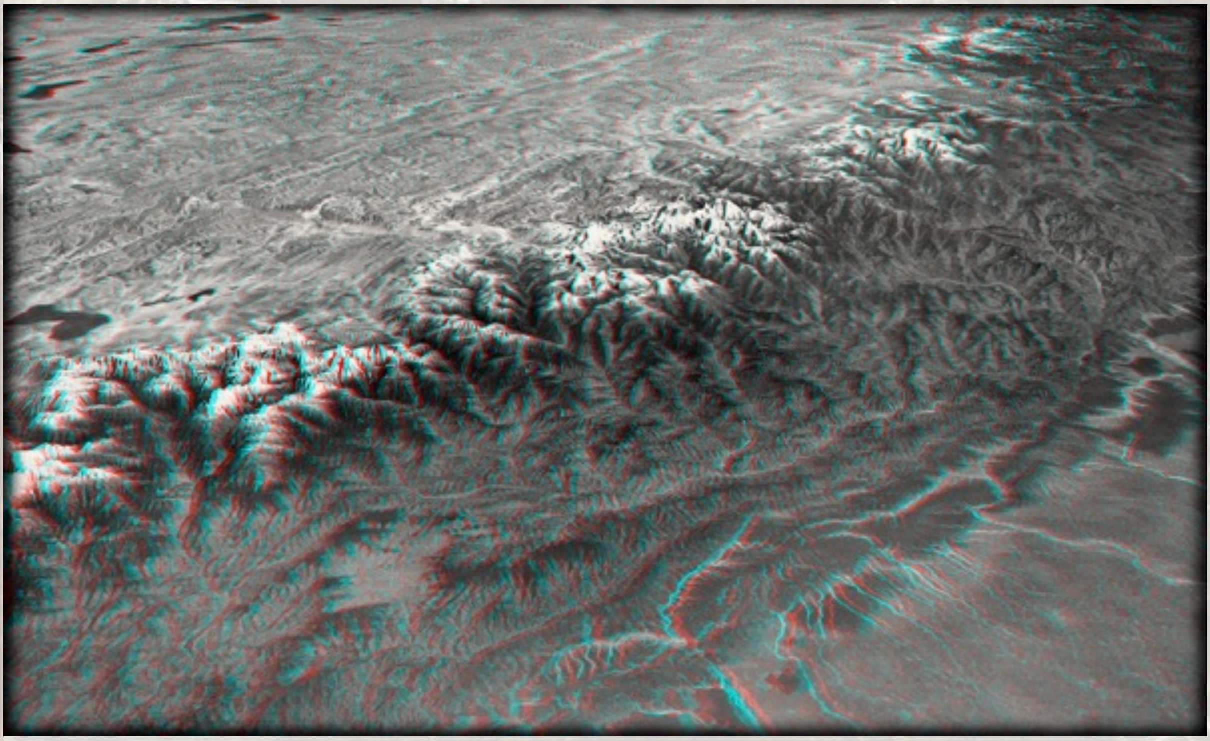
Eastern Nepal Landscape

Water Resources

and

Climate Change Sensitivity

Analysis



For WWF's Asia High Mountains Initiative, funded by USAID

By Nikolai Sindorf

June 2017

Sindorf N, *Eastern Nepal Landscape Water Resources and Climate Change Sensitivity Analysis*, High Mountains Initiative, WWF/USAID, 2017

Frontpage images are based on Google Earth imagery, 2017

Find updates on: http://thirdpolegeolab.org/#snowy

About the author:

This work has mainly been produced and compiled by Nikolai Sindorf as a consultant on spatial freshwater analysis under the Asia High Mountains Inititiative. This is one of the six landscape analyses under that project.

Nikolai is located in the Mekong region (Vientiane, Laos) where he is working on spatial freshwater vulnerability assessments and environmental analysis. He has experience in the following geographies: Southeast Asia, Central Asia, Egypt, USA, Netherlands

He holds an M.Sc. in Tropical Land- and Water Management of Wageningen University, Netherlands, with specializations in irrigation engineering and geographic information systems.

Specialties: water resources development, conservation hydrology, freshwater climate change sensitivities, environmental flows, sustainable hydropower planning, irrigation, land-water management and geographic information systems

Nikolai Sindorf
about.me/niksin
niksin@gmail.com
Vientiane, Laos, +7 GMT

w a t e r , *d e v e l o p m e n t* , n a t u r e
---~~~--~------~~~~------~~------~~~~------~~~----~~-~-----
"A person cannot step in the same river twice,
for it will neither be with the same flow,
nor be with same character."
after Herakleitos

Acknowledgements:

Rinjan Shrestra, WWF-Canada

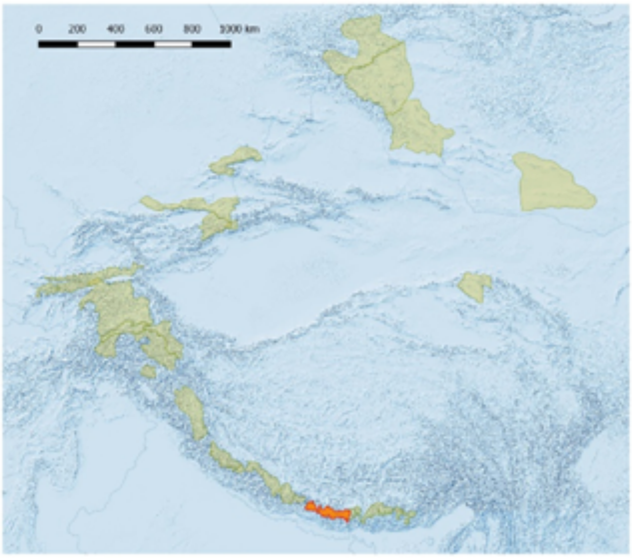
Ryan Bartlett, WWF-USA

Jessica Forrest, WWF-USA consultant

Corey Lesk, CCSR, Earth Institute, Columbia University

Danielle Peters, CCSR, Earth Institute, Columbia University

Eastern Nepal Landscape



Country: Nepal
Size: ~12,000 km^2
Population: ~200,000 (WorldPop 2011)
Highest elevation: ~8,848 MSL
Lowest elevation: ~500 MSL

Connections:
East: Sikkim/Kanchenchungga Landscape
West: Central Nepal landscape

Introduction

This report is part of an effort to map out and analyze water provision functions of snowleopard landscapes in six different countries under USAID's and WWF's Asia High Mountain Inititative.

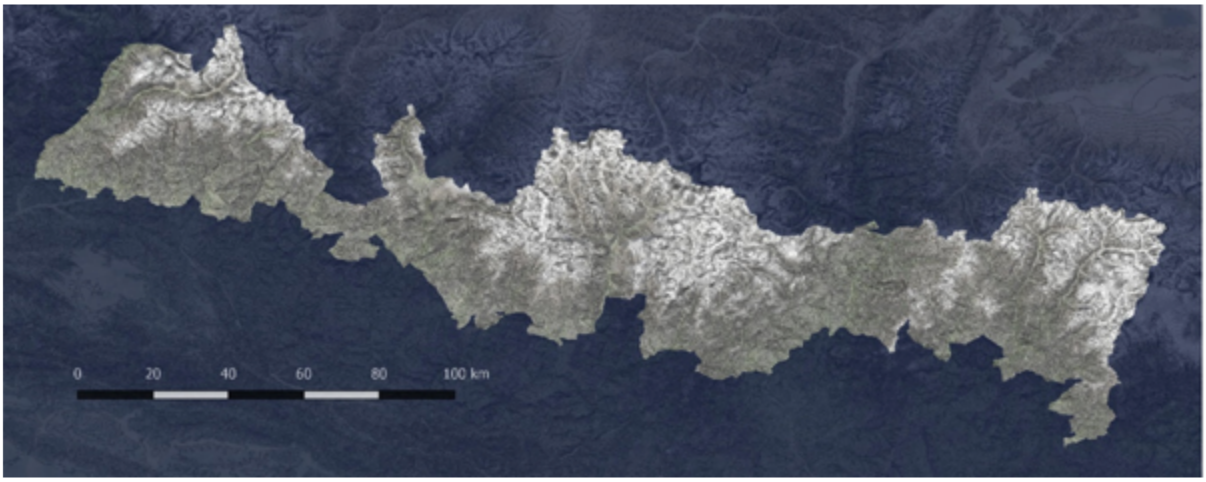
The starting point of this analysis was to measure to which extent snow leopard landscapes are essential in providing water to downstream areas, in order to build ecosystem service arguments on that assumption. Yet, an earlier continental assessment (Guardians of the Headwaters, 2014), already confirmed that most of the rainfall seems to fall just below (or downstream) of the landscapes, especially in the monsoon-dominated regions. In order to understand the full importance of water provision, not only in quantity, but also in quality, timing and reliability, this report attempts to construct a baseline for the different functions that underly water provision, and their sensititvity to projected climate change.

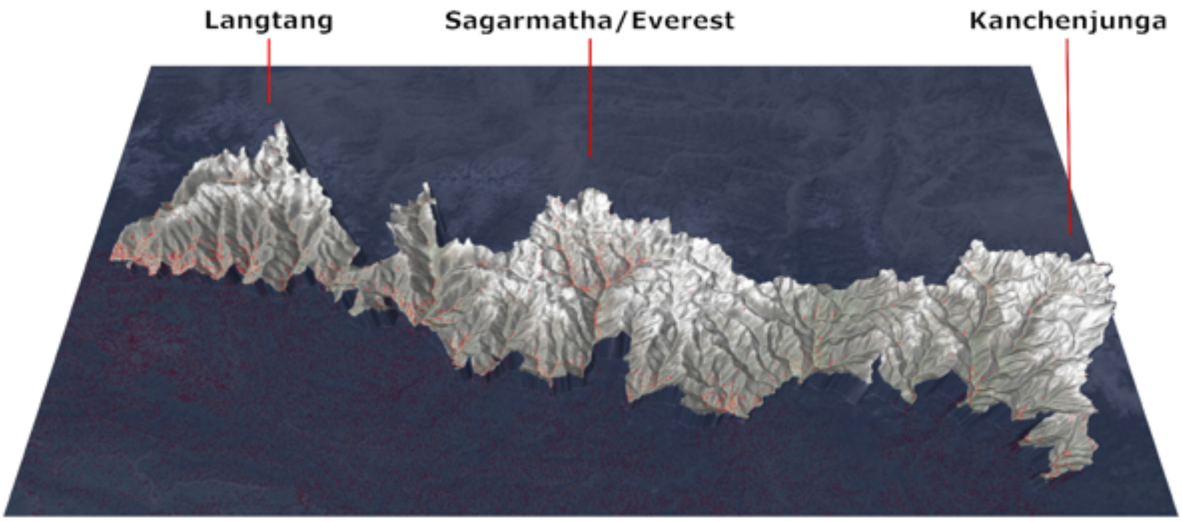
In order to construct such a baseline, the report goes into rather deep technical detail, to such an extent that not all snowleopard conservation practitioners will be interested in the methods and findings. The most important findings are therefore linked to snowleopard habitat analysis in a separate summary report for each landscape, while the table on pages 16/17 provides summarizes outcomes of the analysis. One of the intends of this report is to act as a technical annex to that summery report. But the analyses here help to put detailed perspective to the different water provision functions, while it is important to communicate not only where or why overlap occurs between snow leopard conservation and water resources management, but also where and why these links are not that important.

In general, the analyses as they are presented here can be considered to be cutting-edge for water resource practitioners as well as climate modellers. With a very high level of consistency, at a relatively high resolution, these analysis go into detail to the importance of seasonality in water resources, and the shifts in seasonality under projected climate change. The analysis elevate climate models from the pixel into watershed functionality and connectivity in the landscapes. The projections closely follow the Center for Climate Systems Research' climate projections methodology and apply these to flag tipping points in water balances or spatial footprints in the landscapes. Some of these findings have already been refined based on observations from snowleopard conservationists, and sometimes also informed them about their landscape-specific water resources or climate characteristics.

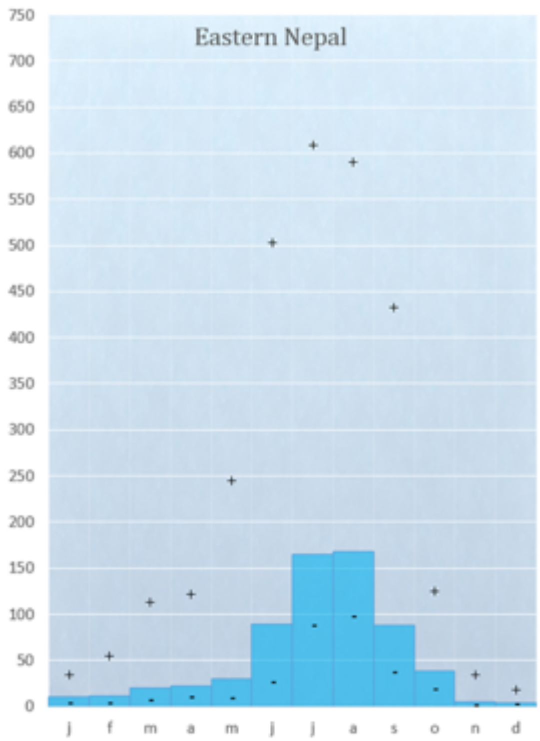
One of the more important messages of this report should be that water provision as an ecosystem service cannot simply be expressed as a function of annual volumes of water provided by th upstream areas towards its downstream. River-, groundwater-, and climate systems are too complex for that. The geography of this analysis illustrates that many of the river basins in which the landscapes are located experience a sequence of drought (water in high demand) and floods (water in low demand), often on the very same locations; it is a consistent annual cycle of 'too little' followed by 'too much'. Under such conditions -and under increased uncertainty- the ecosystems can only be considered as a *bad service provider*. Yet, even though ecosystem seem to mess up what is considered to be reliable water provision, there is inherent value to conserving these ecosystems since they drive the natural water balance.

