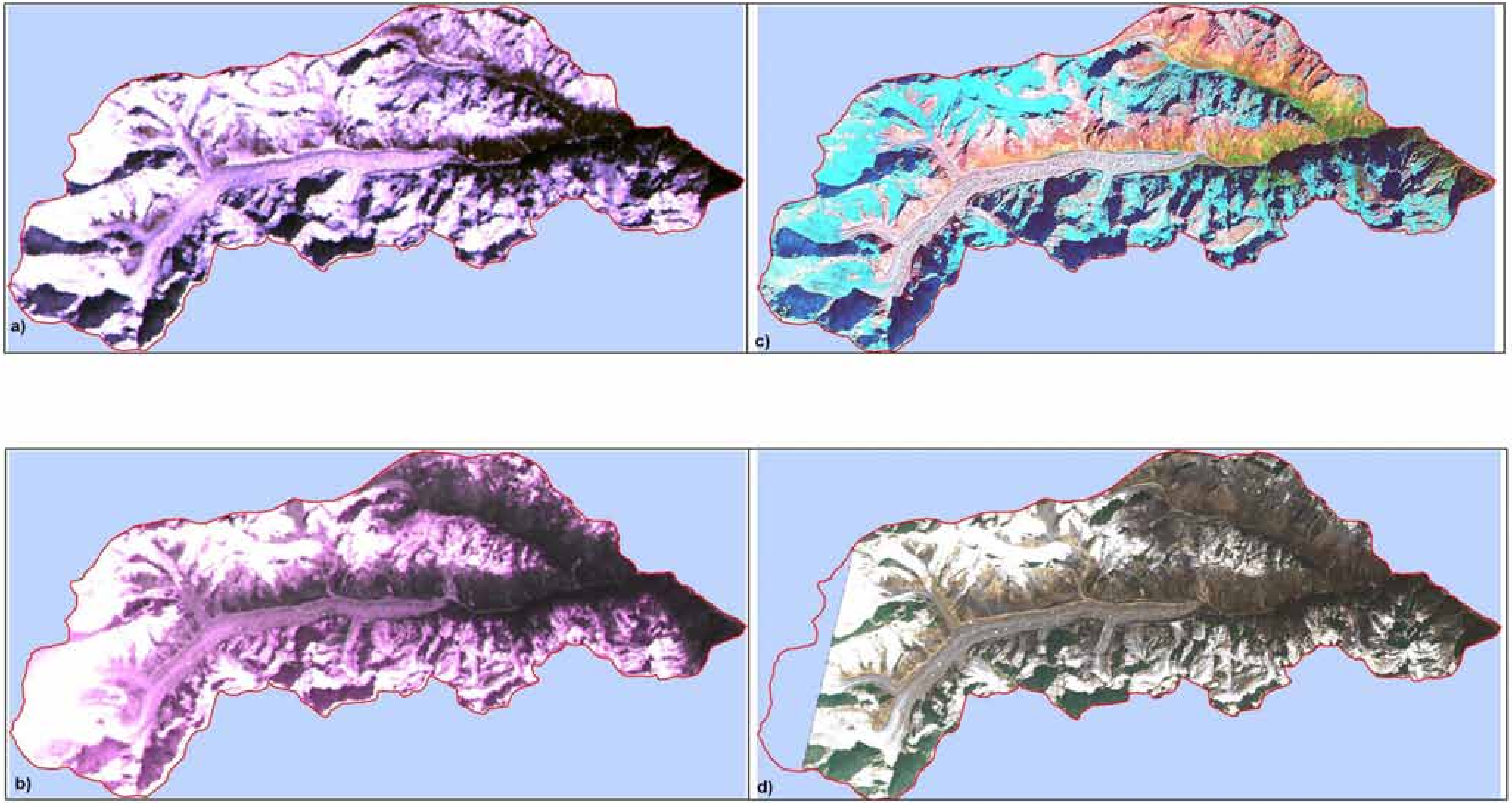


Fig. 3.12 Setallite Imgaes showing the Zemu glaciers with different dates: a) November, 1989 Landsat-4 TM; b) November, 1990 IRS-1C LISS-II; c) December, 2000 Landsat ETM+ and d) November, 2002 IRS-1D LISS-III

Fig. 3.13 Three dimensional (3D) view of Zemu glacier in Sikkim Himalaya

from different individual bands as well as by combining the different possible colour composite bands. The colour composite bands of 4,3,2, 9,8,2, and 9,3,2 were found useful and easy to differentiate between the rock outcrop and glacier, clean glacier and debris glacier, snow and cloud, and identification of lake. The lakes and glaciers were further confirmed from the images of individual bands as well as with the combination of bands of IRS-1D LISS-3 and also from band ratioing of band 3 – band 2/ band 3 + band 2 (Fig. 3.14). The cloud free satellite images used in the study are of 06 December 2000 (Landsat-7 ETM+) and November, 2002 (IRS-1D).

The lakes associated with perennial snow and ice originates from glaciers. But the isolated lakes found in the mountains and valleys far from the glaciers may not have a glacial origin. The lakes are classified into erosion lakes, valley trough lakes, cirque lakes, blocked lakes, lateral and end moraine-dammed lakes, and supraglacial lakes.

3.10.3 Erosion lakes

Glacial erosion lakes are the water bodies formed in a depression after the glacier has retreated. They are stable lakes. Most of these erosion lakes might have formed in the past glacial ice age and are isolated and far away from the present glaciers (Figs 3.15 & 3.16).

3.10.4 Trough valley lakes

The lakes, which are formed along the river valley due to eruption, are known as valley trough lakes. Generally these lakes are formed in the wide and deep trough along the river due to glacial erosion. These lakes are located in the downstream of the glacier. Any change in the mother glacier will impact the valley trough lake downstream. The lake Khora Chho, Chhora Chhobuk and Tso Chhobek shown in Fig. 3.17 are trough valley type lakes in the Sikkim Himalaya.

3.10.5 Cirque lakes

Cirque lakes are formed in separate, rounded, steep-walled recess on a mountain due to the glacial erosion. Generally the cirque lakes are smaller in size.

3.10.6 Blocked lakes

Blocking lakes formed due to glaciers and other factors, including the main glacier blocking the branch valley (Fig. 3.18), the glacier branch blocking the main valley, and the lakes formed through snow avalanche, collapse, and debris flow blockade from main or branch valley. The two lakes located on either side of the Choktsering Chhu glacier are formed due to the blocking by the moraine of the glacier.

3.10.7 Supra-glacial lakes

The supra-glacial lakes are small and change their position in the glacier. The history of past GLOF events of moraine-dammed lakes indicates that they are initially derived from supra-glacial lakes. If supra-glacial lakes are situated at the toe of a valley glacier, larger in size, or grouping rapidly to expand their size, then they are potentially dangerous

Fig.3.14 Subset and band ratio image of Landsat-7 ETM+ of December, 2000 to show glacial lakes of Teesta basin in Sikkim

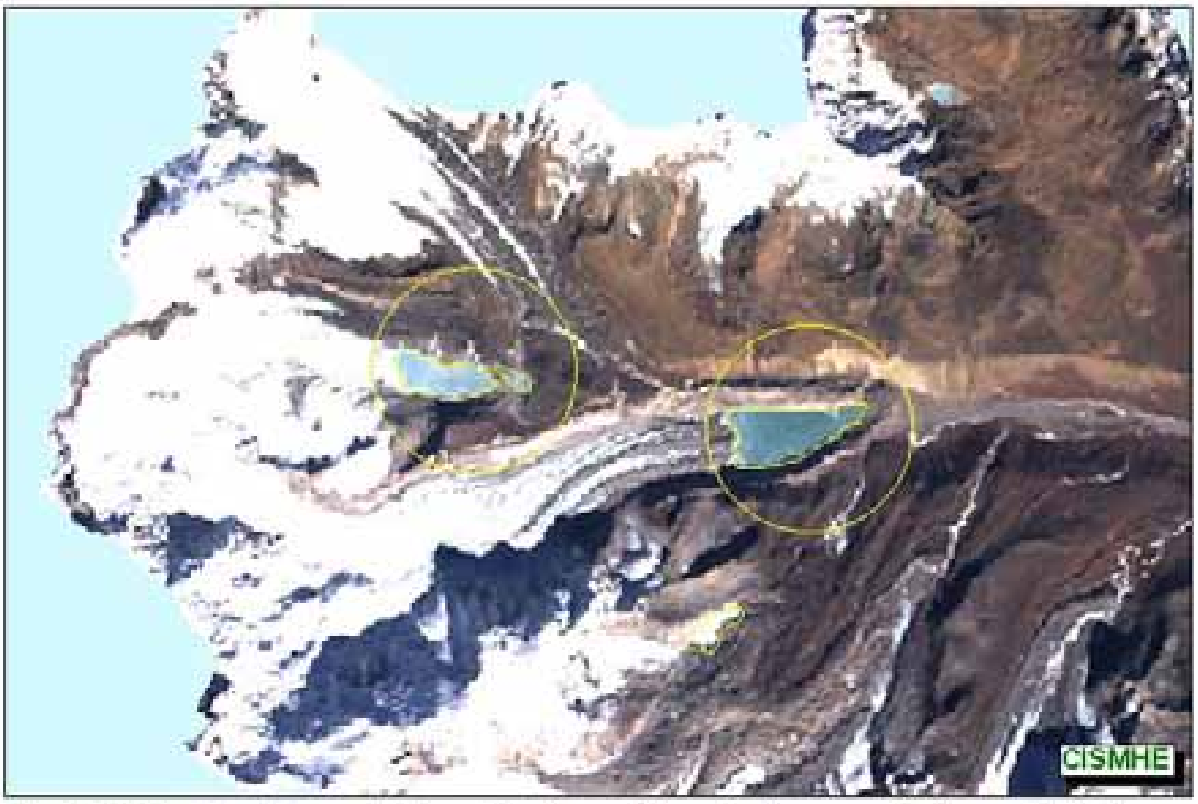


Fig. 3.15 Moraine dammed lake at the toe of the glaciers seen in the satellite image of Landsat-7 ETM+ in the colour composite of bands 4,3,2 (RGB) of December, 2000

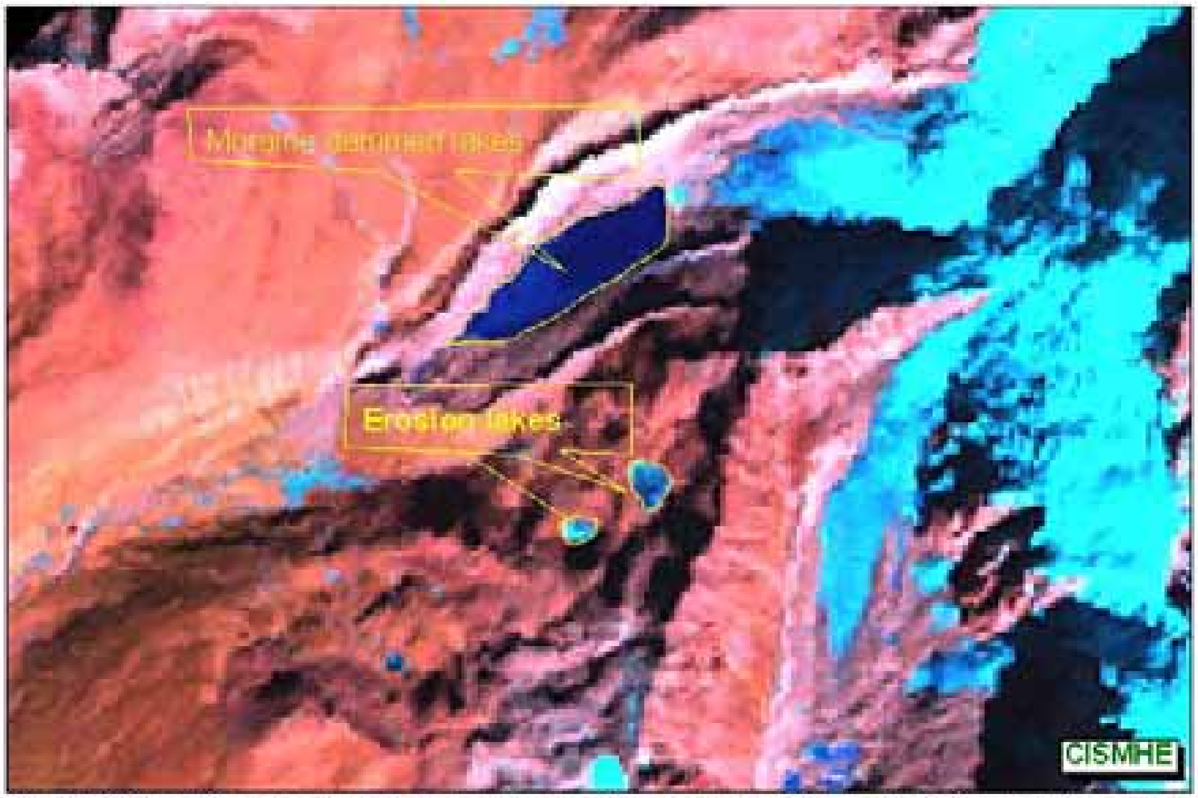


Fig. 3.16 Moraine dammed lakes and erosion lakes in Chhombo Chhu watershed of Teesta basin in Sikkim

