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The Impact of Climate Change on Water Availability in Eastern Nepal: A Presentation of the Project Methodology taking into Account the Various Origins of Water

O. Aubriot, J. Smadja, Y. Arnaud, P. Chevallier, F. Delclaux, P. Laj, L. Neppel, O. Puschiasis, M. Savéan and J. L. Seidel



Abstract: The paper reflects the main methodological aspects of the PAPRIKA Project based on the following objectives: (i) to contribute to a more accurate assessment of glacier retreat, snow cover and climate change in Koshi Basin, Nepal; (ii) to have a better understanding of the contribution of glacier and snow melting to water availability; (iii) to correlate the results with local people's perceptions of climate change and their socio-economic impact. For this, the paper:

- highlights the fact that the water used by the population comes from different origins (glacier melting, snow melting, frost, rain) the combination of which varies between the four main landscape units: high, middle and low mountains, and finally the Terai plain;
- describes the methodology adopted to observe and analyse current as well as future environmental changes in the atmosphere, cryosphere and hydrosphere;
- shows that, for each origin, different reasons may explain the changes in water availability, and thus the impact on agriculture and the different water usages.

Key words: Water resources, water uses, climate changes, precipitations (snow and rain), Eastern Nepal

Introduction

One of the aims of the PAPRIKA project (Cryospheric responses to Anthropogenic Pressures in the Hindu Kush-Himalaya regions: impact on water resources and society adaptation in Nepal) is to assess the effects of climate change on water availability and consequently on the populations' activities and practices. In a mountainous country such as Nepal, ranging from the sub-tropical Gangetic plain to the high snow-capped mountains, the impact of climate change (which in itself is a complex process involving many variables) on water obviously varies from one place to another. Some studies related to the consequences of climate change for Himalayan populations do exist; they are based on case studies chosen among various climatic and topographic conditions (Dixit, Upadhyay et al 2009; Manandhar, Vogt et al 2011). However, these studies do not situate the results in an analytical framework that would take into account the geographical characteristics of the selected sites and their related water issues. In this project we set out to show how the impact of climate change on water use varies according to geographical units and therefore according to the water's origin. In this respect, we have decided to focus on four units, which correspond to four parallel belts ranging from the high mountains to the Terai plain (cf. Smadja 2009 [2003]), and to choose one reference site in each belt. Since the project is a pluri-disciplinary project, and since glaciologists and air chemists have

already recorded data in the Everest area at the Italian research centre, Pyramid (located on the path to the Everest base camp), we have decided to choose sites south of Mount Everest along the Dudh Koshi: a high-mountain site in Pangboche, at an altitude of 4,000m; a middle-mountain site in Juving Village Development Committee (VDC), at 2,000m, both situated in Solu Khumbu district;

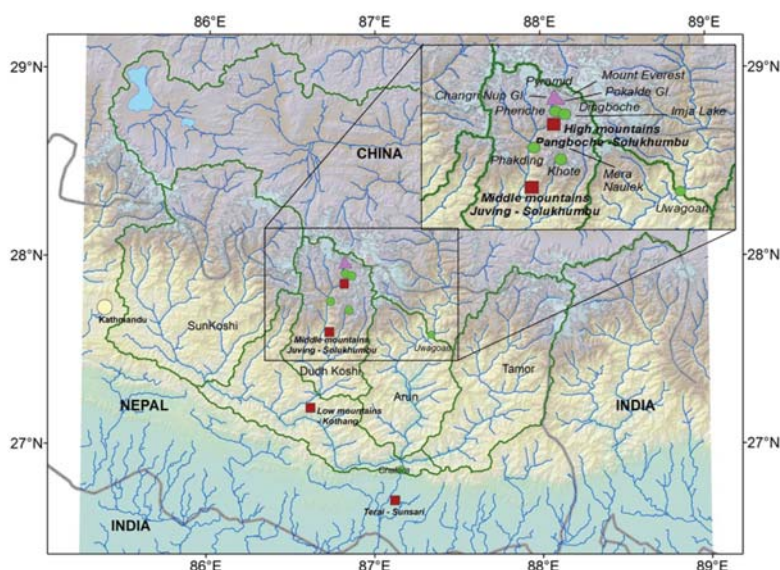


Figure 1. Topographic Map of the Koshi River Basin and Location of the Studied Villages (Red Squares). The Green Lines Correspond to the Limits of the Main River Basins and Sub-basins, the Light Green Circles to the Hydrological Stations Quoted in the Text, and the Magenta Triangle to the Pyramid Observatory.