Overview

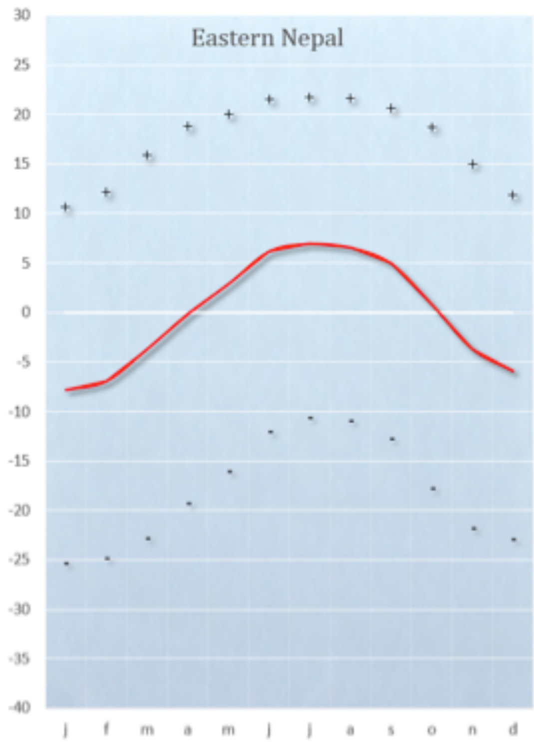

0
20
40
60
80
100 km


Langtang
Sagarmatha/Everest
Kanchenjunga

Basic climate



Historic monthly mean precipitation
in millimeters (WorldClim, 1950 -2000)
+ = highest mean of the landscape
- = lowest mean of the landscape



Historic monthly mean temperature
in centigrades (WorldClim, 1950-2000)
+ = highest mean of the landscape
- = lowest mean of the landscape

The rainfall distribution illustrates that the Eastern Nepal landscape is dominated by the monsoon; rainfall in the months of June to September amounts to about 80 percent of annual rainfall.

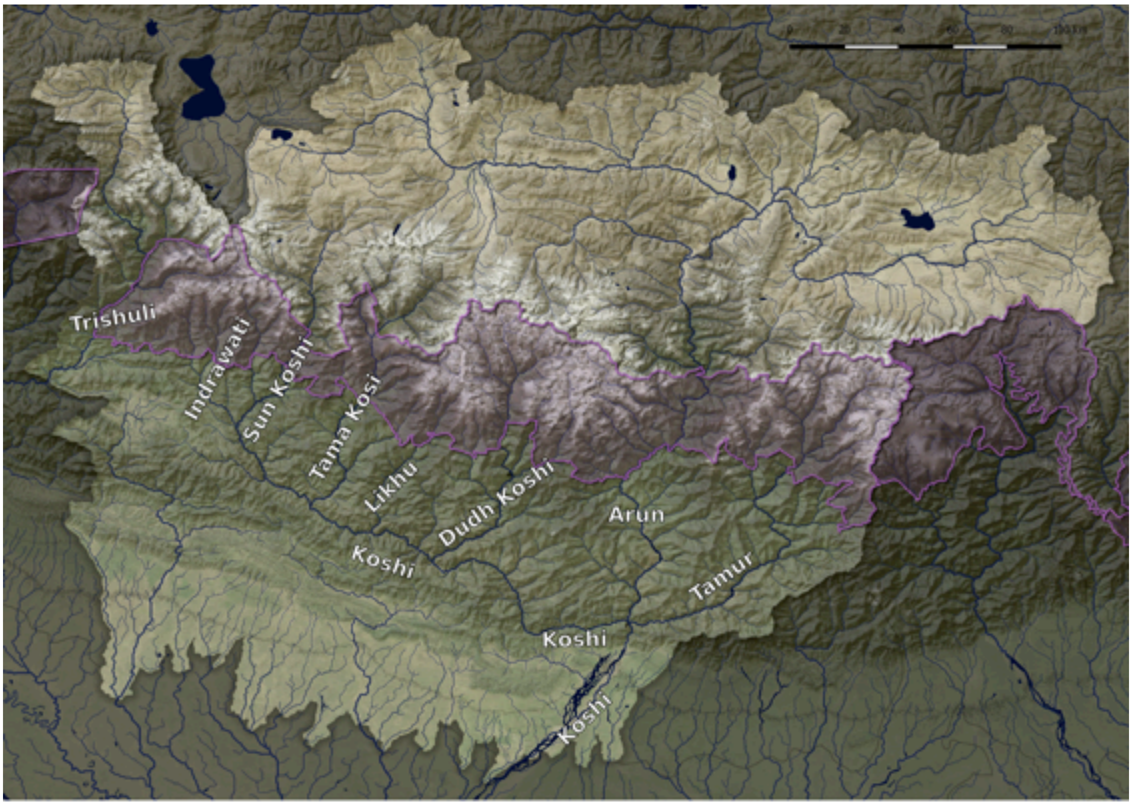
Both of the above graph shows that historically, the temperature and precipitation range inside the Eastern Nepal landscape is very broad;

- E.g. in July the difference between the wettest and driest location inside the landscape is about 500 mm
- For temperature, for every month there seems to be locations inside the landscape that have a temperature difference between 30 - 35^{o} C

Though the graphs do not show how these extreme differences are distributed over the landscape – they might be isolated extremes -like mountain tops- they do illustrate that for the size of the landscape, the Eastern Nepal landscape must be one of the world's most climate diverse contexts.

This high density of micro climates might have historically played an important role in the survival and evolution of the landscape's species. Though movement through the landscape might be a challenge to most of its species, to a certain degree they will be able to find a suitable climate to survive, or move on. This is an important realization when considering species-climate interactions under climate change.

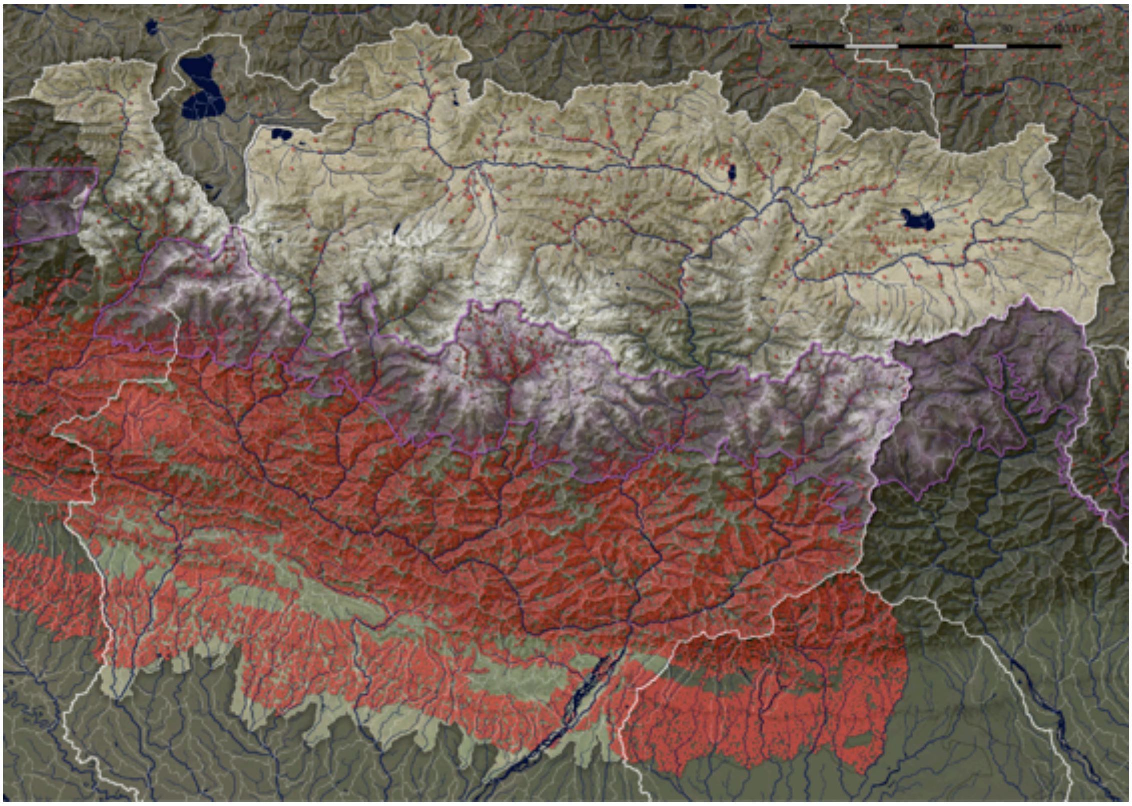
Subbasin context; hydrography



In order to determine the importance of water provision by snow leopard landscapes, it is of importance to consider the landscape's role in its larger subbasin context. For the eastern Nepal landscape this would include the larger Koshi basin, including the part upstream in Tibet, which drain into the Arun river. The most downstream influence of the landscape's importance coincides with Nepal's southern border, and any downstream influence beyond that was already considered in the 2014 Guardians of the Headwaters assessment; at the level of the entire Ganges basin. A smaller western part of the landscape falls outside the Koshi basin and drains into Trishuli tributary.

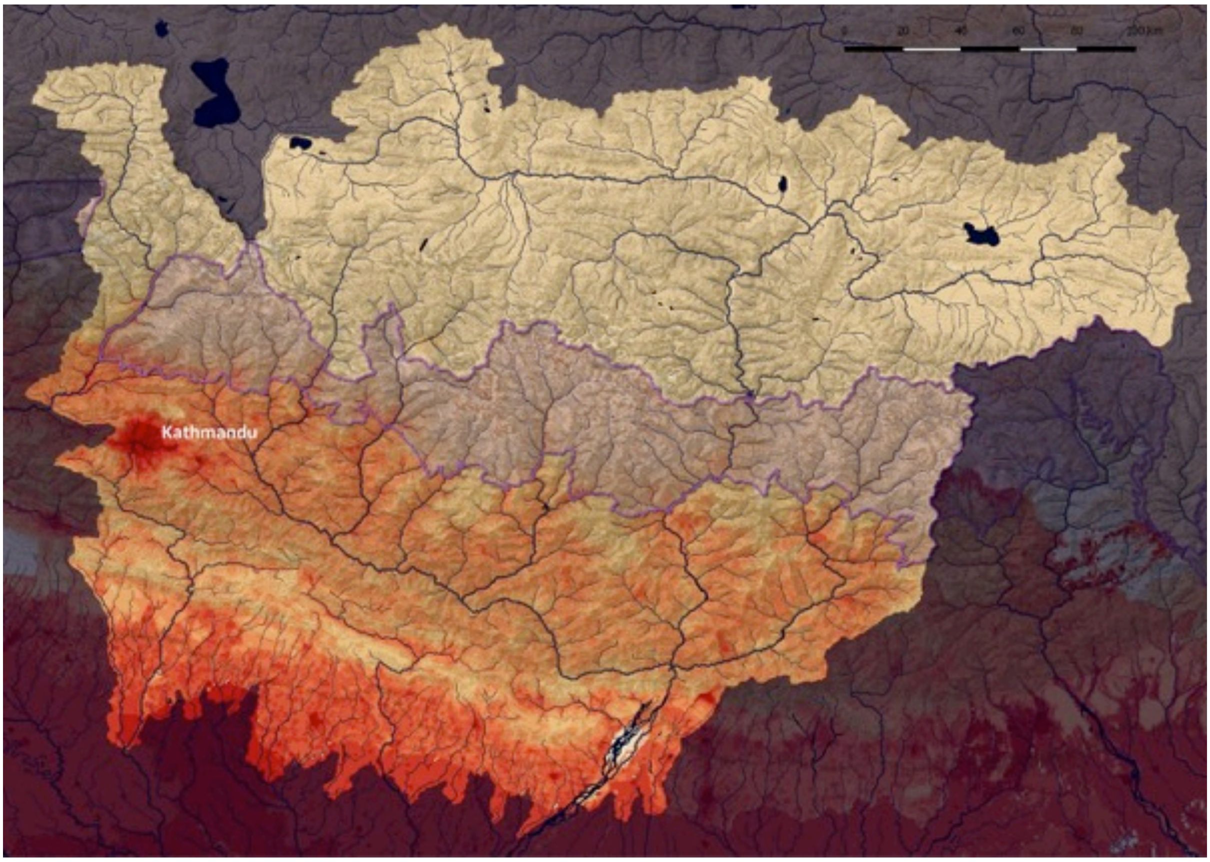
Both the Arun and Sun Koshi valleys cut North-South through this landscape, and form depressions (in elevation) that are of importance when considering east-west connectivity. It is very likely that for these valleys any elevation-based connectivity takes place over the border, in Tibet.

Subbasin context; human settlements



In the broader subbasin context, the distributions of population densities or human settlements shows that there is little human activity in the upstream parts of the basin, in Tibet. Inside the landscape, settlements exist mainly along the streams in the valleys, while directly downstream, there is a high density of settlements. The larger Kosi basin even includes Kathmandu, though it is not directly downstream of the snow leopard landscape, it does get parts of it drinking water through a diversion in the Indrawati tributary (at Melamchi). In terms of arguments for ecosystem service provision, this map shows that there would be an audience; if the landscape would provide different functions of water provision –for example, a dry season flow due to seasonal snow and glacial melt- the audience to benefit from water provision –for example, for irrigation- is located directly downstream in/of the landscape. Settlement points are downloaded from geonames.org.

