# CHAPTER 4

# Hazard Zonation of Moraine Dammed Lakes

# HAZARD ZONATION OF MORAINE DAMMED LAKES

## 4.1:- Moraine Dammed Lakes

A glacial lake is a vast reserve of water in, on or near a glacier formed by glacial processes. When glaciers thaws at the frontal zones, the empty space is filled by ice melt, which eventually becomes a lake owing to the progressive accretion of water. These glacial lakes are classified as either ice dammed or moraine dammed.

The Himalayan region has witnessed the formation of multiple glacial lakes on the recently receeded glacier terminals during the second half of the twentieth century. Glacier retreat and downwasting, particularly of debris-covered glaciers, results in the formation of moraine-dammed glacial lakes (Quincey et al., 2007; Yamada, 1998; Richardson & Reynolds, 2000). Apart from the recent impacts of global warming, the majority of these glacial lakes are formed by unstable moraines damming them. This damming can occasionally result in dam collapse, which can be caused by a variety of factors. As a result, lake outbursts occur, releasing massive amounts of stored water and triggering severe flooding along the river channel downstream (Watanabe et al., 1994). These incidences known as GLOF (Glacier Lake Outburst Floods) are recognized as prevalent problems in the Himalayan Nations often result in devastating consequences.

Moraine Dammed Lake (MDL) outbursts are triggered primarily by the disintegration of the buried ice inside the dam, seepage and piping through the dam or the overflowing and erosion induced by the waves from debris flow within the lake (Richardson & Reynolds, 2000; Clague & Evans, 2000). Although it is hard to predict a GLOF since an outburst is a fracturing event, it is possible and essential to focus on 'where' it will occur (Richardson and Reynolds, 2000). When considering the likelihood for a GLOF, we must consider the geography surrounding a glacial lake.

This study thus suggests that if we correctly identify the topographical features, we may be able to employ remote sensing DEMs more precisely and predict the GLOFs before hand and mark a hazard zonation region for the same (Fujita et al., 2008).

## 4.2:- Data Used

The present research work utilizes the glacier outlines that have been mapped during the Glacier Inventory part of the study. Cloud free data of Landsat – 8 available at (earthexplorer) was used for the temporal mapping of the Moraine Dammed Lakes. The

Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) with a spatial resolution of 30 m was used to derive the depth map, the lake volume and the slope of the region. According to Fujita et al., 2008, SRTM DEM works well near the lake's edge because the borders of water bodies and surrounding debris offer a distinct contrast for the generation of DEM. Hence, this data was used for the present study.

## 4.3:- Methodology

The first stage of preprocessing was to geometrically correct the Landsat images; however, atmospheric corrections were not required because cloud-free data was chosen for the study. There are many methods of supervised and unsupervised classification such as maximum likelihood classification and k-means that have been used in various studies to delineate the glacial lakes. Most of these methods lead to misclassifications like mapping the shadow, hence excessive manual editing is required (Aggarwal et al., 2016). Thus, to avoid all the confusion mapping of the snow covered glaciers and lakes was already done in the first part of the research work. Hence, the manually demarcated lakes were used here and the rechecking of the demarcated lakes was done using the slope maps of the area (Figure 4.2. and Figure 4.15).

### Identification of the Potentially Dangerous Glacial Lakes

First and foremost, the lakes which were on top of the glaciers better known as the ‘Supra Glacial Lakes’ were not considered for the study because even if they burst or flood, their waters will spread on the glaciers itself and will not reach the lower bounds of the valleys. Whereas, on the other side, the Moraine Dammed Lakes are those lakes which are attached to the snout of the glacier or are very near to the parent glacier. They are considered as dangerous as they have a scope to expand as they are directly attached to the snout of the glacier. The ‘Supra Glacial Lakes’ interconnected to the ‘Moraine Dammed Lakes’ were also to be checked for as bursting of one lake could cause the bursting of another connected lake.

### Preparation of Map Layers for the Hazard Zonation Map

The lake Elevation and the calculations for Slope and Curvature Maps were done using the DEM in the ARC GIS environment. The curvature map shows the acceleration or de-acceleration of the water that would release if the glacier lake burst occurs. For example, accelerated flow of water is expected from a positively concave curve (Klingseisen et al., 2008). The maps showing the temporal changes pertaining to the lakes were prepared using the Landsat Satellite Data ranging from year 2000 to 2021.

The Depth of the lake and its Volume were calculated using Inverse Distance Weighted interpolation (IDW) method. Huggel et al., in 2002 developed a relation which demonstrated that lake depth and area were associated for a range of ice-dammed and moraine-dammed lakes in a number of areas throughout the world.

This connection has a formula: - $D = 0.104A^{0.42}$

Where D is the mean lake depth (in metres) and area is measured in square metres. As a result a link between volume (in metre$^3$) and shape was established.

Whereas, Volume of the lake was devised by the formula: - $V= 0.104*A^{1.42}$
Where V is lake volume (in metre$^3$) and A is area is square metres. The area of the lake was calculated from the mapped glacier lake boundaries (ARC GIS).

The importance of all these layers was only judged when all the data was put into the Weighted Overlay Model in ARC GIS environment. The Class Weights of different layers resultant of the model were:-

Elevation: 7,9,5,3,1

Slope: 9,7,5,3,1

Curvature: 7,9,5

Lake Depth: 3,5,7,8,9

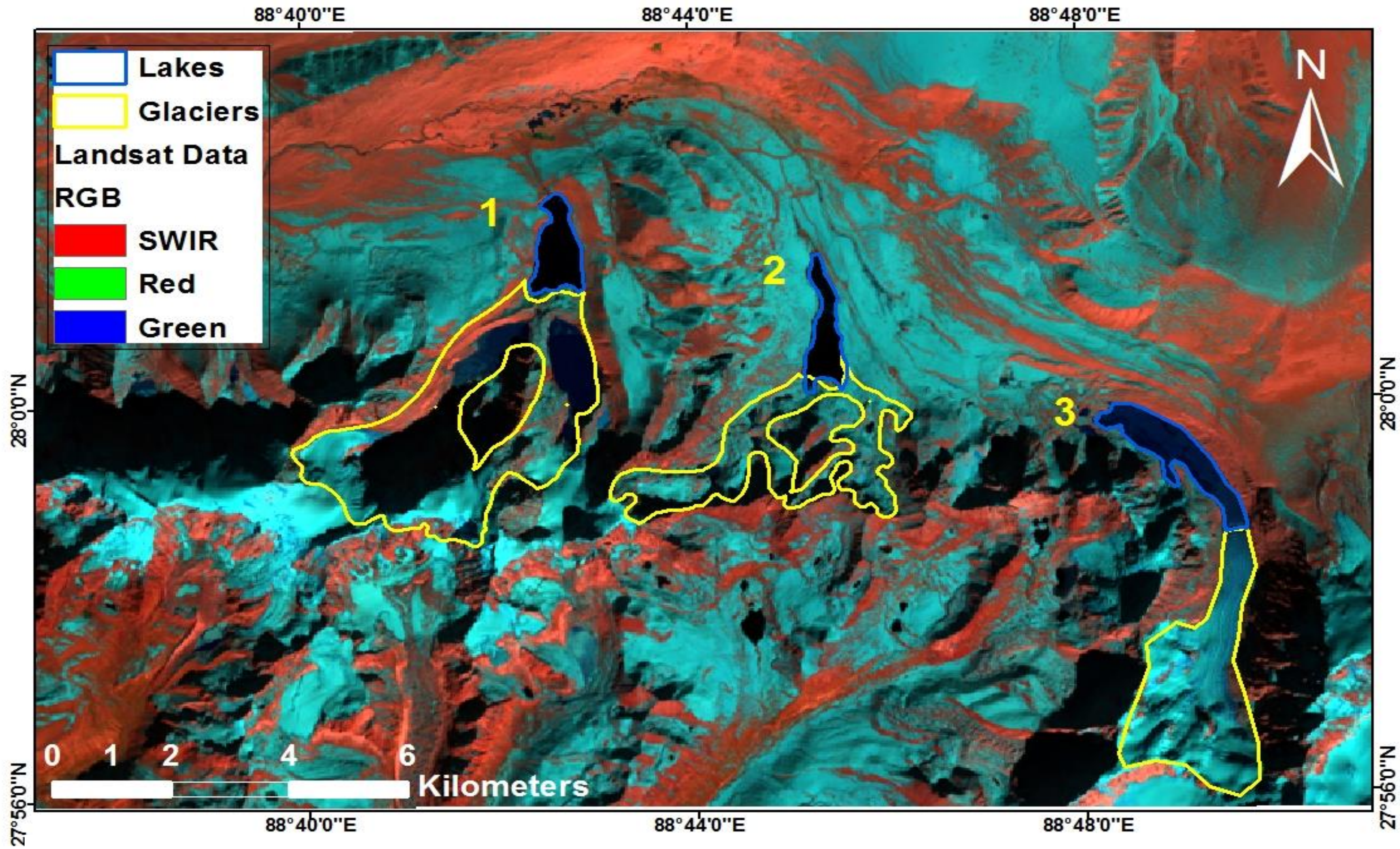
Lake Volume: 3,5,7,8,9

As a result, the percentage weights for distinct layers were computed using the IDW Interpolation Method, with Slope having the highest weight of 40%, followed by Elevation (20%), Curvature (20%), Lake Depth and Lake Volume 10% each.

## 4.4:- Moraine Dammed Lakes in Sikkim

Sikkim has three (3) glaciers, as seen in Figure 4.1, where three (3) moraine dammed lakes were mapped and numbered 1, 2 and 3 for discussion and reference. Glacier number 3 with an area of 6.13 square kilometre had the largest MDL area of 1.70 square kilometre followed by MDL number 1 (1.09 square kilometre) and MDL number 2 (0.98 square kilometre) (Table 4.1. and Table 4.2). The mapping of glaciers is essential for determining the susceptibility of lakes and their location in relation to glaciers.