a low-mountain site in Khotang district, at 1,000m, and a last one in the plain, in Sunsari district of Nepal, with two reference villages, one getting its water from the Koshi River, the other from another source (Figure 1). The current project started in mid-2010 and will last until the end of 2013. As we are still at the data collection stage, here we only present the methodological approach. The results of the modelling and the analysis of the social sciences field work will be available at the end of the project.

Since 84 percent of the Nepalese population live in rural area, we have decided to focus on rural activities. Agriculture and animal husbandry are the main occupations of people living in villages, and tourism is an added seasonal activity in trekking areas, which is the case for our two reference sites in the high and middle mountains. At the four sites, we study the conception people have of water as a resource, their perception of changes in its availability and consequently the measures they may take. We consider two types of water: (1) diffuse water in various states (snow, frost, humidity etc.) necessary for vegetation growth (cultures, pastures...); (2) concentrated water from sources and torrents which is used for domestic activities, for irrigation and to supply water mills or hydroelectric power stations. It is worthwhile noting here that in Nepal-except for religious activities (ablution, cremation) and fishing-people do not use water directly from the main rivers for various reasons including the high level of turbidity, the rapid variation in the water level and in the flow, and the wide range of variation, which are estimated to be too dangerous during the monsoon to install hydraulic intakes or other devices. Only when equipped with large infrastructures (dam with hydroelectric power station, embankment and canal diversion for irrigation), do rivers have some productive use. Finally, and in order to understand the consequences of possible changes, we will analyse these data and their variations according to the origin of water in the different geographical units.

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Water Usages and Geographical Units

The water resources used by people come either:

- from the direct use of precipitations, such as in rainfed agriculture,
- from the local discharge of water in a stored form (soil humidity from permafrost thaw or snow melting), and
- from the flow of water, the origin of this flow being either the discharge of stored water (glacier and snow melting, groundwater outflow, etc.) or the run-off of rainwater; however, in this case, large valley rivers must also be distinguished from springs and water courses on the slope.

Uses of water will differ according to its origin in the four geographical units (Figure 2 and Table 1):

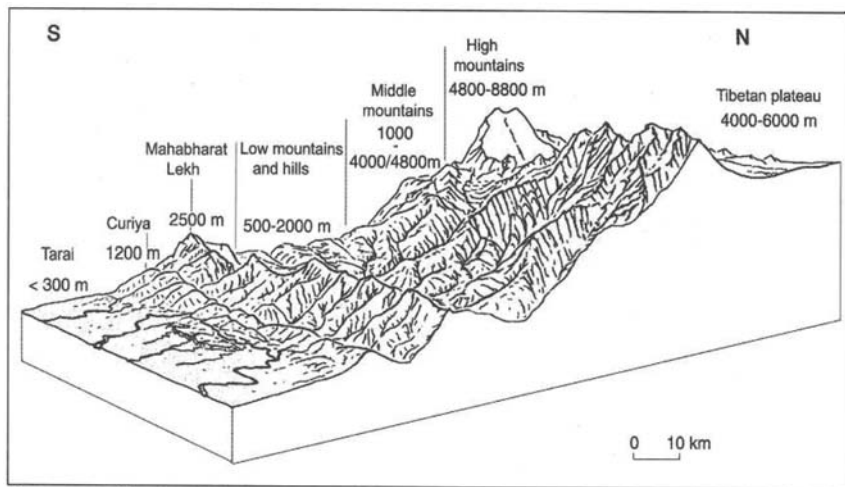


Figure 2. North-South Profile of the Nepalese Himalayas, Focusing on the Four Main Geographical Units: High Mountains, Middle Mountains, Low Mountains and Hills, Plain (Terai).