Population density (WorldPop, 2010)



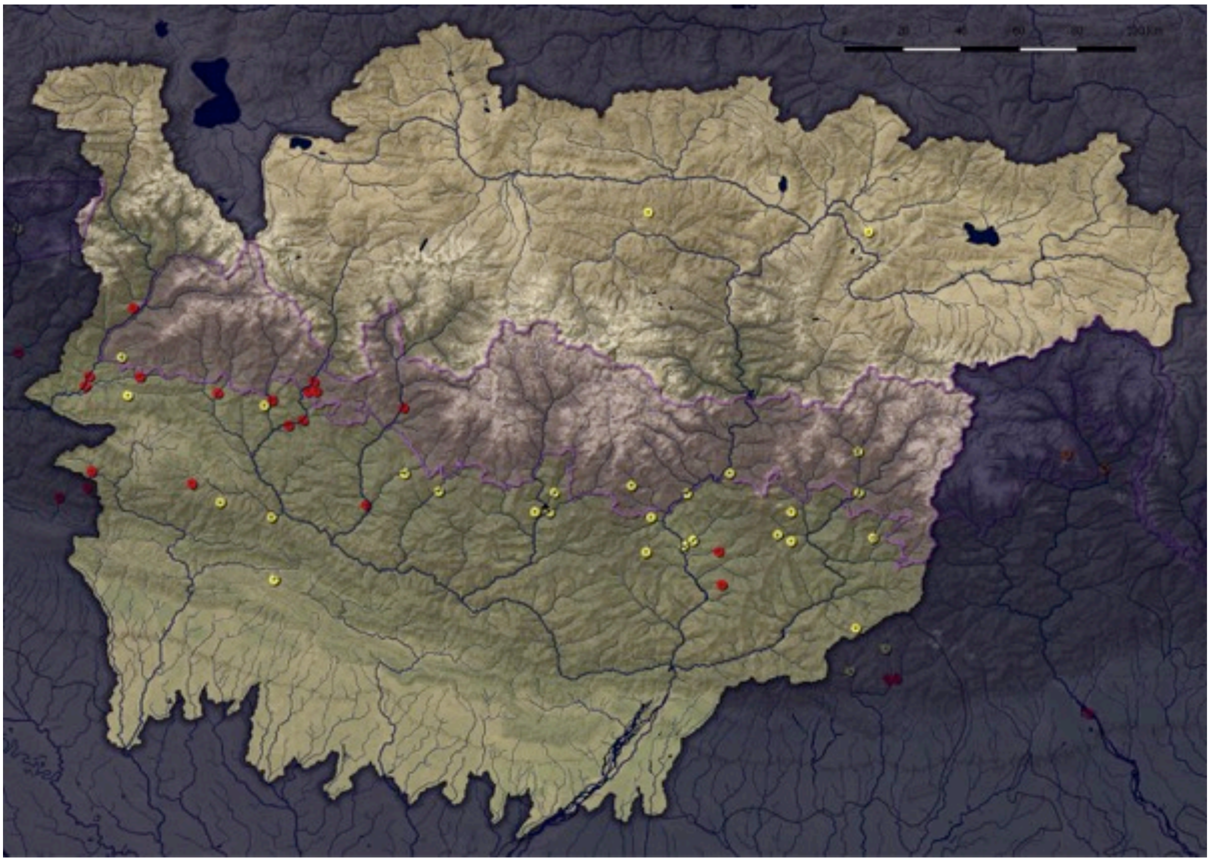
Methodology

This is a map of the WorldPop database, Nepal Data.

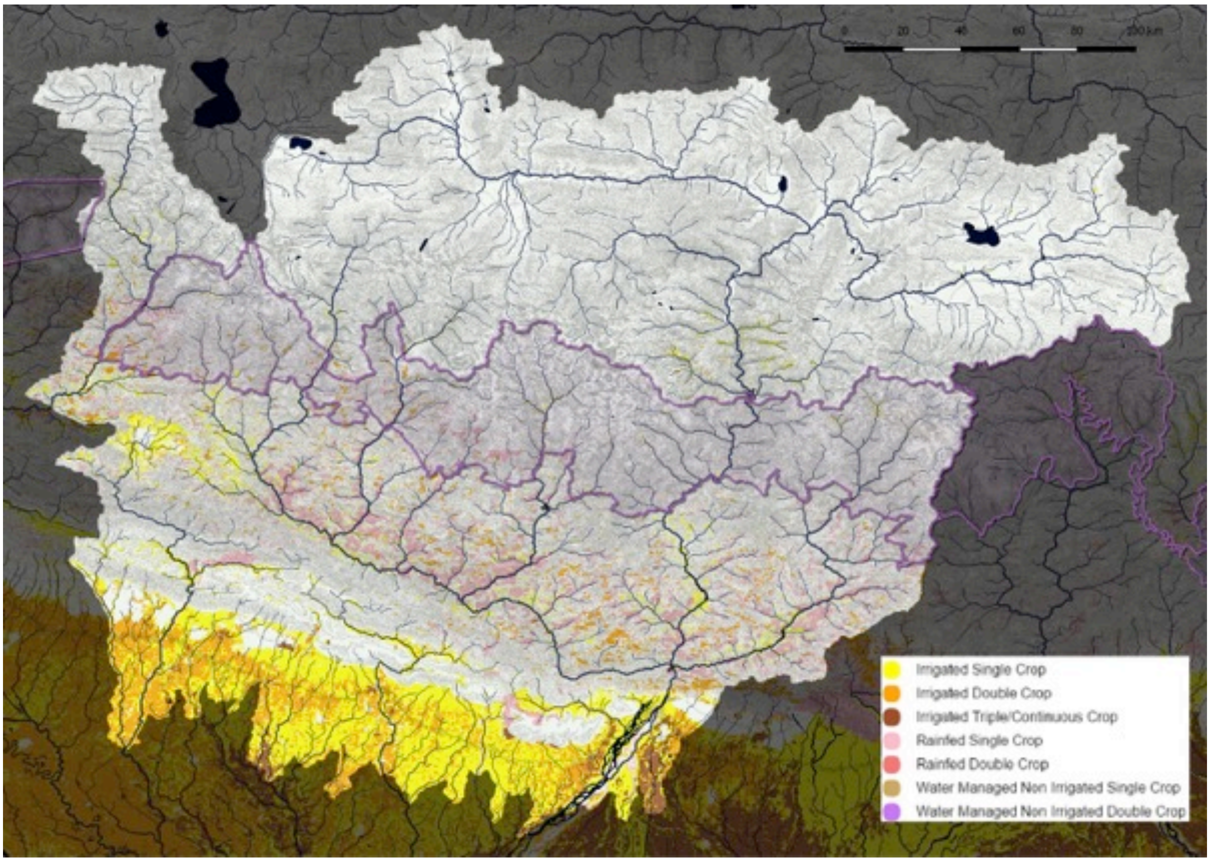
Data

WorldPop: Tatem AJ, Gething PW, Bhatt S, Weiss D and Pezzulo C (2013) Pilot high resolution poverty maps, University of Southampton/Oxford. http://www.worldpop.org.uk/

Dams, exisiting and planned (GRAND, 2011)



Irrigated Area Map Asia (IWMI, 2010)



Analysis

Some irrigated and rainfed agriculture takes place inside the landscape, but most of the irrigated agriculture takes place directly downstream of the landscape, which indicates that the landscape does provide an important role to water provision downstream; this connectivity might mainly be through groundwater.

Towards the more downstream, in the plains, irrigation intensifies both in extent and intensity.

Methodology

From the Irrigated map website:

"*The natural vegetation and croplands exhibit different patterns of seasonal changes. A procedure was developed to utilize the seasonal variations captured in multi-seasonal satellite images to classify the landscape and identifying the irrigated croplands. The mapping was done using 16-day MODIS 250m NDVI composites images (MOD13Q1). A hierarchical classification procedure involving classification techniques and time-series analysis of the NDVI data was followed. Initially, an unsupervised classification using ISODATA algorithm was performed and subsequently, the seasonal patterns of NDVI for each output cluster was analyzed to differentiate various land cover types.*

The developed methodology based on the phenological changes in agriculture areas to map the irrigated and rainfed areas. An image time series created using the MOD13Q1 product of MODIS at 250m spatial resolution has been used to map the phenological stages of crops using advance image processing techniques such as Fourier and Wavelet transformation Analysis of NDVI. The analysis focus was on the quantity of green biomass, annual and semi-annual cycles of vegetation change, and its dependence on the annual rainfall cycle using Canonical Correlation Analysis (CCA) and time lagged regression to separate irrigated and rainfed areas etc.

The agricultural areas were then further categorized into irrigated and rainfed by analyzing the seasonal vegetation trends. Agricultural areas with multiple cropping cycles were identified by analyzing the cyclic nature of vegetation change in agricultural systems. Based on the cropping intensity, agriculture areas were categorized into single, double and continuous crops."

Data

IWMI, http://waterdata.iwmi.org/applications/irri_area/

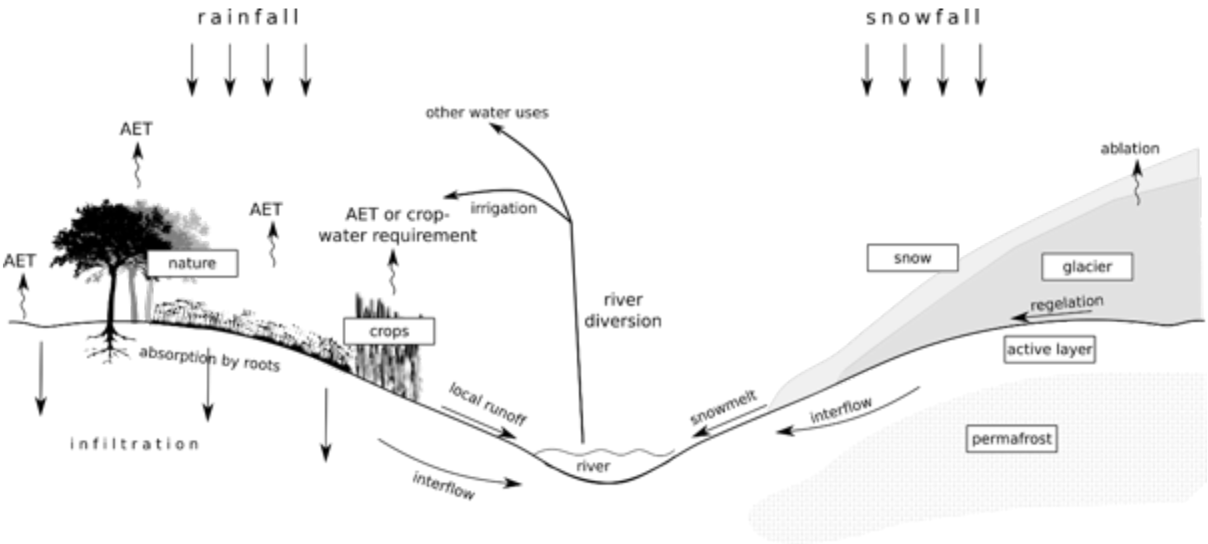
Water provision functions

For the Eastern Nepal landscape four different primary functions are selected that represent different aspects of water provision. These functions are mapped out for the subbasin context, in such a way that it can be assessed what role the snow leopard landscape plays in providing water as an ecosystem service.

- **Local runoff**; is often regarded as the only water provision function. Local runoff is the amount of water in the landscape that ends up in a river or stream and then flows downstream. This is often called "water towers", since local runoff often starts on the upstream mountain slopes. It can be modelled by looking at rainfall and then taking off the component that is "consumed" by vegetation and soils (actual evapotranspiration). On itself, local runoff has to be considered in monthly timing over a year, and in spatial patterns throughout the landscape. In the larger regional contexts, water provision arguments should not only show positive associations with larger quantities of water, since floods are severe and abundant.
- **Snowmelt**; downstream of mountainous regions, the seasonality of water provision is under direct influence of the annual snowmelt cycles. In many locations, the snowmelt cycle has a different timing than timing of rainfall (or local runoff), often providing essential amounts of water just before, or at the end of the dry season. Under changing temperatures and changing amounts of snow, the change in timing and distribution of snowmelt is essential to be understood; it might lengthen the downstream dry season, but timing might also shift in such a way that it exuberates any flood season. For example when precipitation that historically would have been stored as snowfall in the landscape over the winter, might now runoff and coincide with the flood season.
- **Aridity**; aridity concerns the extent to which water is the limiting factor in vegetation development. Often -in a landscape- local water balances range can from being humid to different levels of aridity; where a chronic level of aridity indicates a trend of desertification. In terms of water provision, it helps to see where in the landscape -or its larger subbasin – there is enough water to sustain vegetation or provide water downstream, and where in the landscape there is a demand for extra water. Aridity is calculated as the amount of precipitation compared to the amount of potential evapotranspiration.
- **River system layout**; through river system layout it can be determined to which extent a location has the capacity to provide water to its downstream. As much as a wet location at the very downstream does not hold much capacity to provide water to the rest of the subbasin, an arid area in the upstream does not hold much capacity to receive water from its upstream.
- **Lakes, wetlands, floodplains**; lakes, wetlands and floodplain are freshwater entities that form a relevant part of the river system layout and the overall water provision context. Recent publications of publically shared databases on surface water and lakes allow more advancedanalysis of a landscape's surface waters over time.

