Chapter 5

Terrain Classification, Hazard and Vulnerability Assessment of the Imja and Dudh Koshi Valleys in Nepal[1]

The Khumbu region of Nepal has experienced three GLOF events in the recent past: Nare (1977), Dig Tsho (1985), and Tam Pokhari (1998). Lake Imja Tsho in this same area is noted to be growing at a high rate (Chapter 3); it has a storage capacity of about 36 million cubic metres and is situated at an altitude of 5020m. The rapid expansion of this lake and its extensive storage capacity (more than six times that of the Dig Tsho, which burst in 1985) make it the most hazardous lake in the Khumbu region of the Nepal Himalaya. As seen from the simulations (Chapter 4) the consequences of a Lake Imja Tsho GLOF would be devastating to the downstream areas. The damage would be particulary devastating to the human population since the Khumbu region is one of Nepal's most densely populated high-mountain areas, and its proximity to Mt. Everest makes it one of the most popular tourist destinations in the country. A GLOF event at Lake Imja Tsho would jeopardise populated valleys, tourist areas, trails, and bridges. The tremendous volume of water already retained behind the moraine dam at Lake Imja Tsho requires that it be closely monitored. The terrain classification work discussed in this chapter is essential to support monitoring, evaluation and mitigation work, all of which will help to reduce the GLOF risk.

The most recent GLOF event in the Khumbu region was the Dig Tsho GLOF of 1985. This GLOF had an enormous impact on the downstream areas it shares with Lake Imja Tsho. Impacts like bank erosion and landslides are visible even today in the Langmoche, Bhote Koshi, and lower Dudh Koshi valleys. All indications are that, for several reasons, the impacts of a Lake Imja Tsho GLOF on the river valley below would be much more severe than those resulting from the Dig Tsho GLOF. First, the lake retains about six times more water. Second, lateral erosion in the downstream valleys remains active after the most recent GLOF event, the upper Imja and upper Dudh Koshi valleys already face severe erosion and sedimentation problems, and slope instability has been a longstanding problem in these valleys. Third, old and new lateral erosion could occur over a larger area and at steeper slopes along the river valleys.

GLOFs often set in motion a complex set of catastrophic events including floods, sediment transport, and large debris flow, none of which can be accurately predicted or foreseen; nevertheless, terrain units (TU) can be a good indicator of the magnitude of what might transpire. The GLOF hazard map along the Imja and Dudh Koshi valleys was updated using the terrain unit responses from the 1985 GLOF. This map can be used as a tool to help create awareness among both local people and tourists about the real dangers that GLOFs pose to human life and infrastructure. GLOF hazard awareness is also needed for any further

[1] Contributed by S.R. Bajracharya, P.R. Maskey, and S.P. Joshi

infrastructure development in the area. Construction of many suspension bridges in the downstream valleys after the Dig Tsho GLOF benefited from lessons learned from the catastrophe; they were built at higher elevations to minimise the impact that another flood might have on their infrastructure. However, the bridge at Hilajun (at the Langmoche – Bhote Koshi confluence) in the Dig Tsho basin is located on the flood plain, and remains vulnerable to GLOFs. Although the Dig Tsho GLOF flooded houses located downstream from Phakding village, the number of houses in this flood-prone area is still increasing. Houses located on lower terraces (mostly in the Benkar, Phakding, and other low-lying areas) are at high risk of both flooding and lateral erosion.

Terrain classification

For the purposes of this study, the riverbed slopes were classified (Table 5.1) and the GLOF hazard areas downstream of Lake Imja Tsho divided as shown in Figure 5.1 and summarised in the following box. Past experience with GLOF hazards suggests that river reaches can be categorised into different terrain units (Tables 5.2 and Figures 5.2 to 5.5) to help evaluate the risk from a possible GLOF. The impact that the past Dig Tsho GLOF had on the river valley and the field knowledge gained from that experience were incorporated into the classification of the terrain units. Five terrain units were defined based on the characteristic features of their river reaches: river gradient, valley width, height of the terraces, river curvature, and settlements. The definitions are given in the box. These terrain units will be used as part of the information needed for hazard assessment of the Imja and Dudh Koshi valleys.

The entire Imja Khola riverbed is mostly classed as either S1 or S2; the maximum gradient is 0.126 and the minimum gradient is 0.028. The average gradient of the river bed is 0.075, and on average is classed as S2. The Langmoche Khola (with the exception of its lower reaches) and the Bhote Koshi have gradients similar to the Imja Khola. The lower reaches of the Langmoche are slightly less steep than the upper reaches and can be classed as S2 and S3. The gradient of the lower Dudh Koshi are classed as S2 and S3 and have a maximum gradient of 0.069 and a minimum gradient of 0.017. The average gradient of the lower Dudh Koshi is 0.041 and is classed as S3. The Langmoche river valley and the Imja Khola river valley have similar gradients and share a common river section beyond Larja Dobhan. Using information from the 1985 Dig Tsho GLOF as a guide, and comparing the river morphologies (gradient, curvature, width of the valley, height of the terraces, and others) one could predict that if an Imja GLOF occured, it would have an impact at least six times greater than the Dig GLOF of 1985.

Table 5.1: **Classification of riverbed slopes of Imja, Langmoche, Bhote Koshi and Dudh Koshi**

Valley	Slope		
	Maximum	Minimum	Average
Imja (Lake Imja Tsho to Dudh Koshi confluence	0.126	0.028	0.075
Upper Dudh Koshi (Imja-Dudh Koshi confl. to Larja Dobhan)	0.096	0.043	0.075
Lower Dudh Koshi (Larja Dobhan to downstream)	0.070	0.018	0.041
Langmoche (Dig Tsho to Hilajun)	0.112	0.057	0.084
Bhote Koshi (Hilajun to Larja Dobhan)	0.107	0.072	0.086

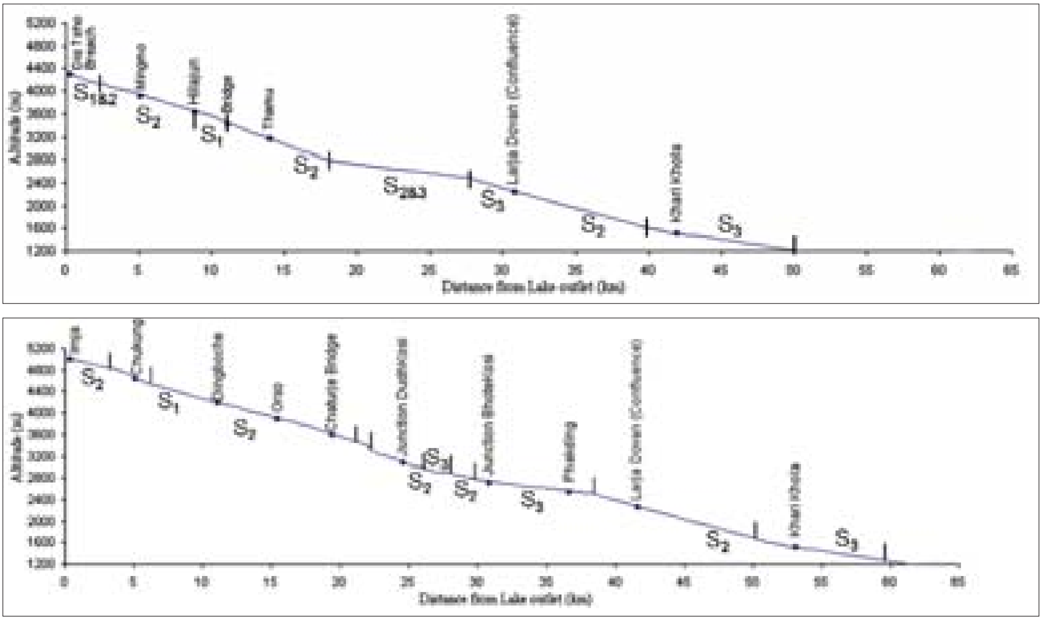

Figure 5.1: Slope profile of the Langmoche (top) and Imja (bottom) Khola down to Khari Khola confluence near Lukla village

Terrain Units in Langmoche, Bhote Koshi, Imja and Dudh Koshi

Segments	**Valley**
I-1 to **I-11**	Imja Valley from Imja outlet to the Dudh Koshi Confluence
I-11 to **DI-1**	Upper Dudh Koshi valley from the Imja – Dudh Koshi confluence near Tengboche to Larja Dovan
DI-downstream	Lower Dudh Koshi from Larja Dovan to Lukla and areas further downstream
D-1 to **D-4**	Langmoche valley from Lake Dig Tsho to the Bhote Koshi confluence
D-4 to **DI-1**	Bhote Koshi valley from the confluence to Larja Dovan

Terraces are classified according to height

- **lower** (<5m above the riverbed)
- **middle** (5 >10m above the riverbed)
- **upper** (>10m from the riverbed)

River valley reaches are classified according to the width of the river valley

- **narrow** <50m wide
- **moderate** 50 >100m wide
- **wide** >100m wide.