**Figure 4.1: Glaciers and Glacial Lakes (Moraine Dammed lakes) - Sikkim**




**Source: Computed, LANDSAT**

| Table 4.1: Dynamics of Glaciers with Moraine Dammed Lakes - Sikkim | | | | |
|---|---|---|---|---|
| **Glacier No.** | **Glacier Area (in sq.km.)** | **Perimeter (in km)** | **Length (in km)** | **Mean Elevation (metres)** |
| **1** | 11.39 | 23.43 | 5.18 | 5665 |
| **2** | 5.22 | 26.11 | 4.26 | 5489 |
| **3** | 6.13 | 13.18 | 4.55 | 5682 |
| **Source:** Computed | | | | |

| Table 4.2: Moraine Dammed Glacier Lake Dynamics - Sikkim | | | | | |
|---|---|---|---|---|---|
| **Glacier Lake No.** | **Lake Area (in sq.km.)** | **Lake Depth (in metres)** | **Lake Volume (in m$^3$)** | **MDL Elevation (in metres)** | **Orientation of Snow Line** |
| **1** | 1.09 | 0.11 | 0.12 | 5151 | W |
| **2** | 0.98 | 0.1 | 0.1 | 5102 | E |
| **3** | 1.70 | 0.13 | 0.22 | 5290 | NE |
| **Source:** Computed | | | | | |

Glacier mapping has been particularly useful in analysing potentially harmful lakes since the slope of glaciers associated with lakes also play a key role (Figure 4.2.). Bearing in mind the elevation of the lakes, their mean elevation has been considered. Where lakes 1 (5151 metres) and 2 (5102 metres) have lower mean elevation in comparison to the lake number 3 (5290 metres) (Table 4.2., Figure 4.3.). Lake 3 (0.13 metres) is the deepest of the three lakes in study followed by Lake 1 (0.11 metres) and 2 (0.1 metres). The volume of water in the lakes also points out towards the positive correlation of lake area, depth and volume i.e. higher the area and greater the depth, more is the volume of water contained in the lake (Table 4.2., Figure 4.4., Figure 4.5.). Figure 4.6 depicts the curvature map of the study area, which is essential to calculate the Hazard Zone in the event of a lake burst. As previously said, it would aid in the analysis of the water's acceleration rate as it approaches the lower portions of the valleys where settlements are located. Direction of Floodwater

Encroachment through Valley can be seen in Figure 4.7. This shows the distance which the flood water would travel to reach the human settlements and pose a threat to them. Figure 4.8. shows the cross – sections from the lake to the outlet of the basin, this was particularly used to model the channel's topography which the flood water would follow. This was prepared by DEM in GIS environment. The Tista River from the location of the glacial lake flowing through the settlements has been represented by cross- sections at five (5) locations covering approximately a distance of 80 kilometre. The valley profile, hence, shows the deep 'U' to 'V' shaped valley from which the flood water would traverse.

As it is evident from the map, the nearest settlement 'Hema' is also approximately at 30 km of distance. Though lake numbers 1 and 3 lie in the 'Very High Hazard Zone' and Lake 2 in 'High Hazard Zone' (Figure 4.9.) but still as human settlements are not nearby the threat to mankind is lowered.

To maintain the harmony with the environment, glaciers constantly modify their size and flow speed. The changing character of glacial lakes may be noticed by comparing current remote-sensing produced glacial lake outlines to earlier data sets gathered from older images.

The analysis of this temporal data revealed that due to accelerated glacial retreat and melting of the glacier, the lakes have expanded in size from 2000 to the present date, 2021, which may be attributed to climate change. The lake areas seen in Figures 4.10, 4.11 and 4.12 has undergone change in 21 years, like for Lake 1 and Lake 2, significant changes cannot be seen as compared to Lake 3. This shows that the lakes are not only important from the disaster point of view but also climatic variations in the last two decades can also be noticed. The equilibrium between the melt water inflow to the lake and the water being drained out of the lake may be attributed for the standstill in the areal expansion of Lakes 1 and 2 between 2000 and 2010. Figure 4.13 and Table 4.3 illustrates a graphical depiction of the areal changes of glacier lakes between 2000 and 2021. Here Lake 3 had the maximum growth among the three lakes i.e. from 1.58 square kilometre in 2000 to 1.70 square kilometre in 2021, followed by Lake 2 where a very minute change of 0.01 square kilometre was observed from the year 2000 to 2021. On the other hand, Lake 1 remain unchanged and stable in a period of 21 years.

Therefore, considering all the factors like depth, elevation, slope, volume of water, temporal changes in lake area and its ranking in the Hazard Zones, Lake Number 3 with a North-Eastern (NE) orientation is considered as the most vulnerable lake out of all the 3 MDL in study in Sikkim.

**Figure 4.2: Slope Map - Sikkim**

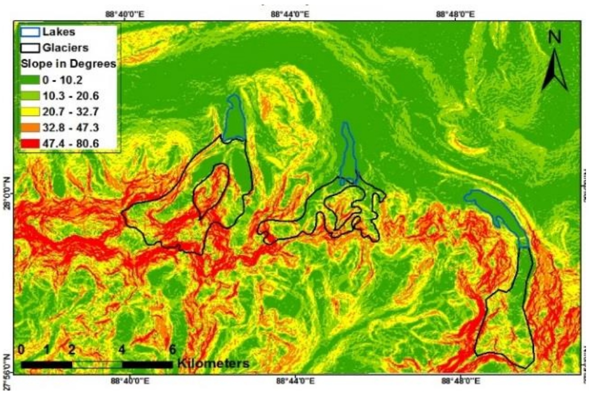



**Figure 4.3: Elevation Map - Sikkim**

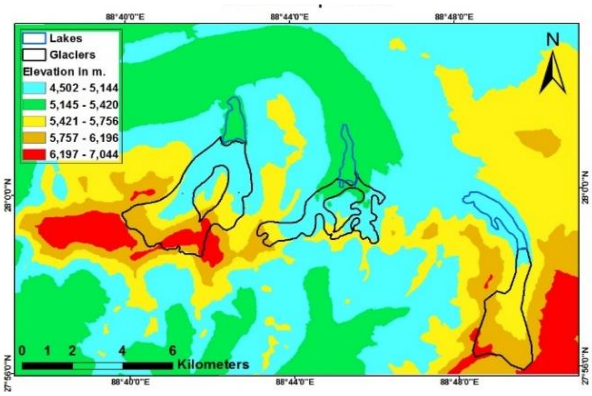



**Figure 4.4. Glacier Lake Volume Map - Sikkim**

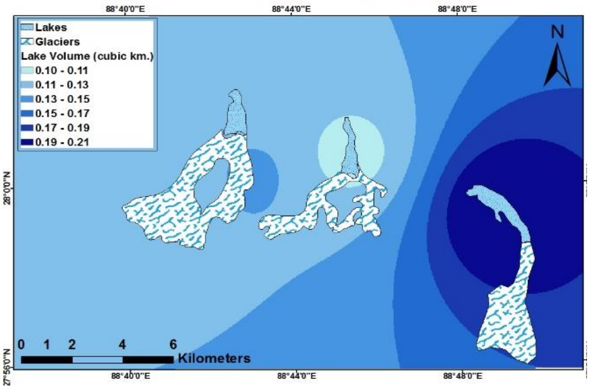



**Figure 4.5. Glacier Lake Depth Map - Sikkim**

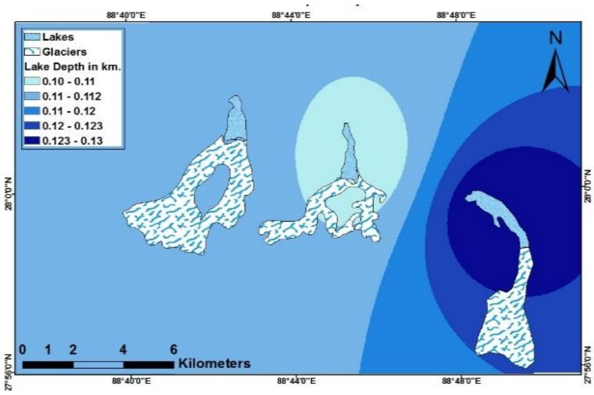
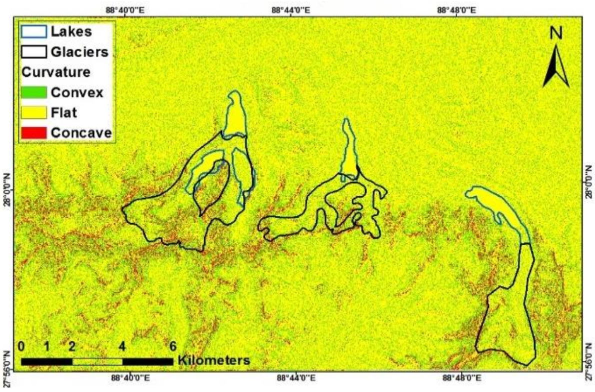