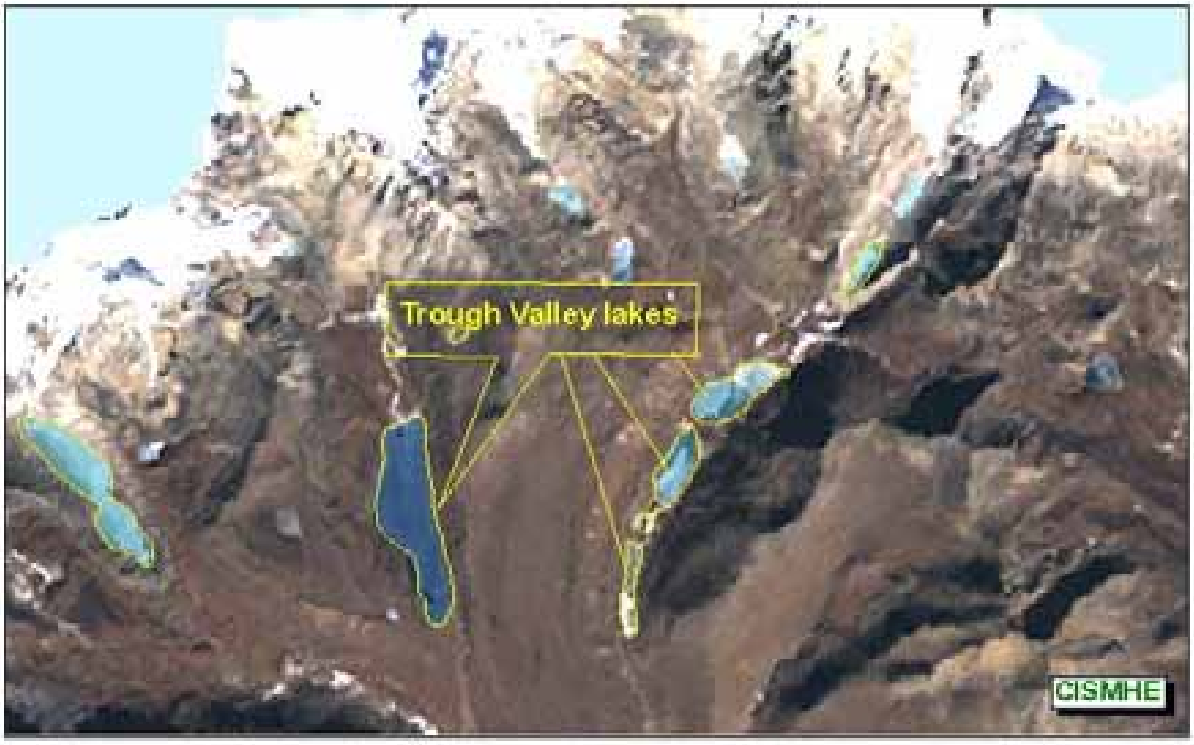


Fig. 3.17 Trough valley lakes formed along the river valley in North Sikkim

Fig. 3.18 The blocked lakes formed adjacent to the glacier by blocking in North Sikkim

and may burst out in the near future. The supra-glacial lakes develop within the ice mass away from the moraine with dimensions of 50 to 100m. These lakes may develop in any position of the glacier but the extension of the lake is less than half the diameter of the valley glacier. Shifting, merging, and draining of the lakes characterised the supra-glacial lakes. The merging of lakes results in expansion of the lake area and storage of a huge volume of water with a high potential energy. The tendency of a glacial lake towards merging and expanding indicates the danger level of GLOF. Group of supra-glacial lakes are formed in the northwestern part of the Sikkim Himalaya as shown in the Figure 3.19.

3.10.8 Moraine-dammed lakes

n the retreating process of a glacier, glacier ice tends to melt in the lowest part of the glacier surrounded by lateral and end moraines. As a result, many supra-glacial ponds are formed on the glacier tongue. These ponds sometimes enlarge to become a large lake by interconnecting with each other and have a tendency to deepen further. A moraine dammed lake is thus born. The lake is filled with melt water and rainwater from the drainage area behin d the lake and starts flowing from the outlet of the lake even in the winter season when the flow is minimum. There are so many moraine-dammed lakes in the Sikkim Himalaya and one example of the moraine-dammed lake, which is formed on the tongue of the glacier is depicted in Figs 3.16, 3.19 and 3.20.

There are two types of moraine: an ice-cored moraine and an ice-free moraine. Before the ice body of the glacier completely melts away, glacier ice exists in the moraine and beneath the lake bottom. The ice bodies cored in the moraine and beneath the lake are sometimes called **dead ice** or **fossil ice**. As glacier ice continues to melt, the lake becomes deeper and wider. Finally, when the ice contained in the moraines and beneath the lake completely melts away; it contains only the bedrock and the moraines.

3.10.9 Ice-dammed lakes

An ice-dammed lake is produced on the side(s) of a glacier, when an advancing glacier happens to intercept a tributary/tributaries pouring into a main glacier valley. A glacial lake is formed and maintained only up to a certain stage of glacier fluctuation. If one follows the lifespan of an individual glacier, it is found that the moraine-dammed glacial lakes build up and disappear with the lapse of time. The moraine-dammed lakes disappear once they are fully destroyed or when debris fills the lakes completely or the mother glacier advances again to lower altitudes beyond the moraine-dam position. Such glacial lakes are essentially ephemeral and are not stable from the point of view of the life of glaciers.

3.10.10 Inventory and Characteristics

The glacial lakes of the Sikkim Himalaya extend from the latitude of 27° 30’ to 28° 03’ 56” and the longitude of 88° 03’ 25” to 88° 53’ 26”. There are altogether 313 glacial lakes throughout the Teesta basin of the Sikkim Himalaya covering an area of 21.5 sq km (see Annexure-I).

The number of glacial lakes in the Sikkim Himalaya as reported by ICIMOD in 266 covering an area of 20.2 sq km (Table 3.6). The largest number (153) of glacial lakes are erosion lakes. There are 43 moraine-dammed lakes; among which one is a lateral moraine dammed lake. There are 33 valley lakes, 19 cirque lakes, 15 blocked lakes and 3 supra-glacial lakes. There are other supra-glacial lakes in the moraine of the glaciers, which are mostly frozen and some of it are quite small in size to map. In general, the erosion lakes are isolated and far away from the glaciers, moraine dammed lakes are close and associated with the present glaciers, valley trough lakes are situated along the river valley floor and some of it are quite close to the glacier end, blocked lakes are formed due to landslide, ice avalanche, etc. from different valleys, and the supraglacial lakes are situated in groups within the ice mass.

Table 3.6 Types of glacial lakes in the Sikkim Himalaya

Types of lake		Number		Area		Largest Lake
		Count	%	(km^2)	(%)	
Blocked		15	5.64	1.56	7.72	0.65
Cirque		19	7.14	1.23	6.09	0.35
Erosion		153	57.52	6.04	29.90	0.26
Dammed	Lateral moraine	1	0.38	0.01	0.05	0.01
	End moraine	42	15.79	7.50	37.13	1.59
Supraglacial		3	1.13	0.07	0.35	0.03
Valley		33	12.41	3.79	18.76	1.06
Total		266		20.2		

Source: ICIMOD

More than 70% of the lake area is covered by erosion lakes and moraine-dammed lakes. The valley trough lake, blocked lake, cirque lake, and supra-glacial lakes occupy around 19%, 8%, 6% and 0.35%, respectively. The total area occupied by the lakes is around 3.8 sq km, which is around 0.054% of the total land cover (7,096 sq km) of the Sikkim Himalaya.

The largest glacial lakes in the Sikkim Himalaya are the moraine dammed Khangchung Chho lake and the Gurudongmar Chho lake 1, which cover an area of about 1.64 sq km and 1.08 sq km, respectively (Fig. 3.21). Both of these largest lakes flow toward the north.

The long dimension of the glacial lakes in the Sikkim Himalaya is distributed randomly in all cardinal directions. The majority of glacial lakes face towards the southwest. Few glacial lakes are also draining towards the east and north. The largest glacial lake with an area more than 1.5 sq km is draining towards northwest. The other large lake, which has an area of more than one sq km is draining towards the north (Table 3.7).

Table 3.7 Distribution of number and area with respect to the aspect of the lakes

Orientation	**Area (km^2)**	**Number**	**Longest (metre)**	**Largest (km^2)**
East	1.50	14	1500	0.59
North	2.74	15	2680	1.07
Northeast	2.42	28	1750	0.65
Northwest	3.17	31	3050	1.59
South	1.96	41	1680	0.57
Southeast	2.72	40	1500	0.37
Southwest	4.22	74	1785	0.47
West	1.47	23	1030	0.28
Total	**20.2**	**266**		

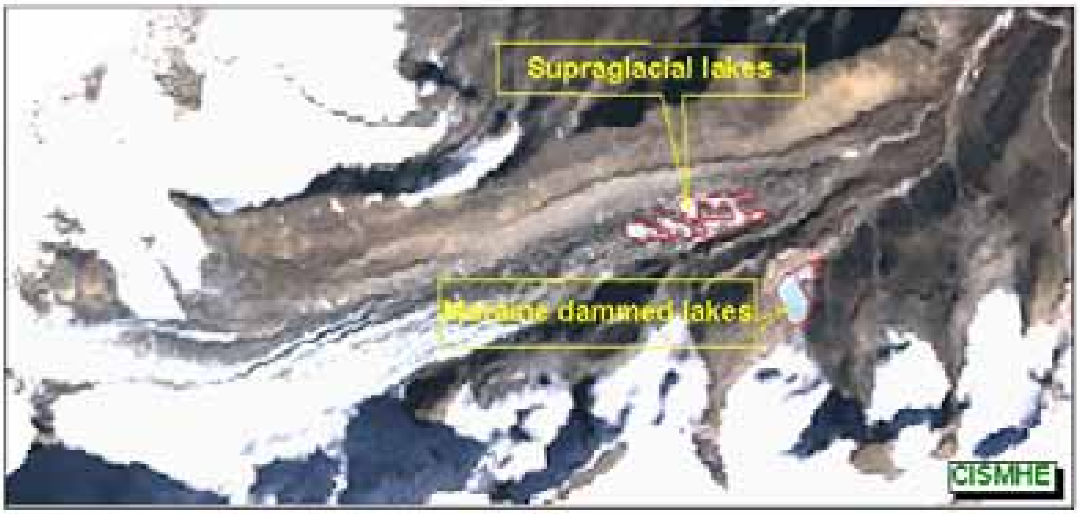


Fig 3.19 Group of supraglacial lakes and moraine dammed lakes in association with the glaciers seen in Chanson glacier in North Sikkim

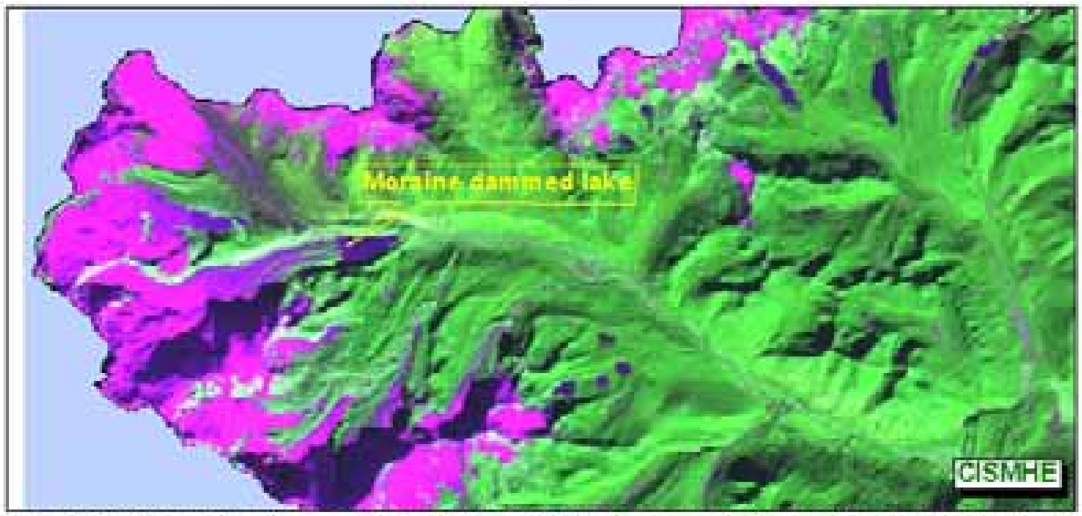


Fig. 3.20 Example of a moraine dammed lake in association with the glacier in the north-westerm part of Teesta basin in Sikkim (Landsat-7 ETM+ band combination 9,8,2)

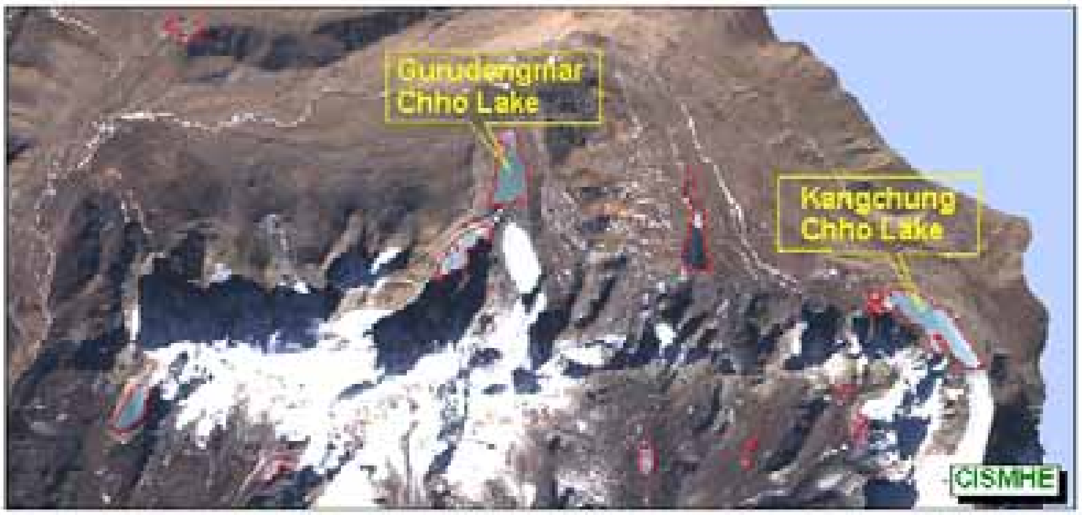


Fig. 3.21 The Khangchung Chho and Gurudongmar Chho lakes are the largest glacial lakes in the Chhombo Chhu watershed of Teesta basin in Sikkim mapped from Landsat-7 ETM+ satellite image of 26 December 2000

The number of glacial lakes are maximum in Chhombo Chhu watershed i.e. 69 covering lake area of 8.56 sq km. Incidently two of the largest lakes, Khangchung Chho – the source of Teesta river and Gurudongmar Chho are located in this source watershed of Teesta river (Fig. 3.22). Yumthang Chhu watershed has 59 ha (0.50 sq km). Majority of the glacial lakes are located in the altitudinal range of 4,000 m to 5,000 m, i.e. more than 62% of the lakes (196 in number out of total 316 lakes) are located in this elevation range (Fig. 3.23). However, 99 lakes are located above 5,000 m, with lake area ranging from 0.09 ha to 164.24 ha (1.64 sq km). Four largest lakes with area more than Khangchung Chho, Gurudongmar Lake 1, Gurudongmar Lake 2 and Chho Lhamo. The last three mentioned drain toward north.