The water provision functions that are listed below are acknowledged to be of certain importance to water provision and can be mapped out, but at the moment lack essential scientific insights to be incorporated as water provision functions for any of the landscapes.

- **Presence of glaciers**; as much as snowmelt, glaciers provide essential water provision outside of the seasonal precipitation. An important process that lies at the basis of this, is the amount of water that melts off a glacier under pressure (regardless of surface temperature) of the thick ice layers, so-called regelation. Yet modelling quantities of glacial melt has been a challenge; each single glacier act as a reservoir where water melts, or snowfall accumulates, according to many micro factors that underlie the existence of each glacier. In general terms glaciers cannot be considered to be renewable water resources without taking into account at which they accumulate new snowfall, or considering the overall temperature-melt balance through which they have existed for centuries. Under a changing climate, these balances shift, though there is no real rule of thumb for each specific glacier whether it is growing or shrinking.
- **Permafrost coverage**; the presence of permafrost is of direct influence on local hydrology. Season shifts in depths of permafrost are at the base of local hydrology, for example in determining the seasonal water levels in wetlands. Often the permafrost layer is impermeable, and soil-water interaction take place on top of the permafrost layer; the so-called active layer. Naturally the thickness of the active layers is a very local soil characteristic, where issues of soil temperature, aspect, and vegetation cover are all of influence. Any change to this, as well as changes in temperature will all trigger a chain of event, which often leads to permafrost degradation. There is a high correlation between the presence of permafrost, and the larger snow leopard landscape. At the moment there are not enough scientific insights on how locally and region-wide permafrost degradation will be taking place, and whether this would be of influence of snow leopard habitat.
- **Snow cover and freeze line**; the seasonal presence of snow and temperatures below zero centrigrades are an important landscape characteristic that guide seasonality of most of the landscape processes, including hydrology. Under changing temperatures, it is real important how much the freeze line would shift, when and where. Seasonality will change when the freeze line changes, though this change might not always happen linear; a shorter winter will result in earlier spring snowmelt, or maybe also in an extended flood season at the start of winter.
- **Groundwater interactions**; such as recharge, infiltration, interflow or baseflow. Though there is monthly information available on soil-water-balances and recharge flows, this is often too general, too coarse and simplistic to predict the complexity of groundwater interactions inside the landscape, for example in relation with permafrost depths. This study takes an "upstream" approach, any signal in the surface water component will evidentally lead to a change in groundwater interactions, but is is beyond the scope of this study to look further into this component.



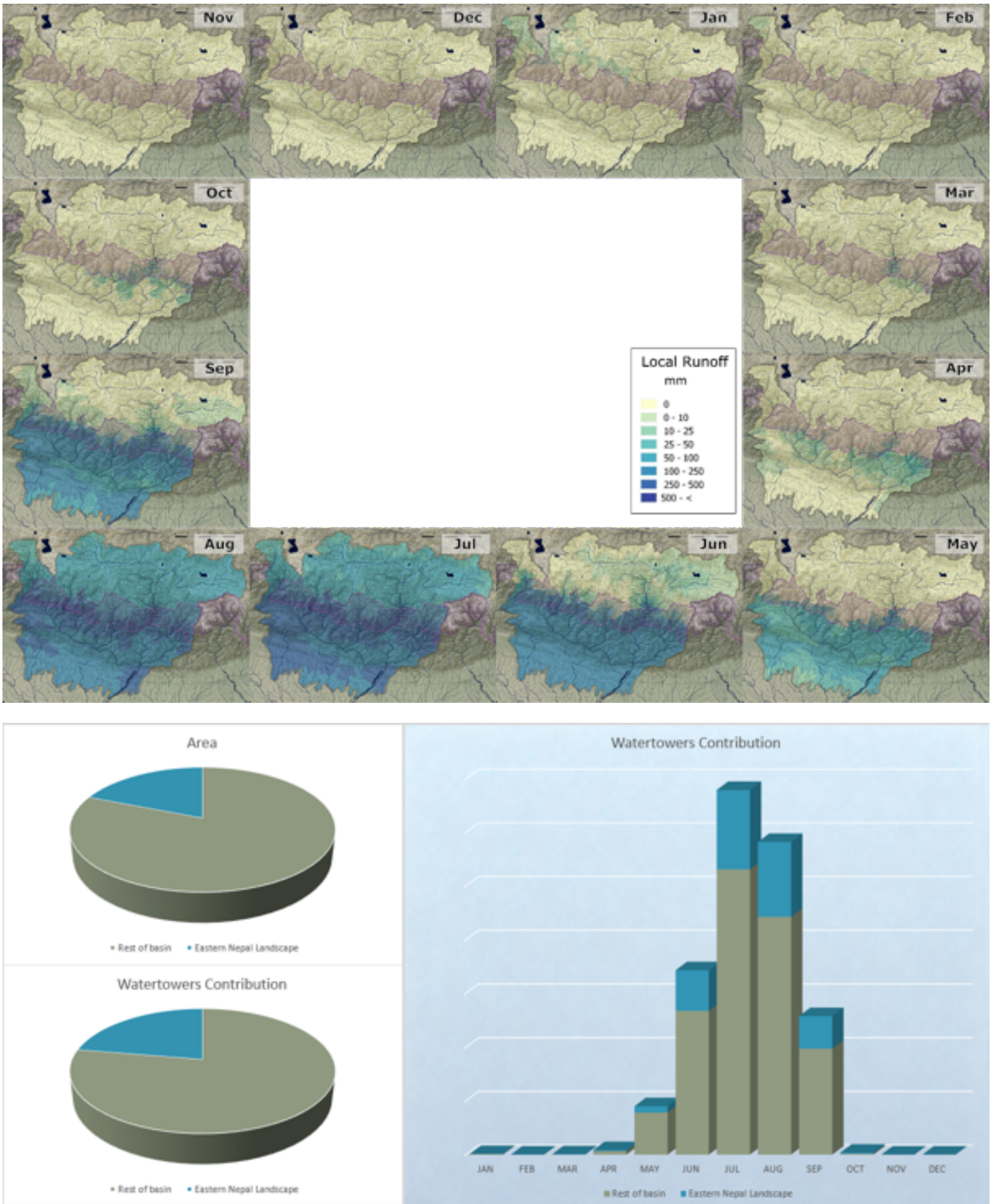
A simplified water balance including the components of rainfall, actual evapotranspiration, and local runoff. To the right: a simplified water balance of the cryosphere, including the components of snowfall, snowmelt, glaciers and permafrost.

Summarized findings for the Eastern Nepal landscape

Water Towers/ Local Runoff	
Water provision	The landscape does not provide water in quantities or in timing to be of importance to downstream water provision, the landscape is located just upstream of the wettest part in the subbasin. The water quantity coincides mostly with the monsoon season, when there is the lowest demand for water in the system, or when there even might be too much water in the system, causing floods downstream.
Projected Climate change	The relative role of the landscape in water provision would not change much; under drier conditions, the landscape would get as much drier as the rest of the basin, under wetter conditions the landscape and basin would both get wetter. Since there is a proprtionality in landscape response and basin response, there is no argument in favour of the landscape providing better runoff provision than other parts of the basin under climate change.
Snowmelt	
Water provision	In timing, the landscape captures most of the spring snowmelt that occurs at the end of the dry season, just before the monsoon. Yet for the locations that generate the highest amount of snowmelt (mountaintops), the timing coincides with peak monsoon, when any water provision gets overwhelmed by monsoon rainfall
Projected Climate change	The shift in freeze line will specifically affect the timing of snowmelt on the (upstream) plateau in spring (March-May) and the accumulation of snow and timing of snowmelt at mountainpeaks later in the monsoon. There will be extra snowmelt occuring earlier in the year, which would coincide more with monsoon runoff and most probably exuberate downstream floods.
Aridity	
Water provision	The landscape is located just upstream of the more humid parts in the subbasin, and there is no month in the year that the landscape is more humid than its downstream areas, neither is it drier than its upstream areas; so there is no clear water provision argument for this function.
Projected Climate change	The largest change in humidity and aridity is expected to take place directly after the monsoon; the low-end estimate predicts a drier start of the dry season, for which the effects will mainly be felt at the end of the dry season. The high-end estimate show a slightly longer wet season, which coincides with the flood season after the monsoon. The difference beteeen both estimates indicate a high level of uncertainty.
River system layout	
Water provision	The entire landscape covers a significant part of the subbasin's headwaters, and therefore it performs an important function to the people living in the downstream plains. Though the most upstream parts of the subbasin are located on the Tibetan plateau, which is connected through Arun river.
Projected Climate change	The headwaters inside the landscape coincide with a wide range of cyrospheric components: seasonal snow, glaciers, permafrosts.

	Under projected climate change, the timing and extent of the cryosphric process will change, leaving dramatic impacts not only inside the landscape, but also to its downstream.
Glaciers	
Water provision	Glaciers inside the landscape are essential part of the subbasin water provision context, the landscape itself contains an estimated 50% of the subbasin's glaciated area.
Projected Climate change	A shift in timing and extent of the freeze zone will directly impact the glaciers and will likely result in increased meltoff and less snow and ice accumulation over the winter months. Directly downstream an increase in number and size of glacial lakes has been reported.
Permafrost	
Water provision	Permafrost covers the entire headwaters of the subbasin, and all the headwaters inside the landscape. Permafrost presence is a master variable to local hydrology, and any permanent change will have direct impact on water provision to the downstream.
Projected Climate change	A decrease in duration of sub-zero temperatures will have direct impact on the presence of permafrosts. As permafrost extents also cover large parts of the Tibetan Plateau, temperature rise there leaves a large spatial footprint, so change to permafrost will be widespread. A more detailed classifaion of permafrost is required in order to understand and record changes.
Snow cover and freeze line	
Water provision	Snow cover and freeze line coincide with the southern landscape boundary in winter, and with the northern boundary –on the mountaintops- in summer. Hence, the landscape covers the seasonal fluctuation of minimum and maximum freeze/snow extent (together with the more upstream parts on the Tibetan plateau), and therefore provides an essential role in the generation of snowmelt and cryosphere interactions.
Projected Climate change	Though there is not much precipitation on the Tibetan Plateau, the shift in freeze line leaves a large spatial footprint which will very likely result in a large downstream change in the hydrology of snowmelt. Locations that still got some monsoon precipitation during the freeze season (some mountaintops throughout the landscape) are historically an important source of snowmelt and glacial ice. With a shift in timing and extents of temperature, these areas are very vulnerable to change, and will possibly trigger extra floods.
Lakes, wetlands and floodplains	
Water provision	There are many small glacial lakes in the landscape, these may play a role in local water management, but some of them also pose a risk for glacial lake outburst floods (GLOFS). Floodplains exist mainly where Arun river cuts through the landscape. Downstream of the landscape, in the southern parts of the subbasin –the Ganges floodplain- floods are recurring and devastating.
Projected Climate change	There is a reported increase on the size and number of glacial lakes inside the landscape. With a change in the timing of snowmelt upstream, it is very likely that the glacial lakes and floodplains will change constantly, which poses serious threats to people living downstream.

Water provision functions; water towers (local runoff)



Analysis

Subbasin context

There is a distinctive South-North gradient in the subbasin runoff generation, which is entirely driven by the monsoon (June-September). In general, the downstream areas receive much more water throughout the year, and the upstream areas are much drier. In this setup it would be difficult to justify a water provision argument. The landscape itself is in the transition zone between the dry and the wet parts of the basin, but located in such a way, that for the largest part of the year, it is just outside of the areas that can be considered to be providing water.

When comparing the annual local runoff that is 'generated' inside the Eastern Nepal snow leopard landscape with the rest of the subbasin, there is a very slight argument in favour of service provision in water quantities over the entire year; the landscape covers 19 % of the subbasin, yet 'provides' 22% of its runoff.

But when looking closer at the spatial distribution and the timing of this water provision, the quantity coincides mostly with the monsoon season, when there is the lowest demand for water in the system, or when there even might be too much water in the system, causing floods downstream.

Throughout the dry season (October-May), when water demand is highest, there is a certain mismatch between the landscape location and water provision areas in the subbasin.

Landscape context

Throughout the landscape, and in every month, there is a gradient in local runoff that decreases from;

- south to north,
- lower to higher elevations, and
- downstream to upstream.

There are little differences in timing from east to west, but the Arun valley -that cuts through the landscape- shows a local runoff pattern that is associated with its lower elevation; it therefore stands out inside the landscape as having higher runoff quantities.

Methodology

Local runoff is the difference between monthly precipitation (P) and actual evapotranspiration (AET). Monthly precipitation and AET are downloaded and, through a simple GIS command, summarized by their watershed 'mean', using HydroBASINS level 12 watersheds. The mean values are multiplied by each of the watershed area in order to convert from millimetres to cubic meters. Then these values are subtracted (P – AET); local runoff values that are less than zero are displayed and flagged as being zero. Inside the subbasin, those watersheds that drain the snow leopard landscape are flagged. See download links below.