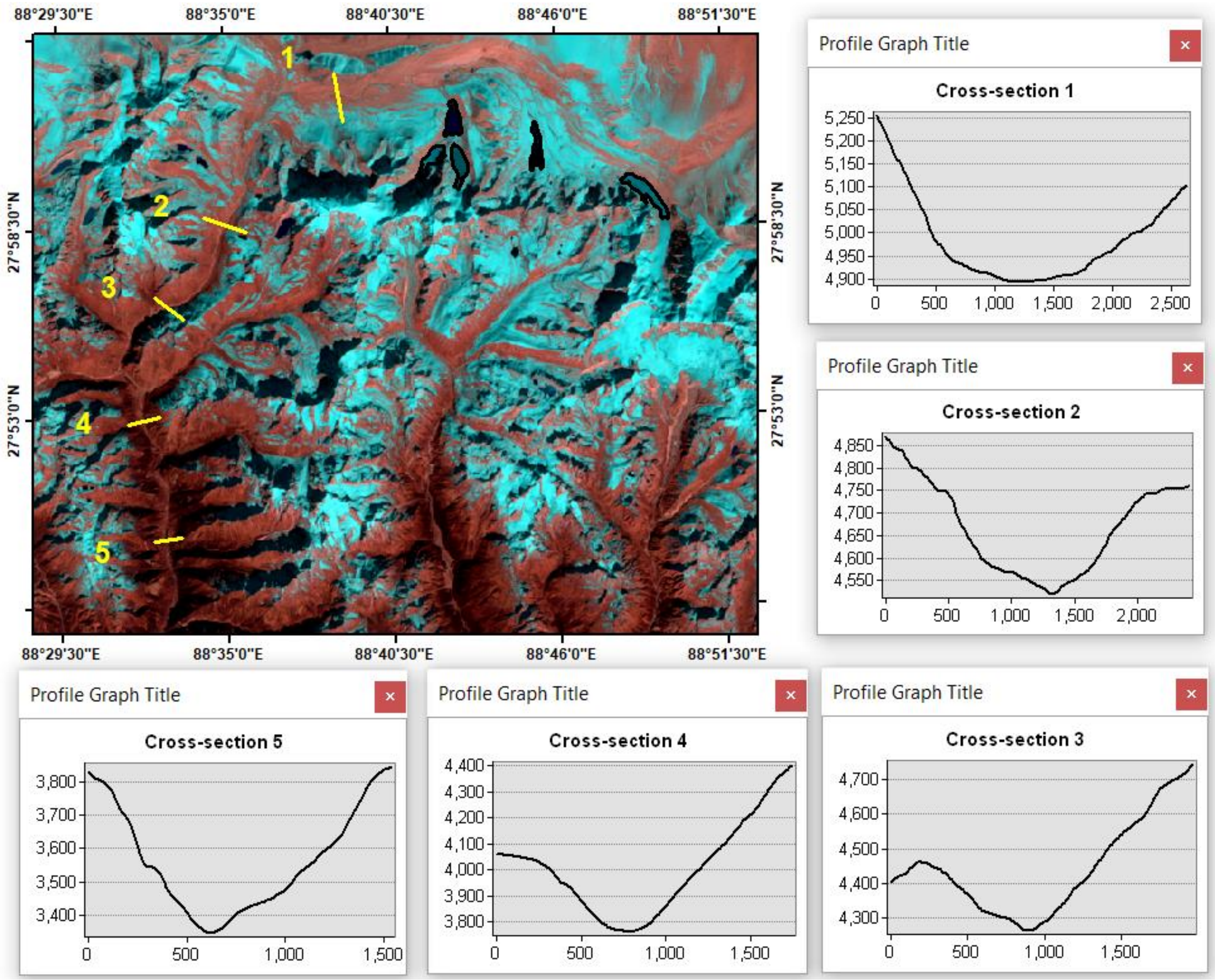

**Figure 4.6: Curvature Map - Sikkim**




**Note:** Figure 4.2, 4.3, 4.4, 4.5 and 4.6 are input layers required for the computation of the Hazard Zones in GIS

**Source:** Computed

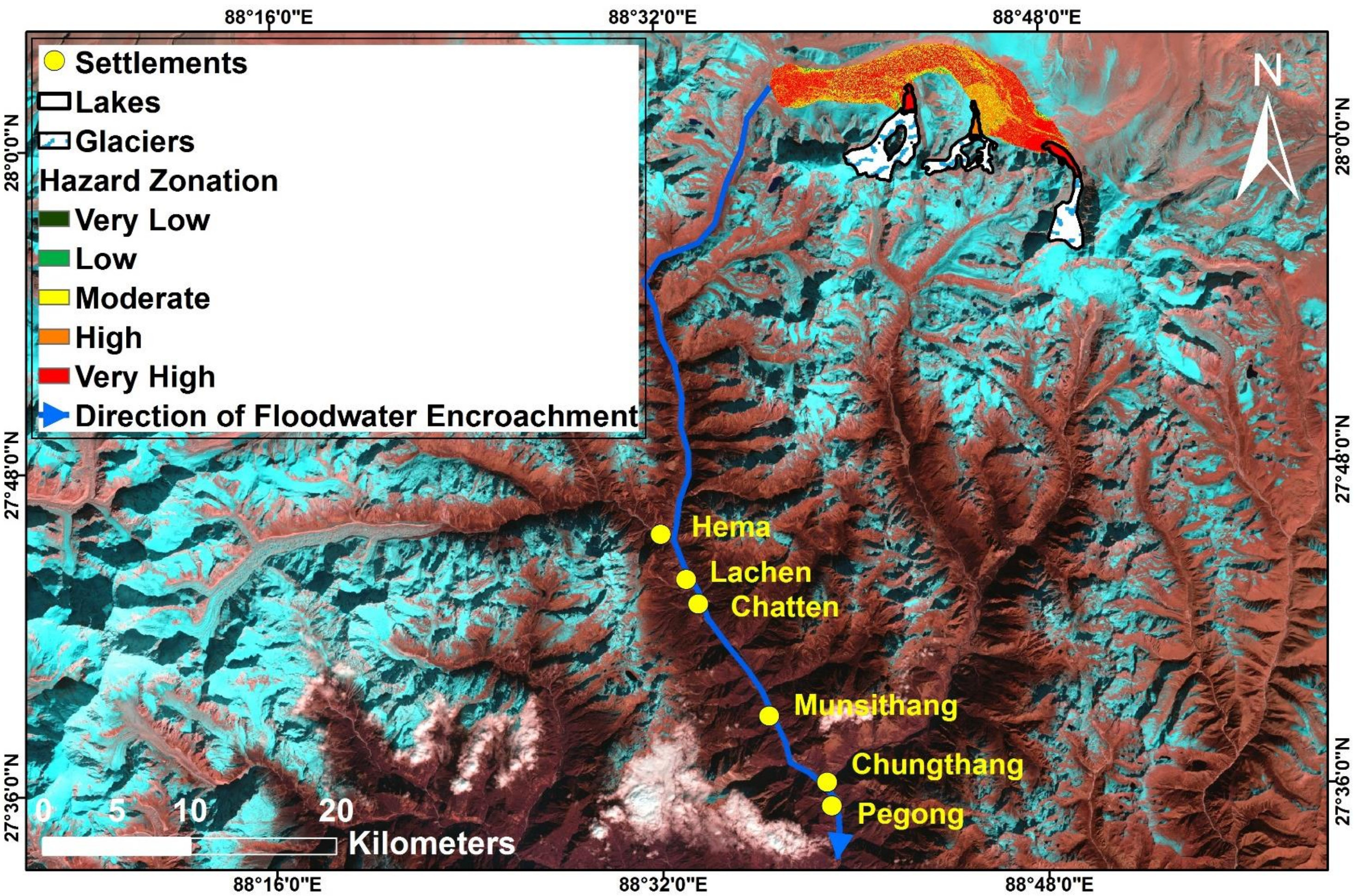
**Figure 4.7. Cross Sections from Lakes to Outlet Basins - Sikkim**




**Note:** Cross-Sections made on the Outflowing Stream, illustrating the Channel Topography

**Source:** Computed

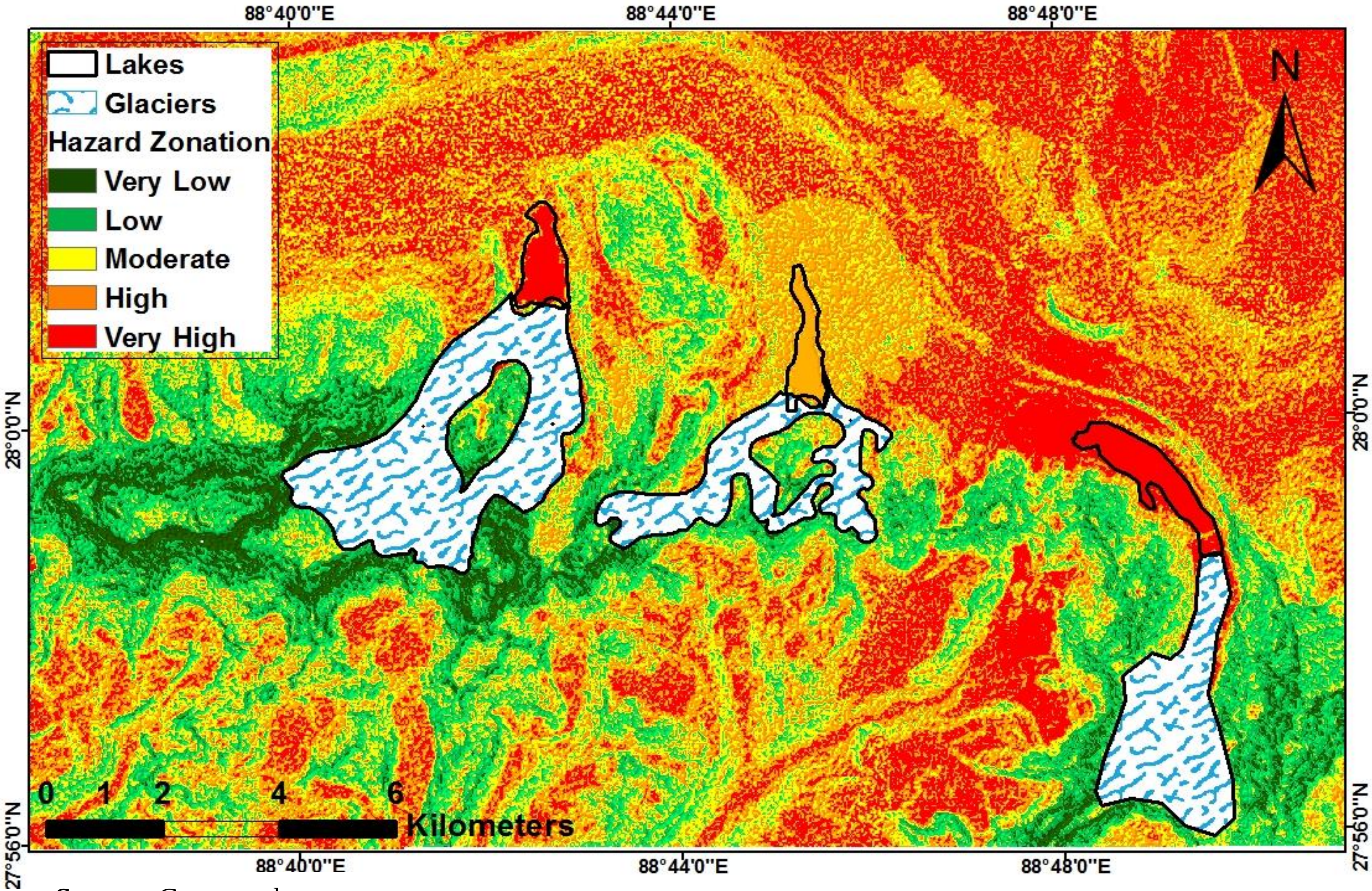
**Figure 4.8. Direction of Floodwater Encroachment through Valley - Sikkim**