3.11 MAJOR LAKES

Sikkim is very small in area even though there are many lakes and most of it are fed by glaciers and considered as sacred and holy lakes. They generally remain snow covered during winter season (Roy and Thapa, 1998). The lakes are popularly called as Chhokha or Tso or Chhona (in Bhutia), Chho (in Lepcha) and Pokhari or Jheel or Tal (in Nepali).

i) **Chhangu (Tsomgo) Lake**

It is situated at an altitude of 3,660 m on the Gangtok-Nathu La Highway about 40 km away from Gangtok. The lake is oval in shape, about 1 km long, and 15 metres deep and is considered sacred by the local people. This lake remains frozen during the winter months till mid-May.

ii) Menmoi Chho

The Menmoi Chho lake is around 0.22 sq km in area and 650 m long. It is formed along the valley and is located about 20 km before Chhangu lake. It lies between the mountains below the Jelepla Pass. The lake is fed by melting snow and ice and the source of the Rangpo Chhu. The lake is also famous for trout fish farming.

iii) Khecheopalri Lake

The lake is around 0.067 sq km in area and 370 m long situated in the center of the dense forest. The lake is cirque type and is considered as one of the most sacred lakes by the Sikkimese people both by the Buddhists and the Hindus (Jain *et al*. 1999 and 2000 and Jain, 2000). It is accessible by a motorable road from Pemayangtse right up to the lake area.

iv) Green Lake

Green lake is formed due to the damming of the left lateral moraine of the Zemu glacier. The hollow enclosed between the covering moraines of Zemu and the Green Lake does not exist anymore in the form of a lake but in the form of the remnant of the lake basin.

v) Samiti Lake

It is around 0.02 sq km in area and 200 m long. This lake is also of glacial origin and lies in the Onglakthang valley. It is clearly visible from the Geochala Pass.

vi) Chho Lhamo Lake

This is blocked type lake, with an area of about 1.04 sq km and 11,750 m long. It is situated on the plateau close to the border of Sikkim

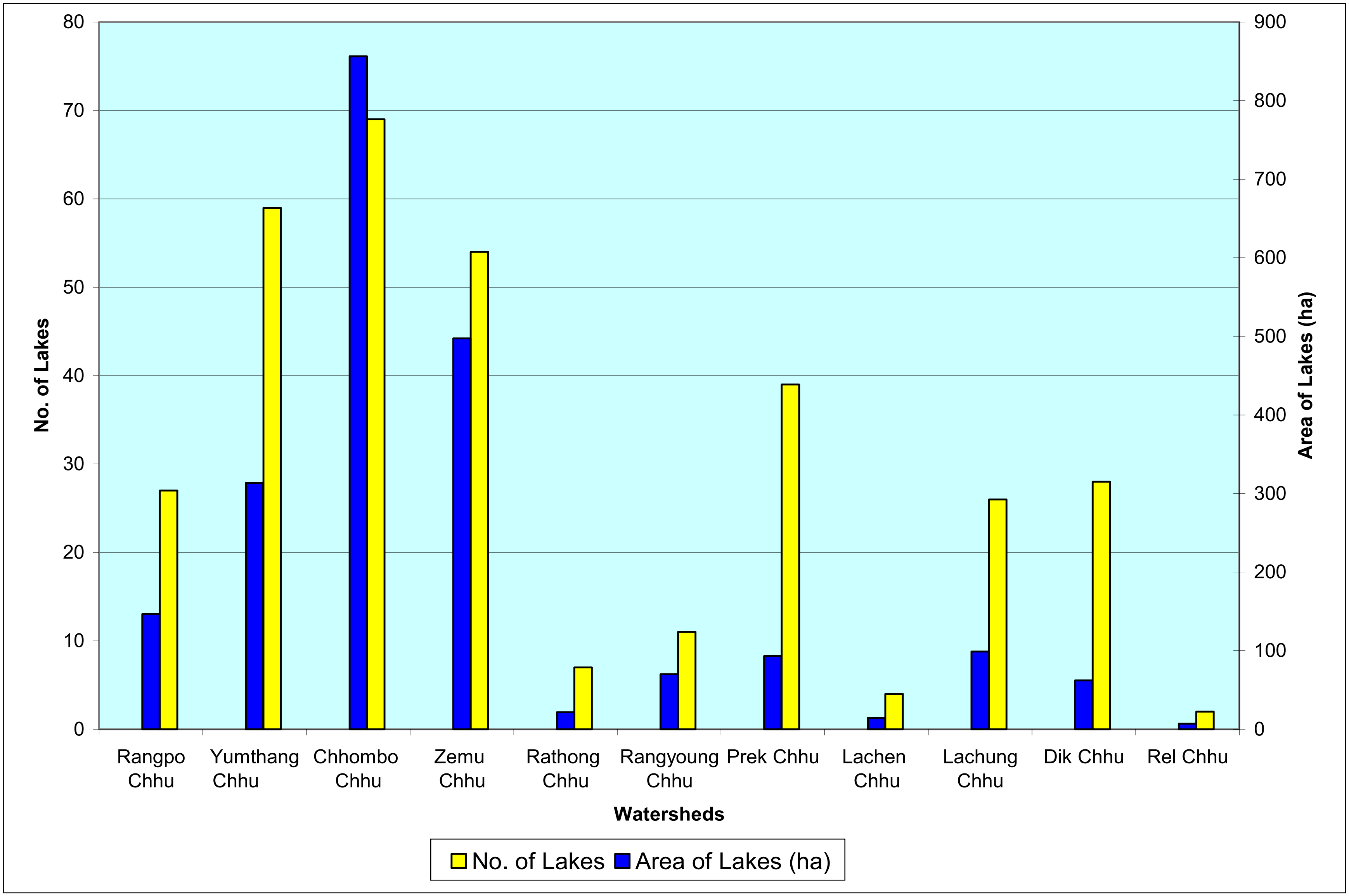


Fig. 3.22 Number and area (ha) of glacial lakes in different watersheds of Teesta basin in Sikkim

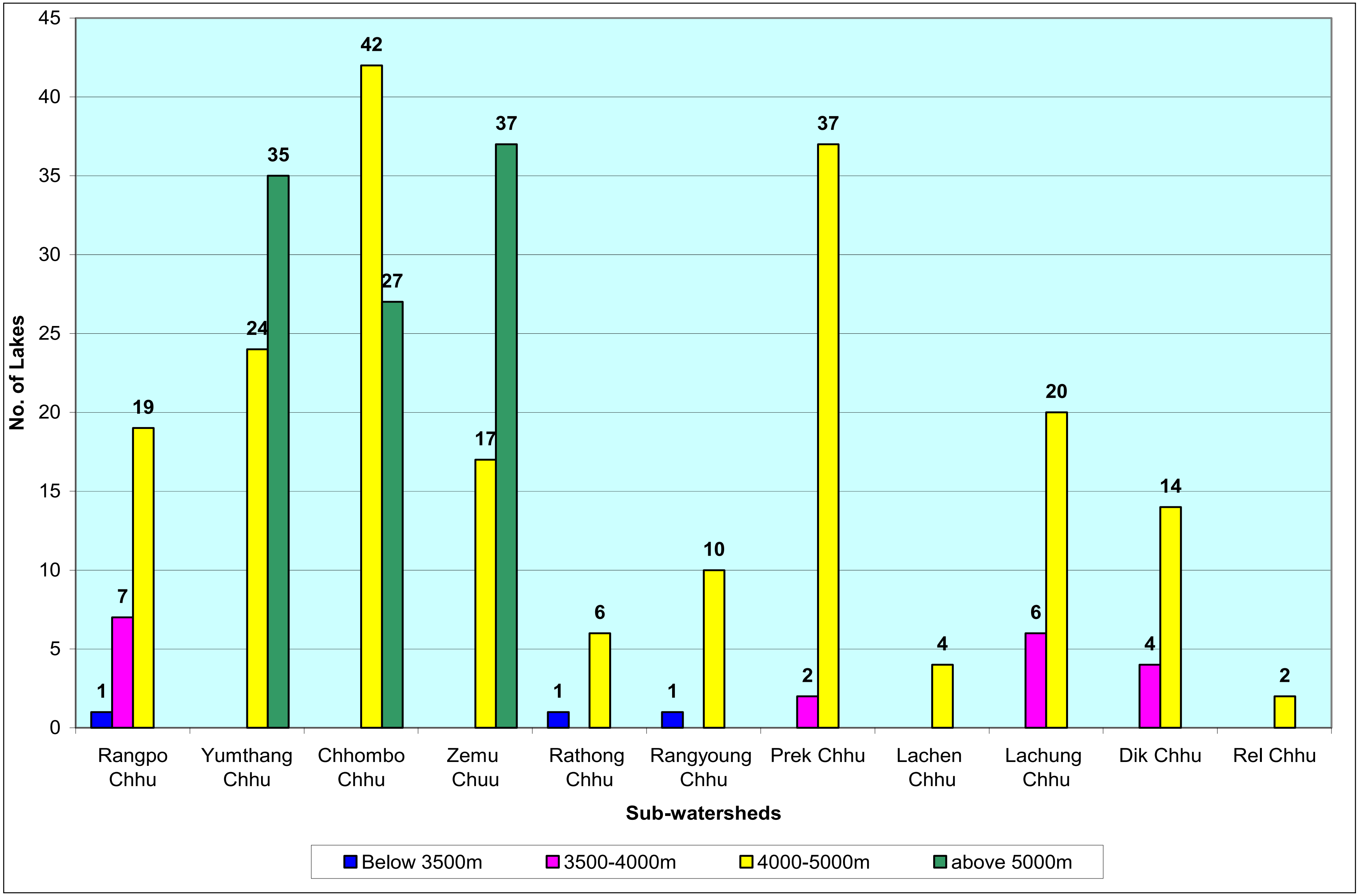


Fig. 3.23 Distribution of glacial lake in various altitudinal zones in different watersheds of Teesta basin in Sikkim

and Tibet in Chhombo Chhu watershed, the source watershed of Teesta river, China. The lake is of glacial origin and feed the Teesta river. The lake water is frozen during winter.

vii) **Gurudongmar Chho 1**

It is one of the largest lake with an area of about 1.09 sq km and 1.8 km long. It is the north flowing moraine dammed lake and one of the potentially dangerous glacial lakes in the Sikkim Himalaya.

viii) **Dalle Lake**

It is typically rounded in shape and named as Dalle Lake. This is Cirque type with an area of around 0.017 sq km and 100 m long.

ix) **Lam Pokhari**

It is elongated in shape and named as Lam Pokhari (Lake). This is Erosion type with an area of around 0.10 sq km and 600 m long.

x) **Lachhmi Pokhari**

This is Cirque type Lake with an area of around 0.16 sq km and 450 m long.

xi) **Chhangu (Tsomgo) Lake**

This is Erosion type Lake with an area of around 0.23 sq km and 985 m long.

3.11.1 Glacial Lake Outburst Floods

Periodic or occasional release of large amounts of stored water in a catastrophic outburst flood is widely referred to as a **Glacial Lake**

Outburst Flood in the Himalaya. GLOF is a catastrophic discharge of water under pressure from a glacier. GLOF events are severe geo-morphological hazards and their floodwaters can wreak havoc on all human structures located on their path. Much of the damage created during GLOF events is associated with the large amounts of debris that accompany the floodwaters. Damage to settlements and farmland can take place at very great distances from the outburst source, for example, in Pakistan the damage occurred 1,300 km from the outburst source (WECS 1987).

3.11.2 Causes of Lake Creation

i) *Global warming*

There is a growing concern that human activities may change the climate of the globe. Past and continuing emissions of carbon dioxide (CO_2) and other gases will cause the temperature of the earth's surface to increase- this is popularly termed 'global warming' or the 'greenhouse effect'. The 'greenhouse effect' gives an extra temperature rise.

ii) *Glacier retreat*

An important factor in the formation of glacial lakes is the rising global temperature ('greenhouse effect'), which causes glacial retreat in many mountain regions. During the so-called 'Little Ice Age' (AD 1550–1850), many glaciers were longer than today. Moraines formed in front of the glaciers at that time block the lakes nowadays. Glaciation and inter-glaciation are natural processes that have occurred several times during the last 10,000 years.