(Source: Smadja, 2009 [2003] adapted from Ramsay 1986)

- In the high mountains** (ranging from over 8,800m to 4,000m) characterised by the significant presence of the cryosphere in the headwaters, water is either in an icy state (glacier, frozen torrent, permafrost), in the form of snow (falling during winter, beginning of

spring or even monsoon season at high altitude) or liquid fluid when the temperature or stream turbulence permits. Thus, the streaming water used comes either from the melting of a glacier, the melting of snow, resurgence of groundwater, or rainfall (800mm per year in Pangboche). Any change in one of these parameters will have some impact on the discharge of streams and therefore on the operation of mills (only water mills in

	High Mountains	Middle Mountains	Low Mountains	Plain	
Precipitation in the Koshi Basin	500 to 800 mm	1,500 to 2,600 mm	1,000 to 2,000 mm	1,000 to 2,000 mm	
Spring storms (March- May)	+	++	+	+	
Monsoon (June-Sept)	+	+++	+++	+++	
Winter precipitations (Nov-Feb)	+	+	+	+	
	(snow)				
Water flowing in torrents and rivers is due to				Rivers coming from high mountains	Other rivers or streams
Melting of glaciers	+			+	
	May-Sep			May-Sep	
Melting of snow	+	+		+	
	Apr-May	Apr-May		Apr-May	
Discharge of groundwater	Year round various quantities				
Rain run-off	++	++++	+++	++++	+++
	Jun-Sep	Apr-Sep	Jun-Sep	Apr-Sep	Jun-Sep

Table 1. Main Origin of Water in the Four Geographical Units of Nepal Examined Here.

Khumbu) and of hydroelectric power stations, on the consumption of domestic water, on the irrigation of barley fields (in Khumbu, irrigation of such fields is still practised only in Dingboche, an alluvial terrace on the Dudh Koshi). Due to tourism, new usages (shower in lodges, watering of vegetable plants, purification of drinking water, bottled water) and an increase in the demand for water supplied by springs and streams, have led to social pressure on accessing the resource in some places. As far as precipitation distribution and pattern (either snow or monsoon rain) or temperature (influencing permafrost thaw, snow melting or frost creation) are concerned, they have a significant impact on plant growth and cropping activities such as potato farming and grass harvesting. Moreover, any change in the duration, period or thickness of the snow cover, which both serve to protect soil and crops against frost, and to supply soil with humidity may have different effects on plant growth and on the use of high-altitude pastures. In Khumbu, these changes would have major consequences on the local economy since potatoes are used to feed tourists, cattle is used as pack animals for carrying goods and their dung is used as fuel. Here, for many families, the production of grass for feeding animals is indeed a limiting factor in animal husbandry. Finally, the melting of permafrost in this belt may increase slope instability and cause landslides.

- **In the middle mountains**—defined by long slopes ranging from 4,800-4,000m to 1,000m in altitude which are intensively exploited (fields, forest, pasture) and with mainly a westerly and easterly exposure—the climate is characterised by snowy precipitations above 2,200m in winter, storms during spring, and plenty of rainfall during the monsoon (June to September). Annual rainfall is quite high (1,500 to 2,600 mm in the Dudh Koshi area). Thus, villages located in this belt do not suffer from a shortage of water. In such areas, there is no glacier, so that fluctuations in glacier melting will have no direct effect on the populations' activities (except for Glacial Lake Outburst Flood which may destroy land located near the river, which happened in 1985). However, fluctuations in snow cover and frost, as well as any change in the monsoon pattern, may have a major impact on the population's activities (like those described above), especially those regarding the use of pastures and of water during the dry season.
- **In the low mountains and hills**—characterised by shorter slopes ranging from 2,500-2,000m to 500m with a northerly and southerly exposure—the climate is less humid. These mountains benefit neither from the melting of snow nor from that of glacier as they are snow-free and glacier-free. Moreover, rainstorms during the spring are less frequent and less abundant. The sowing of rainfed crops, such as corn, relies on rainfall during the months of April and May, and can therefore be delayed or even abandoned some years. This belt is characterised by a very long dry season and a shortage of water for vegetation and domestic consumption over a period of many months as highlighted by ombrothermic diagrams. Populations