**Note:** Figure 4.8 represents the Direction of the Floodwater towards the Settlement

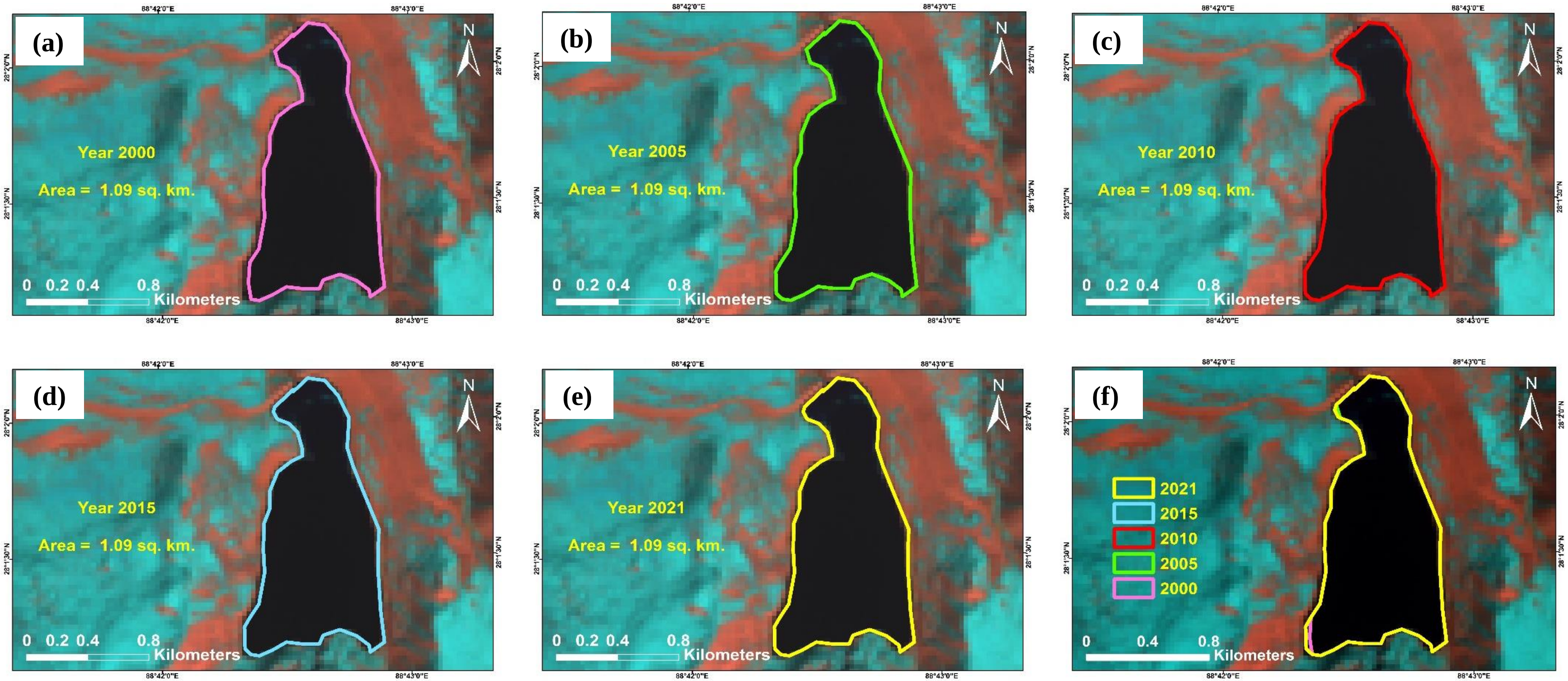
**Source:** Computed

Figure 4.9: GLOF Hazard Zonation Map - Sikkim




**Source:** Computed

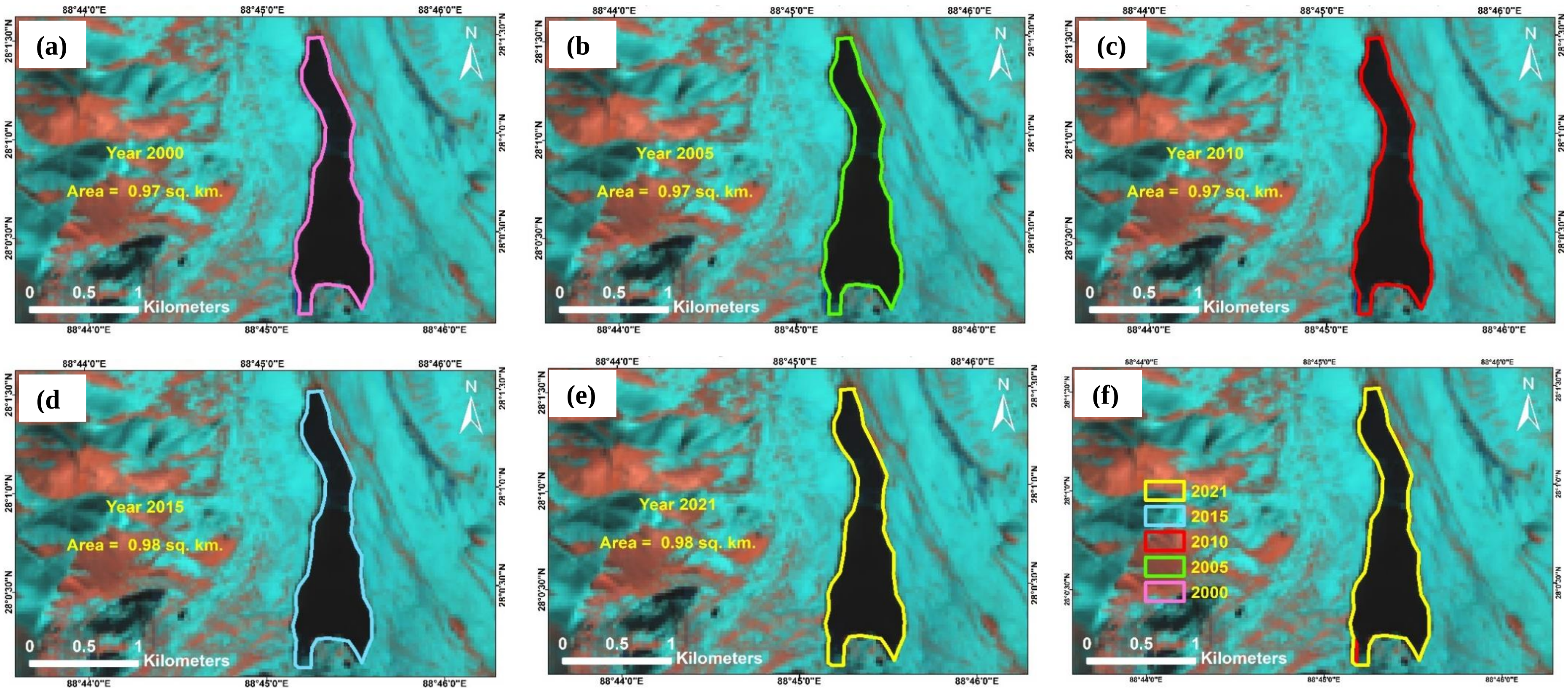
**Figure 4.10: Temporal Dynamics of Moraine Dammed Lake No.1 - Sikkim**




Dimensions for Moraine Dammed Lake (MDL) No. 1 (Sikkim) for Years 2000 (a), 2005 (b), 2010 (c), 2015 (d) and 2021 (e) represented in the above Sub-Figures. (f) Represents the Temporal Changes in Area of MDL No. 1 from 2000 – 2021 (Refer Table 4.3)

**Source:** Computed

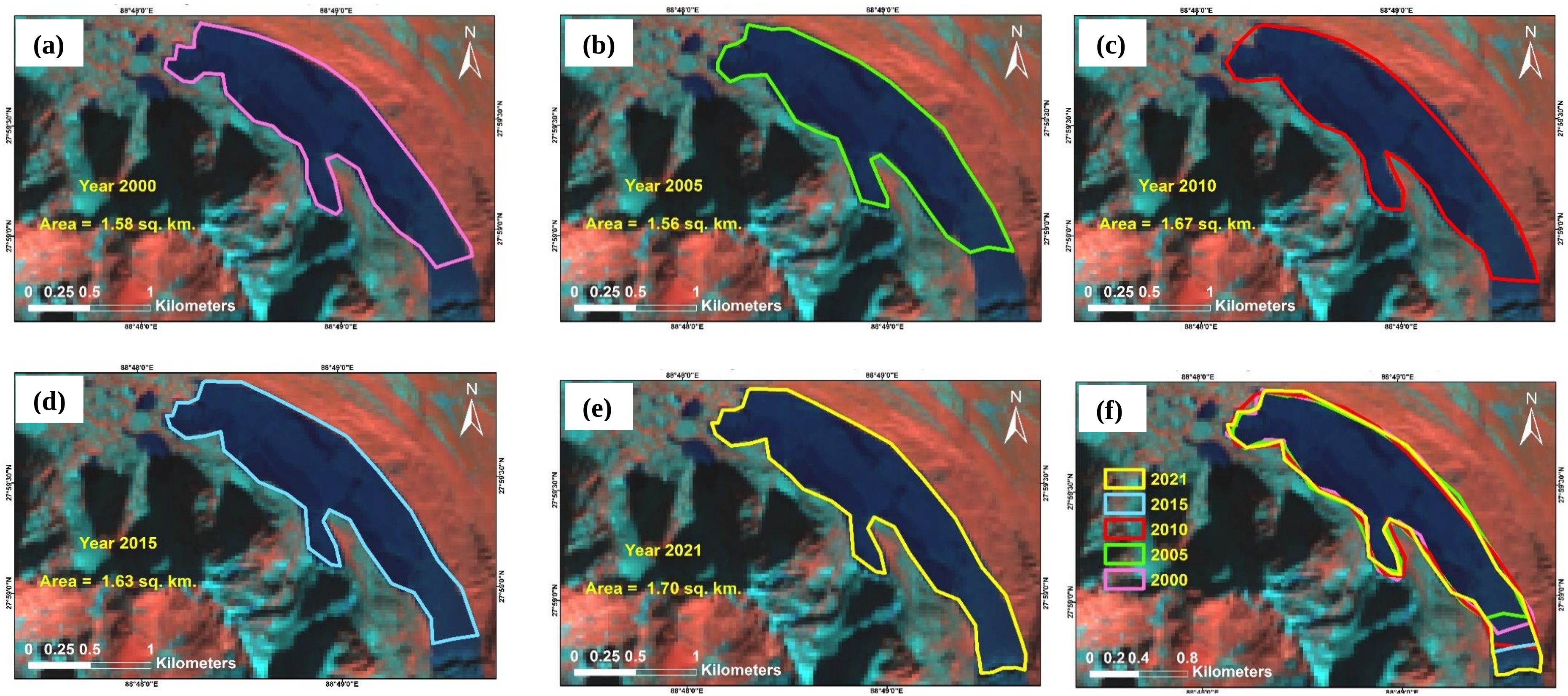
**Figure 4.11: Temporal Dynamics of Moraine Dammed Lake No. 2 - Sikkim**




Dimensions for Moraine Dammed Lake (MDL) No. 2 (Sikkim) for Years 2000 (a), 2005 (b), 2010 (c), 2015 (d) and 2021 (e) represented in the above Sub-Figures. (f) Represents the Temporal Changes in Area of MDL No. 2 from 2000 – 2021 (Refer Table 4.3)

**Source:** Computed

**Figure 4.12. Temporal Dynamics of Moraine Dammed Lake No. 3 - Sikkim**

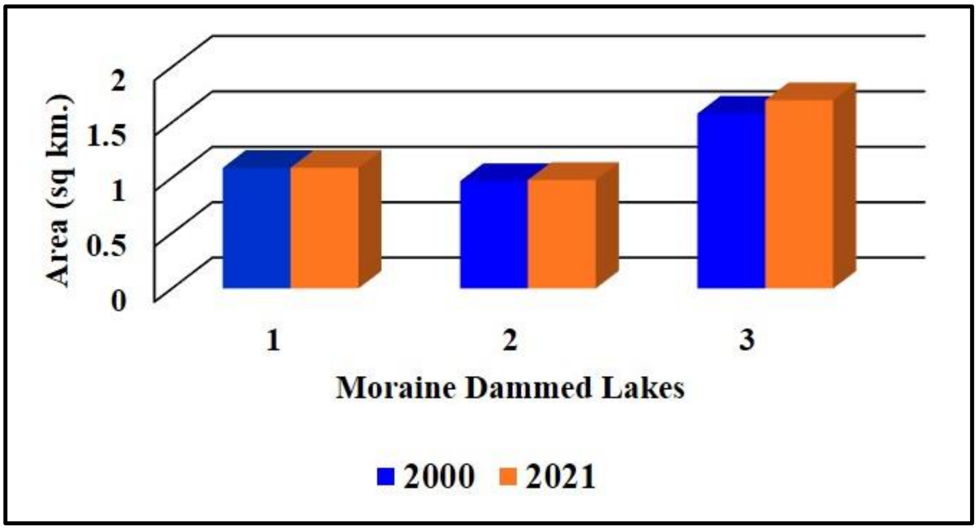



Dimensions for Moraine Dammed Lake (MDL) No. 3 (Sikkim) for Years 2000 (a), 2005 (b), 2010 (c), 2015 (d) and 2021 (e) represented in the above Sub-Figures. (f) Represents the Temporal Changes in Area of MDL No. 3 from 2000 – 2021 (Refer Table 4.3)