As a general rule, it can be said that glaciers in the Himalaya have retreated about one km since the Little Ice Age, a situation that provides a large space for retaining melt water, leading to the formation of moraine-dammed lakes (LIGG/WECS/NEA 1988). Röthlisberger and Geyh (1985) conclude in their study on ‘glacier variations in the Himalaya and Karakorum’ that a rapid retreat of nearly all glaciers with small oscillation was found in the period from 1860/1900–1980.

3.11.3 Causes of Glacial Lake Water Level Rise

The causes of rise in water level in the glacial lake dammed by moraines that endanger the lake to reach a breaching point are given below.

- Rapid change in climatic conditions that increase solar radiation causing rapid melting of glacier ice and snow with or without the retreat of the glacier
- Intensive precipitation events
- Decrease in sufficient seepage across the moraine to balance the inflow because of sedimentation of silt from the glacier runoff, enhanced by the dust flow into the lake
- Blocking of ice conduits by sedimentation or by enhanced plastic ice flow in the case of a glacial advance
- Thick layer of glacial ice (dead ice) weighed down by sediment below the lake bottom, which stops subsurface infiltration or seepage from the lake bottom.

- Shrinking of the glacier tongue higher up, causing melt water that previously left the glacier somewhere outside the moraine, where it may have continued underground through talus, not to follow the path of the glacier
- Blocking of an outlet by an advancing tributary glacier
- Landslide at the inner part of the moraine wall, or from slopes above the lake level
- Melting of ice from an ice-core moraine wall
- Melting of ice due to subterranean thermal activities (volcanogenic, tectonic)
- Inter-basin sub-surface flow of water from one lake to another due to height difference and availability of flow path

3.11.4 Bursting Mechanisms

Different triggering mechanisms of GLOF events depend on the nature of the damming materials, the position of the lake, the volume of the water, the nature and position of the associated mother glacier, physical and topographical conditions, and other physical conditions of the surroundings.

3.11.5 Mechanism of Ice Core-Dammed Lake failure

Ice-core dammed (glacier-dammed) lakes drain mainly in two ways.

- through or underneath the ice
- over the ice

Initiation of opening within or under the ice dam (glacier) occurs in six ways.

- Flotation of the ice dam (a lake can only be drained sub-glacially if it can lift the damming ice barrier sufficiently for the water to find its way underneath)
- Pressure deformation (plastic yielding of the ice dam due to a hydrostatic pressure difference between the lake water and the adjacent less dense ice of the dam; outward progression of cracks or crevasses under shear stress due to a combination of glacier flow and high hydrostatic pressure)
- Melting of a tunnel through or under the ice
- Drainage associated with tectonic activity
- Water overflowing the ice dam generally along the lower margin
- Sub-glacial melting by volcanic heat

The bursting mechanism for ice core-dammed lakes can be highly complex and involve most or some of the above-stated hypothesis. Marcus (1960) considered ice core-dammed bursting as a set of interdependent processes rather than one hypothesis. A landslide adjacent to the lake and/ or subsequent partial abrasion on ice may lead to overtopping as the water flows over, the glacier retreats, and the lake fills rapidly, which may subsequently result in the draining of ice core moraine-dammed lakes.

3.11.6 Mechanisms of Moraine-Dammed Lake failure

Moraine-dammed lakes are generally drained by rapid incision of the sediment barrier by outpouring waters. Once incision begins, the hustling water flowing through the outlet can accelerate erosion and enlargement of the outlet, setting off a catastrophic positive feedback process resulting in the rapid release of huge amounts of sediment-laden water. The onset of rapid incision of the barrier can be triggered by waves generated by glacier calving or ice avalanching, or by an increase in water level associated with glacial advance (examples include an ice avalanche from Langmoche Glacier on 4 August 1985 and another on 3 September 1998 from Sabai Glacier).

Dam failure can occur due to the following reasons:

- melting ice core within the moraine dam,
- rock and/or ice avalanche into a dammed lake,
- settlement and/or piping within the moraine dam,
- sub- glacial drainage, and
- engineering works.

3.11.7 Surge Propagation

As GLOFs pose severe threats to humans and man-made structures, it is important to make accurate estimates of the likely magnitude of future floods. Several methods have been devised to predict peak discharges, which are the most erosive and destructive phases of floods. The surge propagation hydrograph depends upon the type of GLOF event, i.e. from moraine-dammed lake or from ice-dammed lake.

3.11.8 Sediment Processes during a Glacial Lake Outburst Flood

During a GLOF, the flow velocity and discharge are exceptionally high and it becomes practically impossible to carry out any measurement.

3.11.9 Socio-economic effects of Glacial Lake Outburst Floods

The impact of a GLOF event downstream is quite extensive in terms of damage to roads, bridges, trekking trials, villages, and agricultural lands as well as the loss of human lives and other infrastructures. The sociological impacts can be direct when human lives are lost, or indirect when the agricultural lands are converted to debris filled lands and the village has to be shifted. The records of past GLOF events show that once every three to ten years, a GLOF has occurred in Nepal with varying degrees of socio-economic impact. Therefore, proper hazard assessment studies must be carried out in potentially problematic basins to evaluate the likely economic loss and the most appropriate method of mitigation activities.

The assessment of tangible benefits in respect to mitigation of GLOFs is, however, difficult. Reduced damage is considered a benefit and can be quantified, but the frequency of the reduced damage is difficult to ascertain due to lack of data. One cannot simply predict the timing and occurrences of GLOFs. It is extremely difficult to simulate numerically the flood level and velocities at a particular place.

At this stage, from brief studies of GLOFs throughout the world, it appears that there are no simple direct means of estimating the recurrence of GLOFs.

3.11.10 Potentially Dangerous Glacial Lakes

From an inventory of glacial lakes, on the basis of remote sensing satellite images, the spatial and attribute database is developed. The potentially dangerous glacial lakes were identified on the basis of attribute database in relation to the mother glacier and other criteria. In addition to the other factors, detailed geomorphic studies, type of the glacial lake, size of the lake, and the relation of lakes with the mother glacier are the prime factors for the identification of potentially dangerous glacial lakes. In general, based on geo-morphological characteristics, glacial lakes can be grouped into three types: glacial erosion lakes, glacial cirque lakes, and moraine-dammed lakes. The former two types of glacial lakes occupy the lowlands or emptying cirques eroded by ancient glaciers. These glacial lakes are more or less located away from present-day glaciers and the downstream banks are usually made of bedrock or covered with a thinner layer of loose sediment. Both of these glacial lakes do not generally pose an outburst danger. On the other hand, the moraine-dammed glacial lakes have the potential for bursting. A standard index to define a lake that is a source of potential danger because of possible bursting does not exist.

Moraine-dammed glacial lakes, which are still in contact or very near to the glaciers, are usually dangerous. The present study defines all the lakes formed by the activity of glaciers including in the past as 'glacial lakes'. Moraine-dammed glacial lakes are usually dangerous. These glacial lakes were partly formed between present-day glaciers and Little Ice Age moraine. The depositions of Little Ice Age moraines are usually about 300 years old, form high and narrow arch-shaped ridges usually with a height of 20-150 m and often contain dead glacier ice layers beneath them. These end moraines are loose and unstable in nature. The advance and retreat of the glacier affect the hydrology between the present-day glacier and the lake dammed by the moraines. Sudden natural phenomena with a direct effect on a lake, like ice avalanches or rock and lateral moraine material collapsing on a lake, cause moraine breaches with subsequent lake outburst events. Such phenomena have been well known in the past in several cases of moraine-dammed lakes, although the mechanisms at play are not fully understood.

3.11.11 Criteria for Identification

The criteria for identifying the potentially dangerous glacial lakes are based on field observations, processes and records of past events, geo-morphological and geo-technical characteristics of the lake and surroundings, and other physical conditions. The potentially dangerous lakes were identified based on the condition of lakes, dams, associated mother glaciers, and topographic features around the lakes and glaciers.

i) *Rise in lake water level*

In general, the lakes, which have a volume of more than 0.01 km^3 are found to have past events. A lake, which has a larger volume than this, is deeper, with the deeper part near the dam (lower part of lake) rather than near the glacier tongue, and has rapid increase in lake water volume is an indication that a lake is potentially dangerous.

ii) *Activity of Supra-glacial Lakes*

Groups of closely spaced supra-glacial lakes of smaller size at glacier tongues merge as time passes and form bigger lakes in Zemu glacier, which is associated with many supra-glacial lakes.

The Sikkim Himalaya also, has many such types of supra-glacial lakes in the form of groups (see Fig. 3.19). The supraglaical lakes are more distinct and sufficiently large enough and eventually it will merge to form a large lake of potential danger.

iii) *Position of Lakes*

The potentially dangerous lakes are generally at the lower part of the ablation area of the glacier near to the end moraine, and the mother glacier should be sufficiently large to create a potentially dangerous lake environment. Regular monitoring needs to be carried out for such lakes with the help of multi- temporal satellite images, aerial photographs, and field observations.

In general, the potentially dangerous status of moraine-dammed lakes can be defined by the conditions of the damming material and the nature of the mother glacier. The valley lakes with an area bigger than 0.1 sq km and a distance less than 0.5 km from the mother glacier of considerable size are considered to be potentially dangerous. Cirque lakes even smaller than 0.1 sq km associated (in contact or distance less than 0.5 km) with steep hanging glaciers are considered to be potentially dangerous. Even the smaller size steep hanging glacier may pose a danger to the lake.

iv) *Dam conditions*

The natural conditions of the moraine damming the lake determine the lake stability. The lake stability will be less if the moraine dam has a combination of the following characteristics:

- narrower in the crest area
- no drainage outflow or outlet not well defined
- steeper slope of the moraine walls
- ice cored
- very tall (from toe to crest)
- mass movement or potential mass movement in the inner slope and/or outer slope
- breached and closed in the past and refilled again with water
- seepage flow at moraine walls

A moraine-dammed lake, which has breached and closed subsequently in the past and has refilled again with water, can breach again. Lhonak Chho in the north-west of Sikkim burst out (Fig. 3.24). The study of recent aerial photographs and satellite images shows a very quick regaining of lake water volume. At present it is refilled again with water and poses danger. Regular monitoring of such lakes is necessary using multi-temporal satellite images.

Although there are no reports on the GLOF events in the Sikkim Himalaya, many debris flow along the glacial lake valley are seen in the satellite images. The erosion and deposition of debris along the valley can be seen clearly from the satellite images.

v) *Condition of Associated Mother Glacier*

Generally, the bigger valley glaciers with tongues reaching an elevation of below 5,000 m have well-developed glacial lakes. Even the actively retreating and steep hanging glaciers on the banks of lakes may be a potential cause of danger. The following general characteristics of associated mother glaciers can create danger to moraine-dammed lakes:

- hanging glacier in contact with the lake,
- bigger glacier area,
- fast retreating,
- debris cover at glacier tongue area,
- steep gradient at glacier tongue area,
- presence of crevasses and ponds at glacier tongue area,
- toppling/collapses of glacier masses at the glacier tongue,
- ice blocks draining to lake, and

- hanging glacier in contact with the lake

vi) *Physical conditions of the surroundings*

Besides moraines, mother glaciers, and lake conditions, and other physical conditions of the surrounding area as given below may also cause the lake to be potentially dangerous:

- potential rockfall/slide (mass movements) site around the lake which can fall into the lake suddenly,
- snow avalanches of large size around the lake which can fall into the lake suddenly,
- neo-tectonic and earthquake activities around or near the lake area,
- climatic conditions of successive years being a relatively wet and cold year followed by a hot and wet or hot and arid year,
- very recent moraines damming the lake at the tributary glaciers that used to be just a part of a former complex of valley glacier middle moraines as a result of the fast retreat of a complex mother valley glacier, and
- sudden advance of a glacier towards the lower tributary or the mother glacier having a well-developed lake at its tongue

3.11.12 Major Glacial Lakes Associated with the Glaciers

For identification of potentially dangerous glacial lakes, the glacial lakes associated with glaciers like supra-glacial lakes and/or dammed by lateral moraine or end moraine with an area larger than 0.02 sq km have been considered and they have been defined as major glacial lakes. The area of the inventorised glacial lakes is larger than 0.003 sq km. There are 266 such glacial lakes in the Sikkim Himalaya. Among these glacial lakes, 55 of them have an area that is larger than 0.02 sq km and less than 1.4 km distance from the mother glacier. Twentyfour (24) major glacial lakes are in contact with or within the glacier, 19 glacial lakes are within the distance of 500 and the rest is within the distance of 1,400 m (Table 3.8).