River bed gradients (slope): the reach of the river from Dig Tsho and Lake Imja Tsho to Lukla village is classified as

- **S1** $\geq$ 0.10: very steep
- 0.05 < **S2** <0.1: steep
- 0.05 $\leq$ **S3**: moderately steep

Terrain units are classified as:

- **TU1**: Narrow valley with steep river gradient and breach fan
- **TU2**: Upper terrace with narrow valley
- **TU3**: Middle upper terrace with moderately wide valley
- **TU4**: Lower terrace with wide valley
- **TU5**: Upper terrace with wide valley

The maximum gradient (0.126) is found in the Imja valley and the minimum gradient (0.018) in the lower Dudh Koshi valley (Figure 5.2 and Table 5.1).

Table 5.2: **Terrain classification of the Langmoche, Bhote Koshi, Imja, and Dudh Koshi valleys (up to Ghat village)**

Terrain Unit	Riverbed materials	Characteristic features	Erosion / Sedimentation from GLOF	Section	
				Langmoche Khola and downstream	Imja Khola and downstream
TU1: Narrow steep river with breach fan	*Straight reach:* very big boulders >1 m dominant, huge amount of sediment deposit	Very steep river (S1), V-shaped side slopes at outlet, rapids and falls, severe bed and bank erosion	Severe bed abrasion, bank widening and erosion, huge sedimentation of large boulders >1 m dominant	Outlet, breach, immediate downstream valley	Imja outlet, immediate downstream valley
TU2: Upper terrace with narrow valley	*Narrow:* 0.5m dominant, 1-2m scattered	Very steep river (S1), rapids, jump, extensive landslides upstream and downstream of narrow section and bends	Severe lateral erosion extending to 10m height, about 200 m upstream and downstream, upstream sedimentation, downstream erosion of bed and bank	Thame gorge	Imja constriction, Milingo gorge
		Steep (S2), rapids, jumps, and sharp bends within a relatively wide river valley	Severe erosion of bends, deposition at bed	Bhote Koshi-Langmoche and Bhote Koshi- Dudh Koshi confluence	Bhote Koshi-Dudh Koshi and Tsuro confluence
		Steep (S2), rapids, jumps, narrow, incised bed rock, highly dissected by channels, inaccessible river valley	Severe lateral and bed erosion at narrow sections and sharp bends, location for temporary damming	Thamu- Larja Dovan	Milingo Bridge – Larja Dovan, Syomare
			Severe lateral and bed erosions at narrow sections and sharp bends; settlements at upper terrace affected by landslide	Thado Koshi, Nachipan, Senma, Chheplun, Tate, Muse, Rondinma, Lukla, Chaurikharka,	
TU3: Middle c upper terrace with moderately wide valley	*Bends:* sedimentation <0.5m dominant, 1m few	Moderately steep (S3), short sharp bends, rapids, falls, over-topping of lower terraces, reactivation of old slope instability	Over-topping of banks, severe lateral erosion of shorter length and medium height, series of lateral erosion on outer bends	Ghat, Chutawa, Chermading, Phakding, Benkar Tawa, Jorsalle	
TU4: Lower terrace with wide valley	*Bends:* sedimentation with <0.3m dominant, 0.5-2m significant	Steep (S2), rapids, jumps, bed bars, meander, moderate bed slope, wide valley	Severe lateral erosion of low height and short length at outer sharp bends, lateral erosions of low heights extending higher level at steep slopes.	Langmoche	Pipre Goth, Chhukung (next valley)
	Straight reach: <0.3m dominant, 1-2m scattered	Steep (S2), rapids, meander, channel bars, wide valley	Bed abrasion, widening and deposition of boulders, bank erosion to lower terraces extending to upper terraces on weak geological locations	Langmoche valley Hilajun, Thamo Teng	Imja valley
TU5: Upper terrace with wide valley	*Bends:* <0.3m dominant, 0.5-1m significant 1-2m scattered	Steep (S2), braided, channel bars, meander	Lateral erosion at lower terrace level, sedimentation of river valley with finer materials	Chamuwa, Kamthuwa, Mingmo	Chamuwa, Tsuro, Orsho, Pangboche, Dingboche
	Straight reach: <0.5 m dominant, 0.5-1 m significant, 1-2m scattered	Moderately steep (S3), meander, channel bars	Settlements not affected by flood, lateral erosion at bends at low level, sedimentation of fine materials	Monjo, Thamu	Monjo, Tsuro

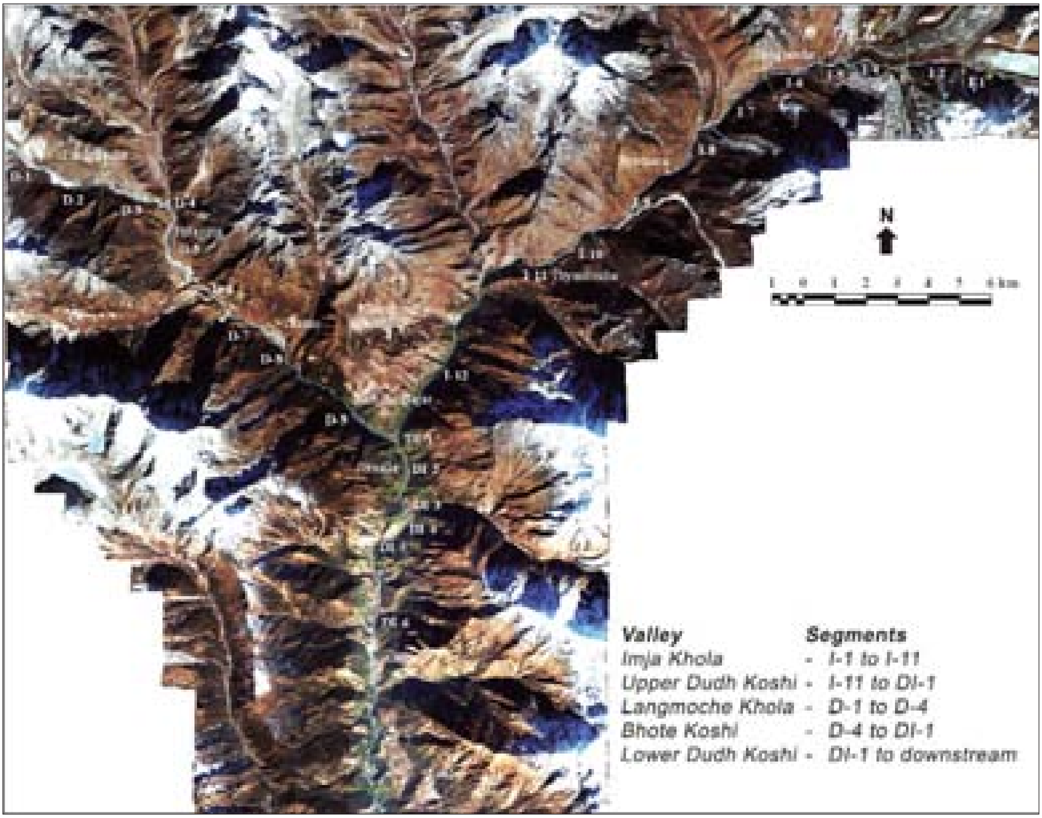

Figure 5.2: Homogeneous geomorphic segments used to classify Langmoche, Bhote Koshi, Imja, and Dudh Koshi valleys into terrain units, as shown in Figures 5.3 - 5.5, base image IKONOS

Figure 5.3: Terrain units (see Table 5.2) from Lake Imja Tsho to Namche Bazar (Larja Dobhan)

Figure 5.4: Terrain units (see Table 5.2) along the Langmoche valley and Bhote Koshi valley from Lake Dig Tsho to Namche Bazar (Larja Dobhan)

