CALIBRATING ABOVE AND BELOW SNOW LINE PRECIPITATION AS INPUTS TO MOUNTAIN HYDROLOGY MODELS

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Executive Summary

Calibrating above and below snow line precipitation as inputs to mountain hydrology models

EXECUTIVE SUMMARY

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Importance of mountain precipitation

Mountains are the water towers of the world [*Viviroli et al.*, 2007], particularly for Asia, whose rivers all are fed from the High Asian Mountains such as the Hindu-Kush-Himalaya-Karokoram (HKH) range. In this area, referred to as the Third Pole together with the Tibetan Plateau [*Qiu*, 2008], snow and glacier melt are important hydrologic processes [*Immerzeel et al.*, 2010], and climate change is expected to affect melt characteristics and related runoff [*Lutz et al.*, 2014]. The Third Pole contributes the water resources to sustain the lives of nearly two billion people in Asia and provides the source of water for ten major river basins [*Immerzeel et al.*, 2010]. Water is a key resource in the region, as it sustains billions of people but also holds promise to transform the economics of some of the countries with its enormous potential for use for energy production. One of the most prominent uncertainties in Asian mountain hydrology is the spatial distribution of precipitation, which is crucial to understand the high altitude hydrology and this differential response in particular. The relation between precipitation and the Asian mountain ranges remains poorly defined due to the remoteness and the lack of reliable rainfall networks [*Bookhagen and Burbank*, 2006]. Over short horizontal distances precipitation can vary enormously due to orographic effects [*Higuchi et al.*, 1982] but precipitation gauge networks are virtually non-existing at high altitude and even if they exist they are mostly located in the valley bottoms and have difficulty in capturing snowfall. Snow accumulation measurements using snow pillows, snow courses, pits and cores from accumulation zones are also scarce and usually confined to short observation periods.

In many hydrological studies, simulation models are used and these models are forced by precipitation data observed at precipitation gauges located in valleys [*Singh and Bengtsson*, 2004; *Rees and Collins*, 2006; *Singh et al.*, 2006; *Immerzeel et al.*, 2012; *Ragettli et al.*, 2013]. Precipitation measurements are subject to large systematic errors that can amount up to 30% and even more in those cases when a significant part of precipitation falls in the form of snow and undercatch prevails [*Rubel and Hantel*, 1999; *Cheema and Bastiaanssen*, 2011]. In addition, valley stations in mountain regions are generally not representative of basin precipitation because of strong vertical precipitation lapse rates. Several regional studies show that this is particularly valid for the Karakoram.

Accurate information on precipitation distribution is crucial to glacio-hydrological modeling as outlined by [*Pellicciotti et al.*, 2012], but currently only a very limited number of stations measuring rain and snow at high altitude are available. There is a need to develop a long-term monitoring system for collecting high elevation (above snowline) and middle elevation (just below snowline) climate data in the HKH. Such short-term multi-season studies from a set of sites across the HKH range would help in calibrating precipitation inputs into mountain hydrological models.

Achievements

Observations of precipitation and temperature in the Langtang

The project contributed greatly to enhancing our understanding of high altitude precipitation patterns and the distinction between solid and liquid precipitation. The field work of the project focussed on the Langtang catchment in Nepal (Figure 1). In the Langtang catchment a network of high quality pluviometers, tipping buckets and temperature sensors were installed. The pluviometers are able to measure the total precipitation (rain and snow), the snow height and the temperature, while the cheaper tipping buckets allow accurate measurements of rain only and they are installed below the snow line. The temperature sensors are installed on the surface along an altitudinal gradient and they are used to detect whether the surface is snow covered or not. This set-up is unique in the entire Himalayas and it is probably the only site in the entire region where high altitude measurements of precipitation are made with these kinds of instruments. These measurements in combination with other meteorological and hydrological observations done by the project partners were analysed and several key findings were identified.