Table 3.8 Major glacial lakes of Teesta basin in Sikkim

Sl. No.	Latitude and Longitude	Lake Name	Class	Area (sq m)	Dist. from glacier (m)
1.	27°32’01.48"N, 88°05’15.33"E	?	Moraine-dammed	2,90,742	0
2.	27°33’52.64"N, 88°07’30.82"E	?	Valley	99,727	500
3.	27°29’46.27"N, 88°14’11.89"E	?	Blocked	33,086	1125
4.	27°42’40.05"N, 88°23’09.78"E	?	Erosion	32,859	58
5.	27°45’36.69"N, 88°29’13.26"E	Lamgepui Cho	Moraine-dammed	99,114	0
6.	27°45’45.87"N, 88°22’01.78"E	?	Supraglacial	25,129	0
7.	27°45’17.75"N, 88°15’55.96"E	?	Supraglacial	24,577	0
8.	27°48’54.92"N, 88°16’19.93"E	?	Moraine-dammed	24,828	0
9.	27°49’08.11"N, 88°15’47.65"E	?	Blocked	1,30,341	232
10.	27°49’34.76"N, 88°15’22.96"E	?	Moraine-dammed	95,476	0
11.	27°49’28.13"N, 88°15’07.27"E	?	Moraine-dammed	36,342	0
12.	27°50’39.02"N, 88°14’02.71"E	?	Blocked	1,46,479	329
13.	27°51’14.76"N, 88°14’40.23"E	?	Moraine-dammed	1,47,034	0
14.	27°52’59.75"N, 88°15’09.68"E	?	Erosion	1,63,915	490
15.	27°53’44.32"N, 88°11’33.33"E	?	Moraine-dammed	1,15,446	0
16.	27°54’53.26"N, 88°12’04.89"E	?	Moraine-dammed	5,92,231	0
17.	27°55’15.53"N, 88°09’51.43"E	?	Moraine-dammed	3,95,971	0
18.	27°55’47.68"N, 88°11’38.66"E	?	Moraine-dammed	20,112	179
19.	27°56’55.14"N, 88°13’14.19"E	?	Erosion	50,325	143
20.	27°56’17.69"N, 88°16’07.37"E	?	Erosion	73,116	163

21.	27°56’40.94"N, 88°16’28.27"E	?	Cirque	55,314	337
22.	27°56’24.76"N, 88°16’41.20"E	?	Valley	25,994	988
23.	27°57’17.99"N, 88°17’54.44"E	?	Erosion	33,705	307
24.	27°57’05.96"N, 88°18’27.78"E	?	Moraine-dammed	3,73,345	366
25.	27°58’01.22"N, 88°21’06.54"E	?	Moraine-dammed	32,900	541
26.	27°58’18.06"N, 88°20’50.24"E	?	Moraine-dammed	41,649	0
27.	27°57’41.14"N, 88°22’01.75"E	?	Valley	26,516	583
28.	27°58’00.18"N, 88°22’18.06"E	?	Moraine-dammed	42,017	791
29.	27°58’18.30"N, 88°22’33.87"E	?	Moraine-dammed	25,624	174
30.	27°58’16.20"N, 88°25’59.76"E	Thang Chho1	Blocked	1,36,254	1060
31.	28°00’26.98"N, 88°29’50.13"E	?	Moraine-dammed	3,51,703	0
32.	27°59’51.52"N, 88°29’01.35"E	?	Valley	33,674	0
33.	28°00’32.65"N, 88°34’33.65"E	La Chho	Valley	2,69,253	1515
34.	28°00’59.42"N, 88°33’56.00"E	?	Moraine-dammed	1,97,485	275
35.	28°02’25.43"N, 88°34’42.64"E	?	Moraine-dammed	38,064	256
36.	28°03’28.51"N, 88°34’54.18"E	?	Erosion	20,845	860
37.	27°59’34.95"N, 88°49’18.78"E	Kangchung	Moraine-dammed	15,88,660	0
38.	27°59’22.61"N, 88°44’32.75"E	?	Cirque	97,372	456
39.	28°01’35.08"N, 88°42’58.63"E	Gurudongmar Chho1	Moraine-dammed	10,67,899	600
40.	28°00’34.46"N, 88°42’16.28"E	Chho Lhamo	Blocked	6,50,773	1395
41.	27°58’34.80"N, 88°37’16.49"E	?	Moraine-dammed	4,70,713	0
42.	27°57’44.41"N, 88°39’18.32"E	?	Moraine-dammed	1,69,278	0
43.	27°52’24.48"N, 88°38’33.30"E	?	Moraine-dammed	33,461	0
44.	27°48’55.15"N, 88°39’35.37"E	?	Erosion	59,062	453
45.	27°49’03.98"N, 88°39’45.62"E	?	Erosion	48,543	390
46.	27°55’18.08"N, 88°40’35.02"E	Sebu Chho	Moraine-dammed	3,38,963	0
47.	27°57’08.64"N, 88°42’39.72"E	?	Valley	20,805	700
48.	27°58’11.23"N, 88°48’15.62"E	?	Moraine-dammed	1,32,732	75
49.	27°57’53.28"N, 88°48’14.77"E	?	Moraine-dammed	92,108	430
50.	27°52’11.07"N, 88°44’51.36"E	?	Moraine-dammed	49,555	0
51.	27°49’38.52"N, 88°46’13.74"E	?	Moraine-dammed	32,917	0
52.	27°52’28.29"N, 88°47’46.25"E	?	Moraine-dammed	83,582	0
53.	27°52’27.23"N, 88°51’49.24"E	?	Moraine-dammed	48,046	131
54.	27°51’56.13"N, 88°52’12.84"E	?	Moraine-dammed	1,07,950	0
55.	27°51’41.49"N, 88°52’23.34"E	?	Moraine-dammed	28,781	0

Out of 55 major glacial lakes associated with glaciers, 32 glacial lakes are moraine dammed lakes with an area ranging from 20,112 sq m to 1,588,660 sq m, 8 glacial lakes are erosion lakes with an area ranging from 20,845 sq m to 1,63,915 sq m, 5 glacial lakes are blocked lakes with an area ranging from 33,086 sq m to 650,773 sq m, 6 lakes are valley lakes with an area ranging from 20,805 sq m to 269,253 sq m, 2 lakes are supra-glacial lakes with an area of around 25,000 sq m, and 2 cirque lakes with an area ranging from 55,314 to 97,372 sq m. Most of the major glacial lakes are moraine dammed lakes and cover around 57%. Other lakes cover less than 15%.

3.11.13 Potentially Dangerous Glacial Lakes

Based on the analysis of inventory data using different criteria and the study of satellite images, 18 glacial lakes are identified as potentially dangerous lakes in the Sikkim Himalaya. Out of these, there are three glacial lakes (i.e., Chanson Chho, South Lhonak Chho and North Lhonak Chho) that seem to have past outburst events and 11 glacial lakes without a record of past GLOF events. The identified potentially dangerous lakes are recommended for further detailed investigation and field survey to understand their activity (Fig.3.25 and Table 3.9). Among the identified potentially dangerous glacial lakes, 14 are moraine-dammed lakes, two are blocked lakes and two are valley lakes.

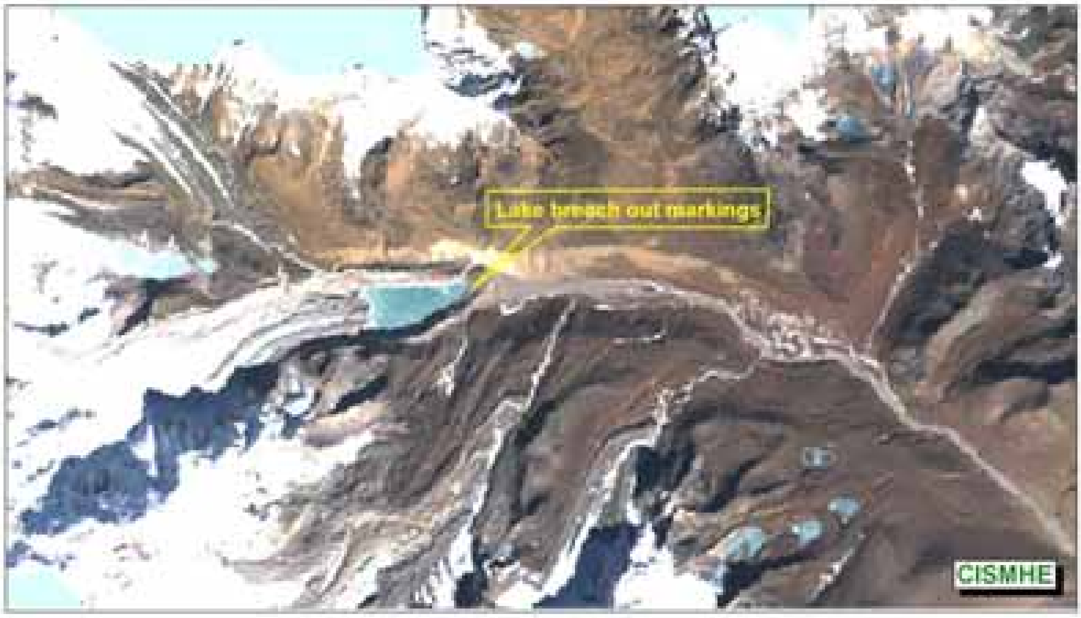


Fig.3.24 Lake breach out markings in the lake boundary as well as in the river valley in image of Landsat-7 ETM+ of December, 2000

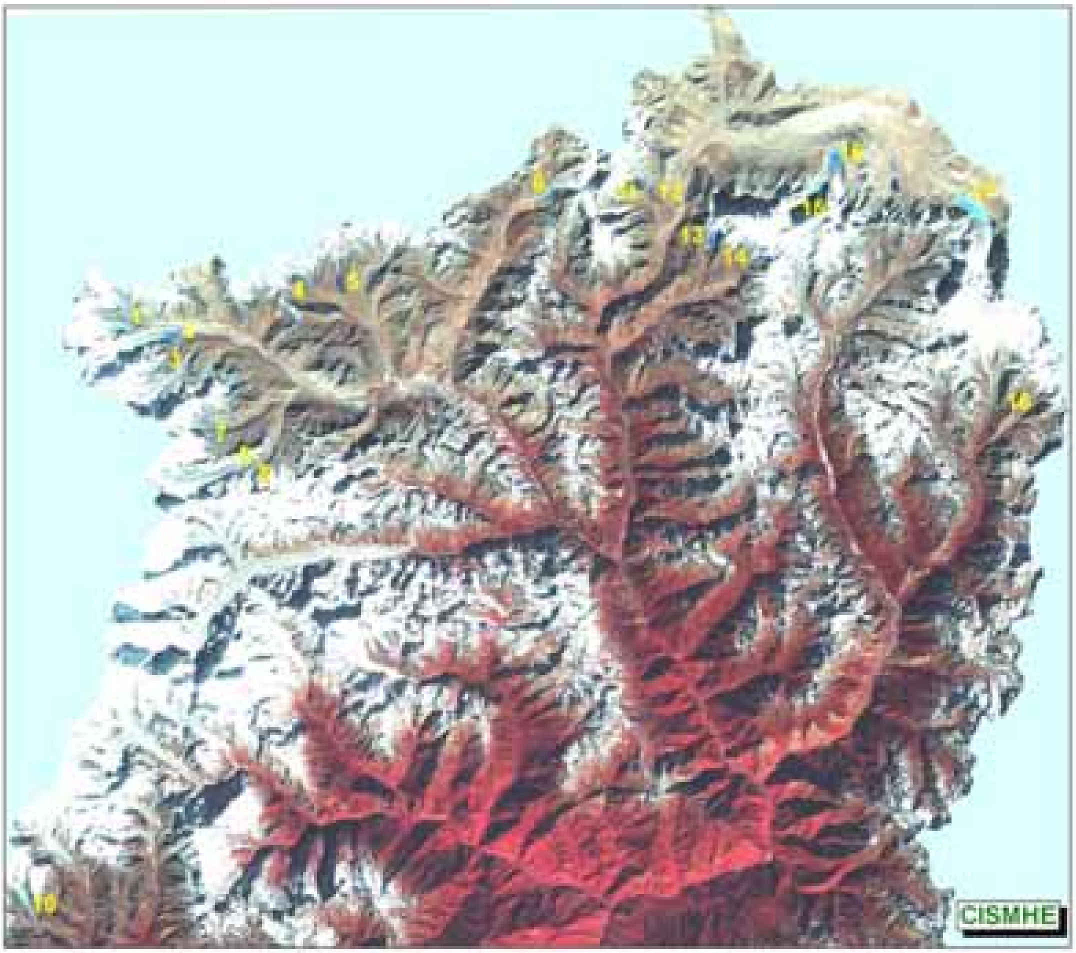


Fig.3.25 Location and distribution of potentially dangerous glacial lakes in the Teesta basin in Sikkim (For the details of numbers 1-18 see Table 3.9)

Table 3.9 Potentially dangerous glacial lakes requiring further studies and monitoring in different watersheds of Teesta basin in Sikkim

Sl. No	Lakes	Lat and Long	Class	Remarks
1	South Lhonak Chho	27°54’53.26”N 88° 12’04.89”E	Moraine-dammed	Seems to have past GLOF event, steep hanging glacier, one side is bounded by rock other by moraine
2	North Lhonak Chho	27°55’.15.53”N 88°09’51.43”E	Moraine-dammed	Seems to have past GLOF event, steep hanging glacier, one side is bounded by rock other by moraine
3	No name Lhonak Chho	27°53’44.32”N 88°11’33.33”E	Moraine-dammed	High elevation, contact with steep hanging mother glacier.
4	Zemu Chho	27°56’54.73”N, 88°18’30.40”E	Moraine-Dammed	Thin lateral moraine and steep hanging valley
5	Khora Chho	27°56’46.32”N 88°20’02’.47E	Valley	Steep hanging valley About 2 km from upstream glacier
6	No name Langpo Chho	28°00’26.98”N 88°29’50.13”E	Moraine-dammed	Thin lateral moraine and attach with steep hanging valley
7	Langpo Chho	27°51’.14.76”N 88°14’40.23”E	Moraine-dammed	Thin lateral moraine, supraglacial lakes side by side
8	Pandon Chho	27°49’34.76”N 88°15’22.96”E	Moraine-dammed	Thin lateral moraine, supraglacial lakes side by side
9	Chason Chho	27°49’08.11”N 88°15’22.96”E	Blocked	Seems to have past GLOF event, steep hanging glacier, one side is bounded by rock other by moraine
10	Khangla Chho	27°32’01.48”N 88°05’15.33”E	Moraine-dammed	Thin lateral moraine, supraglacial lakes, possibly of ice core, two mother hanging glaciers
11	La –Tso	28°00’59.42”N 88°33’56.00”E	Moraine-dammed	Thin lateral moraine and steep hanging valley
12	La-Jheel	28°00’32.65”N 88°34’33.65”E	Valley	Around 400m downstream of glacial lake (La-Tso)
13	Gyapji Chho	27°58’26’.32”N 88°37’07.00”E	Moraine-dammed	Thin lateral moraine and attach with steep hanging valley
14	No Name – Chhombo Chho	27°57’36.55”N 88°39’05.07”E	Moraine dammed	High elevation, contact with steep hanging mother glacier.
15	Gurudongmar 1	28°01’35.08”N 88°42’58.63”E	Moraine-dammed	Around 600m downstream of glacial lake (Mashya -Tso)
16	Mashya -Tso	28°00’34.46”N 88°42’16.28”E	Blocked	Blocked by glacier moraine and the distance of glacier is less than 200m.
17	Khangchung Chho	27°59’34.95”N 88°49’18.78”E	Moraine-dammed	3km and 600m associated with the supraglacial lakes at the toe and valley glacier
18	Phyakuchen Chho	27°51’56.13”N 88°52’12.84”E	Moraine-dammed	Attach with hanging glacier

3.11.14 Glacial lake outburst flood mitigation measures, monitoring and early warning systems

There are several possible methods for mitigating the impact of glacial lake outburst flood (GLOF) surges, for monitoring, and for early warning systems. The most important mitigation measure for reducing GLOF risk is to reduce the volume of water in the lake in order to reduce the peak surge discharge. Downstream in GLOF prone areas, measures should be taken to protect infrastructure against the destructive forces of the GLOF surge. There should be monitoring systems prior to, during, and after construction of infrastructures and settlements in the downstream area.