face major water supply issues since most rain falls during the monsoon. Thus, any change in the rainfall pattern but mainly in the monsoon flow would have significant consequences in this belt.

- **In the Terai plain** at the foothills of the Himalayas, two areas can be identified: (1) one that benefits from the rivers flowing from the high mountains - only four outlets of such river basins exist in Nepal. In this case, glacier and snow melting would have consequences on the river flow and would directly impact irrigation and hydroelectricity generation; (2) one that is watered by rivers coming from the first or second range of mountains (Churia or Mahabarat), but not from the high mountains. The flow here relies mainly on monsoon rainfall and its fluctuations would have the most significant impact on farmers' activities.

Water Resources and Impact of Environmental Change Information Available and Data Collection

The information used in the project in order to assess the water resources and their future concerns:

The Atmosphere and the Cryosphere (Snow and Glaciers)

Our main objectives in monitoring them are: (i) to provide data in order to assess the relative contribution made by seasonal snow cover, glacier ice and rainfall to the runoff of streams draining from highly glacierized basins; (ii) to analyse the impact of aerosol absorption by changing the radiative forcing in the atmosphere and after their depositions on snow and glaciers. Work is based on measuring black carbon and the dust concentration in the atmosphere at the Pyramid scientific station—maintained by the Italian institution Ev-K2 CNR and located in the high Khumbu (5050m) and in fresh snow on Changri Nup and Pokalde glaciers. We are proceeding with the mass balance (winter and summer mass balances) series, which has been measured since 2007 on Mera/Naulek (Hinku Valley) and we have started taking new measurements on Changri Nup and Pokalde glaciers (Khumbu Valley). These measurements on Pokalde and Changri Nup glaciers are taken very close to the Pyramid's atmospheric station in order to compare the mass balance of these glaciers and the seasonal cycle of the atmospheric composition of the atmosphere. These glaciers are rather small and therefore easily monitored for mass balance and temporal albedo variation (using albedometer) and thereby suitable for quantifying the impact of pollutant deposition on glacier melting. A glacier survey is being carried out using the “Glacioclim observation system” method used on Alpine and Andean glaciers, and more recently in northern India (Wagnon, Linda et al 2007).

The relative importance of monsoon and winter precipitations on accumulation processes and glacier mass balance is still being debated due to the lack of appropriate glacier field data in this area. The heterogeneity of the debris covering the glacier's surface (different debris thickness, ice, ponds) does not allow classical glaciological methods to be used for mass balance monitoring. As a matter of fact, little is known of the mass balance under debris cover which constitutes the major part of glacier

tongues in this region. Thus, atmospheric pollution (through albedo modification) on glacier mass balance will mainly impact the accumulation area of the glaciers.

Climate monitoring also receives input from observations by the Department of Hydrology and Meteorology of Nepal (DHM), which has a series of stations in the Koshi basin and surroundings area, some of which have a long history. The data available mainly concerns the temperature and precipitations. Regarding the latter, two delicate aspects are the direct measurement of snowfall, which is hugely underestimated, and more generally the large local variability, which has led to using existing spatialized data-bases for precipitation fields or, to be more accurate, to building them. Another weakness of this system is that it has so far been impossible to obtain data from the Chinese section of the Koshi basin. As for the extension of the snow cover, remote information from satellite imagery is used. Daily snow products and 8-days synthesis have been available from the MODIS sensor of the TERRA satellite since February 2000 at a resolution of 15"×15" (approx. 500m). The project also intends to use the VEGETATION sensor of the SPOT series of satellites, with a longer duration for observation, but a larger resolution of 30"×30". The weakness of this approach is the difficulty in estimating the equivalent water depth (or volume), which calls for knowledge about snow density, which is impossible to measure on such a scale.