**Source:** Computed

| Table 4.3: Changes in Moraine Dammed Lake Areas between 2000 and 2021 - Sikkim | | | | | |
|---|---|---|---|---|---|
| **Moraine Dammed Lakes No.** | **Lake Area (in sq. km.) between 2000 – 2021 (Sikkim)** | | | | |
| | 2000 | 2005 | 2010 | 2015 | 2021 |
| **1** | 1.09 | 1.09 | 1.09 | 1.09 | 1.09 |
| **2** | 0.97 | 0.97 | 0.97 | 0.98 | 0.98 |
| **3** | 1.58 | 1.56 | 1.67 | 1.63 | 1.70 |
| **Source:** Computed | | | | | |

**Figure 4.13. Changes in Moraine Dammed Lake Areas between 2000 and 2021 - Sikkim**

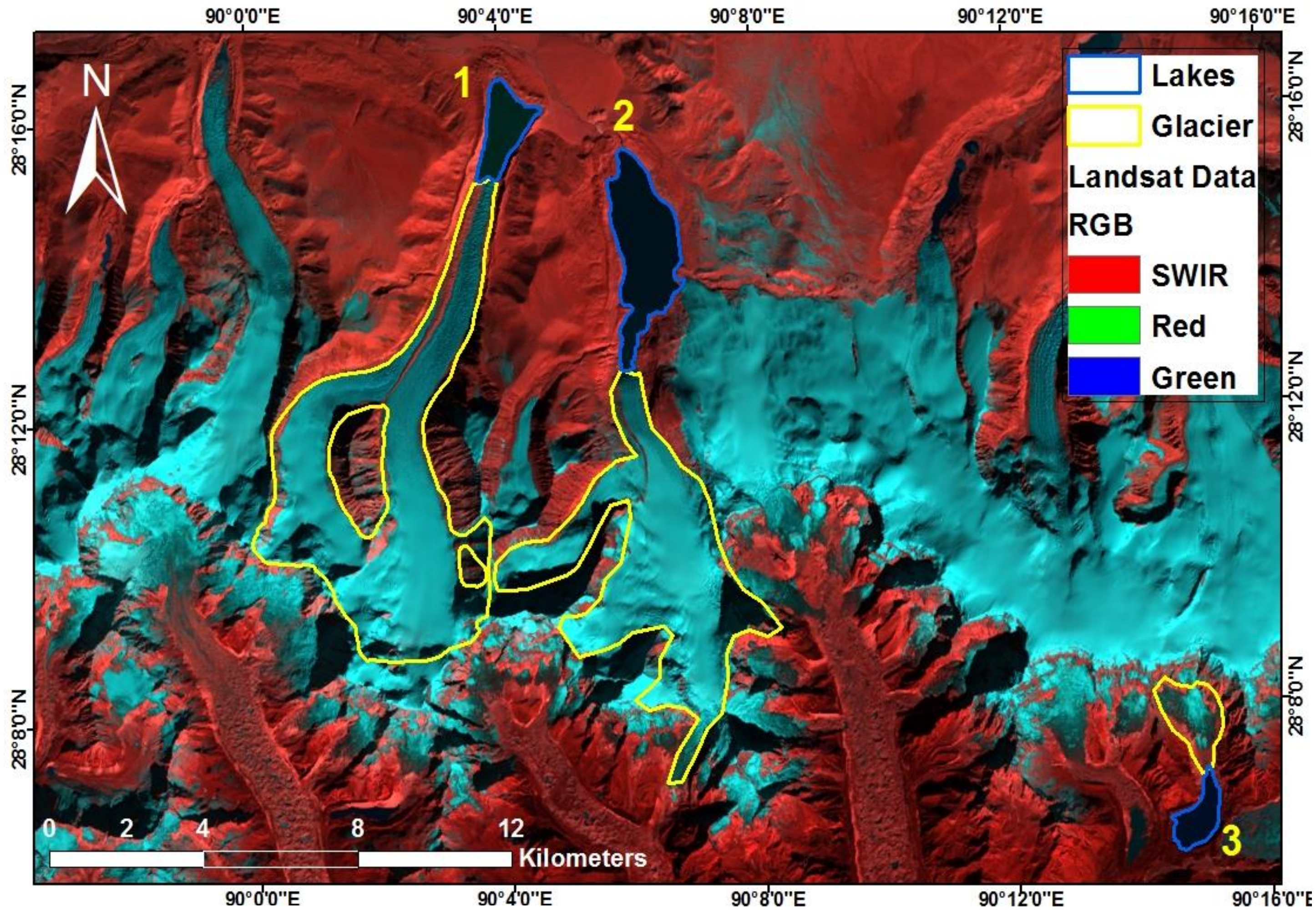



**Source:** Computed

## 4.5:- Moraine Dammed Lakes in Bhutan

Figure 4.14 illustrates a panorama of Bhutan showing three glaciers, each with Moraine Dammed Lakes. For convenience, these MDLs are labelled 1, 2 and 3. Glacier number 2 with an extent of about 23.30 square kilometre., feeds the largest moraine dammed lake (5.41 square kilometre) identified for Bhutan during this study (Table 4.4.). This was followed by lake number 1 (1.37 square kilometre) and then lake number 2 (1.13 square kilometre). Mapping of the MDL's alone would not sort the purpose of assessing

**Figure 4.14: Glaciers and Glacial Lakes (Moraine Dammed lakes) - Bhutan**




**Source:** Computed, LANDSAT

how hazardous the lakes could be. Thus, studying the related glaciers and the glaciers in near proximity helps assess the vulnerability of the lakes more unmistakably (Aggarwal et al., 2016). Another important factor that is the degree of slope (Figure 4.15.) of the glaciers associated with the MDL's. This is attributed to the reason that if the lake comes into contact with a steep slope in its surroundings, it may function as a trigger point for avalanches or rock falls, which might then impact the lake and cause displacement waves. (Emmer and Cochachin, 2013).

**Table 4.4. Dynamics of Glaciers with Moraine Dammed Lakes - Bhutan**

| Glacier No. | Glacier Area (in km.) | Perimeter (in km) | Length (in km) | Mean Elevation (meters) |
|---|---|---|---|---|
| **1** | 30.07 | 44.02 | 12.3 | 5732 |
| **2** | 23.30 | 39.10 | 9.48 | 5622 |
| **3** | 2.40 | 6.79 | 2.55 | 4895 |
| **Source:** Computed | | | | |

Elevation is also an essential component in GLOF, the higher the elevation of the MDLs, the more potential energy the lake water possesses after the dam is ruptured (Che et al., 2014). Thus, here the mean elevation of the lakes have been considered. Lake number 1 has the highest mean elevation (5145 metres) followed by Lake 2 (5096 metres) and 3 (4339 metres) (Table 4.5, Figure 4.16.).

**Table 4.5: Moraine Dammed Glacier Lake Dynamics - Bhutan**

| Glacier Lake No. | Lake Area (in sq.km.) | Lake Depth (in metres) | Lake Volume (in $m^3$) | MDL Elevation (in meters) | Orientation of Snow Line |
|---|---|---|---|---|---|
| **1** | 1.37 | 0.14 | 0.28 | 5145 | NE |
| **2** | 5.41 | 0.22 | 1.26 | 5096 | N |
| **3** | 1.13 | 0.12 | 0.15 | 4339 | SW |
| **Source:** Computed | | | | | |

Lake number 2 with the largest lake area (5.41 square kilometre) is the deepest (0.22 metres) of the three MDL's, holding the largest volume of water (1.26 metre$^3$), followed by Lake number 1 which was 0.14 metres deep with a water holding capacity of 0.28 m$^3$ and Lake number 3 having a depth of 0.12 metres and 0.15 metre$^3$ volume of water (Figure 4.17, Figure 4.18). As pointed out by Huggel et al, in 2002, the size of the lake is directly related to the flood volume, the length of the lake, lake width and volume of water in the lake. Figure 4.19 illustrates the curvature map of the study area, which was one of the input layers required for the computation of the Hazard Zones in GIS environment.

Figure 4.21 shows the Direction of Floodwater Encroachment through valley which is representative of the distance travelled by the flood water to reach the human settlements and act as a danger to them. The only lake posing a threat to the Punakha village was MDL number 3, which was orientated SW (South – West). Even if the lake breached, the floodwaters would not destroy the settlement because it was more than 65 kilometres distant from the MDL. This water must transit the basin's outflow course, thus cross sections (Figure 4.20.) were created at various places to illustrate the channel topography.

This exhibited that the valley was originally U-shaped, but morphed into a V-shaped in the lower levels near human habitation.

Monitoring of GLOF prone regions, in addition to routine monitoring of the MDL, should be done not only geographically, but also temporally. As a result, the MDLs were mapped across a 21-year period, from 2000 to 2021. The lake areas seen in the Figures 4.23, 4.24 and 4.25 have undergone a lot of change through time. MDL number 2 which was located at the highest elevation (5145 metres) of the three lakes, expanded the greatest in area i.e. 0.57 square kilometre, over a 21- year period. This was followed by lake number 2, which grew by 0.21 square kilometre from 2000 to 2021 and lake number 3, which increased by 0.12 square kilometre from 2000 to 2021. All the three MDL's identified in Bhutan expanded in extent, indicating a negative mass balance of the glaciers or the considerable glacier retreat over a 21-year period (Figure 4.26).

According to the Bhutan Hazard Zonation Map (Figure 4.22) Lakes 1 and 2 are in the Very High Hazard Zone, however, Lake 3 is in the 'High Hazard Zone' due to its lower volume of water, size and depth in contrast to the other two lakes. Despite being in the 'High Hazard Zone', the two lakes pose no significant threat to humankind because they are not in the route of any habitable locations.