Careful evaluation by detailed studies of the lake, mother glaciers, damming materials, and the surrounding conditions are essential in choosing an appropriate method and in starting any mitigation measure. Any measure taken must be such that it should not create or increase the risk of a GLOF during and after the mitigation measures are in place. Physical monitoring systems of the dam, lake, mother glacier, and the surroundings are necessary at different stages during and after the mitigation process.

3.11.15 Reducing the Volume of Lake Water

Possible peak surge discharge from a GLOF could be reduced by reducing the volume of water in the lake. In general, any one or combination of the following methods may be applied for reducing the volume of water in the lake:

i) controlled breaching,
ii) construction of an outlet control structure,
iii) pumping or siphoning out the water from the lake, and
iv) making a tunnel through the moraine barrier or under an ice dam.

3.11.16 Preventative Measures around the Lake Area

Any existing and potential source of a larger snow and ice avalanche, slide, or rock fall around the lake area, which has a direct impact on the lake and dam has to be studied in detail. Preventative measures have to be taken such as removing masses of loose rocks to ensure there will be no avalanches into the lake.

3.11.17 Protecting infrastructure against the destructive forces of the surge

The sudden hydrostatic and dynamic forces generated by a rapid moving shock wave can be difficult to accommodate by conventionally designed river structures such as diversion weirs, intakes, bridges, settlements on the river banks, and so on. It will be necessary to build bridges with appropriate flow capacities and spans at elevations higher than those expected under GLOF events. Settlements should not be built at or near low river terraces but at heights well above the riverbed in an area with GLOF potential. Slopes with potential or old landslides and steep slopes on the banks of the river near settlements should be stabilized. It is essential that appropriate warning devices for GLOF events be developed in such areas.

3.11.18 Monitoring and early warning systems

A programme of monitoring GLOFs throughout the state of Sikkim should be implemented using a multi-stage approach, multi-temporal data sets, and multi-disciplinary professionals. Focus should first be on the known potentially dangerous lakes and the river systems on which infrastructure is developed. Monitoring, mitigation, and early warning system programmes could involve several phases as follow.

- Detailed inventory and development of a spatial and attribute digital database of the glaciers and glacial lakes using reliable large-scale (1:25,000 to 1:10,000) topographic maps
- Updating of the inventory of glaciers and glacial lakes and identification of potentially dangerous lakes using remote-sensing data such as the Land Observation Satellite (LANDSAT) Thematic Mapper (TM) and Enhanced Thematic Mapper plus (ETM+), Indian Remote Sensing Satellite IRS-ResourceSat-1 Linear Imaging and Self-scanning Sensor (LISS-IV), Cartosat-1 (Ortho Rectified and Stereo) images, Système Probatoire d’Observation de la Terre (SPOT) multi-spectral (XS), SPOT panchromatic (PAN) (stereo), IKONOS, Quickbird and others.

- Semi-detailed to detailed study of the glacial lakes, identification of potentially dangerous lakes and the possible mechanism of a GLOF using aerial photos
- Annual examination of medium- to high-resolution satellite images, e.g. Landsat TM and ETM+, IRS1D, ResourceSat-1, SPOT, and so on to assess changes in the different parameters of potentially dangerous lakes and the surrounding terrain
- Brief over- flight reconnaissance with small format cameras to view the lakes of concern more closely and to assess their potential for bursting in the near future
- Field reconnaissance to establish clearly the potential for bursting and to evaluate the need for preventative action
- Detailed studies of the potentially dangerous lakes by multi-disciplinary professionals
- Implementation of appropriate mitigation measure(s) in the highly potentially dangerous lakes
- Regular monitoring of the site during and after the appropriate mitigation measure(s) should be carried out
- Development of a telecommunication and radio broadcasting system integrated with on-site installed hydro- meteorological, geophysical, and other necessary instruments at lakes of concern and downstream as early warning mechanisms for minimizing the impact of a GLOF
- Interaction/cooperation among all of the related government departments/institutions/agencies/broadcasting media, and others

for detailed studies, mitigation activities, and preparedness for possible disasters arising from GLOF events.

As the mountain system is bestowed with all microclimates (from dry-cold to wet-hot), it is one of the mega-biodiversity region for flora and fauna, supporting a huge human population. This sensitive and fragile region needs continuous monitoring to understand the physical processes for effective utilization of its natural resources and timely corrective measures to reduce the occurrence of natural disasters for harmonious environmental conditions.

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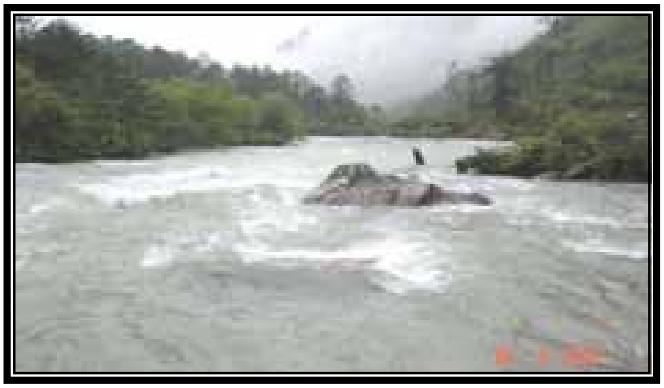
PLATES



Teesta River

Gurudongmar Chho

Chho Lhamo

Chhangu Lake

PLATE – 3.1

Green Lake

Menmoi Chho

Mt. Khangchendzonga

Mt. Narsingh

PLATE – 3.2

Lam Pokhari

Courtesy: E. Sharma & Chhetri (ICIMOD)

Lachhmi Pokhari

Courtesy: E. Sharma & Chhetri (ICIMOD)

Origin of Rathong Chhu at Rathong glacier

PLATE 3.3

Dalle Pokhari

Courtesy: E. Sharma & Chhetri (ICIMOD)

Jore Pokhari

Khecheopalri Lake

Courtesy: E. Sharma & Chhetri (ICIMOD)

PLATE – 3.4

ANNEXURE

Annexure-1

Glacial Lakes of Teesta basin in Sikkim

ID	Lakes Name	Area (sq m)	Elevation	District	Watershed	Longitude, Latitude
1	No Name	36075.196	5190 m	North	Chhombo_Chhu	88:44:46 27:59:47
2	Naku_Chok_Tso	10,355.82	3970 m	East	Dik_Chhu	88:46:57 27:24:30
3	No Name	12,781.36	4300 m	North	Lachen_Chhu	88:31:33 27:40:47
4	Tosa Chho	205,618.39	4120 m	North	Lachung_Chhu	88:45:13 27:27:58
5	No Name	7,387.49	4240 m	North_West	Prek_Chhu	88:07:06 27:25:16
6	No Name	10,672.69	4100 m	East	Rangpo Chhu	88:46:46 27:23:47
7	Kishong Chho	189,417.31	4120 m	North	Rangyong_Chhu	88:27:19 27:43:19
8	Chhejo Pokhari	140,803.70	1820 m	West	Rathong_Chhu	88:11:25 27:21:00
9	no name	55,256.74	4610 m	west	Reli Chhu	88.14.00 27.29.41
10	No Name	14,294.88	4780 m	North	Yumthang_Chhu	88:50:28 27:41:26
11	No Name	8,691.93	4640 m	North	Zemu_Chhu	88:26:35 27:44:34
12	Gayum Chhona	259924.247	4993 m	North	Chhombo_Chhu	88:37:57 28:03:27
13	No Name	11,469.45	4360 m	East	Dik_Chhu	88:47:48 27:24:41
14	No Name	11,472.47	4540 m	North	Lachen_Chhu	88:30:55 27:42:14
15	No Name	32,709.24	4480 m	North	Lachung_Chhu	88:45:42 27:36:40
16	Chamliya Pokhari	116,733.80	4560 m	North_West	Prek_Chhu	88:11:28 27:34:52
17	No Name	10,798.08	4060 m	East	Rangpo Chhu	88:47:29 27:23:47
18	Laha Jheel	32,943.87	4320 m	North	Rangyong_Chhu	88:30:11 27:40:44
19	Lachhmi Pokhari 2	20,478.86	4380 m	West	Rathong_Chhu	88:04:43 27:25:37
20	no name	16,083	4660 m	west	Reli Chhu	
21	No Name	10,444.20	4720 m	North	Yumthang_Chhu	88:49:55 27:43:03
22	Mukti Boul Jheel	33,508.84	4860 m	North	Zemu_Chhu	88:23:29 27:44:42
23	No Name	63214.88	5305 m	North	Chhombo_Chhu	88:48:13 27:59:65
24	Chho_Pinsum2	99,815.14	3980 m	East	Dik_Chhu	88:46:24 27:24:06
25	No Name	45,993.05	4100 m	North	Lachen_Chhu	88:32:03 27:41:07
26	No Name	25,495.00	4500 m	North	Lachung_Chhu	88:48:09 27:38:53
27	No Name	8,620.82	4520 m	North_West	Prek_Chhu	88:11:31 27:34:32
28	No Name	6,861.49	4000 m	East	Rangpo Chhu	88:46:47 27:23:32
29	No Name	8,569.22	4510 m	North	Rangyong_Chhu	88:30:37 27:40:39
30	Lachhmi Pokhari 1	12,229.04	4420 m	West	Rathong_Chhu	88:05:04 27:25:44
31	No Name	3,233.72	5280 m	North	Yumthang_Chhu	88:50:58 27:44:21
32	No Name	39,104.15	4540 m	North	Zemu_Chhu	88:26:06 27:44:42
33	No Name	51942.963	5305 m	North	Chhombo_Chhu	88:48:10 27:59:46
34	Chho_Pinsum1	24,087.12	3970 m	East	Dik_Chhu	88:46:12 27:24:15
35	No Name	76,399.66	4520 m	North	Lachen_Chhu	88:30:57 27:41:55
36	No Name	60,787.54	4620 m	North	Lachung_Chhu	88:50:09 27:40:20
37	No Name	10,504.06	4580 m	North_West	Prek_Chhu	88:11:01 27:34:32
38	No Name	29,433.15	4200 m	East	Rangpo Chhu	88:49:04 27:23:24
39	No Name	33,685.56	4280 m	North	Rangyong_Chhu	88:29:50 27:40:29
40	No Name	4,363.33	4350 m	West	Rathong_Chhu	88:04:47 27:25:27