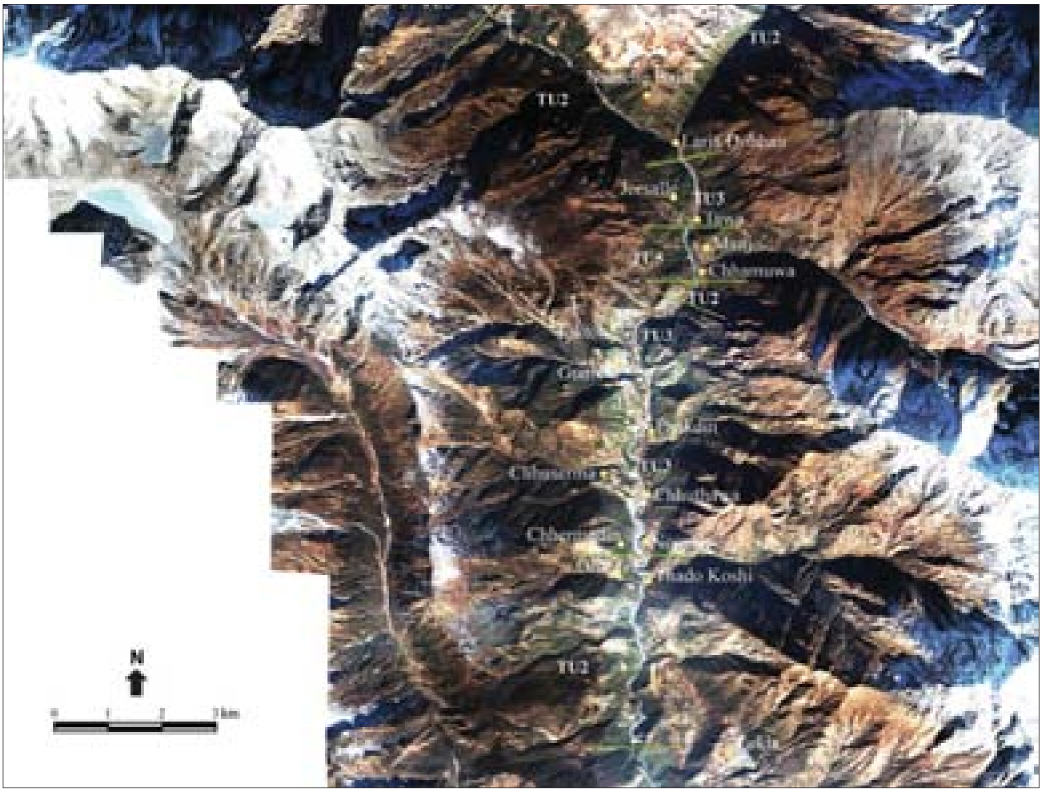

Figure 5.5: Terrain units (see Table 5.2) from Larja Dobhan to Lukla in the Dudh Koshi river valley

Terrain Unit TU1: Narrow valley with steep river gradient and breach fan

The characteristics of TU1 are:
- bed scour,
- bank erosion and widening,
- sedimentation of large boulders, and
- destruction of infrastructure.

TU1a – Dig Tsho (lake outlet, breach section, and downstream; Langmoche – Bhote Koshi valley)

The Dig Tsho GLOF of 1985 deposited a large amount of sediment, ranging in size from big boulders to silt, on the immediate downstream valley (Figure 5.6). The sediment gradually diminishes in size the further it is from the lake outlet. The valley is characterised by a large amount of sediment and many huge boulders. The wide valley, with the debris fan resulting from the GLOF, is shown in Figure 5.7.

GLOF events also cause riverbank erosion. Past GLOFs of Nare, Dig Tsho, and Tam Pokhari in the Dudh Koshi valley have caused extensive erosion of riverbanks and have deposited massive breach fans in their respective river valleys.

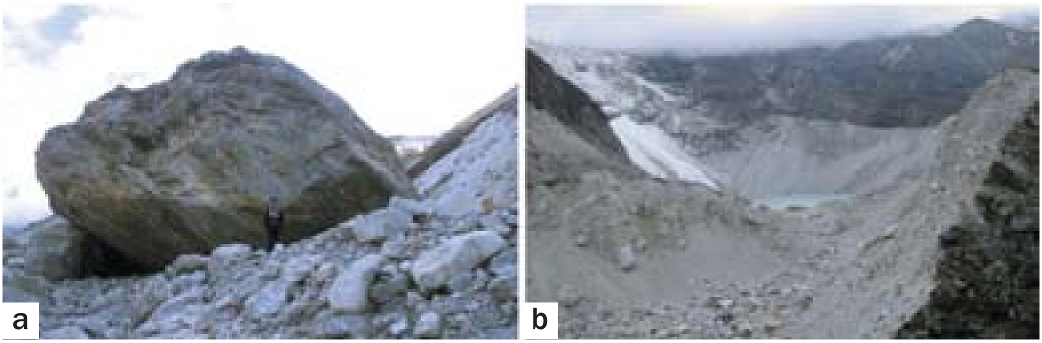

Figure 5.6: Lake Dig Tsho, breached channel and GLOF fan deposits: a) A big boulder resting on debris in the breached valley; b) Lake and breached section

TU1b – Lake Imja Tsho (lake outlet and immediate downstream Imja valley)

Lake Imja Tsho is dammed by a thick, large area of end moraine and exhibits hummocky terrain near the outlet; these are indications that an Imja GLOF may carry with it a very large amount of debris, predictably more so than any other previously recorded GLOF in Nepal (Figure 5.8).

Figure 5.7: Sediments deposited downstream of Dig Tsho

The outlet of Lake Imja Tsho drains through a sloping moraine that opens up into a wide valley immediately after the moraine dam (Figure 5.9). In the case of a GLOF, the wide valley below will experience extensive bed and bank erosion and large amounts of debris will be deposited.

Before the GLOF enters the narrow valley constriction near Pipre Goth, it first traverses a very wide valley where the sediments will most probably be sorted. The bigger size boulders are expected to be deposited nearer the outlet while finer ones will accumulate further downstream. By the time the flow reaches the constriction (4.5 km downstream) the sediment is expected to be quite small (Figure 5.10).

Figure 5.8: Supraglacial lakes and hummocky terrain around Lake Imja Tsho

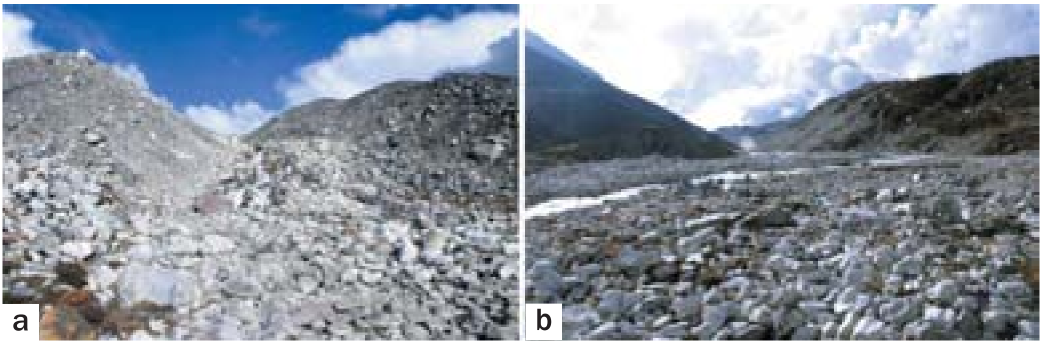

Figure 5.9: Cobble-size sediments deposited at the Lake Imja Tsho outlet (a) and downstream (b)

Figure 5.10: The downstream view of the wide Imja valley before reaching the constriction near Pipre Goth

Terrain Unit TU2: Upper terrace with narrow valley

The characteristics of TU2 are:

- severe abrasion of bed and banks at narrow sections,
- severe lateral erosion upstream and downstream of bends at narrow section extending to terraces of heights of 10m and more,
- deposition of sediment at river bed upstream but scour downstream of narrow section, and
- sedimentation at middle wide river confluence.

TU2a – Dig Tsho (Thame gorge, Bhote Koshi – Langmoche and Bhote Koshi – Dudh Koshi confluence, and Thamu – Larja Dovan)

The terrain unit TU2a consists of upper terraces, narrow valleys and/or sharp bends; it is characterised by lateral erosion at bends upstream and downstream of the river reach (approx. 400m). Bed erosion is prominent at narrow sections and/or sharp bends. This section is very narrow when compared to the adjoining upstream and downstream sections. This narrow section of the river reach acts as a flood control structure during peak GLOF flow and helps retain the flood and debris upstream. This type of section is found at the Thame gorge, Bhote Koshi–Langmoche confluence, Bhote Koshi–Dudh Koshi confluence and Thamu–Larja Dovan.