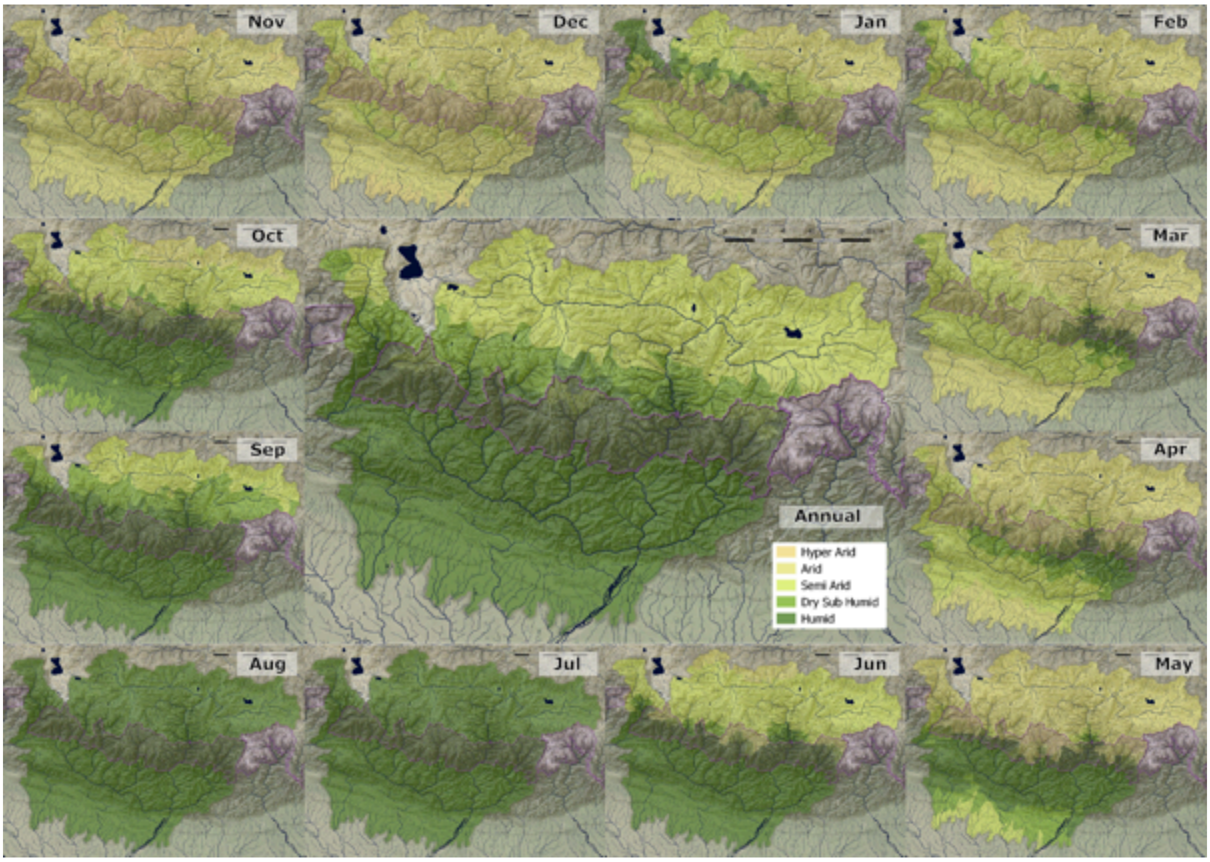
Data

Current Mean Monthly Precipitation, based on historic WorldClim, 30s resolution; Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978. www.worldclim.org

Current Mean Monthly Actual Evapotranspiration, based on historic Global Soil-Water-Balance, CGIAR, 30s resolution; Trabucco, A., and Zomer, R.J. 2010. Global Soil Water Balance Geospatial Database. CGIAR Consortium for Spatial Information. Published online, available from the CGIAR-CSI GeoPortal at: http://www.cgiar-csi.org

HydroBASINS, level 12, ~100 km^2 watershed outlines; Lehner, B., Grill G. (2013): Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. Hydrological Processes, 27(15): 2171–2186. Data is available at www.hydrosheds.org

Water provision functions; aridity



Analysis

Subbasin context

In the subbasin, the upstream areas are in general more arid than the downstream areas. In terms of water provision this implies that downstream water demand does not coincide with upstream water surpluses.

Yet the monthly aridity maps show that downstream areas do experience some level of aridity for six months (November-April), this is the dry season. This pattern does not show up in the overall annual balance, since there, the total amount of annual rainfall (during the monsoon) is such that it provides enough water to shadow the dry season drought.

There is a slight East- to-West trend in March-April that coincides with the snow leopard landscape, mainly around the Arun valley. It illustrates that those areas experience a shorter dry season and earlier start of the wet season. This trend is of importance, because for most of the subbasin this period will be the driest in the year, toward the end of a six-month dry season.

The more humid values in winter (January and February specifically) are unrealistic, aridity is a factor of precipitation divided by potential evapotranspiration (PET), and PET gets very close to zero because there is no water demand for vegetation during that time, at those locations.

Landscape context

Again, the landscape itself forms the boundary between the arid and the humid parts of the subbasin. There is a strong North-South, upstream-downstream, elevation component in the landscape's aridity.

Seasonally, the eastern parts of the landscape are the earliest parts that go from arid to humid after the dry season (starting February/March), while for the most of the landscape the dry seasons lasts two months longer.

Methodology

Aridity measures to which extent precipitation (P) is the limiting factor in water demands for vegetation growth (potential evapotranspiration, PET). Monthly precipitation and PET are downloaded and, through a simple GIS command, summarized by their watershed 'mean', using HydroBASINS level 12 watersheds. Then these values are divided (P/PET) and classified according to the following aridity classes:

Aridity (P/PET)	
< 0.03	Hyper arid
0.03 – 0.2	Arid
0.2 – 0.5	Semi arid
0.5 – 0.65	Dry sub humid
0.65 <	Humid

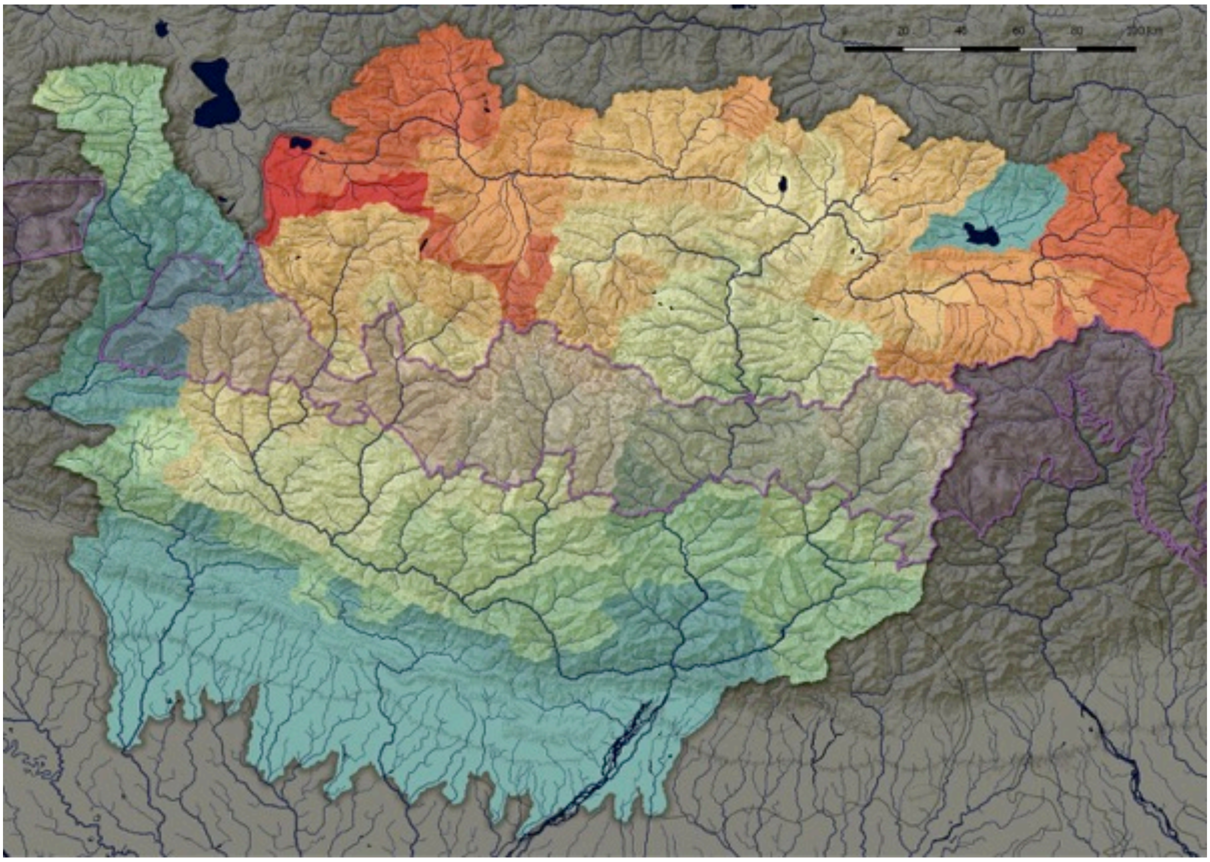
Data

Current Mean Monthly Precipitation, based on historic WorldClim, 30s resolution; Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978. www.worldclim.org

Current Mean Monthly Actual Evapotranspiration, based on historic Global Soil-Water-Balance, CGIAR, 30s resolution; Zomer RJ, Trabucco A, Bossio DA, van Straaten O, Verchot LV, 2008. Climate Change Mitigation: A Spatial Analysis of Global Land Suitability for Clean Development Mechanism Afforestation and Reforestation. Agric. Ecosystems and Envir. 126: 67-80.

HydroBASINS, level 12, ~100 km^2 watershed outlines; Lehner, B., Grill G. (2013): Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. Hydrological Processes, 27(15): 2171–2186. Data is available at www.hydrosheds.org

Water provision functions; river system layout



Analysis

Subbasin context

The river layout function helps to visualize where in the river system important features are located; in the upstream or downstream. For water provision and ecosystem service arguments, it is important that there is some upstream-downstream connectivity.

The boundary between Nepal and Tibet follows the most upstream watershed divides in the Tamur, Dudh Koshi, Likhu, Indrawati and Trishuli rivers. Only the Arun, Tama Koshi, and Sun Koshi cross the boundaries between Tibet and Nepal.

The Arun river is the longest river in this subbasin context; the most upstream parts of this subbasin are therefore located in Tibet.

The river system layout function can best be understood in relative terms; what is more upstream and therefore has better opportunity to provide water to its downstream. In that perspective, there are a significant downstream parts in Nepal that have their headwaters in the Himalayas, where there is overlap with the snow leopard landscape.

Landscape context

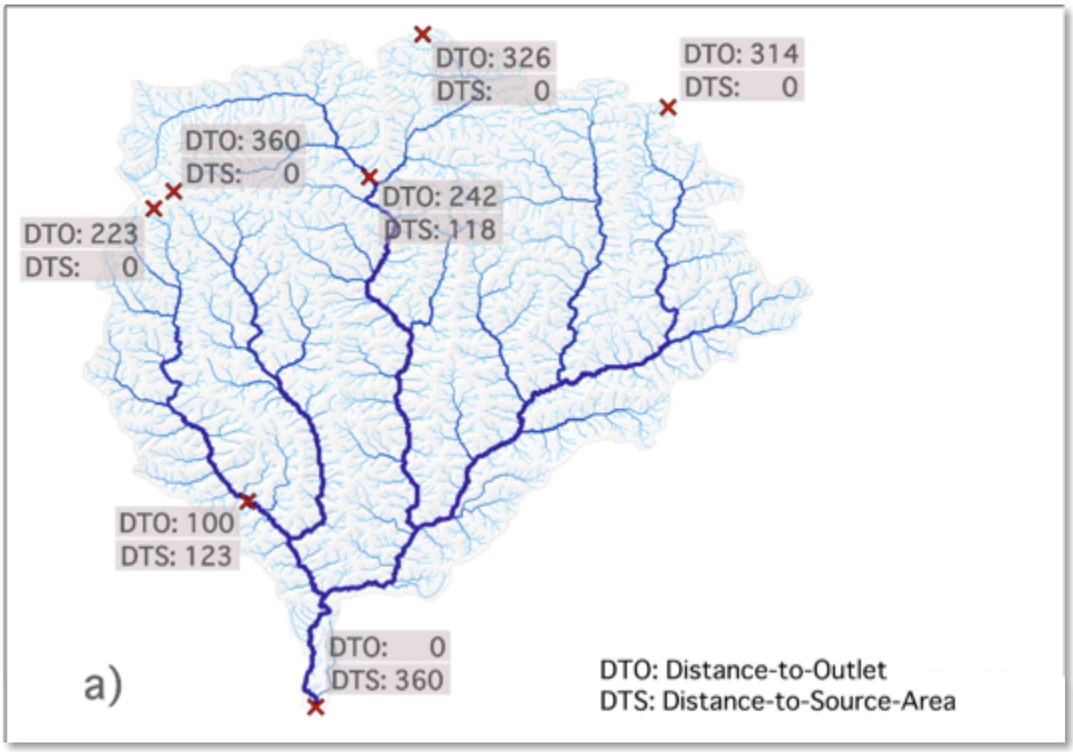
The northern boundary of the Eastern Nepal snow leopard landscape follows the national boundary between Nepal and China, and this boundary follows –for-the largest part- the watershed divides. In relative terms, the landscape occupies the headwaters of some of the subbasin's larger tributaries. Yet, three of the tributaries flow through the landscape, and have their headwaters upstream of the landscape.

The analysis illustrates that, inside this subbasin, not all headwaters are located within the snow leopard landscape, and that the most upstream headwaters are located –hydrographically- far outside the landscape, but just over the border in Tibet.

Methodology

HydroSHEDS 15 drainage directions are used to calculate flow distances; first local flow distances (the distance that a virtual stream flows over each individual cells) and then calculating the distance to source area and distance to outlet. These functions work as follows:

- ***distance to source*** (DTS) areas measures for any location inside a river basin, along the stream, the distance to the most upstream source,
- ***distance to outlet*** (DTO) measures for any location inside a predefined river basin, the point furthest downstream, i.e. the point where the entire basin drains to,
- ***longest stream***, the maximum values DTS and DTO of a river basin are identical and measure the longest stream in the basin.