Figure 4.15: Slope Map - Bhutan

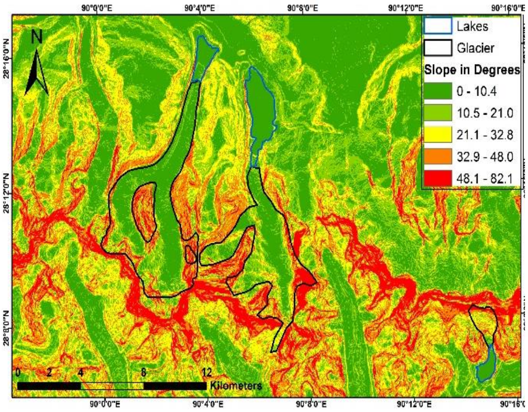



Figure 4.16: Elevation Map -

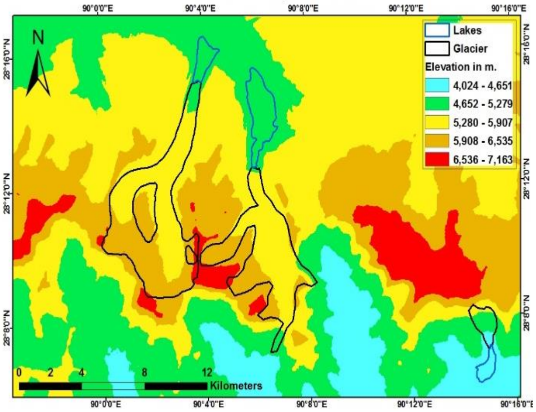



Figure 4.17: Glacier Lake Volume Map - Bhutan

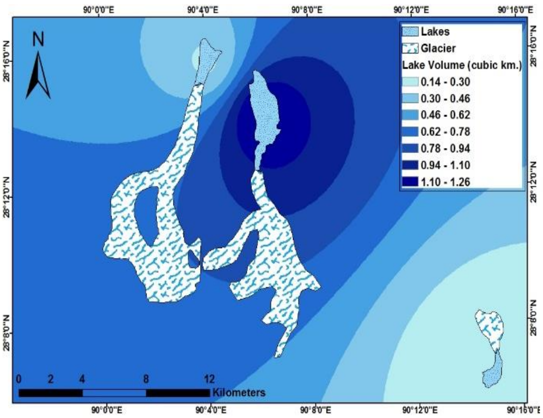



Figure 4.18: Glacier Lake Depth Map - Bhutan

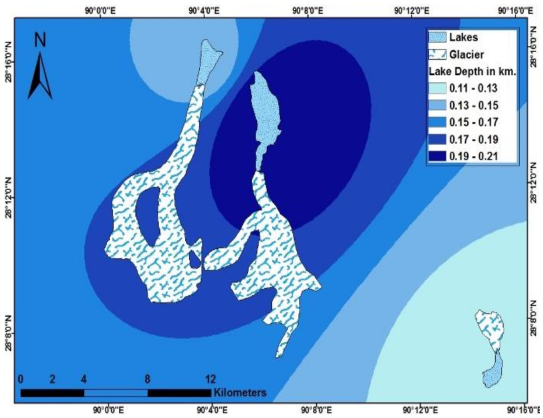
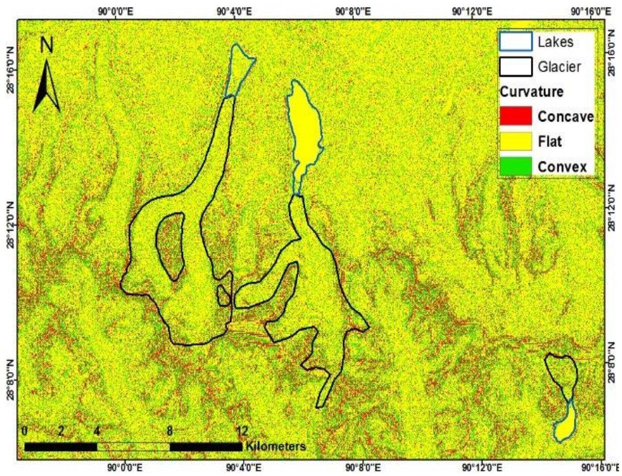


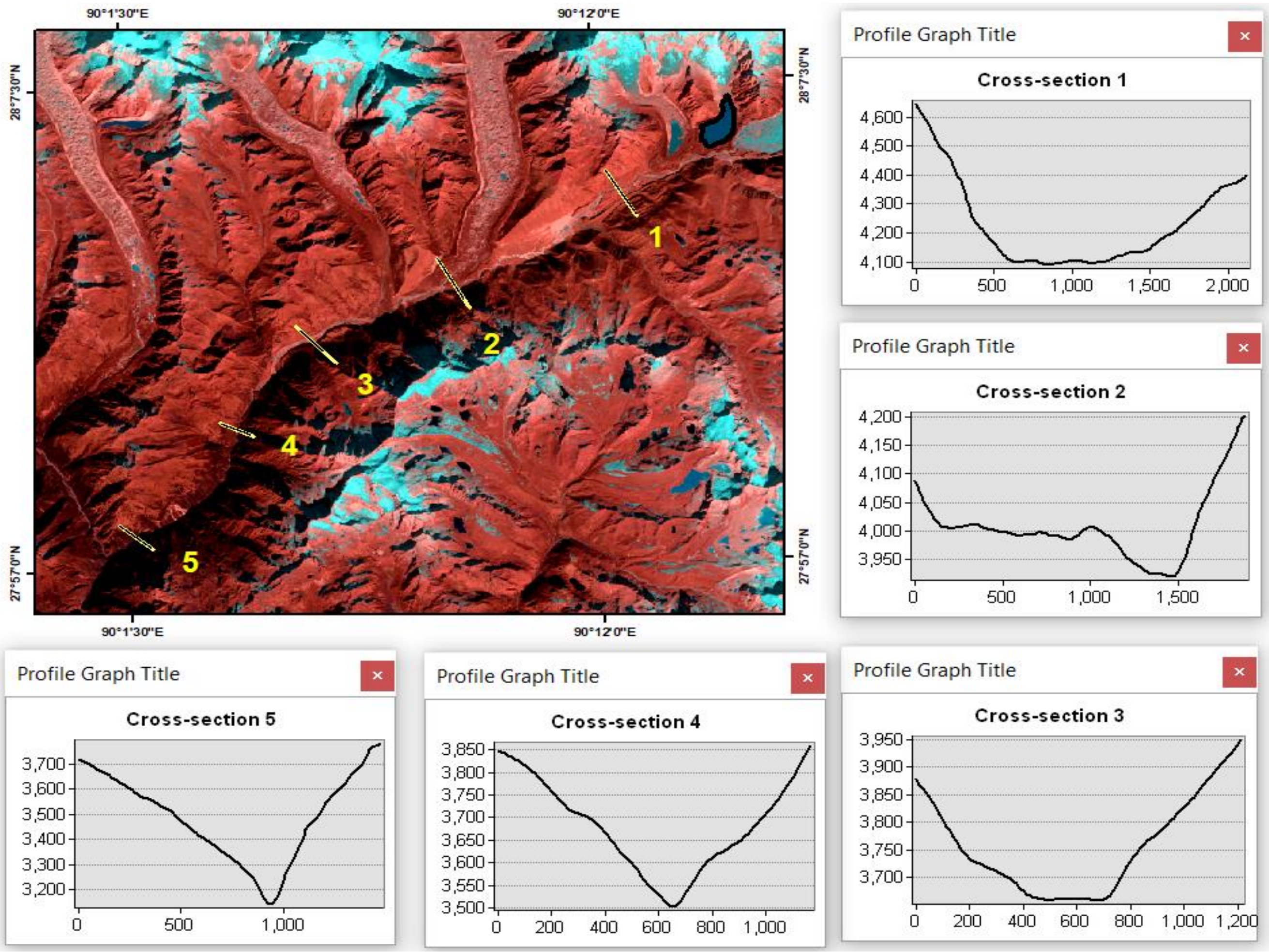

Figure 4.19: Curvature Map - Bhutan




**Note:** Figure 4.15, 4.16, 4.17, 4.18 and 4.19 are input layers required for the computation of the Hazard Zones in GIS

**Source:** Computed

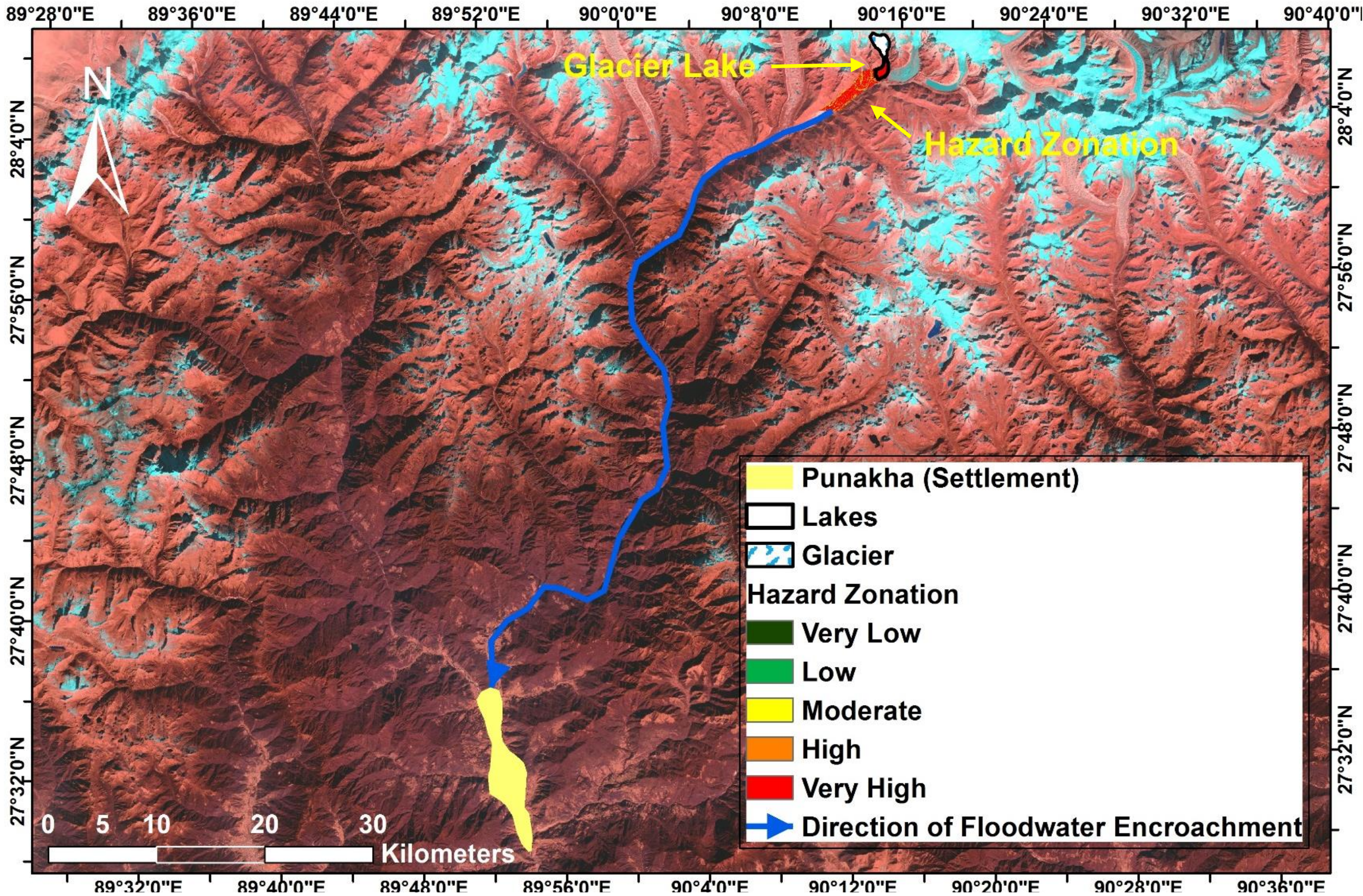
**Figure 4.20. Cross Sections from Lakes to Outlet Basins - Bhutan**