41	No Name	25,181.81	4760 m	North	Yumthang_Chhu	88:50:12	27:44:32
42	No Name	2,292.40	4500 m	North	Zemu_Chhu	88:26:14	27:44:55
43	No Name	42880.495	5170 m	North	Chhombo_Chhu	88:45:00	27:59:55
44	Naku_Chho2	6,912.60	4160 m	East	Dik_Chhu	88:45:34	27:26:38
45	No Name	14,277.80	4480 m	North	Lachung_Chhu	88:48:55	27:14:03
46	No Name	14,163.70	4440 m	North_West	Prek_Chhu	88:10:65	27:33:59
47	Syebiruka Chho	128,366.55	4060 m	East	Rangpo Chhu	88:48:14	27:23:14
48	No Name	9,124.26	4470 m	North	Rangyong_Chhu	88:30:18	27:40:58
49	Lam Pokhari	26,837.45	4340 m	West	Rathong_Chhu	88:05:02	27:25:26
50	No Name	9,382.67	4720 m	North	Yumthang_Chhu	88:49:28	27:44:50
51	Lamgepui Chho	96,901.71	4560 m	North	Zemu_Chhu	88:29:12	27:45:34
52	No Name	20559.938	5140 m	North	Chhombo_Chhu	88:45:08	27:59:57
53	Naku Chho	108,423.01	4080 m	East	Dik_Chhu	88:45:19	27:26:32
54	No Name	59,617.04	4480 m	North	Lachung_Chhu	88:48:43	27:40:58
55	Sungmoteng Chho	23,095.44	4300 m	North_West	Prek_Chhu	88:11:23	27:33:41
56	Sherathang Chho	27,856.51	3880 m	East	Rangpo Chhu	88:48:47	27:23:02
57	No Name	44,769.86	4040 m	North	Rangyong_Chhu	88:29:46	27:39:55
58	Gounian Pokhari	5,340.34	4180 m	West	Rathong_Chhu	88:05:21	27:24:42
59	No Name	135,256.92	4740 m	North	Yumthang_Chhu	88:48:11	27:47:47
60	Thomphyan Tso	28,361.99	4700 m	North	Zemu_Chhu	88:24:54	27:47:10
61	Gurudongmar Lake2	689861.371	5300 m	North	Chhombo_Chhu	88:42:01	28:00:28
62	Pemthang_Chho3	39,894.45	4080 m	East	Dik_Chhu	88:45:36	27:25:34
63	No Name	5,800.86	3990 m	North	Lachung_Chhu	88:40:04	27:39:36
64	Nor Pokhari	29,770.96	4240 m	North_West	Prek_Chhu	88:12:05	27:30:28
65	No Name	60,304.66	4120 m	East	Rangpo Chhu	88:50:01	27:22:49
66	No Name	60,421.31	4040 m	North	Rangyong_Chhu	88:29:59	27:40:09
67	Sukhia Pokhari	5,643.50	4200 m	West	Rathong_Chhu	88:04:15	27:25:17
68	No Name	29,954.94	4340 m	North	Yumthang_Chhu	88:42:38	27:45:08
69	No Name	9,947.10	4720 m	North	Zemu_Chhu	88:26:44	27:48:27
70	Gyapji_Chho2	111982.838	4740 m	North	Chhombo_Chhu	88:35:44	27:58:11
71	Pemthang_Chho4	18,634.23	4080 m	East	Dik_Chhu	88:45:26	27:25:27
72	No Name	8,958.57	3940 m	North	Lachung_Chhu	88:40:08	27:39:43
73	Tinkone Pokhari	20,818.20	3980 m	North_West	Prek_Chhu	88:12:02	27:29:24
74	No Name	44,197.25	4060 m	East	Rangpo Chhu	88:49:45	27:22:50
75	Shingo Chho	287,670.86	4520 m	North	Rangyong_Chhu	88:30:54	27:40:18
76	No Name	155,170.95	4620 m	North	Yumthang_Chhu	88:39:32	27:48:55
77	No Name	12,081.57	4580 m	North	Zemu_Chhu	88:26:10	27:48:34
78	No Name	48209.49	4760 m	North	Chhombo_Chhu	88:36:23	27:55:29
79	Pemthang_Chho2	7,505.64	4080 m	East	Dik_Chhu	88:45:44	27:25:35
80	No Name	12,073.17	4220 m	North	Lachung_Chhu	88:40:40	27:39:43
81	Jokte Pokhari	10,255.46	4200 m	North_West	Prek_Chhu	88:09:54	27:29:58
82	Namnang Chho(Chho Sum)1	33,679.00	4400 m	East	Rangpo Chhu	88:51:18	27:22:48
83	No Name	14,389.88	4640 m	North	Rangyong_Chhu	88:26:06	27:43:53
84	No Name	160,539.10	5000 m	North	Yumthang_Chhu	88:48:26	27:50:29

85	No Name	4,454.33	4680 m	North	Zemu_Chhu	88:25:21	27:48:45
86	No Name	9812.87	4500 m	North	Chhombo_Chhu	88:38:23	27:47:00
87	No Name	7,269.52	4140 m	East	Dik_Chhu	88:47:10	27:25:05
88	No Nae	76,094.55	4200 m	North	Lachung_Chhu	88:41:14	27:40:07
89	Khangla Khang Tso	43,134.75	4680 m	North_West	Prek_Chhu	88:05:07	27:30:36
90	Namnang Chho(Chho Sum)2	38,992.03	4120 m	East	Rangpo Chhu	88:51:06	27:22:34
91	No Name	10,867.79	4400 m	North	Rangyong_Chhu	88:27:33	27:43:45
92	No Name	12,198.42	5030 m	North	Yumthang_Chhu	88:48:21	27:51:05
93	No Name	4,826.11	4500 m	North	Zemu_Chhu	88:28:10	27:48:51
94	No Name	3418.963	5060 m	North	Chhombo_Chhu	88:38:13	27:52:11
95	No Name	11,329.47	4200 m	East	Dik_Chhu	88:47:38	27:25:13
96	Chhunzomui Chhokha	237,301.37	4320 m	North	Lachung_Chhu	88:43:11	27:41:51
97	No Name	11,120.93	4750 m	North_West	Prek_Chhu	88:05:47	27:29:44
98	Tsomgo Chho	234,146.53	3740 m	East	Rangpo Chhu	88:46:00	27:22:28
99	No Name	10,098.24	3280 m	North	Rangyong_Chhu	88:25:59	27:42:03
100	Chhopup Chho	39,888.89	4760 m	North	Yumthang_Chhu	88:51:00	27:49:48
101	No Name	3,623.32	4670 m	North	Zemu_Chhu	88:27:48	27:48:54
102	No Name	4072.643	4920 m	North	Chhombo_Chhu	88:38:08	27:51:58
103	Ratechhungu_Chho	8,459.59	4420 m	East	Dik_Chhu	88:48:07	27:25:09
104	No Name	16,621.70	3840 m	North	Lachung_Chhu	88:40:58	27:42:31
105	No Name	27,169.72	4720 m	North_West	Prek_Chhu	88:04:14	27:29:59
106	Namnang Chho	69,856.42	4040 m	East	Rangpo Chhu	88:50:55	27:22:17
107	Chhopup Chho 2	57,783.65	4800 m	North	Yumthang_Chhu	88:51:13	27:49:33
108	No Name	17,472.80	4840 m	North	Zemu_Chhu	88:25:23	27:48:58
109	No Name	21239.671	5040 m	North	Chhombo_Chhu	88:37:48	27:52:20
110	Tamze_Chho(Hans_Pokhri)	66,968.75	3931 m	East	Dik_Chhu	88:46:23	27:25:58
111	Jockchen2	11,485.89	4060 m	North	Lachung_Chhu	88:40:44	27:43:08
112	No Name	4,398.91	4680 m	North_West	Prek_Chhu	88:04:26	27:30:02
113	No Name	7,215.13	4040 m	East	Rangpo Chhu	88:49:09	27:22:13
114	No Name	36,883.70	4920 m	North	Yumthang_Chhu	88:52:08	27:50:09
115	No Name	10,342.36	4500 m	North	Zemu_Chhu	88:28:02	27:49:02
116	No Name	22136.271	5040 m	North	Chhombo_Chhu	88:38:08	27:52:16
117	No Name	48,235.57	4480 m	East	Dik_Chhu	88:47:35	27:25:58
118	Jockchen	32,621.47	4280 m	North	Lachung_Chhu	88:40:40	27:43:20
119	No Name	2,312.69	4770 m	North_West	Prek_Chhu	88:04:19	27:30:01
120	No Name	250,690.11	3925 m	East	Rangpo Chhu	88:49:38	27:22:05
121	No Name	50,130.00	5320 m	North	Yumthang_Chhu	88:52:48	27:50:30
122	No Name	6,196.93	4620 m	North	Zemu_Chhu	88:27:48	27:49:01
123	No Name	21060.562	4920 m	North	Chhombo_Chhu	88:37:22	27:55:02
124	Chhu_Lu	13,036.79	4240 m	East	Dik_Chhu	88:47:11	27:26:17
125	No Name	40,335.06	3920 m	North	Lachung_Chhu	88:41:09	27:43:43
126	Khangla Chho	53,540.93	4860 m	North_West	Prek_Chhu	88:03:25	27:30:01
127	No Name	22,705.56	4040 m	East	Rangpo Chhu	88:49:12	27:22:07
128	Kasang Chho	56,953.72	4940 m	North	Yumthang_Chhu	88:52:14	27:50:51

129	No Name	10,172.86	4830 m	North	Zemu_Chhu	88:24:51	27:49:03
130	Burum Chokha	16426.159	4410 m	North	Chhombo_Chhu	88:36:14	27:47:34
131	Pemthang_Chho5	48,089.52	4080 m	East	Dik_Chhu	88:45:22	27:25:42
132	No Name	10,698.83	4620 m	North	Lachung_Chhu	88:46:40	27:44:14
133	No Name	6,624.68	4580 m	North_West	Prek_Chhu	88:03:07	27:29:44
134	No Name	8,732.63	4100 m	East	Rangpo Chhu	88:49:01	27:22:04
135	No Name	47,244.60	4980 m	North	Yumthang_Chhu	88:52:41	27:51:02
136	No Name	29,010.61	4740 m	North	Zemu_Chhu	88:26:15	27:49:05
137	No Name	6299.606	4440 m	North	Chhombo_Chhu	88:34:30	27:51:13
138	Pemthang_Chho1	74,087.43	4080 m	East	Dik_Chhu	88:45:41	27:25:46
139	No Name	8,300.03	4600 m	North	Lachung_Chhu	88:41:42	27:44:09
140	Khangla Chho	21,146.59	4450 m	North_West	Prek_Chhu	88:03:11	27:29:24
141	No Name	9,437.35	4040 m	East	Rangpo Chhu	88:48:48	27:22:04
142	No Name	19,068.21	4940 m	North	Yumthang_Chhu	88:52:28	27:51:04
143	No Name	30,040.50	4880 m	North	Zemu_Chhu	88:25:02	27:49:11
144	No Name	11912.156	4300 m	North	Chhombo_Chhu	88:34:39	27:51:27
145	No Name	18,116.42	4160 m	East	Dik_Chhu	88:46:04	27:26:26
146	No Name	10,045.90	4840 m	North	Lachung_Chhu	88:41:59	27:44:34
147	No Name	21,589.66	4540 m	North_West	Prek_Chhu	88:03:03	27:28:15
148	No Name	8,552.26	4040 m	East	Rangpo Chhu	88:49:20	27:22:03
149	No Name	15,336.71	4840 m	North	Yumthang_Chhu	88:52:02	27:51:36
150	No Name	6,462.73	4940 m	North	Zemu_Chhu	88:24:40	27:49:22
151	No Name	9222.369	4440 m	North	Chhombo_Chhu	88:35:08	27:52:56
152	No Name	19,003.63	4700 m	North	Lachung_Chhu	88:40:56	27:44:44
153	Mujur Pokhari	93,703.57	4250 m	North_West	Prek_Chhu	88:03:25	27:28:42
154	No Name	11,770.82	4080 m	East	Rangpo Chhu	88:48:55	27:21:58
155	No Name	130,357.90	4880 m	North	Yumthang_Chhu	88:51:54	27:15:50
156	No Name	56,733.76	5040 m	North	Zemu_Chhu	88:25:21	27:49:28
157	Shera_Phu	114983.029	4840 m	North	Chhombo_Chhu	88:37:09	27:55:19
158	No Name	18,291.75	4000 m	North	Lachung_Chhu	88:36:52	27:44:40
159	Khangla Chho	19,035.64	4450 m	North_West	Prek_Chhu	16:03:42	27:28:54
160	Elep Chho 1	44,603.19	4600 m	East	Rangpo Chhu	88:52:22	27:21:31
161	No Name	52,230.14	5080 m	North	Yumthang_Chhu	88:51:29	27:52:23
162	No Name	137,049.79	5280 m	North	Zemu_Chhu	88:19:15	27:49:49
163	No Name	34863.392	4720 m	North	Chhombo_Chhu	88:30:34	27:50:37
164	No Name	27,566.97	4000 m	North	Lachung_Chhu	88:37:39	27:45:33
165	No Name	6,070.81	4520 m	North_West	Prek_Chhu	88:04:26	27:28:36
166	Elep Chho 2	57,151.71	4600 m	East	Rangpo Chhu	88:52:37	27:21:25
167	No Name	9,435.93	4520 m	North	Yumthang_Chhu	88:49:59	27:51:10
168	Langpo Chho	109,946.27	5320 m	North	Zemu_Chhu	88:14:04	27:50:33
169	No Name	27957.702	4880 m	North	Chhombo_Chhu	88:30:38	27:51:00
170	No Name	9,625.98	4420 m	North	Lachung_Chhu	88:38:56	27:46:02
171	No Name	16,608.53	4045 m	North_West	Prek_Chhu	88:05:59	27:28:17
172	Elep Chho 3	35,752.32	4640 m	East	Rangpo Chhu	88:52:46	27:21:17