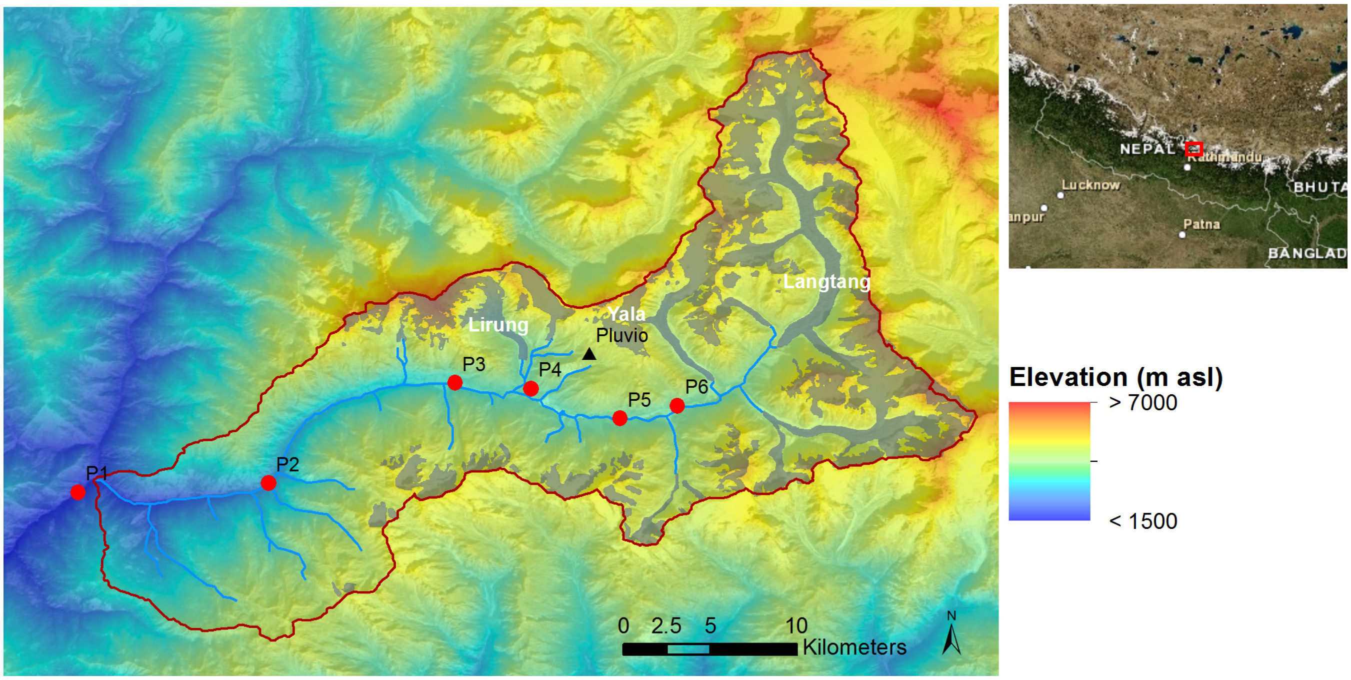

FIGURE 1THE LANGTANG RIVER BASIN WITH OUTLET NEAR SYAFRU BESI (P1), THE LOCATION OF THE TIPPING BUCKETS (P1–P6, RED DOTS), AND THE HIGH-ALTITUDE PLUVIOMETER (PLUVIO, BLACK TRIANGLE). THE GLACIERS ARE SHOWN IN GREY, AND THE NAMES OF SEVERAL REFERENCE GLACIERS IN WHITE.

Precipitation patterns in the valley are highly variable both in time and space. The Langtang catchment is located in the monsoon dominated part of the Himalayas and depending on the location in the valley between 68 and 89% falls during the monsoon season between June and September [*Immerzeel et al.*, 2014]. During monsoon there is almost daily precipitation as the moist air originating from the Bay of Bengal collides with the Himalayas. During winter the systems works completely different and precipitation is produced by disturbances from the west, which cause low pressure areas along the southern periphery of the Tibetan plateau. These low pressure areas cause cyclonic circulation which transport warm moist air from the south resulting in winter precipitation. These events are infrequent, but if they occur they can provide considerable amounts of precipitation. There is also great variation in space within the valley in precipitation. The village of Kyangjin (P4 in Figure 1) is for example twice as dry (867 mm / year) than Lama Hotel (1819 mm / year) (P2 in Figure 1) and these spatial patterns also depend on the season. During monsoon there is a general decreasing trend in precipitation following the valley gradients, while in winter an opposite pattern is observed. Precipitation also increases with altitude, but the elevation of maximum precipitation during monsoon is located at a lower elevation than during winter as a result of the different mechanisms producing the precipitation.

Temperature variations throughout the valley and seasons were also studied. In many studies temperature is assumed to decrease with altitude by about 6.5 °C per 1000 meter elevation gain. This lapse rate is generally a very important parameter in modelling studies as it determines the temperature at the higher areas where snow and ice are melting. It is also a very sensitive parameter, for example, an error of 2 °C / 1000 meter could results in a temperature difference of 4 °C between the valley floor and this may greatly impact the amount of melt water modelled. The temperature observations revealed a very clear seasonal cycle and a high correlation with elevation throughout the year, which is expected, however the lapse rates show great seasonal variation. During monsoon the temperature decreases only by 4.6 °C degrees / 1000 m, where as in winter the lapse rate is - 5.8 °C / 1000 m. The steepest lapse rate is observed in the pre-monsoon season from March to mid-June (- 6.4 °C / 1000m). There is also strong variation in diurnal variations throughout the valley.