**Note:** Cross-Sections made on the Outflowing Stream, illustrating the Channel Topography

**Source:** Computed

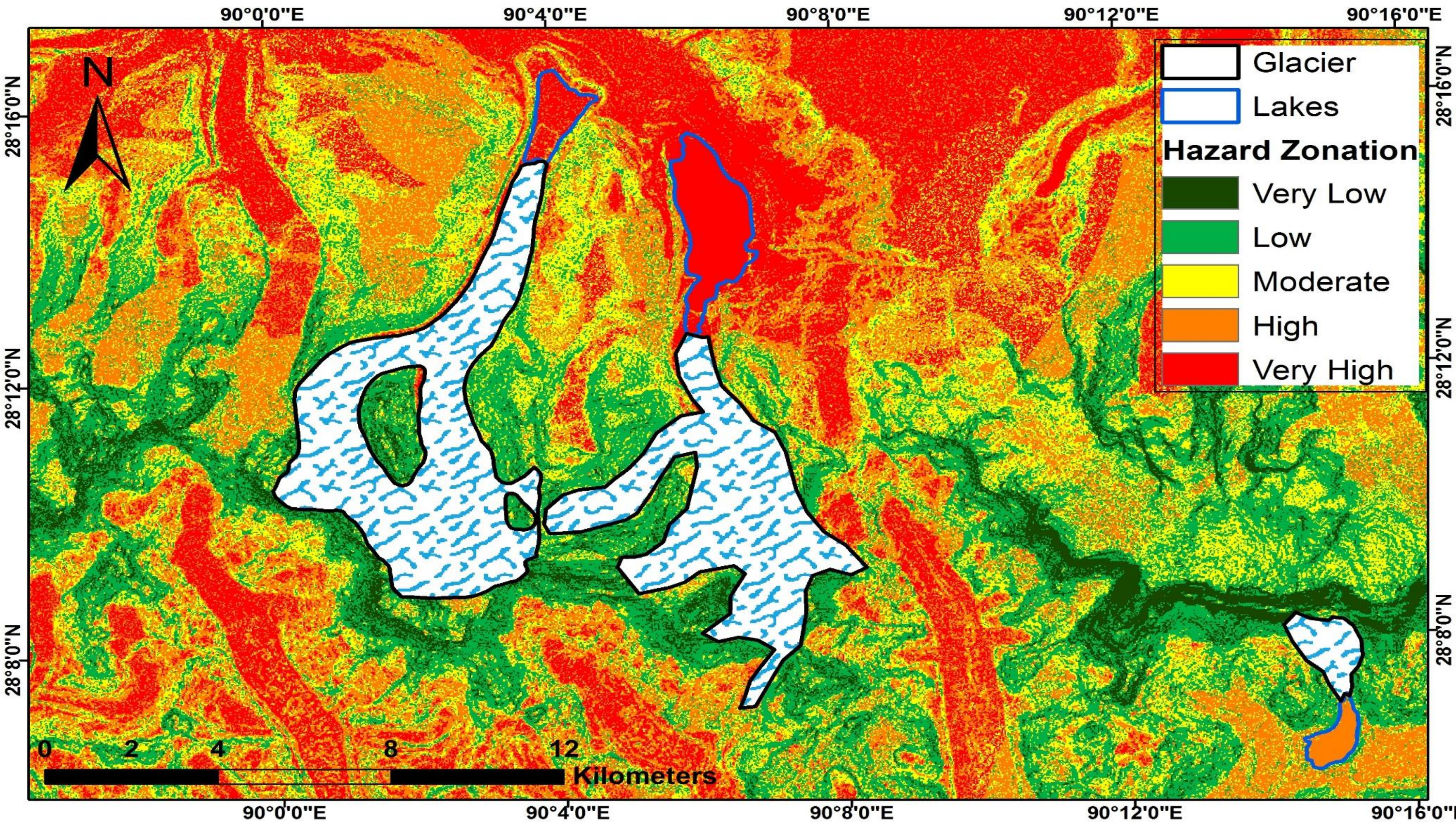
Figure 4.21. Direction of Floodwater Encroachment through Valley - Bhutan




**Note:** Figure 4.21 represents the Direction of the Floodwater towards the Settlement

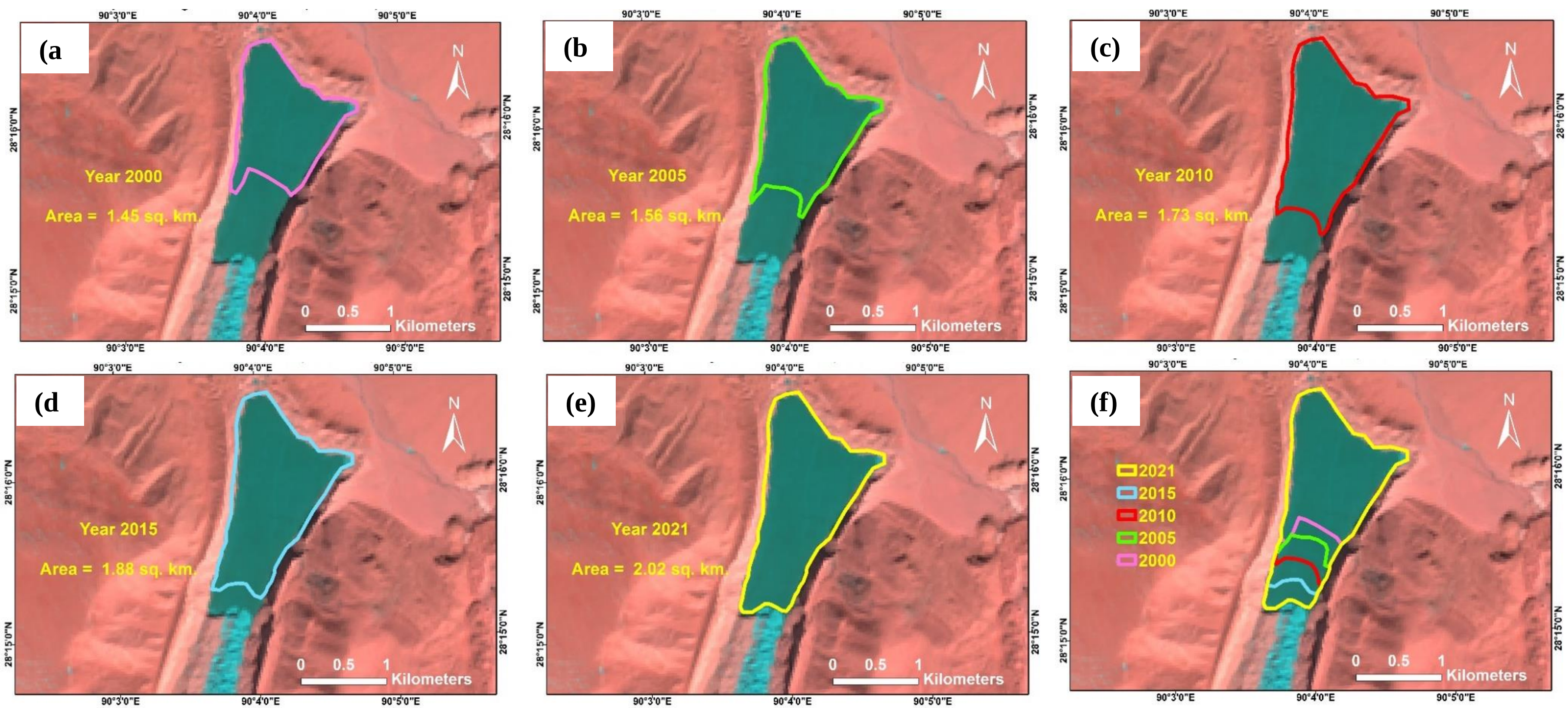
**Source:** Computed

**Figure 4.22. GLOF Hazard Zonation Map - Bhutan**




**Source:** Computed

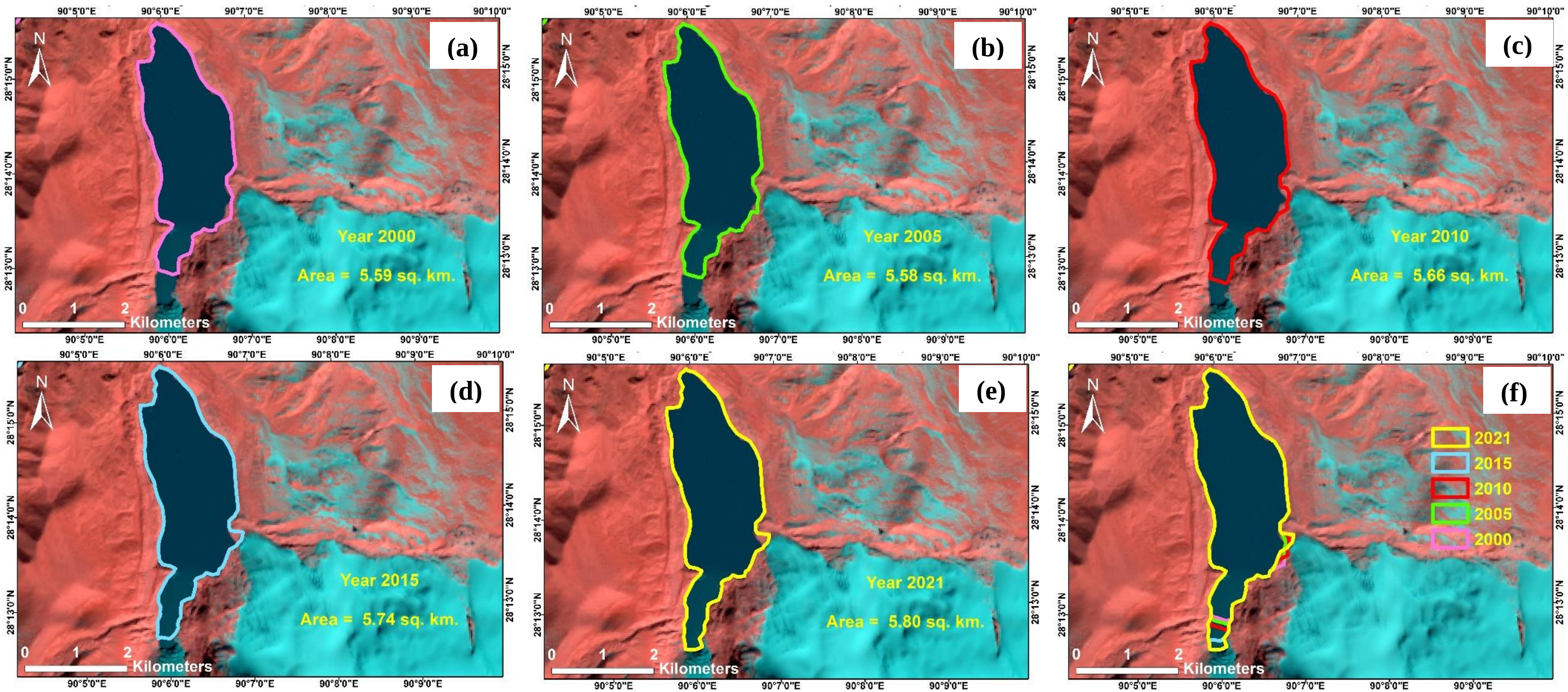
**Figure 4.23: Temporal Dynamics of Moraine Dammed Lake No.1 - Bhutan**