The narrow sections would experience a high velocity of flow, a series of falls and rapids, severe abrasion of rock surfaces and both downstream bed and lateral erosion. Examples of this type of terrain unit are the Thame and Milingo gorges. Areas both upstream and downstream of these narrow sections would be affected by lateral erosion that would extend some 10m or more on both sides of the river valley. The Thame gorge is about 15m wide and is incised in the bedrock. It contains a series of falls. The bedrock has been extensively abraded in the narrow section. Both the upstream and downstream portions of this reach have lateral erosion of both banks. The erosion at the steep slopes is still active on both banks (Figure 5.11). The Thyanmoche (Thame Teng) located upstream of this narrow section has bank erosion at several points and sedimentation is seen on the river bed. The bed material at Thame Teng is smaller than at the lake-breach area.

Both the Langmoche Khola and Bhote Koshi rivers have sharp bends upstream of the confluence. Lateral erosion has occurred at the bends of both rivers. The sediment scoured from these sections is deposited at the confluence (Figures 5.12 to 5.14). Erosion of the

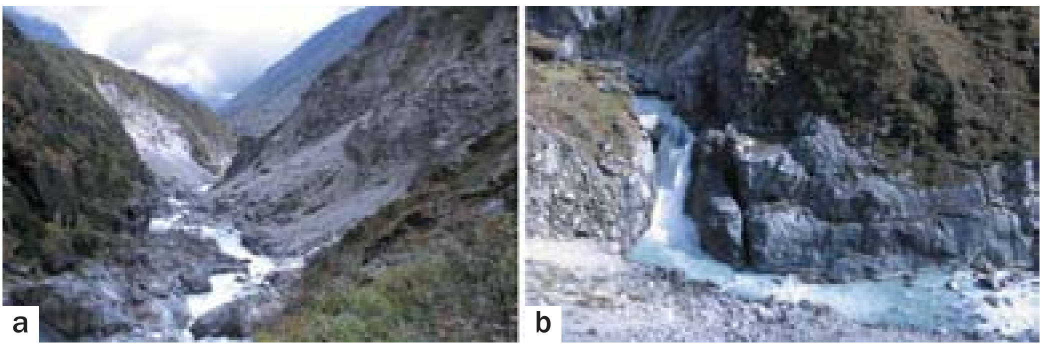

Figure 5.11: Narrows in the Langmoche valley: a) downstream view of both banks with landslides; b) upstream view of the Thame gorge

Figure 5.12: Erosion and sedimentation at the Langmoche (background) and Bhote Koshi (right and foreground) confluence. View upstream

Figure 5.13: Erosion and sedimentation observed at the confluence of the Langmoche Khola and Bhote Koshi. View upstream

Figure 5.14: Bank erosion at the Bhote Koshi–Langmoche confluence

bedrock on the left bank and the palaeo-moraine on right bank is observed. The erosion on the palaeo-moraine extends from the riverbank to the upper river terraces. Similarly, both banks of the Langmoche Khola, which consist of old moraine sediments, have experienced extensive lateral erosion. The lateral erosion extends from the valley floor to the upper terraces.

The river section between Thamu and Larja Dovan passes through a narrow valley. This river section is incised in the bedrock and vegetation cover on both valley slopes (Figures 5.15 to 5.17). The tributaries to this section are also steep, with highly dissected valleys, and can transport larger boulders to the Bhote Koshi. These local streams deposit large boulders and sediment. This type of sediment deposit can be observed in the Larja Dovan, Jorsalle, Tawa, Benkar, and Ghat villages. The lower valley sections are steeper and are covered by thick forest. Settlements are situated only on the upper terraces where the GLOF should have no effect at all.

Figure 5.15: Narrows at Phunki Thanga. View downstream

Figure 5.16: A boulder caught in the narrows between Latho Goth and Larja Dovan. View downstream

Figure 5.17: The deep valley of Lower Dudh Koshi near Larja Dovan. View downstream

Both the Bhote Koshi and Dudh Koshi flow through a narrow valley composed of bedrock near the confluence. The concave bend of the Dudh Koshi records bank erosion while the convex side contains many big boulders (larger than 50 cm) presumably deposited during the Dig Tsho GLOF (Figure 5.18). Due to the deposits of boulders, the level of the right bank is higher than the left bank (Figures 5.19 and 5.20).

Figure 5.18: Erosion and sedimentation at the confluence of the Dudh Koshi (foreground) and Bhote Koshi coming from the left (background) looking upstream of the Bhote Koshi

Figure 5.19: Downstream view of the Dudh Koshi River from Larja Dovan

Figure 5.20: The Bhote Koshi (right) and Dudh Koshi (left) at Larja Dovan looking downstream

TU2b – Lake Imja Tsho (Pipre Goth [Imja Constriction], Milingo gorge, Tsuro confluence, Milingo Bridge – Larja Dovan and Syomare)

This type of terrain unit includes narrow sections in the Imja valley at Pipre Goth (Imja Constriction), Milingo gorge, Tsuro confluence, and Milingo Bridge–Larja Dovan section, and in the lower Dudh Koshi valley at Thado Koshi, Nachipan, Senma, Chheplun, Tate, Muse, Rondinma, Lukla, and Chaurikharka.

The section upstream of the Milingo Bridge is characterised by narrow sections passing through bedrock and by a series of falls similar to the Thame Gorge. The sections both upstream and downstream of the Milingo Gorge have severe bank erosion. The trekking trail on the left bank is affected by river scouring resulting in active landslides (Figure 5.21).

During a GLOF, the Milingo gorge may suffer from extreme bed and lateral erosion similar to the Thame gorge. The lateral erosion both upstream and downstream of the Milingo george will extend to the upper terraces at steeper slopes. Similarities between the narrows of Milingo and Thame are shown in Figures 5.21 and 5.22. A total washout of the trekking trail and a reactivation of massive landslides are inevitable.

Immediately downstream from Lake Imja Tsho, the river valley is very wide, gradually reducing to a narrow section called the Imja constriction. The constriction was caused primarily by the convergence of two lateral moraines. There is another narrow valley below Milingo. The wide valley narrows at the sharp bends of the river section. A possible GLOF impact on the Imja

Figure 5.21: Landslides on the narrows of Milingo, view upstream

Figure 5.22: Downstream view of the narrows of Thame with landslides on the right bank

constriction can be inferred from the scenario at the Thame gorge during the 1985 GLOF, and extreme bed and lateral erosion is expected.

The section of the Imja River that extends from Latho Goth to Larja Dovan has characteristics similar to those at Thamu–Larja Dovan. This reach is also characterised by a narrow river valley with tributaries of steep gradient and a dissected topography with dense vegetation (Figure 5.23). Settlements are located only on the upper valley terraces. Figure 5.16 shows a boulder caught in the narrows where temporary damming during GLOF is possible.

The Imja River has a sharp bend downstream of the Imja constriction at Pipre. The sharp bend can cause severe bank erosion at the outer bend similar to that at the Hilajun outer bend. A wide downstream valley at Chhukung would receive a deposit of dominant boulders larger than 50 cm as occurred at Hilajun and Thame Teng following the Dig Tsho GLOF. Extreme lateral erosion with many landslides on the banks of lower terraces would probably occur downstream of the confluence.

In the areas upstream of the Tsuro confluence is a wide valley. The debris seen on the left bank derive mainly from the Nare GLOF (Figure 5.24). Before reaching the confluence, the Imja River passes through a narrow valley made up of the Tsuro glacial deposits. The area at the confluence of the rivers from the Khumbu Glacier and the Imja River (near Pheriche village) is a wide valley but the river narrows near the Tsuro confluence (Figures 5.25 and 5.26). Upstream of the confluence (towards the Imja River) are several bends where extensive erosion is possible; this area consists of the palaeo-moraine of the Tsuro glacier. These sediments might be transported long distances, possibly even beyond Orsho. Such a process is seen at the Langmoche–Bhote Koshi confluence and the Bhote Koshi–Dudh Koshi confluence (which experienced the Dig Tsho GLOF).

