Glaciers as Indicators of Climate Change – the special case of the high elevation glaciers of the Nepal Himalaya

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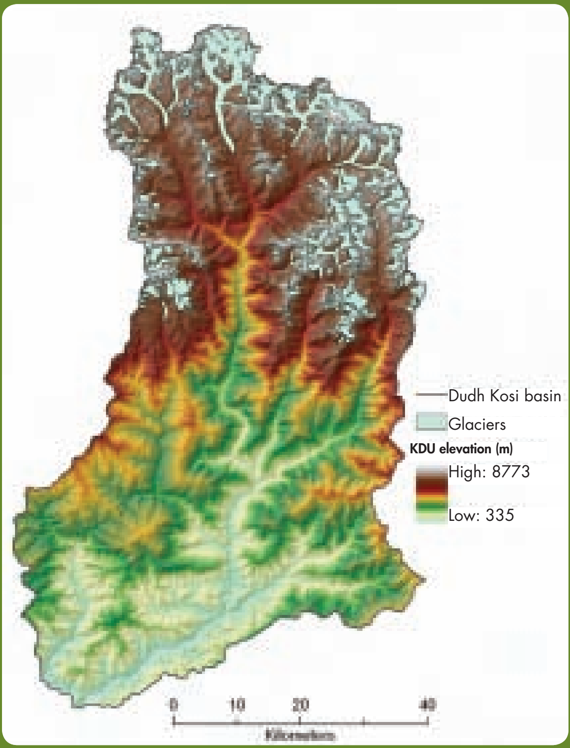
Glaciers represent perhaps the most dramatic and direct visual evidence of climate change. Glacier retreat provides a clear indication of a global climate that has been warming since the Little Ice Age (LIA), which occurred from approximately 1650 to 1850. Throughout North America, Europe, and Asia, the evidence left by glacier moraines shows the maximum extent of these glaciers during the LIA and quantifies the fact that glaciers have been retreating since this period in response to a warmer climate.

In addition, there is clear evidence that indicates that the retreat of glaciers in most locations of the world has accelerated in recent decades. However, while it is safe to say that almost all glaciers of the world have been losing mass to some degree, and retreating, since the LIA, it is important to point out that glacier systems at the highest elevations, 4000-7000 m, have not responded to recent climate warming in the same way as lower elevation glaciers. Therefore, although glaciers are retreating both in the European Alps and in the Himalayas, one cannot always make direct comparisons

Elevation model and glaciers in the Dudh Kosi basin



- Digital elevation model (DEM) from the NASA Shuttle Radar Topography Mission (SRTM v.4), (90m spatial resolution).
- Glacier outlines for Nepal from topographic maps, 3250 glaciers, 5,300 sq.km (ICIMOD)
- Catchment basins from ICIMOD (basic topographic unit in water budget analysis)
- Runoff data from Department of Hydrology and Meteorology (DHM), Nepal
- Maximum annual altitude of the 0 deg. isotherm from extrapolation and upper air data
- Nine glacierised and gauged basins were selected for the study.

and extrapolations from the well studied lower elevation glaciers to the higher elevations.

Glacier monitoring: terminus and mass balance

Terminus location: Recording the annual changes in the location of a glacier terminus is the simplest measurement that indicates the status of a glacier with respect to climate. Abundant terminus histories are available in some parts of the world, Europe in particular, while in regions such as the Himalaya, these data are more limited (WGMS 2008). An example of a summary of terminus data available for the Himalayan region can be found in Eriksson et al. (2009). In summary, these publications report that Himalayan glaciers are retreating at rates of 10 to 60 m per year and many small glaciers (<0.2 sq.km) have already disappeared.

It should be understood that the monitoring of the terminus location of a glacier is neither a complete nor a comprehensive assessment of total glacier condition or health. For example, if a glacier is noted to be retreating, this simply means that the ice volume at the terminus is melting faster than the rate at which ice is being supplied to that location by the dynamic movement of ice from further upslope in the system. On an annual basis, it is possible that a glacier could be gaining in total mass due to increasing amounts of snow arriving in the accumulation zone by precipitation, wind deposition and avalanching, while, at the same time, the terminus is retreating. Data that report glacier retreat describe only the conditions at the lowermost elevation of the glacier where the current climate does not support the extension, or even stability of the glacier. Thus, terminus data alone cannot comprehensively represent those conditions controlling the changes in volume and mass across the entire elevation range of a glacier system. And to put the Himalayan region in a global perspective, the elevation range of the glacier systems in this region is the greatest in the world.

Mass balance: Glacier mass balance studies in the Himalayan region have been rare and often sporadic over recent decades, with measurements on only about a dozen glaciers, and with only a very few of those studies having a duration of more than a few years. The conventional methods for measurement of mass balance, relatively common in Europe and North America, have simply not been practical across the remote and rugged terrain of these ranges. As a result, very few data are available to assess the comprehensive 'health' of Himalayan glaciers. In addition, the limited results that are available may only be representative of those specific glaciers where the measurements have been made, typically the more accessible sites at lower elevations. Therefore, it is important to develop more spatially comprehensive methods to provide a truly regional assessment of glacier health across the Himalaya.