The Hydrosphere

DHM monitors approximately 25 gauging stations in the Koshi basin, many of which have been in operation for more than 20 years, and the acquired information proves very useful. Downstream, the Chatara station (57,800 km²) controls the entire basin and its four main sub-basins of the Sun Koshi River, of the Dudh Koshi River, of the Arun River and of the Tamor River (Figure 1). Nevertheless, due to its difficult access and the high cost of maintenance, the quality of this information is heterogeneous and must be used with care. For the PAPRIKA Project, the station of Uwagoan on the Arun River (29,700 km²) has been rehabilitated, due to its strategic location controlling the flow issued from the Tibetan part of the basin, where no hydrologic or meteorological information is currently available. Another strategic DHM station has been commissioned on the Imja River at Dingboche (136 km²), considering the high altitude and the survey of the glacial Imja Lake, which could threaten the Solu Khumbu district. Finally for an accurate view of the processes on a small to middle scale, three new hydrological stations have been installed at Pheriche (146 km²), controlling the Khumbu glacial area, at Khote (148 km²), controlling the Mera Peak / Upper Hinku glacial area, and on the Dudh Koshi at Phakding (1,210 km²), controlling the largest part of the Sagarmatha National Park.

For a better understanding of the hydrological processes and especially the origins of the water flows, a geochemical approach has been developed in the Pangboche area (high mountain site). Five sampling points have been selected representing different conditions: main river and mountain watercourses influenced by glacier melt, snow melt, direct runoff, underground transfer and/or human uses. Physical and chemical parameters (conductivity, pH,

major and trace elements) have been monitored during the all seasonal cycle for the year 2011.

Methods of Analysis

Monitoring the atmosphere and cryosphere has been completed by the implementation of global, regional and local models and by downscaling methods. Results of climate and snow models will constitute input data for the hydrological model. To analyze snow, glacier, and rainfall production responses to large-scale monsoon dynamics and atmospheric aerosol loadings, different (present and future) climate scenarios will be generated to run hydrological models in the Koshi basin. Moreover, hydrological modelling enables the understanding of physical processes to be linked to the actual perception of change by local communities and to the development of adaptation strategies. In this high altitude context, a degree-day model (Hock 2003) is used to represent snow/ice melting and to estimate the different contributions of snow, ice, rainfall and groundwater to the stream flow. Two models have been applied in Dudh Koshi basin:

- Snow Runoff Model (SRM), developed by Martinec (1975) is used for the simulation of daily stream flow in mountainous catchments. SRM has been applied to a large number of basins (Martinec 2008). This model is distributed according to altitude areas. Required input data are daily precipitation, air temperature and snow cover area for each altitude area. Snow cover area is provided with snow MODIS product. Eight parameters are required for each altitude area. These parameters are estimated or calibrated according to daily stream flow observations.
- Hydrological Distributed Snow Model (HDSM) is a conceptual daily distributed model under development in the laboratory "Hydrosociences Montpellier", which will be used for simulating stream flow, lake level and snow cover. Spatial resolution is presently 2 km². Required input data are: 1) elevation grid data (DEM) and derived datasets such as accumulation map, and 2) daily climatic grid datasets: liquid and solid precipitation, air temperature, evapotranspiration. Eight parameters are required for this model. Snow melt parameters are calibrated according to snow MODIS products while water production and transfer are evaluated with observed daily stream flows. One of the main characteristics of this degree-day implementation is its ability to simulate the snow cover extent and to use remote sensing data for estimating snow melt parameters, which is relatively rare for this type of model.