Dimensions for Moraine Dammed Lake (MDL) No. 1 (Bhutan) for Years 2000 (a), 2005 (b), 2010 (c), 2015 (d) and 2021 (e) represented in the above Sub-Figures. (f) Represents the Temporal Changes in Area of MDL No. 1 from 2000 – 2021 (Refer Table 4.6)

**Source:** Computed

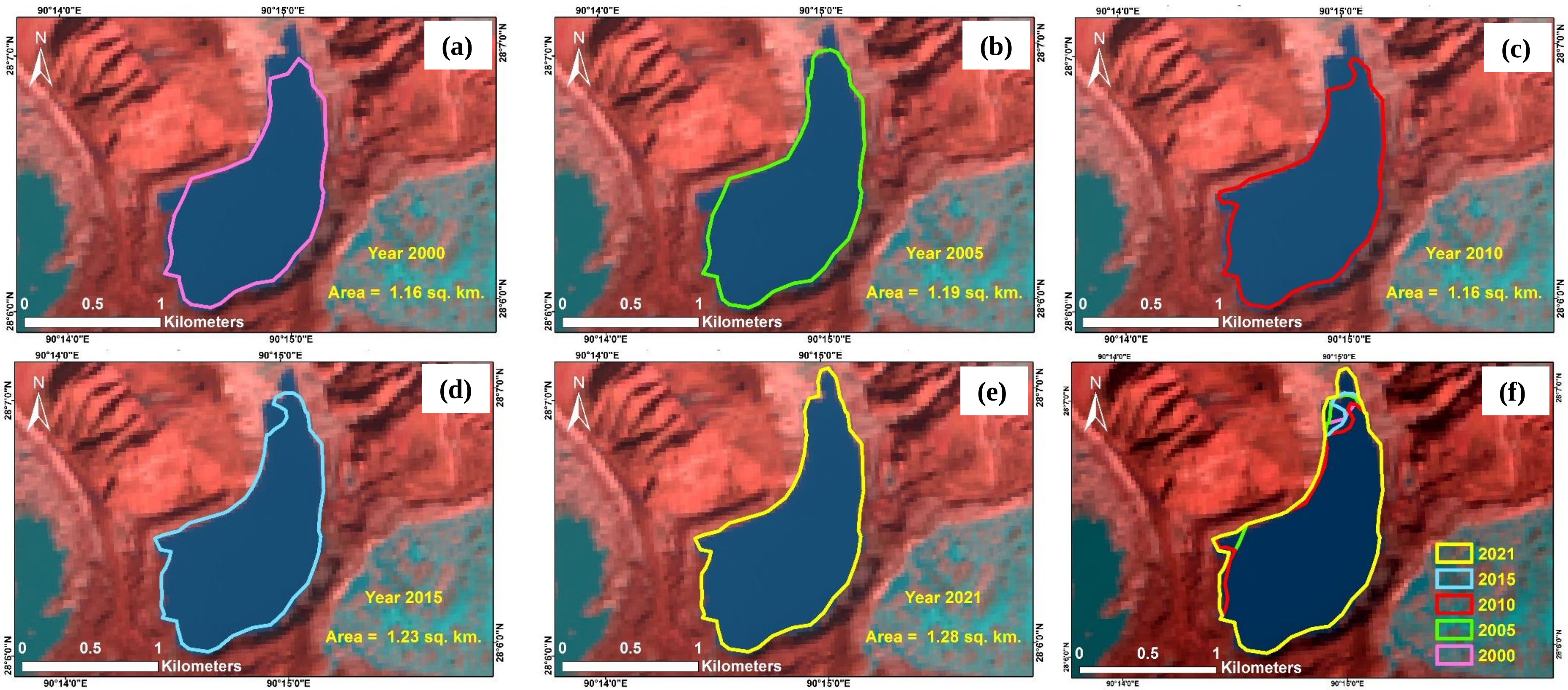
**Figure 4.24: Temporal Dynamics of Moraine Dammed Lake No. 2 - Bhutan**




Dimensions for Moraine Dammed Lake (MDL) No. 2 (Bhutan) for Years 2000 (a), 2005 (b), 2010 (c), 2015 (d) and 2021 (e) represented in the above Sub-Figures. (f) Represents the Temporal Changes in Area of MDL No. 2 from 2000 – 2021 (Refer Table 4.6)

**Source:** Computed

**Figure 4.25: Temporal Dynamics of Moraine Dammed Lake No. 3 - Bhutan**

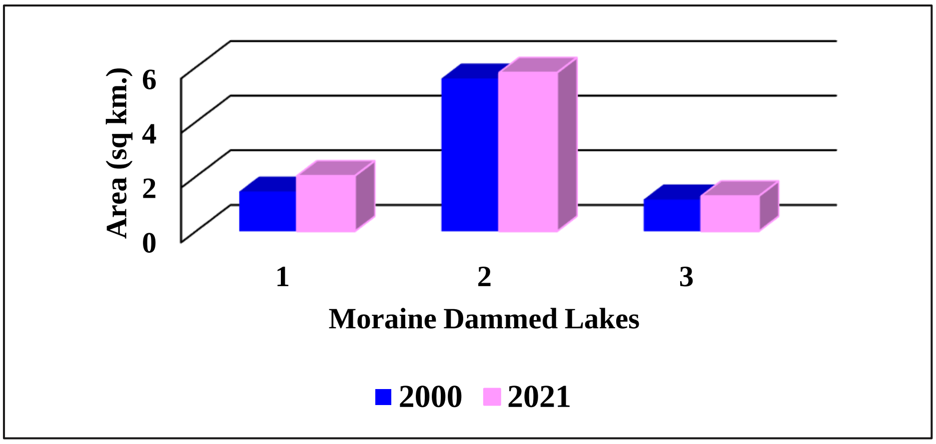



Dimensions for Moraine Dammed Lake (MDL) No. 3 (Bhutan) for Years 2000 (a), 2005 (b), 2010 (c), 2015 (d) and 2021 (e) represented in the above Sub-Figures. (f) Represents the Temporal Changes in Area of MDL No. 3 from 2000 – 2021 (Refer Table 4.6)

**Source:** Computed

| Table 4.6. Changes in Moraine Dammed Lake Areas between 2000 and 2021 - Bhutan | | | | | |
|---|---|---|---|---|---|
| **Moraine Dammed Lakes No.** | **Lake Area (in sq. km.) between 2000 – 2021 (Bhutan)** | | | | |
| | 2000 | 2005 | 2010 | 2015 | 2021 |
| **1** | 1.45 | 1.56 | 1.73 | 1.88 | 2.02 |
| **2** | 5.59 | 5.58 | 5.66 | 5.74 | 5.80 |
| **3** | 1.16 | 1.19 | 1.16 | 1.23 | 1.28 |
| **Source:** Computed | | | | | |

**Figure 4.26: Changes in Moraine Dammed Lake Areas (2000- 2021) - Bhutan**




**Source:** Computed

## 4.6:- Comparative Analysis of Moraine Dammed Lakes of Sikkim and Bhutan

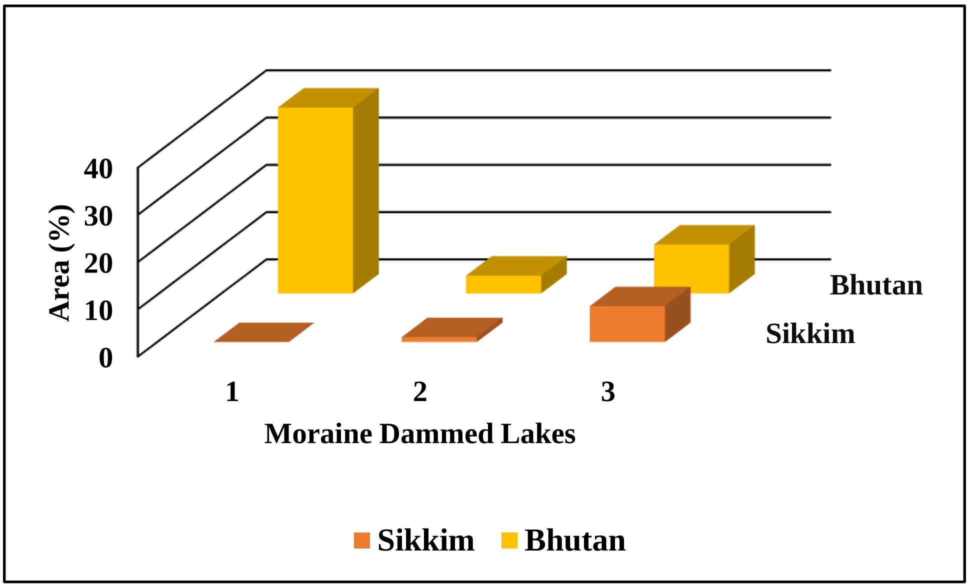
The Glacier Lake Outburst Flood Hazard Zonation Maps of both Sikkim and Bhutan reveal that Lake Number 1 and 3 of Sikkim and Lake Numbers 1 and 2 of Bhutan fall under the Very High Risk Zones. This outcome indicates that if these lakes breach in the near future they would risk the landscape as well any settlement falling in the direction of flood water flow. On the other hand, Lake Number 2 of Sikkim and Lake Number 3 of Bhutan lie in the High Risk Zone in case GLOF occurs. Table 4.7 and Figure 4.27 show the Moraine Dammed Lakes increase in percentage between the years 2000 – 2021 in both Sikkim and Bhutan. Lakes in Bhutan showed significant increase in area as compared to the MDL's of Sikkim. Two of these lakes, Lake 3 from Sikkim and Lake 1 from Bhutan which increased in area the most, were oriented towards the NE direction. These findings require more examination because these lakes and the glaciers that sustain them have the highest elevation of all of the lakes assessed.

**Table 4.7. Percentage Increase of Moraine Dammed Lakes – Sikkim & Bhutan**

| Moraine Dammed Lakes No. | Lake Area Increase (in %) between 2000 – 2021 | |
|---|---|---|
| | **Sikkim** | **Bhutan** |
| **1** | 0.00 | 39.31 |
| **2** | 1.03 | 3.76 |
| **3** | 7.59 | 10.34 |

**Source:** Computed

**Figure 4.27: Percentage Increase of Moraine Dammed Lakes – Sikkim & Bhutan**




**Source:** Computed

## *Resume*

*This chapter concentrated solely on Moraine Dammed Lakes and its Hazard Zonation. The mechanism for this zonation was defined first and then the possibly harmful glacial lakes were identified. Various essential layers, such as slope, depth, volume and so on, were produced for inclusion in the final set model in the Arc GIS environment. Hazardous Zones corresponding to MDLs were therefore delineated as a result of modelling.*