Figure 5.23: The downstream view of the Dudh Koshi River from the Milingo bridge, showing extensive erosion

Figure 5.24: A wide valley upstream of the Tsuro confluence. The debris on the left bank derives from the 1977 Nare GLOF

Figure 5.25: Upstream view of the Imja valley from the Tsuro confluence

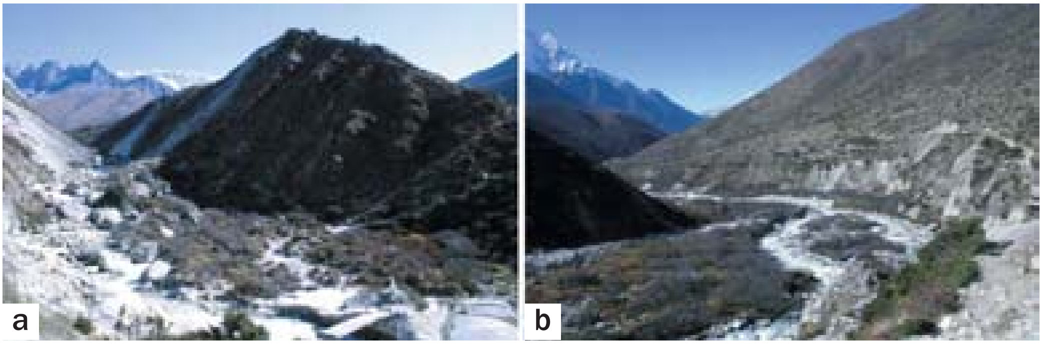

Figure 5.26: Situation near the Tsuro confluence: a) Upstream view to Pheriche, b) downstream view to the Imja valley

TU2c – Lower Dudh Koshi (Thado Koshi, Nachipan, Senma, Chheplun, Tate, Muse, Rondinma, Lukla, and Chaurikharka)

Narrow valley sections are also observed in the lower Dudh Koshi valley at Thado Koshi, Nachipan, Senma, Chheplun, Tate, Muse, Rondinma, Lukla, and Chaurikharka. In these areas, extensive erosion is expected to occur and large amounts of sediment may be deposited on the adjoining sections.

Terrain Unit 3: Middle upper terraces with moderately wide valleys

The characteristics of TU3 are:

- moderately wide river valleys with settlements located at middle to upper terraces,
- many short and sharp bends both upstream and downstream of the settlements,
- direct impact and overtopping of lower terraces (<5m) by flood,
- lateral erosion of banks mostly to lower terraces (<5m), occasional progression of lateral erosion to upper terraces at points where the geology is weak, and
- sedimentation of riverbeds by boulders >0.5m with significant boulders of >1m due to local erosion and sedimentation process both upstream and downstream.

TU3 – Lower Dudh Koshi (Jorsalle, Tawa, Benkar, Phakding, Dukdinma, Chermading, Chhuthwa, Nurnin, Ghat, and Nakchun)

The river reach in this terrain unit has moderate width but is characterised by a series of sharp bends at frequent intervals. The river gradients are moderately steep with a number of rapids and falls. This type of terrain unit is mainly confined to Jorsalle, Tawa, Benkar, Phakding, Dukdinma, Chermadin, Chutawa, Nurnin, Ghat, and Nakchun (Figure 5.27). The river banks are unstable where lateral erosion is dominant. The stable and the critical slopes are mostly covered by vegetation. Extensive lateral erosion is caused by the presence of a series of sharp bends at short intervals. Most of the alluvial fans result from local tributaries. With few exceptions, these areas are distant from Lake Imja Tsho. Here sedimentation of cobble size boulders and overtopping of the lower terrace with settlements is expected.

Most of the bridges, agricultural land, and settlements of Ghat, Nurnin, Chutawa, Chermadin, Dukdinma, Phakding, and Benkar lie on lower terraces that could be overtopped by debris and flood from a GLOF at Lake Imja Tsho (Figure 5.27). The cultivated land and settlements of Chuthawa, Chermading, Phakding, and Benkar are directly at high risk from a GLOF event and could also suffer damage from secondary events such as landslides on medium to upper terraces. Since these areas were previously affected by the Dig Tsho GLOF, the likelihood of their being affected by a GLOF event at Lake Imja Tsho is high.

Infrastructure, such as bridges destroyed in the 1985 GLOF, was rebuilt at higher elevations and is now nominally above flood level. However, commercial structures at Phakding, Benkar, and Chutawa such as hotels and lodges are typically built on lower terraces that are prone to flood hazards. These areas are highly vulnerable to hits from primary GLOFs and are not immune to secondary hits from lateral erosion extending to the upper terraces. The impact of the 1985 Dig Tsho GLOF is still visible in the form of old erosion scars and unstable zones with sparse vegetation.

Figure 5.27: Vulnerable river sections near main villages (between Larja dovan and Ghat) in the Dudh Koshi valley: a) Chutawa village and surroundings; b) Lateral erosion at Benkar village; c) Phakding village on the lower terrace near a river bend; d) Jorsalle village on the lower terrace looking upstream; e) River section at Tok Tok village; f) Status of bank erosion downstream of Jorsalle in 1996; g) Situation of river section downstream of Nakchun in 1996; h) The unstable riverbank downstream of Ghat in 1996

Terrain Unit 4: Lower Terrace with wide valley

The characteristics of TU4 are:

- very wide river valleys, more or less straight reach, and settlements located at lower terraces (<5m),
- low chance of bank overtopping of lower terraces (<5m) by flood,
- lateral erosion of banks, mostly at bends within lower terraces (<5m), occasional progression of lateral erosion to upper terraces at weak geological formations, and
- sedimentation in river beds by dominant boulders larger than 50 cm and boulders less than 1m that are significant due to sedimentation at wide valleys.

TU4a – Dig Tsho (Upper reach of Langmoche Valley [Hilajun] and Thamo Teng)

The upper Langmoche river section, immediately after the outlet of the lake, is a wide river valley with river gradients of class S1 and S2. The upper reaches, closest to the breach, have suffered from severe lateral erosion. The Langmoche valley, which contains the villages of Langmoche and Chaserwa (tail end) had extreme riverbank erosion, extending for about 2 km downstream. The boulders (Figure 5.28a) deposited on the river valley are large where the area is closer to the lake outlet, becoming smaller further downstream. The widening of the river valley is conspicuous at Chaserwa village (Figure 5.28b), where the river eroded and outflanked its banks during the Dig Tsho GLOF.

Hilajun is located downstream of the Langmoche–Bhote Koshi confluence. The valley at Hilajun is wide and only the outer bend of the river was eroded, but the riverbed has extensive deposits of sediments. Boulders larger than 30 cm are dominant and are deposited as distinctive layers over large stretches of the river until Thamo Teng. The banks have many lateral erosion scars extending down to the lower river terraces, which have been overtopped at several locations (Figure 5.29).

Thamo Teng is located just upstream of the Thame gorge. The river valley at Thamo Teng experienced severe lateral erosion extending to the upper terraces. Catastrophic GLOFs have made this section of the Thame gorge more unstable. The lower to middle river terraces suffered the secondary impact of lateral erosion extending to upper terraces (Figure 5.30).

TU4b – Lake Imja Tsho (Upper Imja Valley, Pipre Goth [downstream of Chhukung] and Chhukung)

Chhukung village (Figures 5.3 and 5.31) is located on the end moraines of the Lhotse Nup and Nuptse glaciers. This area is separated from the median morain of the Lhotse and Imjatse glaciers by the Lhotse Khola (Figure 5.32) originating from the Lhotse glacier. The median moraine which separates the village from the Imja Khola is about 300m wide, 3 km long, and less than 40m high (Figures 5.3 and 5.32b). The hydrodynamic modelling showed inundation of Chhukung, but the field verification revealed less chance of such inundation. However, about 1 km downstream from the village, the valley narrows at the Pipre confluence. If this is blocked, the backwater can extend up to Chhukung.