Impact on water availability projections

These strong variations in temperature and precipitation in time and space play determine for a large part the amount of water generated in such catchments. Water availability projections are very commonly made using hydrological simulation models and these models are forced by temperature and precipitation time series. In many case accurate observational data is absent and in those cases publically available gridded datasets are used, but these are grossly inaccurate at high-altitudes and possess a resolution that is much too coarse to be of use for high-resolution hydrological assessments [*Palazzi et al.*, 2013]. In other cases just a single station is used and crude assumptions are made for the spatial variation in precipitation and temperature. To illustrate how important the use of local observations are, the hydrological model TOPKAPI-ETH [*Immerzeel et al.*, 2014; *Ragettli et al.*, 2015] was used and five different cases were analyzed ([*Immerzeel et al.*, 2014], Figure 2). The figure shows the relative difference from a reference run where only observations of a single station are used and precipitation does not vary in space and temperature is lapsed using the environmental lapse rate of -6.5 °C / 1000m. Run 5 is the optimum run where all observations are used and run 1 to 4 are intermediate runs where different amounts of observations are used. The results show that run5 is the most realistic run as it simulated the snow line most accurately and the differences in the amount of runoff, snow melt, glacier melt and rain are striking. The runoff is much higher for the case when all observations are used. This has two primary reasons: (i) the real temperature lapse rates are shallower and this result in higher temperature at higher altitude and more melt, (ii) there is more precipitation at high altitude because of the positively observed precipitation gradients.

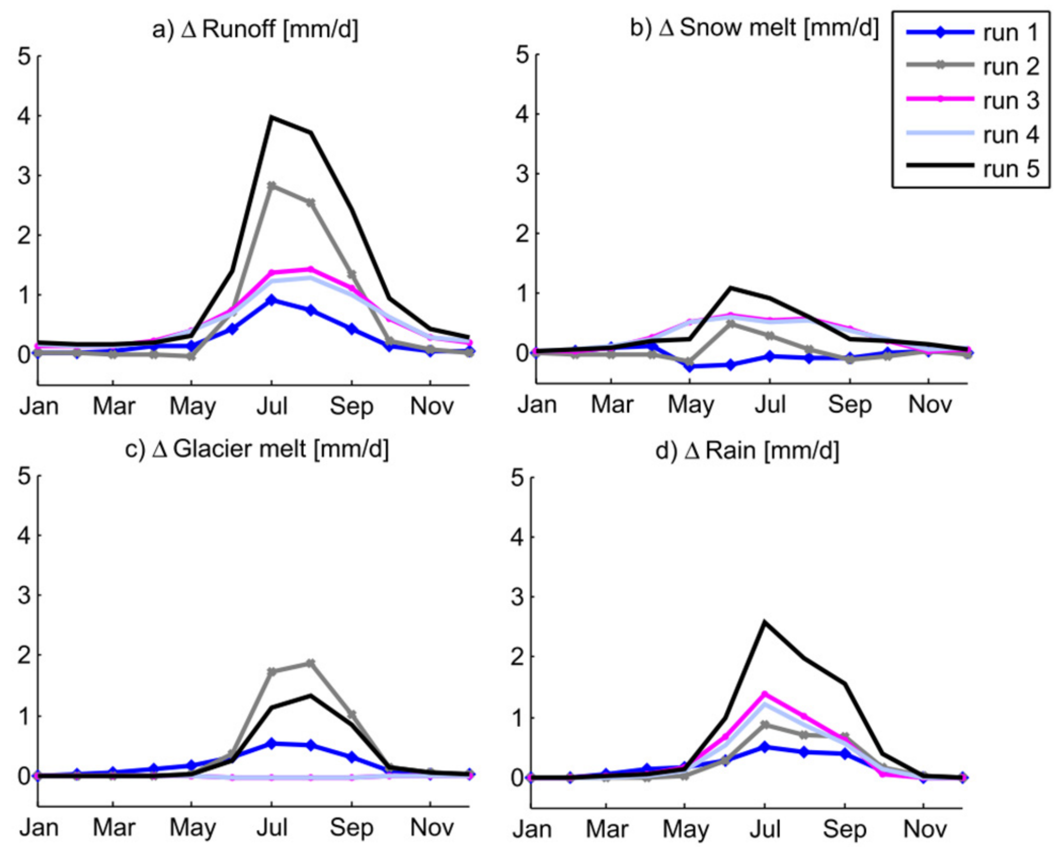

FIGURE 2 EFFECT OF USING DIFFERENT CONFIGURATIONS FOR PRECIPITATION GRADIENTS AND TEMPERATURE LAPSE RATES ON MEAN MONTHLY SIMULATED RUN- OFF, SNOW MELT, GLACIERMELT, AND RAIN. THE FIGURE SHOWS THE MONTHLY MEAN DIFFERENCES WITH RESPECT TO THE REFERENCE RUN [*IMMERZEEL ET AL.*, 2014].