173	No Name	16,809.63	4600 m	North	Yumthang_Chhu	88:49:27	27:51:26
174	Goma Sechen Tso1	159,793.19	5240 m	North	Zemu_Chhu	88:15:13	27:52:50
175	No Name	44487.386	4540 m	North	Chhombo_Chhu	88:34:45	27:54:09
176	No Name	8,730.42	4420 m	North	Lachung_Chhu	88:38:53	27:46:00
177	No Name	6,433.11	4210 m	North_West	Prek_Chhu	88:13:28	27:28:50
178	Menmoi Chho	221,221.95	3660 m	East	Rangpo Chhu	88:49:34	27:20:56
179	No Name	108,532.22	4940 m	North	Yumthang_Chhu	88:47:30	27:52:23
180	Goma Sechen Tso2	84,323.63	5180 m	North	Zemu_Chhu	88:15:46	27:52:56
181	No Name	2497.533	4490 m	North	Chhombo_Chhu	88:34:07	27:54:09
182	No Name	37,477.81	4420 m	North	Lachung_Chhu	88:38:50	27:46:22
183	Dalle Pokhari	17,333.51	4280 m	North_West	Prek_Chhu	88:13:10	27:29:03
184	Chhokhya Chho	40,072.72	3960 m	East	Rangpo Chhu	88:50:36	27:18:30
185	Khang Kyong	502,396.46	5320 m	North	Yumthang_Chhu	88:45:51	27:53:40
186	Goma Sechen Tso3	108,450.65	5160 m	North	Zemu_Chhu	88:16:05	27:53:07
187	No Name	39158.367	4880 m	North	Chhombo_Chhu	88:30:25	27:51:00
188	No Name	4,915.67	4170 m	North_West	Prek_Chhu	88:13:43	27:28:35
189	No Name	23,510.13	3860 m	East	Rangpo Chhu	88:50:20	27:18:16
190	No Name	7,669.12	5300 m	North	Yumthang_Chhu	88:39:45	27:55:06
191	Goma Sechen Tso4	96,229.09	5140 m	North	Zemu_Chhu	88:15:49	27:53:32
192	No Name	7728.059	4720 m	North	Chhombo_Chhu	88:30:13	27:54:55
193	No Name	2,384.35	4465 m	North_West	Prek_Chhu	88:14:08	27:28:38
194	No Name	29,730.61	1640 m	East	Rangpo Chhu	88:40:45	27:11:11
195	Sebu Chho 1	72,518.41	4820 m	North	Yumthang_Chhu	88:40:59	27:55:21
196	No Nmae	22,556.16	5220 m	North	Zemu_Chhu	88:19:48	27:53:39
197	No Name	8338.876	4790 m	North	Chhombo_Chhu	88:30:08	27:55:06
198	No Name	3,436.82	4480 m	North_West	Prek_Chhu	88:14:13	27:28:43
199	Sebu Chho 2	147,218.75	4840 m	North	Yumthang_Chhu	88:40:25	27:55:08
200	No Nmae	29,641.64	5220 m	North	Zemu_Chhu	88:19:44	27:53:49
201	No Name	3100.503	4860 m	North	Chhombo_Chhu	88:30:24	27:55:01
202	No Name	3,004.03	4270 m	North_West	Prek_Chhu	88:14:06	27:28:17
203	No Name	28,088.40	5100 m	North	Yumthang_Chhu	88:40:10	27:55:41
204	S. Lhonak Chho	707,403.63	5300 m	North	Zemu_Chhu	88:12:14	27:54:45
205	Khangchung_Chho	1642411.686	5310 m	North	Chhombo_Chhu	88:49:02	27:59:28
206	No Name	2,152.37	4320 m	North_West	Prek_Chhu	88:14:08	27:28:14
207	No Name	10,647.71	5120 m	North	Yumthang_Chhu	88:40:07	27:55:52
208	N. Lhonak Chho	105,253.50	5540 m	North	Zemu_Chhu	88:10:22	27:55:08
209	No Name	17548.426	5230 m	North	Chhombo_Chhu	88:44:26	27:59:24
210	No Name	2,219.59	3900 m	North_West	Prek_Chhu	88:06:19	27:27:32
211	No Name	43,971.35	5170 m	North	Yumthang_Chhu	88:39:43	27:56:00
212	No Name	138,291.41	5180 m	North	Zemu_Chhu	88:19:00	27:55:12
213	Mashya_Tso	77974.139	5240 m	North	Chhombo_Chhu	88:45:57	27:59:37
214	No Name	10,722.73	4340 m	North_West	Prek_Chhu	88:04:25	27:27:00
215	No Name	5,941.20	4930 m	North	Yumthang_Chhu	88:41:11	27:56:06
216	No Name	19,743.31	5540 m	North	Zemu_Chhu	88:10:25	27:55:17

217	No Name	5139.293	4990 m	North	Chhombo_Chhu	88:39:09	27:57:43
218	No Name	13,542.96	4410 m	North_West	Prek_Chhu	88:04:35	27:26:51
219	No Name	5,458.51	4930 m	North	Yumthang_Chhu	88:41:12	27:56:00
220	No Name	91,317.53	5240 m	North	Zemu_Chhu	88:16:10	27:56:10
221	No Name	6987.067	4785 m	North	Chhombo_Chhu	88:39:06	27:57:49
222	Lachhimi Pokhari	161,008.10	4300 m	North_West	Prek_Chhu	88:05:08	27:26:14
223	No Name	3,285.06	5030 m	North	Yumthang_Chhu	88:41:14	27:56:42
224	Khora Chho	550,688.25	5160 m	North	Zemu_Chhu	88:20:03	27:56:47
225	No Name	4772.922	4790 m	North	Chhombo_Chhu	88:38:52	27:57:46
226	Thullo Lumle Pokhari 2	18,327.77	4440 m	North_West	Prek_Chhu	88:05:24	27:25:15
227	No Name	9,516.10	5020 m	North	Yumthang_Chhu	88:41:20	27:56:43
228	No Name	70,113.05	5240 m	North	Zemu_Chhu	88:16:29	27:56:33
229	Gurudongmar Lake1	1087435.095	5165 m	North	Chhombo_Chhu	88:42:47	28:01:29
230	Thullo Lumle Pokhari 1	7,651.30	4410 m	North_West	Prek_Chhu	88:05:13	27:25:56
231	No Name	4,407.33	5040 m	North	Yumthang_Chhu	88:41:16	27:56:51
232	No Name	332,720.35	5180 m	North	Zemu_Chhu	88:18:30	27:56:57
233	No Name	18482.737	5020 m	North	Chhombo_Chhu	88:38:07	27:57:49
234	Sano Jumle Pokhari 2	1,716.98	4340 m	North_West	Prek_Chhu	88:07:00	27:25:31
235	No Name	7,329.58	5050 m	North	Yumthang_Chhu	88:41:29	27:56:52
236	No Name	24,786.10	5180 m	North	Zemu_Chhu	88:19:28	27:56:45
237	Simala_Jheel2	46473.283	5640 m	North	Chhombo_Chhu	88:39:25	28:00:15
238	Sano Jumle Pokhari 1	3,409.02	4360 m	North_West	Prek_Chhu	88:07:02	27:25:34
239	No Name	6,306.75	5070 m	North	Yumthang_Chhu	88:41:27	27:57:00
240	Tso Chik	46,386.71	5460 m	North	Zemu_Chhu	88:13:17	27:56:47
241	Cheora_Tso	47952.534	4990 m	North	Chhombo_Chhu	88:41:18	28:02:41
242	Sukhe Pokhari	6,310.63	4060 m	North_West	Prek_Chhu	88:11:38	27:29:46
243	No Name	2,666.26	5110 m	North	Yumthang_Chhu	88:14:17	27:57:20
244	Chhora Chhobuk	111,494.21	5020 m	North	Zemu_Chhu	88:21:22	27:57:00
245	Chho_Lhamo1	1042844.868	5060 m	North	Chhombo_Chhu	88:45:31	28:00:39
246	Lam Pokhari	100,878.52	4280 m	North_West	Prek_Chhu	88:12:56	27:29:16
247	No Name	10,062.87	5250 m	North	Yumthang_Chhu	88:42:58	27:56:36
248	No Name	42,651.19	5220 m	North	Zemu_Chhu	88:17:55	27:57:08
249	Simala_Jheel1	132315.454	5540 m	North	Chhombo_Chhu	88:39:15	28:00:44
250	No Name	13,936.60	5320 m	North	Yumthang_Chhu	88:43:19	27:56:32
251	No Name	61,769.31	5160 m	North	Zemu_Chhu	88:24:05	27:57:15
252	Gurudongmar Lake3	1075692.87	5360 m	North	Chhombo_Chhu	88:42:55	28:00:21
253	No Name	16,636.96	5320 m	North	Yumthang_Chhu	88:43:21	27:56:52
254	Tso Chhobek	170,911.79	5020 m	North	Zemu_Chhu	88:21:39	27:57:19
255	Taga_Chho	13246.866	4815 m	North	Chhombo_Chhu	88:35:35	27:57:44
256	No Name	32,581.91	4920 m	North	Yumthang_Chhu	88:42:24	27:57:02
257	Bhut Pokhari	75,342.52	5180 m	North	Zemu_Chhu	88:23:27	27:57:26
258	Gongng_Tso	20535.932	4740 m	North	Chhombo_Chhu	88:34:09	27:57:32
259	No Name	6,546.95	5360 m	North	Yumthang_Chhu	88:43:52	27:56:21
260	No Name	13,211.40	5260 m	North	Zemu_Chhu	88:20:17	27:57:35

261	Sugu_Chho	121510.214	4780 m	North	Chhombo_Chhu	88:36:17 27:59:23
262	No Name	15,302.40	5280 m	North	Yumthang_Chhu	88:44:06 27:56:38
263	No Name	16,509.64	5100 m	North	Zemu_Chhu	88:26:07 27:57:40
264	La_Jheel	260013.799	5000 m	North	Chhombo_Chhu	88:34:25 28:00:23
265	No Name	12,454.93	5320 m	North	Yumthang_Chhu	88:43:45 27:57:27
266	Dub Pokhari	35,957.04	5040 m	North	Zemu_Chhu	88:22:16 27:57:20
267	No Name	52990.27	5140 m	North	Chhombo_Chhu	88:33:30 27:59:42
268	No Name	11,090.00	5300 m	North	Yumthang_Chhu	88:43:57 27:57:13
269	Kale Pokhari 2	59,043.02	5220 m	North	Zemu_Chhu	88:21:06 27:57:53
270	No Name	1794.429	4820 m	North	Chhombo_Chhu	88:31:45 27:56:16
271	No Name	10,716.11	5260 m	North	Yumthang_Chhu	88:04:04 27:57:30
272	No Name	151,331.56	5040 m	North	Zemu_Chhu	88:25:57 27:58:08
273	No Name	1505.63	5090 m	North	Chhombo_Chhu	88:31:47 27:56:35
274	No Name	9,194.23	5260 m	North	Yumthang_Chhu	88:44:04 27:58:07
275	Dub Pokhari 2	40,080.41	5110 m	North	Zemu_Chhu	88:22:31 27:58:10
276	No Name	921.434	5090 m	North	Chhombo_Chhu	88:31:44 27:56:34
277	No Name	5,428.18	5160 m	North	Yumthang_Chhu	88:44:56 27:58:23
278	Kale Pokhari	44,318.41	5380 m	North	Zemu_Chhu	88:20:50 27:58:10
279	No Name	3990.98	4960 m	North	Chhombo_Chhu	88:31:36 27:56:43
280	No Name	23,177.01	5080 m	North	Yumthang_Chhu	88:44:38 27:58:07
281	Thang Chho	100,012.96	5100 m	North	Zemu_Chhu	88:26:29 27:58:21
282	No Name	19931.128	4820 m	North	Chhombo_Chhu	88:31:27 27:56:21
283	No Name	8,661.11	5060 m	North	Yumthang_Chhu	88:44:43 27:57:55
284	Thang Chho	122,775.72	5240 m	North	Zemu_Chhu	88:25:29 27:58:23
285	No Name	1044.703	4840 m	North	Chhombo_Chhu	88:31:22 27:56:22
286	Sanglaphui Chho	206,774.72	5040 m	North	Yumthang_Chhu	88:44:44 27:57:43
287	No Name	18,296.65	5180 m	North	Zemu_Chhu	88:25:29 27:59:43
288	No Name	3289.825	4890 m	North	Chhombo_Chhu	88:31:25 27:56:36
289	No Name	54,486.74	5200 m	North	Yumthang_Chhu	88:46:12 27:57:40
290	No Name	422,655.05	5120 m	North	Zemu_Chhu	88:29:48 27:00:23
291	No Name	1028.955	4785 m	North	Chhombo_Chhu	88:30:53 27:56:42
292	No Name	34,894.64	5220 m	North	Yumthang_Chhu	88:46:18 27:57:53
293	No Name	40,100.63	5290 m	North	Zemu_Chhu	88:27:33 27:00:21
294	No Name	1431.703	4680 m	North	Chhombo_Chhu	88:30:47 27:56:36
295	No Name	152,344.64	5600 m	North	Yumthang_Chhu	88:47:44 27:58:37
296	Nake Tso	172,243.95	5320 m	North	Zemu_Chhu	88:29:22 28:01:47
297	No Name	1184.995	4745 m	North	Chhombo_Chhu	88:30:39 27:56:50
298	No Name	175,894.63	5360 m	North	Yumthang_Chhu	88:47:58 27:58:06
299	No Name	29,927.63	5340 m	North	Zemu_Chhu	88:28:49 27:01:39
300	No Name	1023.495	4785 m	North	Chhombo_Chhu	88:30:39 27:56:55
301	No Name	131,096.06	5360 m	North	Yumthang_Chhu	88:47:56 27:57L47
302	No Name	1188.85	4800 m	North	Chhombo_Chhu	88:30:57 27:56:42
303	No Name	4,512.35	4940 m	North	Yumthang_Chhu	88:52:22 27:51:02
304	No Name	7722.564	4940 m	North	Chhombo_Chhu	88:31:22 27:56:41

305	Sima Chhokha	139,410.57	4440 m	North	Yumthang_Chhu	88:50:05 27:43:48
306	No Name	7199.298	4740 m	North	Chhombo_Chhu	88:30:42 27:56:46
307	No Name	6,626.96	5020 m	North	Yumthang_Chhu	88:41:19 27:56:27
308	No Name	2237.502	4635 m	North	Chhombo_Chhu	88:30:22 27:57:33
309	No Name	3265.912	4650 m	North	Chhombo_Chhu	88:30:22 27:57:39
310	No Name	3564.794	4675 m	North	Chhombo_Chhu	88:30:22 27:57:45
311	Bhut Pokhari	160078.422	4920 m	North	Chhombo_Chhu	88:30:34 27:58:47
312	Chho Yummo	35528.537	5220 m	North	Chhombo_Chhu	88:34:33 28:02:15
313	Lha Tso	254055.398	5140 m	North	Chhombo_Chhu	88:33:49 28:00:48
314	Gyapji Chho1	551589.188	5000 m	North	Chhombo_Chhu	88:37:03 27:58:23
315	Mukti Boul Jheel	36063.226	5040 m	North	Chhombo_Chhu	88:36:37 28:01:27
316	Lungma Chho	56808.636	5440 m	North	Chhombo_Chhu	88:34:42 28:03:18

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