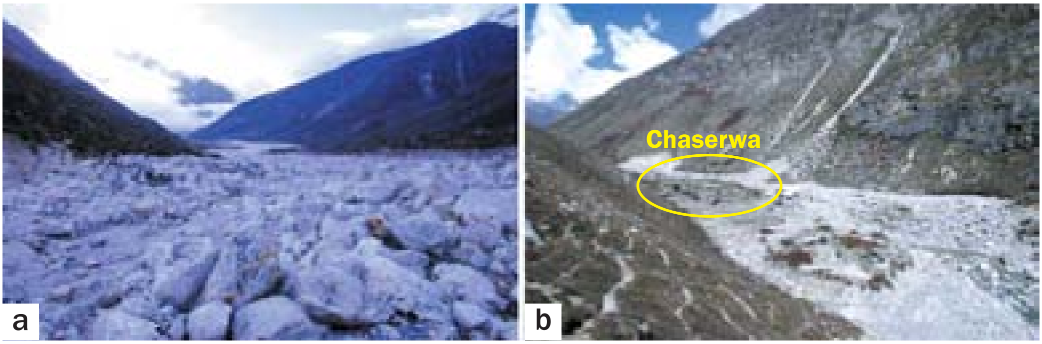

Figure 5.28: Terrace sediment characteristics of the Dig Tsho GLOF: a) Boulders deposited downstream; b) A wide river valley at the Chaserwa village lying on the lower terrace

Figure 5.29: Hilajun (foreground) and Thamo Teng (background). View downstream of Dig Tsho

Figure 5.30: Erosion and deposition along the Bhote Koshi River: a) Sediment deposition and erosion at a river bend; b) Extensive bank erosion and landslides observed upstream of Thame George; c) Thamo Teng village situated on middle terrace

Terrain Unit 5: Upper terrace with wide valley and river bends

The characteristics of TU5 are:

- moderately wide river valleys, with a more or less straight reach and settlements located on upper terraces (>10m),
- less chances of bank overtopping of upper terraces (>10m) by flood,
- lateral erosion of banks mostly at bends extending to lower terraces (<5m), occasional progressing of lateral erosion to upper terraces at weak geology, and
- sedimentation of river beds by dominant boulders of <0.3m and significant numbers of boulders of 0.5m at wide valleys.

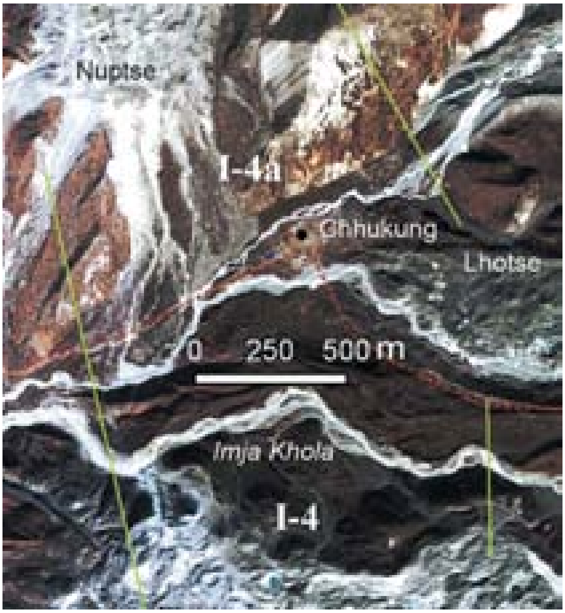

Figure 5.31: Chhukung village lying on the end moraines of the Lhotse Nup and Nuptse glaciers, near the confluence of the Imja and Lhotse Kholas

TU5a – Dig Tsho (Kamthuwa and Mingmo)

This terrain unit is characterised by upper terraces and wide river valleys; villages at Chamuwa, Kamthuwa, and Mingmo fit this profile. The villages of Kamthuwa and Mingmo are located in the upper Langmoche valley towards the breach. Since the valley is wide, settlements at this point are situated on upper terraces and a possible GLOF will have only minimal impact at Mingmo. Nevertheless, lateral erosion could extend towards the upper terraces (Figure 5.33). The dominant riverbed material consists of boulders larger than 1m at the breach becoming smaller than 50 cm, and a significant number of larger boulders (0.5–1m) at Mingmo. The Langmoche, Kamthuwa and Mingmo villages are sparsely populated. The area is mainly used for potato cultivation and as pasture in summer.

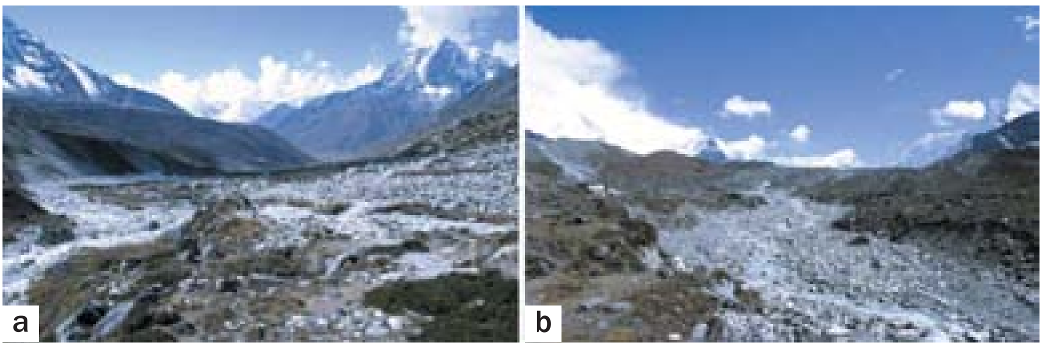

Figure 5.32: Situation in the vicinity of Chhukung: a) Downstream view (from Chhukung) of the confluence of the Imja Khola and the stream from Lhotse glacier. The median moraine is seen in the foreground; b) Upstream view of the Lhotse Khola, Chhukung is located on the left and the median moraine is on the right

Figure 5.33: Precarious positon of Mingmo located on the left bank of the Langmoche River with extensive bank erosion. View upstream

TU5b – Lake Imja Tsho (Dingboche, Pangmoche, Orsho, Syomare, Milingo, Debouche and Tengboche)

Dingboche village is the most densely populated area along the Imja valley and has a large number of hotels and lodges. The village is located at the river bend but the settlement is situated on upper terraces. In the river section, boulders of size <0.5m and cobbles are the dominant riverbed materials. A GLOF from Imja could cause severe lateral erosion at the river bends and sedimentation could occur (Figure 5.34a) in the downstream areas. The area containing the villages of Chhukung to Dingboche is similar to the section containing Hilajun and Thamu in the Dig Tsho GLOF area; however, the impact here will be much greater.

Dingboche village is located very high above the riverbed; the upstream and downstream sections of the village are wide and have a steep gradient. There is only a low possibility of a direct impact by a GLOF at Imja but lateral erosion at the outer bend of the river (nearest to the village) could endanger the houses closest to this riverbank.

Pangboche village is another densely populated area with many settlements, hotels, and lodges. The village is located on the upper terrace (Figure 5.34b). The outer bend of the village Tsuro (Figure 5.34c) confluence could suffer from severe bank erosion and subsequent sedimentation. This comparatively wide valley is similar to the confluence at Langmoche–Bhote Koshi and Bhote Koshi–Dudh Koshi. The settlements of Pangboche and Orsho (Figure 5.34d) would be affected only by secondary impacts of a GLOF event at Lake Imja Tsho, largely caused by propagation of bank erosion to higher elevations.

Both upstream and downstream of Pangboche village, the river section is compariatively wide and sedimentation will occur. The houses in the villages of Orsho, Syomare, Milingo,

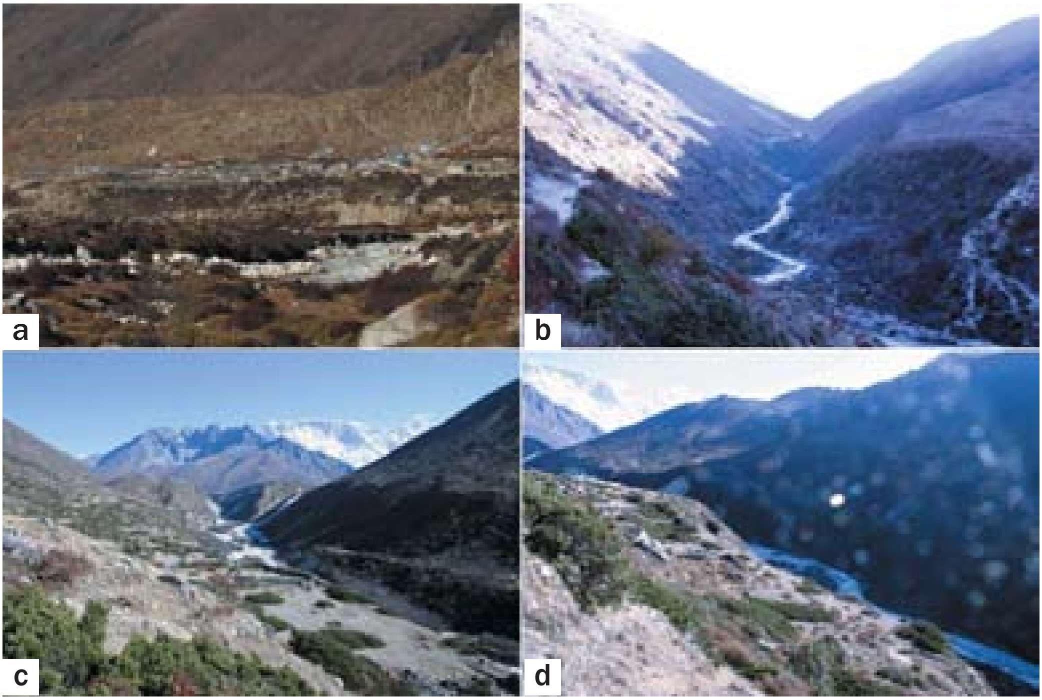

Figure 5.34: Villages and typical landforms in the Imja River valley: a) Dingboche village on the upper terrace of right bank; b) Upstream view depicting Pangmoche (left) and the micro-hydroelectric project (right); c) Tsuro (Churo) village on the right bank; d) Orsho village on the upper terrace of right bank