At this stage in the PAPRIKA project, the required data from both climate models and hydrological models are not yet available. Consequently, we have used climatic data from different sources such as APHRODITE precipitation datasets and NCEP/NCAR reanalysis products. Estimated parameters for the two degree-day models are similar to those proposed in the literature (Hock 2003). The first simulations achieved with both models show that, despite the sensitivity analysis driven on the various parameters,

HDSM overestimates the snow cover extent regarding MODIS products, and that SRM generates rather disappointing results. The latter underline the necessity: (1) to improve the quality of forcing climatic data, and (2) to improve the different snow processes modelling in order to increase the effectiveness of the models.

A complementary modelling approach is also scheduled, based on the MORDOR model (Garçon 1996). This model is also a degree-day model that helps differentiate the snowmelt transfer into several compartments (subsurface water, groundwater, rainfall runoff).

Need for Qualitative Data

Since only two forms of water-rain and flowing river water-can be relatively easily measured by climatic and hydraulic stations respectively, working on the impact of climate change on water availability and use also requires collecting qualitative data at each of the four previously defined sites. This is done in collaboration with researchers and students from the Central Department of Geography of Tribhuvan University.

On the one hand, we focus on villagers' perception of climate change and of the variability of water availability, and on the impact of such changes on people's practices. In this respect, we collect data related to: the way perceptions of climate vary among the population (sex, age, ethnicity, activity, standard of education, social status); villagers' interpretation and evaluation of changes if any, and the impact they might have on their lives and practices; the strategies they have developed so far if rain does not fall in time, or if farm production is damaged by a climatic event; the rituals related to climate phenomena (rain, drought, hail, etc.) over the seasons and years and the introduction of new rituals due to the perception of climate change, etc.

To avoid any bias in the enquiries, and to mainly avoid gathering conventional beliefs spread by the media, we have chosen intentionally to not make any direct mention of climate change. This methodological caution is also taken by Dixit, Upadhyaya et al 2009 and Crate and Nuttall 2009. Consequently, our interviews start with questions on changes in agriculture, in cattle breeding, in the environment, in religious activities and gradually evolve towards questions about the weather.

On the other hand, we have adopted a diachronic and spatial approach to farming practices, to the uses of domestic water and to the socio-economic context of each site in order to understand changes and their origins. Indicators such as places for grazing animals and the way they change over the years, the location of mills used during the year and over time, the introduction of new crops and the abandon of other ones, changes in the religious calendar are tools that provide some clue to understanding possible changes in climate. One of the difficulties in this work is making a distinction between climatic and non-climatic drivers that influence practices and the perception of changes. For example, in Khumbu, farmers have changed their cropping period due to the fact that it overlapped with the tourist season that occupies most of the people in the valley, not because of a specific change in the monsoon pattern. In Juving, people do not so far perceive any change in water availability or in the period in which water is used. The use of water mills in time and space, which is usually a good indicator of any

change in the water supply from torrents, proves to be useless here since new techniques, more efficient for capturing water, have been introduced. Thus they may hide possible changes in the water supply.

Finally, an accurate description of the various usages of water and of the origin of water for each of these usages helps to understand any potential impact on people's practices in the event of a change in climate, water availability or water demand. Some impact may occur in the field of management. In Khumbu, our first research results have shown that in villages facing a shortage of water, a form of structured, collective water management has been introduced, whereas in villages where there is no shortage of water, and so far no major conflicts, water use and management are informal and dictated by individual practices and initiatives.

Conclusion

There has recently been a marked increase in the number of studies related to climate change. Most often, they consider physical data and social data separately. With the PAPRIKA project, we have set out to crosscheck these data with the aim of both recording new rigorous entries in the "climate change file" and examining whether peoples' perceptions and practices correspond or not to the physical data recorded. We would also like to highlight the relevance of taking into account the various origins of water in the main geographical units of Nepal, and thus to show why the consequences of climate change may vary significantly depending on the places selected in eastern Nepal. The difficulties we face in our attempt to fulfil this objective have in fact proved to be the various scales that are used in the different disciplines. In this respect, the hydrological parts, bridging the gap between physical science and social science, helps solve this issue. This is indeed the originality and strength of our programme.

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