Transferability to comparable catchments

The Himalayas show great variation in climate and even within a single country such as Nepal there are considerable climate differences between the west and the east. For the Everest region potential effects of climate change on future glacier evolution was assessed using a high resolution glacier model, locally observed datasets of precipitation and temperature, glacier mass balances and ice thicknesses and remote sensing datasets [*Shea et al.*, 2015]. Using the APHRODITES gridded dataset [*Yatagai et al.*, 2012] and an elevation model, temperature lapse rates were computed and the seasonal pattern in temperature lapse rates showed good agreement with what was directly observed in the Langtang. For precipitation the APHRODITES gridded precipitation dataset was used and corrected using precipitation gradients partly based on the Langtang observations and this showed the best model performance. However, an independent check with local observations showed mixed results from very good for one station to very poor for another. Although there is scope to transfer observed temperature lapse rates and precipitation gradients within similar climate zones, it is concluded that further investigations into high-elevation precipitation gradients, through field studies, remote sensing derivatives, and/or the use of high-resolution numerical weather models, will help to increase our understanding of glacier nourishment in the region.

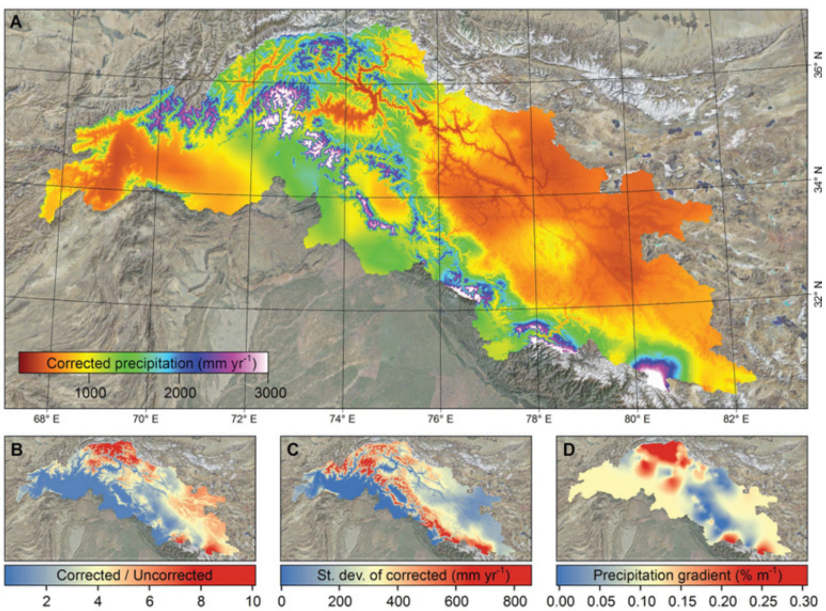

FIGURE 3 CORRECTED PRECIPITATION AND ESTIMATED UNCERTAINTY FOR THE UPPER INDUS. (A) SHOWS THE AVERAGE MODELLED PRECIPITATION FIELD FOR THE PERIOD 2003–2007, (B) SHO WS THE RATIO OF CORRECTED PRECIPITATION TO THE UNCORRECTED APHRODITE PRECIPITATION FOR THE SAME PERIOD, (C) SHOWS THE ERROR AND (D) SHOWS THE AVERAGE PRECIPITATION GRADIENT [*IMMERZEEL ET AL.*, 2015].

Alternatives to estimate high altitude precipitations

Although there is an evident need for more references sites across the Himalayas representative for the entire range of climates, a complete coverage of the entire region with an observational network is simply too expensive and logistically unfeasible. However, other types of information could also be used to approximate the high altitude precipitation. This approached was tested for the upper Indus basin. In this region very large glaciers are found, yet most datasets available indicate very small amounts of precipitation in this region, and this seems counterintuitive. To estimate the amount of snow fall required to sustain these large glacier systems information on the glacier mass balances measured from space was used. For each large glacier system the average annual melt was computed and it was estimate how much snowfall was required to match the observed mass balance. This information was then used to generate a new map of upper Indus precipitation [*Immerzeel et al.*, 2015]. The results were quite striking and there are regions, in particular the Karakoram mountain range, where the precipitation at high altitude may have been underestimated by a factor 10. The results were validated by runoff observations and the approach has a lot of potential to improve high altitude precipitation estimates in high altitude, glacierised areas which are scarce in observations.