These three variable are calculated into a single function, and summarized (mean) for each level-12 watershed:

$$headwater\ function\ = \frac{DTO}{longest\ stream} \times \frac{DTO}{DTO + DTS}$$

For Eastern Nepal, not the entire subbasin is part of a single –connected- river system;

- the Southern Nepal boundary was used, and not a river basin boundary, many smaller river only connect to the Kosi complex more downstream, in India,
- in the most western parts, the landscape drains into Trisuli river, which is not part of the larger Kosi basin.

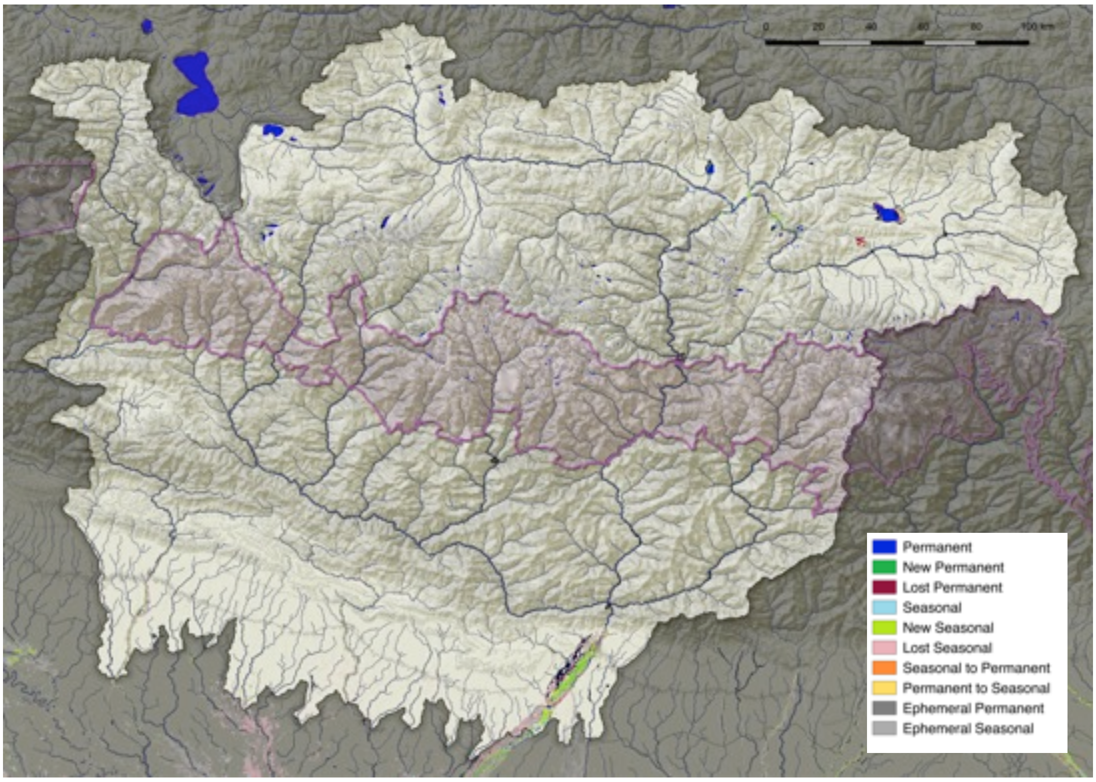
Yet, in the basin context of the Eastern Nepal landscape, it would suffice to take the longest river (Arun) as the main variable, as this puts the potential to provide water of any location in the basin in the same perspective, regardless of which potential downstream the location "provides" with water.

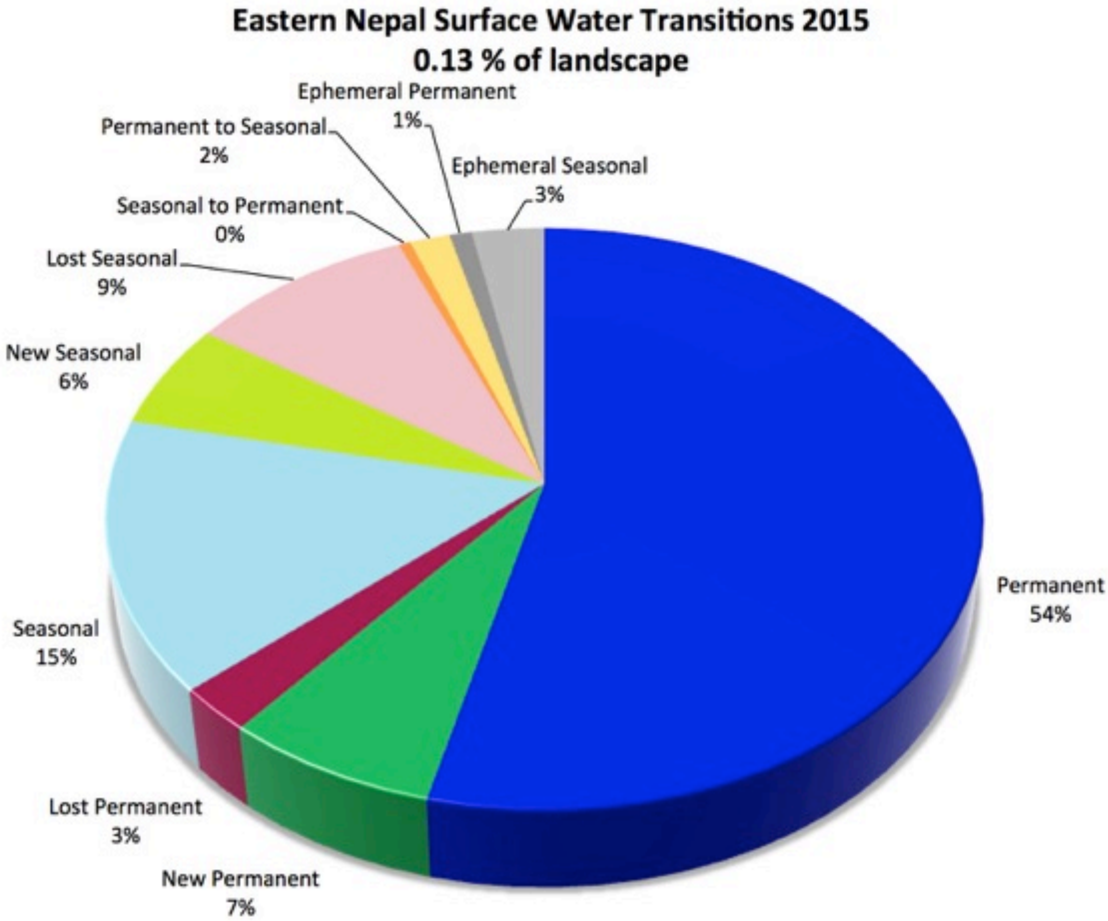
Data

HydroSHEDS 15s drainage directions; Lehner, B., Verdin, K., Jarvis, A. (2008): New global hydrography derived from spaceborne elevation data. Eos, Transactions, AGU, 89(10): 93-94. Data is available at www.hydrosheds.org

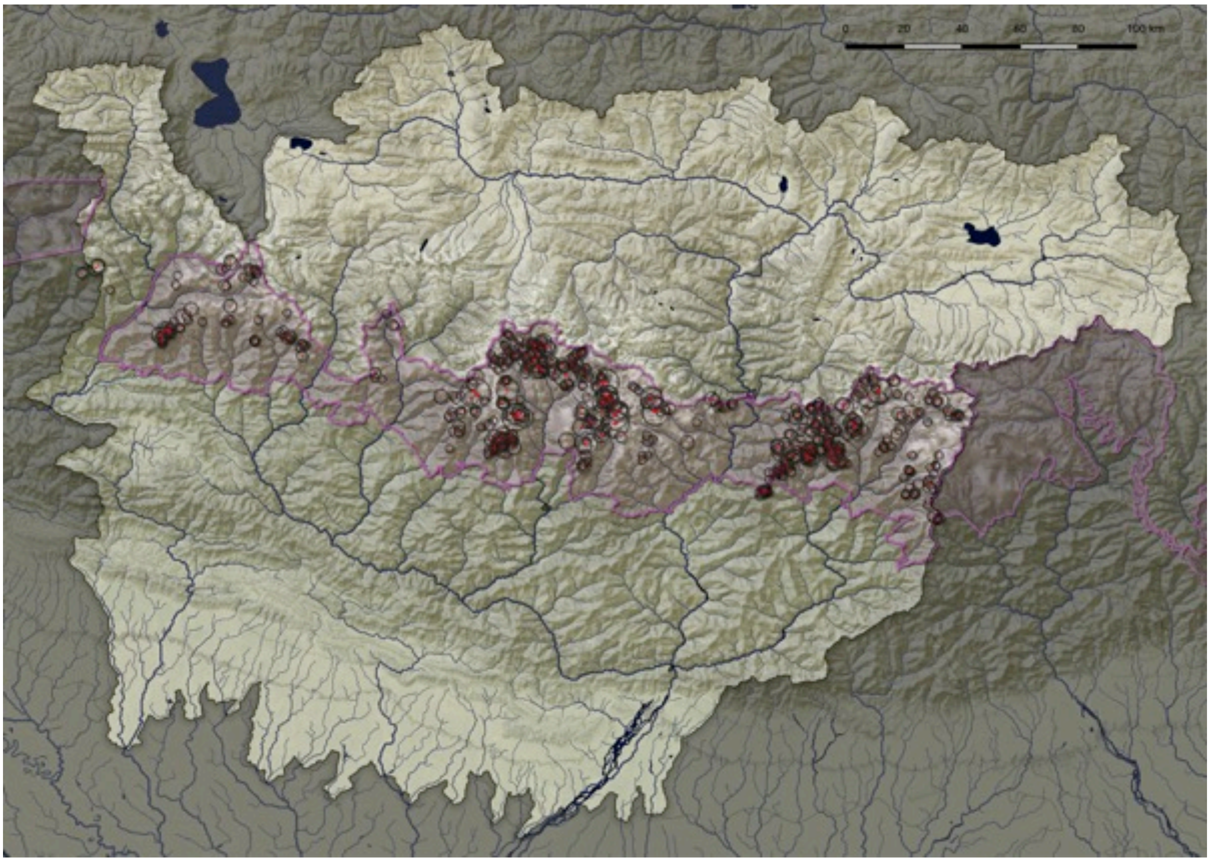
HydroBASINS, level 12, ~100 km^2 watershed outlines; Lehner, B., Grill G. (2013): Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. Hydrological Processes, 27(15): 2171–2186. Data is available at www.hydrosheds.org

Water provision functions; Global surface water transitions (1984-2015)





Location and size of glacial lakes (ICIMOD, 2011)



Overview

Inside the landscape; according to the most recent map of global surface water (Pekel, 2016) only 0.13% is classified as open surface water; it can therefore hardly be identified in the above map. The following transitions occurred between 1984 and 2015:

- 73% of the open water surface was *stable* (permanent 54 %, seasonal 15 %, ephemeral 4 %)
- 12 % of the open water surface *disappeared* (permanent 3 %, seasonal 9 %)
- 13 % classified as *new* surface water (permanent 7 %, seasonal 6 %)
- while 2 % of all open water surface *changed from permanent to seasonal*.

Most probable changes in surface water areas occurred around some of the acitve and floodplains/rivers inside the landscape, but also a possible increase in number and size of glacial lakes is being reported by ICIMOD (2011). Further analysis on the global surface water database is planned in the near future and will be included into this document at a later stage (spring 2017).

The global HydroLAKES database (Messager, 2016) detects 13 lakes inside the Eastern Nepal landscape. ICIMOD's database on glacial lakes in Nepal (2011) detects 634 glacial lakes in the landscape; these show systemic overlap with the global surface water database. The ICIMOD database on glacial lakes only covers Nepal, and therefore misses the relevant connections in the direct upstream of the Sun koshi, Tama Koshi, and Indra Wati rivers, in Tibet/China.