Debouche and Tengboche are situated at elevations much higher than the GLOF level; hence no direct impact of flood is expected in this area. However, Syomare village is located on a fossil landslide, even a small amount of lateral erosion at the toe would render the entire area unstable. At Milingo, landslides would extend to the upper terraces, away from the settlements, but on a trekking route.

Hazard assessment

In the Himalayan region, GLOFs are always a potential hazard, especially when there are glacial lakes at the headwaters of streams and rivers. GLOF hazard assessments can help in disaster preparedness, in the development of early warning systems, and in putting into place mitigation measures as needed. The following section is a hazard assessment of the Imja and Dudh Koshi valleys.

A GLOF from Lake Imja Tsho would pose an immediate danger to the downstream areas up to the village of Ghat. The level of hazard to a given downstream area can be assessed in advance based on the terrain unit and other field data collected along the Dudh Koshi sub-basin as discussed in the previous section. The level of hazard is classified according to the severity of damage an area might experience. Typically, five hazard areas are discussed, ranging in severity from 'very high hazard', a situation of total devastation or washout, to 'very low hazard', where the GLOF has only a minor impact.

Very high hazard

A 'very high hazard area' would be completely and immediately washed out in the case of a GLOF event. This type of area is mostly identified in Terrain Unit 1. At Imja, the very high hazard areas are immediately adjacent to the outlet and just downstream of the breach at the Imja constriction (which lies in the upper reaches of the Imja valley). These areas have no settlements, cultivation, or infrastructure. However, they do contain a famous trekking route to Island Peak.

High hazard

Areas are classified as 'high hazard' if they are at risk from both immediate primary impacts as well as secondary impacts of a GLOF event, such as lateral erosion and landslides. This type of area is mostly identified in Terrain Unit 2 where the strips are narrow, with sections of sharp bends. These areas either have no settlements (for example Larja Dovan) or settlements at high elevations away from the river (for example Lukla). In these areas, severe lateral erosion of bed and banks could have repercussions for areas considerably higher up and away from the water flow in the form of secondary events such as landslides. Any new infrastructure and settlements in this area should be considered as at risk from possible secondary impacts.

Syomare village is a typical example of a high hazard area. This village is situated on a fossil landslide but lies above the high flood level. Any slight lateral erosion at the toe will reactivate the landslide. This village also sits on a concave bend of the Imja Khola; in the case of a GLOF, the flow will reactivate the landslide by scouring its toe and will create a high risk to the village (Figure 5.35). The infrastructure that is at high risk consists of 3 small one-storey wooden house, 11 medium-sized chiselled cement-mortared houses, and 3 large chiselled cement mortared houses (Table 5.3).

Moderate hazard

An area is classified as 'moderate hazard' if there is a possibility of overtopping by the GLOF. Typically, these are low-elevation terraces. This type of area is identified in Terrain Unit 3. The villages of Ghat, Chutawa, Chermading, Phakding, and Benkar (Figure 5.36) can be categorised as such. These villages are populated and contain many domestic dwellings and commercial buildings as well as cultivated land and trekking routes. Both houses and cultivated land (at lower terraces <5m) were overtopped during the last Dig Tsho GLOF.

Figure 5.35: Concave bend of the Imja Khola at Syomare where bank scouring is expected in the case of a GLOF

Table 5.3: **Vulnerability of downstream valleys to potential Lake Imja Tsho GLOF**

Terrain Unit	Type Locality	Causes of Damage	Affected Infrastructure and Landuse	Infrastructure					Vulnerability (%)	Remarks
				Unit	Nr.	Storeys	Type	Class		
TU-II	Syomare	Landslide	House	no	3	1	S	4	100	Syomare on old landslide
		Landslide	House	no	11	1	M	1	100	
		Landslide	House (new)	no	3	1	L	1	100	New house
		Flood	House (NC)	no	2	2	M	2	100	10*50*2 and 10*30*2 (ft)
TU-III	Chermading	Flood	House (NC)	no	4	2			100	
		Flood	House (NC)	no	3	2			40	
		Flood	Cultivation	sq m					100	
	Phakding	Flood	House	no	3	2	M	2	50	right bank
		Flood	House	no	4	2	M		100	
		Flood	House	no	2	2	L		50	after bridge
		Flood	House	no	3	2	M		50	
		Flood	Cultivation	sq m					100	maize field
		Flood	House	no	3	2	M	2	25	
		Flood	Suspension Bridge	m	84				100	metal strip
	Benkar	Flood	Cultivation	sq m					100	vegetables and wheat
		Flood	House	no	4	1			100	wooden
		Flood	House	no	1	1			75	
		Flood	House	no	3	1			90	
		Flood	House	no	2	1			75	left bank of trails
		Flood	Suspension Bridge	m	120				25	
	Jorsalle	Flood	House	no	1	2	M	1	100	at narrow valley
		Flood	House	no	2	2	M	1	70	
		Flood	House	no	2	2	M	3	80	
TU-IV	Pangboche	Flood	MHE Project (15 KW)	no	1	1			100	old moraine,
		Flood	Cultivation						100	right bank
		Flood	Metal Bridge	m	10				100	
TU-V	Dingboche	landslide	House	no	4					

Types: S = small; M= medium; L = large
Class: 1 = chiseled stone block with cement plaster and zinc sheet; 2 = stone block with mud mortar; 3 = wooden house with stone wall; 4 = small goth type house.
NC = non-commercial other/off-trail house; C = Commercial house along a trail
Note: Forested areas extend up to Syomare village

The severity of the impact from a possible Lake Imja Tsho GLOF event is expected to be greater than that of the Dig Tsho GLOF. The settlement area at lower terraces in this zone is at moderate GLOF hazard, and secondary impact by landsliding of upper terraces is expected. The large number of sharp river bends at close intervals and the moderately wide river valley create a scenario where lateral erosion of lower terraces is inevitable. The houses in the settlements at Chermading, Phaking, Benkar, and Jorsalle villages and the trekking routes are highly vulnerable. In addition, the damage will in all likelihood lead to a chain reaction on the upper terraces in Ghat village. A detailed list of likely damage to houses (commercial and non-commercial) and agricultural lands is given in Table 5.3.