Conclusions

It is evident that the high mountains of Asia are of great importance in supplying water to more than 25% percent of the global precipitation. Climate change is likely to affect the timing and patterns of water availability and an accurate understanding of the water cycle in this region is imperative. A first step in understanding the water cycle is to quantify solid and liquid precipitation. In this project important advances were made in this field and the following conclusions are drawn:

- There is a great variation in precipitation even within a relatively small Himalayan catchment. There are very large seasonal differences, diurnal difference, and spatial differences. These differences are caused by the complex interaction of the topography, the monsoon during summer and westerly disturbances during winter.
- Temperature varies very strongly with elevation, season and between day and night. The temperature decrease with altitude is less than the environmental lapse rate as a result of local circulation and seasonal humidity. The use of a constant annual lapse rate is incorrect and may result in erroneous temperature fields.
- The use of local observation and incorporation of spatial variation in precipitation and temperature has a profound impact on rain – snow portioning, snow melt, glacier melt and river runoff and it is essential to incorporate this information in water availability and climate change impact studies.
- Results of local studies may to some extent be transferred to nearby catchments under similar climatic conditions, if local observations are not available. However utmost care should be taken to verify the datasets using as much local observations as possible.
- If for budgetary, logistical or safety reasons local meteorological observations cannot be obtained then there are proxies, such as the mass balances of glaciers, which may be used to make a first order assessment of high altitude precipitation.

Challenges

Doing field-based research in high altitude regions of Asia is very challenging for several reasons and these need to be acknowledged:

- The logistics of organising field expeditions to the Himalayas are complex. The accessibility is poor and there is a strong dependence on local people, their knowledge of the mountains and their strength and endurance.
- Working at high altitude poses the risk of Acute Mountain Sickness (AMS) caused by the lack of oxygen at high altitude. Proper care should be taken beforehand and sufficient medical knowledge and precautionary measures should be taken.
- The weather in the mountain is highly unpredictable. Twice during a field expedition of the project, a cyclone originating from the Bay of Bengal caused large amounts of snowfall which prevented access to several observational sites.
- Nepal is located in a tectonically very active area and the Gorkha earthquake which occurred at the end of the project on 25 April 2015 has hit Nepal and the Langtang catchment in particular very hard. Many people lost their lives, villages were severely damaged and the majority of the hydro-meteorological equipment is destroyed beyond repair.
- Working in strong partnerships and international cooperation is essential for being able to successfully conduct this type of research. The partnership between ICIMOD, ETH, Utrecht University, PMD and

Kathmandu University was successful and none of the outputs would have been possible without this partnership.

- Local institutes and universities like the Department of Hydrology and Meteorology, Kathmandu University and the Tribhuvan University are the obvious partner to manage such observational networks. Yet, these are complex instruments and the capacity of these institutes needs to be further developed until they can independently manage such high altitude observatories.
- Many regions in high mountain Asia are located in geopolitical unstable areas and security and permitting issues can constrain scientific research considerably. This was experienced first handed when a nearby terrorist attack in Pakistan forced the project to cancel the fieldwork in this region.
- Data management is important, but it is sometime challenging to quality control, homogenise and store the data in a high quality manner.

Future directions

The following recommendations are made:

- The 2015 Ghorka earthquake has destroyed much of the Langtang high altitude observatory. It is strongly recommended to rebuild this site as a benchmark catchment for the entire Himalayas. There is a lot of knowledge about this valley, it is relatively accessible and it is more effective to rebuild this site than to start over elsewhere from scratch.
- More catchments like the Langtang should be equipped with hydro-meteorological instruments to improve the scientific basis for water availability projections. Only when we understand the past we can project into the future. These new catchments should be located in contrasting climate zones from the east (upper Brahmaputra) to the west (upper Indus). Selection criteria should be based on representativeness, accessibility and security.
- The capacity of local institutes, government organisations and universities should be improved by hands-on training in the field. A critical component is a transparent selection procedure of candidates which should be based on intellectual capacity, physical and mental strength and motivation.
- International collaboration should be promoted and mechanisms should be in place which ensures long term commitment, maintenance of observatories and central data management.