Methodology

The the map of global surface water and its long-term changes, is a recent high-resolution product (Pekel, 2016). It contains at least 6 different datasets, and allows time-lapse analysis from 1984-2015, which coincides with Landsat coverage. From the https://global-surface-water.appspot.com/ website:

"*The Water Transitions map documents changes in water state between the first year and the last year of observation. It documents:*

- *New permanent water surfaces (i.e. conversion of a no water place into a permanent water place.)*
- *Unchanging permanent water surfaces*
- *Lost permanent water surfaces (i.e. conversion of a permanent water place into a no water place)*
- *New seasonal water surfaces (i.e. conversion of a no water place into a seasonal water place)*
- *Unchanging seasonal water surfaces*
- *Lost seasonal water surfaces (i.e. conversion of a seasonal water place into a no water place)*
- *Conversion of permanent water into seasonal water*
- *Conversion of seasonal water into permanent water*
- *Ephemeral permanent water (i.e. no water places replaced by permanent water that subsequently disappeared within the observation period)*
- *Ephemeral seasonal water (i.e. no water places replaced by seasonal water that subsequently disappeared within the observation period)*

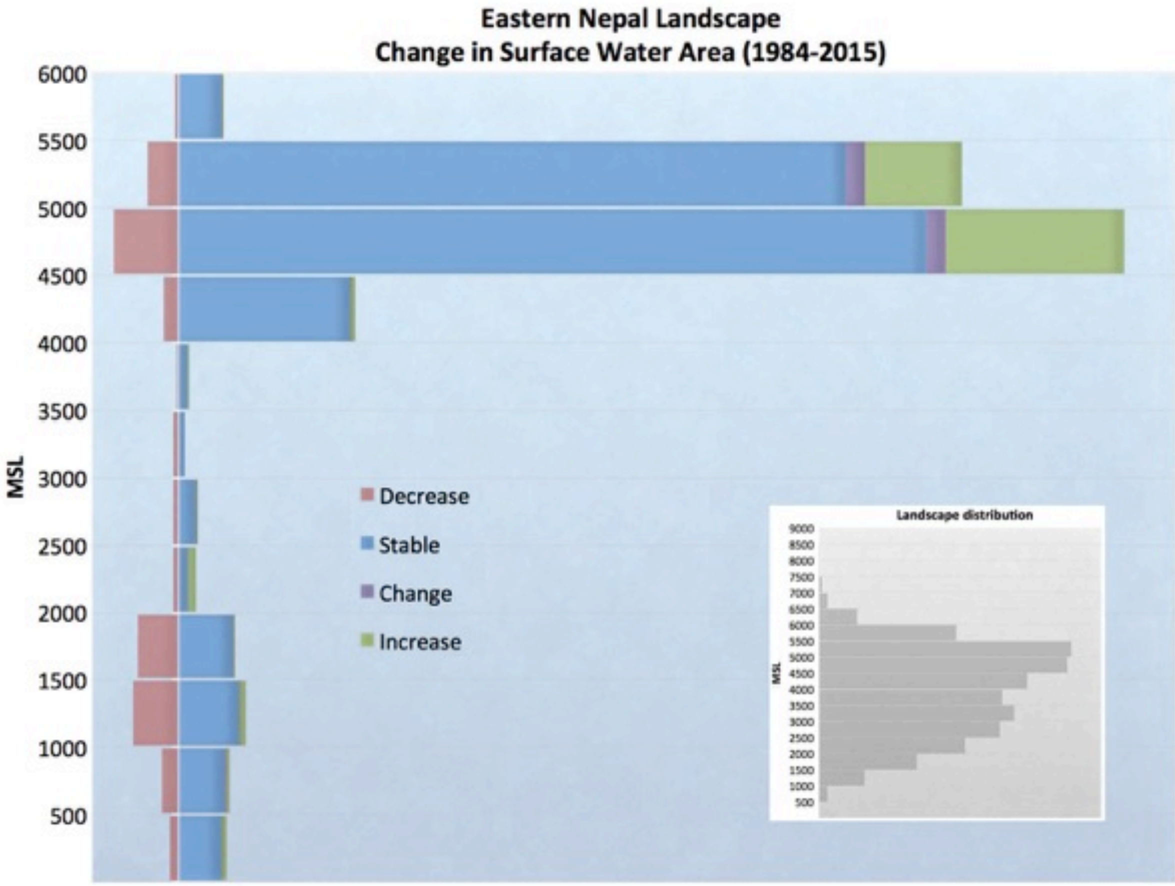
Temporal profiles recording the full history of each pixel are provided. These allow us to define on a monthly basis the water presence or absence (and also the absence of observation) throughout the archive. Using the profiles it is possible to identify specific months/years in which conditions changed, e.g. the date of filing of a new dam, or the month/year in which a lake disappeared. In addition, *profiles documenting the seasonality (and possible transition of seasonality) are provided. These profiles allows to discriminate between occurrence changes resulting from intra and inter-annual variability or resulting from appearance or disappearance of seasonal or permanent water surfaces."*

The ICIMOD database on glacial lakes classifies the 634 lakes into three classes:

- moraine-dammed,
- ice-dammed,
- erosion,
- and other lakes.

"*For the inventory, glacial lakes were defined as all lakes in a river basin that lie above 3,500 m, are greater than 1000 sq.m in area, and are fed by glacial melt. The altitude was selected as representing the approximate lower limit of glacial moraine accumulations in Nepal. Glacial lakes may also exist beneath or within glaciers, but these are not usually visible on aerial images and so cannot be mapped. Thus such lakes were not included."* ICIMOD, 2011 *"A comparison between this inventory and that of 2001 showed changes in many of the glacial lakes, which led to realisation of the need to reappraise these lakes in order to prioritise them for more detailed study. However, in making comparisons between different sets of data, it is important that the types of imagery used and the dates of their acquisition be as similar as possible; the earlier inventory was based on the only sources available at the time, but was far from optimum in this respect. In both inventories, glaciers and glacial lakes were mapped and numbered according to river basins and sub-basins."* ICIMOD, 2011

"Landsat satellite images (World Geodetic System 1984, i.e., 'WGS 84' projection) from 2005/06 were used as the basic source of data for developing the present mapping and inventory work. These images can be downloaded freely from the United States Geological Survey (USGS) and Global Land Cover Facility (GLCF). Satellite images from 2000 and 2001 had to be used for a small area of the Mahakali basin because there were no cloud- and snow-free images available for any date after 2001. Information on the elevation of the glacial lakes was derived from the Shuttle Radar Transmission Mission Digital Elevation Model (SRTM DEM) and Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) Global DEM. This data source was used to detect the boundaries of glacial lakes and to help classify them. Google Earth satellite images were used to verify the glacial lake inventory data. A combination of open source remote sensing and GIS software packages, such as Google Earth, Quantum GIS, Integrated Land and Water Information System (ILWIS), Postgre/ PostGIS, and Python, were used to edit, manage, and analyse the data." ICIMOD, 2011



When the surface water transitions are distributed over the different elevation zones, it becomes clear that the zones of 4,500-5,500 MSL contain the largest open water surfaces. This while the landscape itselfs is more gradually distributed over the elevation zones (see inset). These are the zones that are directly downstream of the glaciers, and are therefore *mainly* glacier-fed. The fact that the open water surfaces at those elevations have **increased dramatically** over the 1985-2015 period, indicates that glaciers mights have been melting off. At lower elevations (lower than 2,000 msl), the overall open water surface is much less, but also has experienced dramatic **loss** in coverage. In general, for the landscape, this is where the larger river flow, so maybe there has been some developments in the floodplains of those rivers. In both perspectives, it is important to mention that this *graph shows **surfaces** and **not volumes*** of water.

Data

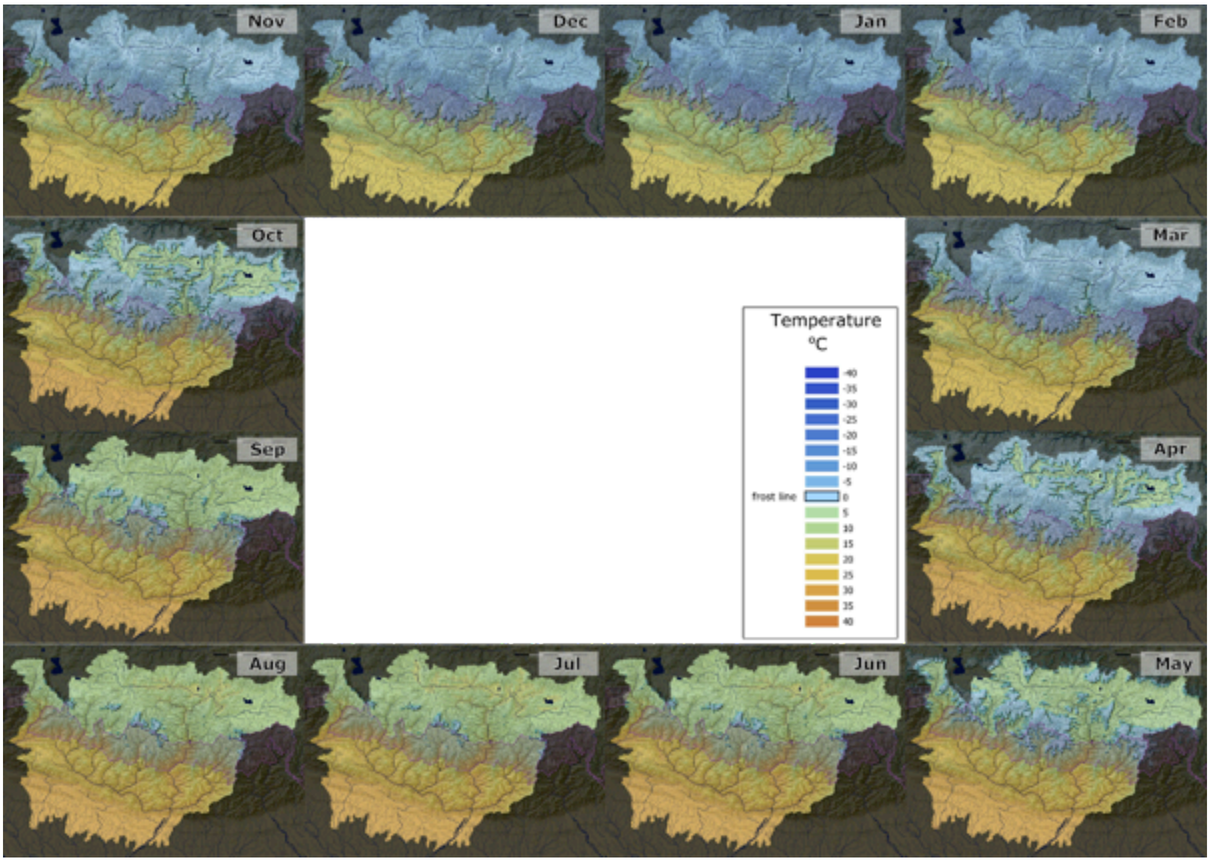
Pekel, J.-F., Cottam, A., Gorelick, N. & Belward, A. S, *High-resolution mapping of global surface water and its long-term changes,* Nature **540**, 418–422 (2016). https://global-surface-water.appspot.com/

Messager, M.L., Lehner, B., Grill, G., Nedeva, I., Schmitt, O. (2016): *Estimating the volume and age of water stored in global lakes using a geo-statistical approach.* Nature Communications: 13603. doi: 10.1038/ncomms13603. Data is available at www.hydrosheds.org.

HydroSHEDS 15s void-filled elevations; Lehner, B., Verdin, K., Jarvis, A. (2008): New global hydrography derived from spaceborne elevation data. Eos, Transactions, AGU, 89(10): 93-94. Data is available at www.hydrosheds.org

ICIMOD (2011) *Glacial lakes and glacial lake outburst floods in Nepal.* Kathmandu: ICIMOD

Water provision functions; freeze line



Analysis

Subbasin context

The freeze line demarks the boundary between freezing and thawing locations. The timing and location of this line is a climatic variable that lies at the base of important ecological and hydrological thresholds.

Throughout a year, the freeze line follows the Himalayan slopes, with two core areas and processes at the base of this:

- around the winter months (November to March) the Tibetan plateau forms the core freezing area, and the freeze line is on the most southern slopes of the Himalayas,
- in the summer and monsoon months (May to September), the three mountain complexes (Kanchenjunga, Sagarmatha and Langtang) form the core freezing areas, and is the freeze line located on the slopes of these mountains,
- in the transition months (April and October), the freeze line is on the –relative- plains of the Tibetan plateau and the valleys between the mountain complexes.

In the months where the freeze line is on the slopes, inter-annual variability (and even temperature rise) will have minimal spatial impact. These are the areas with a so-called high gradient of temperature; within kilometres the temperatures drop to very minimum values (up in elevation). These minimum values mean that the freeze line will still be there even at the most extreme projections of temperature rise. Yet, for micro habitats located on these mountain slope, such events might be fatal.

In the transition months, inter-annual variability and temperature rise will have significant spatial impacts. In general, this implies that winters will be shorter, and that all freeze-related processes (snowfall, snowmelt, and ecological triggers such as seed germination or insect life cycles) will have to move in time and space; or will cease to occur. The monthly timeframe of this exercise helps to map out the spatial footprint of such change, but does not properly capture the time frame; normally this is expressed in weeks. A study of Panday et al (2011) illustrates the spatio-temporal differences in melting seasons over the larger HKH-region, using 4-daily radar-based observations on the freeze/thaw line.

Landscape context

The Eastern Nepal landscape encompasses the most southern extent of the freeze line during winter, and the southern slopes of three mountain complexes where the freeze line lies during summer. Over the year, the monthly freeze line can be found inside the landscape. The landscape covers the part of the subbasin where this is the case; it exclusively ‘follows’ the southern boundary of the freeze line.