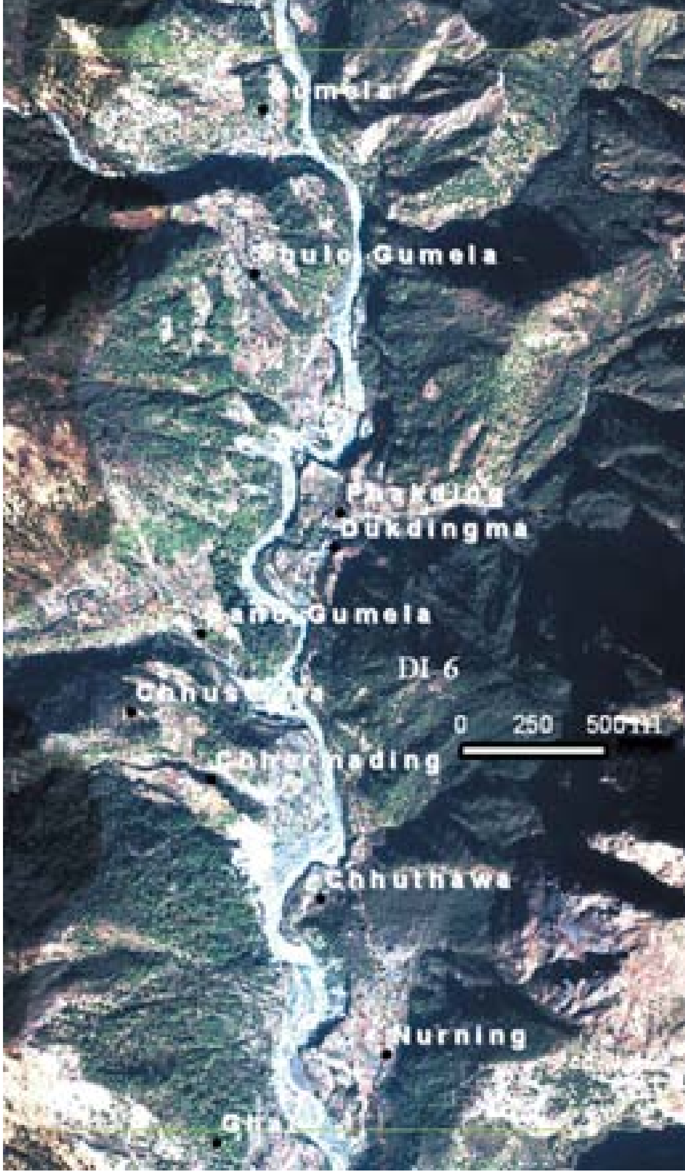

Figure 5.36: Phakding and Chermading villages lying on the lower terrace of the Dudh Koshi River

Low hazard

Areas in both lower and upper terraces in wide river valleys, as well as areas outward from normal debris flow, are considered 'low hazard areas' and are usually found in Terrain Units 4 and 5. Here the GLOF has little chance to do any direct damage but can still be destructive when it cuts across terraces and induces secondary landslides. Some houses at the extreme edge of the terraces could suffer damage. Villages like Tsuro, Dingboche, Orsho, and Pangboche belong to low GLOF hazard areas. Some houses in Dingboche village are located on the edge of upper terraces (Figure 5.37). Such houses could be affected by secondary phenomena from landslides propagated to upper terraces. The area upstream from Dingboche village is very wide; the section of the river between the Tsuro confluence and Dingboche could be an area where sediment accumulates.

Similarly, while the area upstream of Pangboche is wide, the downstream river valley is only moderately wide. Houses situated on upper terraces would not be directly impacted but cultivated areas (at lower elevations) could be affected. The generation plant and the tailrace of the micro hydropower station located on the lower terraces could be damaged by an Imja GLOF. This hydropower station generates 15 kW and supplies electricity to Pangboche and surrounding villages.

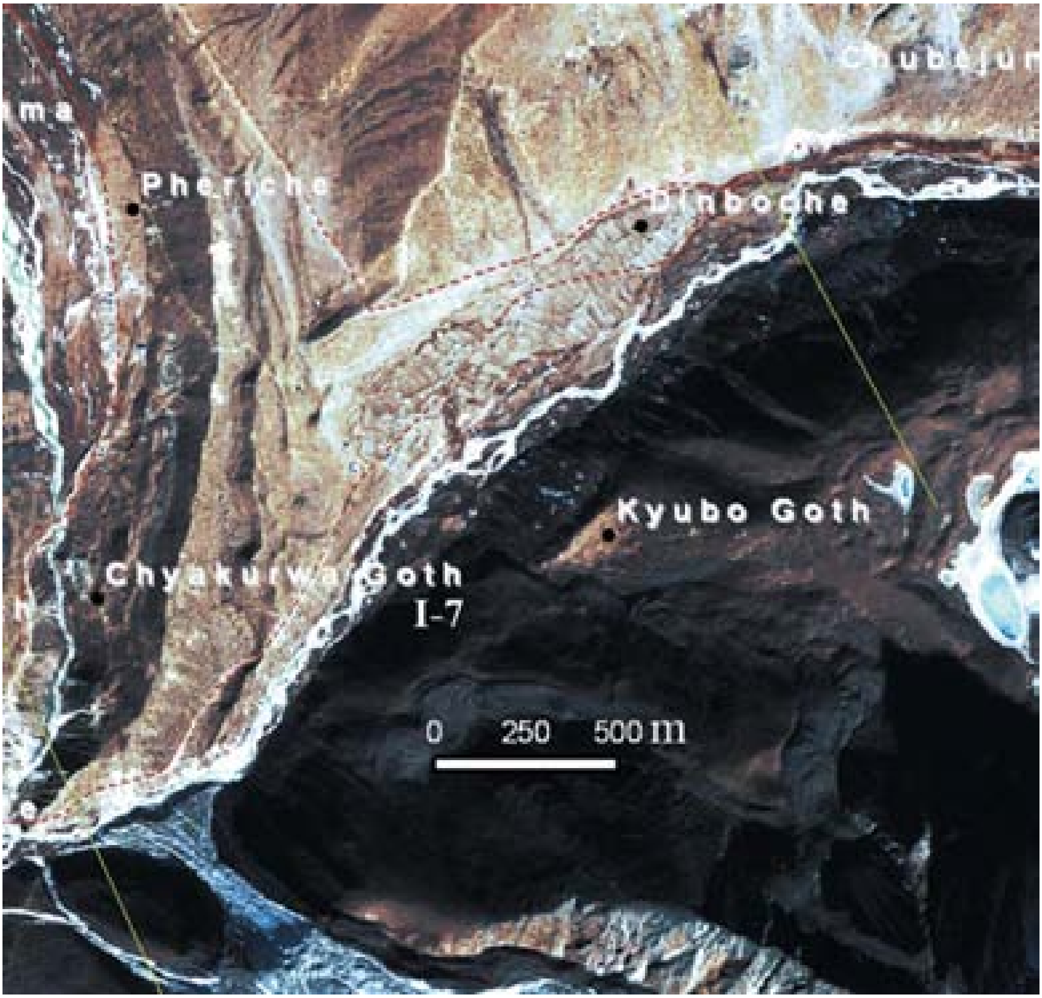

Figure 5.37: Dingboche village on the upper terrace in a wide valley of the Imja Khola

As a result of the past Dig Tsho GLOF, most of the suspension bridges are now constructed at higher elevations. An exception is the Hilajun metal bridge at the confluence of the Langmoche and the Bhote Koshi. The old bridge at Milingo was replaced by a new one at an elevation higher than the past GLOF effect. The wooden bridge at the Tsuro confluence, however, is in the flood hazard area and would be highly vulnerable to a GLOF event.

Very low hazard

Areas categorised as 'very low hazard' are low-lying terraces at some distance from the predicted direct path of the GLOF. Here the hazard would consist of backwater deviated due to obstruction in the debris flow – the chance of this type of event occurring is considered very low. This type of area is identified in Terrain Unit 4. Chhukung village lies on a fossil moraine one valley over from the Imja Khola valley. The flood routing predicted from the hydrodynamic model shows inundation of Chhukung village, but field verification suggests that the village would be inundated only under extraordinary conditions. Hence this area is classified as the lowest level hazard zone.

Vulnerability assessment

Vulnerability assessments were based on visual inspection and walkover surveys along the trekking routes, augmented by the modelling and flood routing results discussed in Chapter 4. The lateral or bed erosion and sedimentation from a possible Lake Imja Tsho GLOF to Larja Dovan is based on estimates made by comparing data from the Langmoche valley (which experienced a GLOF in the past). The Larja Dobhan lies below the confluence of the streams from the Lakes Dig Tsho and Imja Tsho. The area downstream from Larja Dovan has already experienced the Dig Tsho GLOF; an additional GLOF event in this valley would be catastrophic. The slope failure that was generated after the last GLOF event is still active in Ghat and in Phakding. A new GLOF event could trigger new instabilities in many places and reactivate the old ones.

The vulnerability of a given element at risk is based on the probability of a direct or indirect hit by the GLOF. The vulnerability of different infrastructure to a possible Imja GLOF is summarised in Table 5.3. Infrastructure was classified as either commercial or non-commercial and further classified as small, medium or large on the basis of a visual estimation of the coverage of the plinth area to less than 200 sq ft (20 sq m), 500 sq ft (50 sq.m), and more than 500 sq ft respectively. The buildings are further classified into four types: chiselled, cemented, mud-mortared, wooden houses, and small cattle-shed. Bridges are classified based on span, and agricultural land is measured simply in square metres.