A simple methodology to compute glacier ice melt

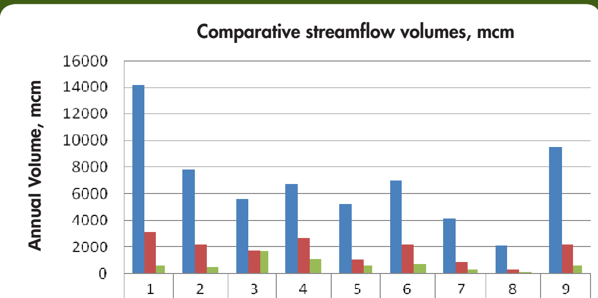
The annual melt from a glacier tends to increase with decreasing altitude and can be represented by an ablation gradient, the inverse relationship between glacier ice melt and altitude. This gradient is purported to remain constant even as the varying temperature and precipitation patterns from year to year may cause changes ranging from extreme positive to extreme negative net mass balance years. While complete energy exchange models exist to compute melt at a specific point on a single glacier, such a methodology is not appropriate for a regional assessment, primarily due to the lack of the required input data. Therefore, we proposed an alternative method that we consider to be an optimal regional scale approach to determine the contribution of glacier ice melt to river runoff based on the data that are available (Alford et al. 2009).

For this study, it was necessary that the basins chosen be glacierised, contain stream gauges, and be covered by quality SRTM (NASA Shuttle Radar Topography Mission) data in order to derive measurements of the elevation

Methodology and Data Sources

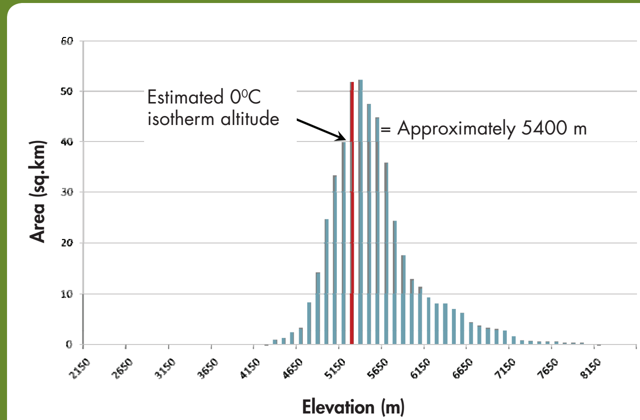
Our methodology is based on previous studies which involve concepts variously referred to as the 'ablation gradient' (Haefeli 1962), the 'mass balance gradient' (Konz et al. 2006), and the 'vertical budget gradient, VBG' (Kaser and Osmanston 2002). For any glacier, it is assumed that the slope of this gradient, defined as melt/metre, (m/100 m) is relatively constant and is determined by the response of the glacier to regional climate variations (Armstrong 1989). The first step in this methodology is to determine the surface area over which annual melt is to be calculated. We introduce the concept of an '$E0_{max}$', which we define as the highest annual altitude reached by the monthly mean zero degree isotherm. By extrapolation from lower elevation station data and from upper air temperature data, we estimate this average altitude to be approximately 5,400 m for the mountains of Nepal. We then compute melt extending down-glacier from the elevation of the $E0_{max}$ to the elevation of the glacier terminus. Melt over this area of the glacier is assumed to represent a net annual loss of mass to the glacier, i.e. it does not include the loss of seasonal snow. For the Himalayas, ablation gradients may range from 0.69 m/100 m for the Chhota Shigri glacier in the Western Himalayas (Wagnon et al. 2007) to 0.81-1.3m/100 m for Yala glacier in the Nepal Himalayas (Konz et al. 2006). In this preliminary study we chose to use a mass balance gradient of 1.4 m/100 in order to estimate possible maximum runoff.

Figure 1: **Estimated average annual streamflow, in million cubic metres per year,** from a) glacier melt, b) 4000-6000 m altitudinal belt, and c) basin total, into glacierised gauged basins in the Nepal Himalaya. Catchment basins are: 1. Bheri, 2. Kali Gandaki, 3. Budhi Gandaki, 4. Marsyangdi, 5. Trisuli, 6. Dudh Kosi, 7. Tama Kosi, 8, Likkhu, 9 Tamor.



	1	2	3	4	5	6	7	8	9
Basin	14149	7765	5624	6672	5192	6929	4153	2091	9510
4-6 km	3118	2197	1682	2669	1007	2130	828	247	2194
Glacier Melt	597	512	1622	1099	609	716	215	68	616

Figure 2 : **Example of glacier area/altitude hypsometry and location of $E0_{max}$ for the Dudh Kosi Basin**



Compute melt below 5400 m using a regional mass balance gradient, estimated range 0.6 to 1.4 m/100 m. Current pilot study uses 1.4 m/100 m for probable maximum runoff volume from ice melt

of land above sea level (hypsometry). Nine basins in Nepal met these criteria. The glaciers of these nine basins contain approximately 80% of the total glacier surface area of the Nepal Himalaya. Figure 1 shows the estimated relative contributions of (1) glacier melt, (2) runoff from all sources in the 4000-6000 m altitude belt, and (3) the total annual catchment basin streamflow volume from these nine basins. The glacier contribution to basin stream flow varies from approximately 20% in the Budhi Gandaki Basin to approximately 2% in the Likhu Khola Basin, averaging approximately 10%. This volume represents approximately 4% of the total mean annual estimated volume of 200,000 million cubic metres for the rivers of Nepal. Under current climate conditions, our preliminary study indicates that the glaciers of Nepal experience no melt over 50% of their surface area at any time of the year (Figure 2). This is in sharp contrast to lower elevation glaciers of the world that do melt over their entire surface during the summer months, often resulting in significant mass loss.

An analysis of the glaciers and hydrological regime of the mountain catchments of the entire greater Himalayas will be required to assess regional variations in the role of glaciers in stream flow production in the western Himalayas, Hindu Kush, and Karakoram. It is assumed, based primarily on anecdotal evidence, that the percentage contribution of glacier ice melt to regional stream flow will increase in an east to west direction across the Himalayas. However, it should be noted that both the precipitation and the total stream flow decrease when moving from the relatively wet monsoon climate of the east to the dry, more continental, climate of the western Himalayas.

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