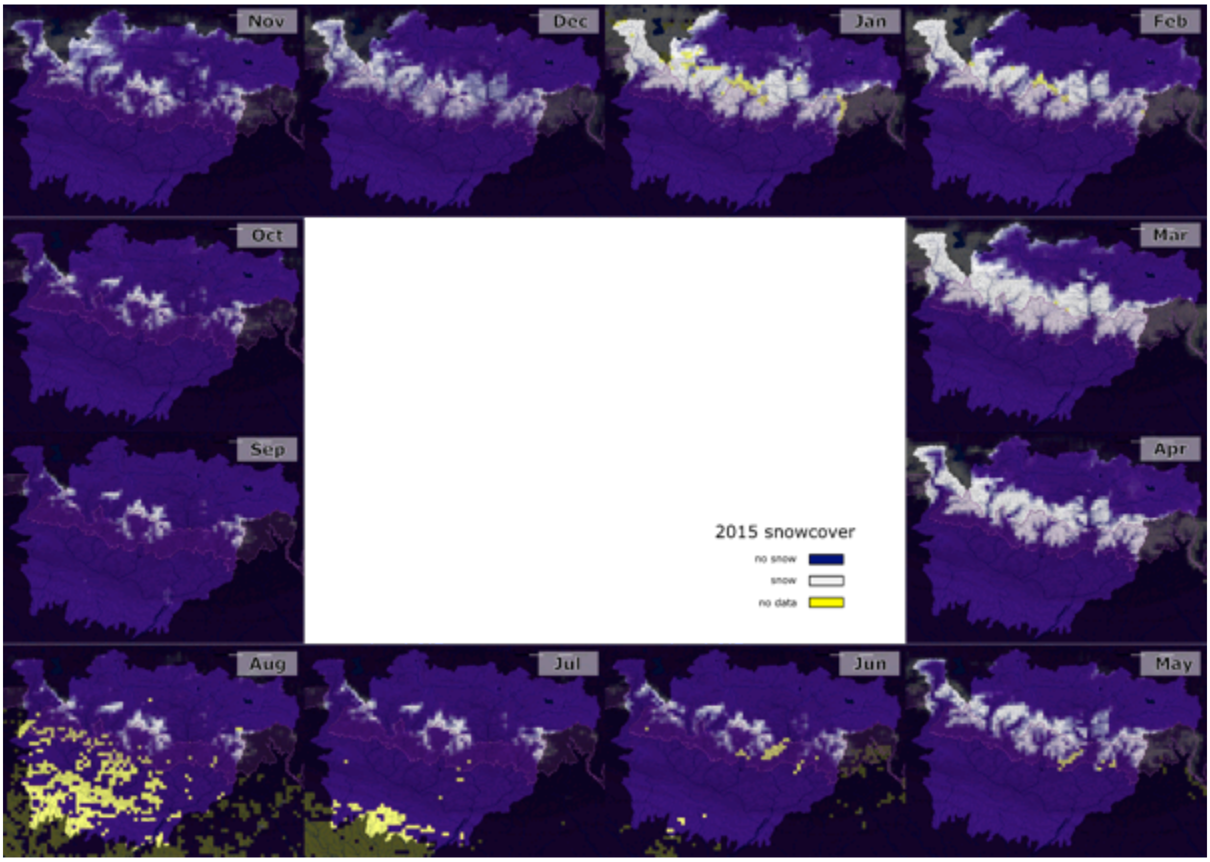
Methodology

This is a map of WorlClim mean monthly temperatures at 30s resolution with the freeze line highlighted.

Data

Current Mean Monthly Temperatures, based on historic WorldClim, 30s resolution; Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978. www.worldclim.org

Water provision functions; snow cover 2015



Analysis

Subbasin context

This snowcover database is a product of satellite image interpretation, part of the MODIS library. It is therefore based on observation and not on modelling. For each 0.05 x 0.05 degree cell, the percentage of monthly snow cover is reported. Due to some of the data artefacts (no data, e.g. through cloud cover), it is difficult to calculate inter-annual means, hence only the snow cover for the year 2015 is mapped out.

The monthly snow cover in winter follows the Himalayan belt, and largely coincides with the snow leopard landscape. Not much snow falls outside the landscape. The southern boundary of this Himalayan belt of snow cover is formed due to the location of the freeze line, the northern boundary of this belt is formed due to lack of precipitation. This makes snowfall particularly sensitive to changing temperatures in the southern part, and changing precipitation in the northern parts of the snow belt.

In the monsoon months (June to September), the remaining snow cover largely coincides with the location of the glaciers, which are mapped out in a separate map.

The map shows snow cover as a landscape attribute, it does not provide information on the amounts of snow, snow depth, or timing of snowmelt. The next map goes into more detail on snowmelt amounts and timing.

Landscape context

Just like with the freeze line over the different months, the snow belt covers the entire Eastern Nepal landscape at its maximum extent in winter. In summer it retreats to the mountaintops and coincides with the glaciers. At any given month in the year, the landscape contains (or directly connects to) the majority of snow cover locations inside the wider subbasin.The next section goes into more detail about the distribution and timing of the snowmelt.

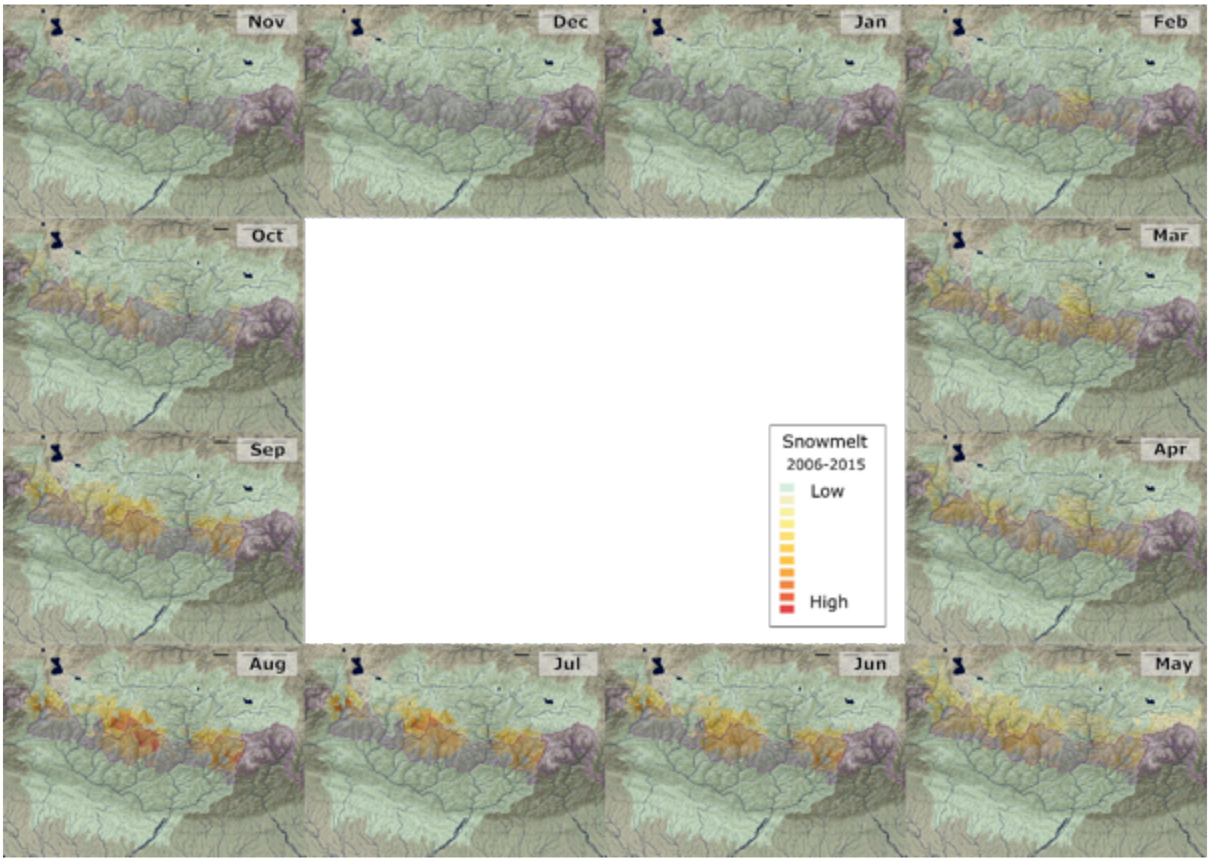
Methodology

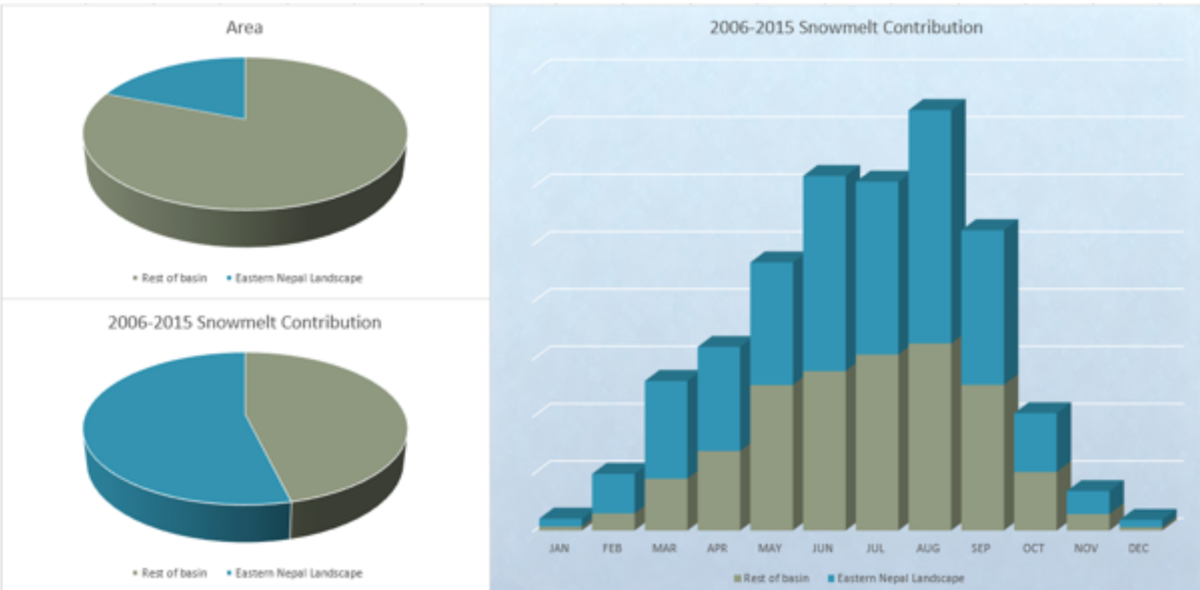
This is a map of MODIS/TERRA snow cover at 0.05 degree resolution with no additional processing required.

Data

<u>MODIS/TERRA Montly Snowcover L3 at 5km (0.05 degree) resolution;</u> Hall, Dorothy K., George A. Riggs, and Vincent V. Salomonson. 2006, updated monthly. *MODIS/Terra Snow Cover Monthly L3 Global 0.05Deg CMG V005*, [Year 2015, downloaded April 2016]. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.

Water provision functions; snowmelt





Analysis

Subbasin context

Most snowmelt originates from the elevational belt where freezing winter temperatures overlap. late-monsoon precipitation; that combination allows to accumulate snowfall over the winter, and 'provide' snowmelt in spring and summer. This belt largely coincides with the snow leopard landscape; the landscape provides 54% of all snowmelt in the subbasin.

Since the snowmelt data comes from a different model (GLDAS-NOAH) than the water towers and aridity calculations (WorldClim); these cannot be linked into a single model. *Nepal et al* (2013) calculate in their model that 17% of the total runoff in Dudh Kosi originates from snowfall, and another 17% originates from glacial melt. In their study they assess that in April and May the flow contribution from glacier and snowmelt is 69% and 79% respectively; this is a very considerable amount, also given the timing at the very end of the dry season, pre-monsoon.

For the analysis here, the spring snowmelt (February to May) are considered to be of most importance for water provision; the timing coincides with the end of the dry season on the downstream, when water is in highest demand.

The highest areas (around Mount Everest, Kanchenchunga, and Langtang) generate the largest amount of snowmelt, yet their contribution mainly coincides in timing with the monsoon rainfall. Only in the months of June-September the temperatures have risen enough in those mountain areas to melt off snow. Yet these quantities are overwhelmed by the monsoon rainfall. So, even those areas are most productive in terms of snowmelt, this snowmelt has relatively limited importance to overall seasonal subbasin water provision.

Increasing temperatures will have two direct consequences regarding snowmelt;

- historically, there is an amount of precipitation that falls as snow in the late monsoon and stays in the landscape over the winter, only to melt off during spring and summer (February to September). Under increased temperatures, this precipitation would no longer fall as snow, but as rainfall, and directly runoff in a landscape that has been saturated with monsoon rainfall; this would cause extra floods in the downstream at the end of the monsoon. This trend will be mainly taking place at the lowest elevations of snow accumulation, as temperatures at higher elevations will remain below zero even under considerable temperature rise.
- in spring, higher temperatures means that the more snow will start to melt off earlier in the year, and therefore less of the snowmelt would coincide with the monsoon. This would mean that more water becomes available at the end of the dry season, but it might even result in new floods in spring. This trend has to be regarded in consideration of the previous point, which concerned decreased snowfall before and during winter.

In both cases, it is of importance where the historic freeze line is located, what the temperature slope is, and, how precipitation patterns might change. In general, the temperature slope is flatter in landscapes with lower elevations (or with lower elevation differences) and steeper at higher elevations; this means that a temperature shift at lower elevations has a bigger spatial footprint than a shift at higher elevations. Though this would not be the case at high elevation plateaus.

Landscape context

In the landscape, snowmelt concentrates around three mountain complexes (around Mount Everest, Kanchenchunga, and Langtang). There are two elevational components driving snowmelt;

- as seasonal temperature rises over the year -from winter to summer- the snow melts higher off these mountains
- there are higher amounts of snowmelt at higher elevations.

The headwaters of Dudh Kosi, that form the southern slopes of the Everest/Sagarmatha mountain region, score high on overall snowmelt provision. As calculated for the water towers, this area does not provide much of local runoff, and is as well characterized by high aridity, yet as it shows here; it does play an important role in the provision of snowmelt. For the warmer seasons, the area acts as a kind of snow-dome, that provides a continuous flow of water through snowmelt.

The landscape captures the most significant part of the entire subbasin's snowmelt. Any climate adaptation strategy that combines landscape-based snow leopard conservation with climate adaptation strategies on snowmelt management will significantly impact the entire subbasin and its downstream.

Methodology

NOAH-GLDAS monthly data 2006-2015 is downloaded, it contains 28 bands of data; snowmelt is band 11 in this dataset. For every month, the 2006-2015 mean snowmelt component is calculated in a GIS, through adding all individual months.

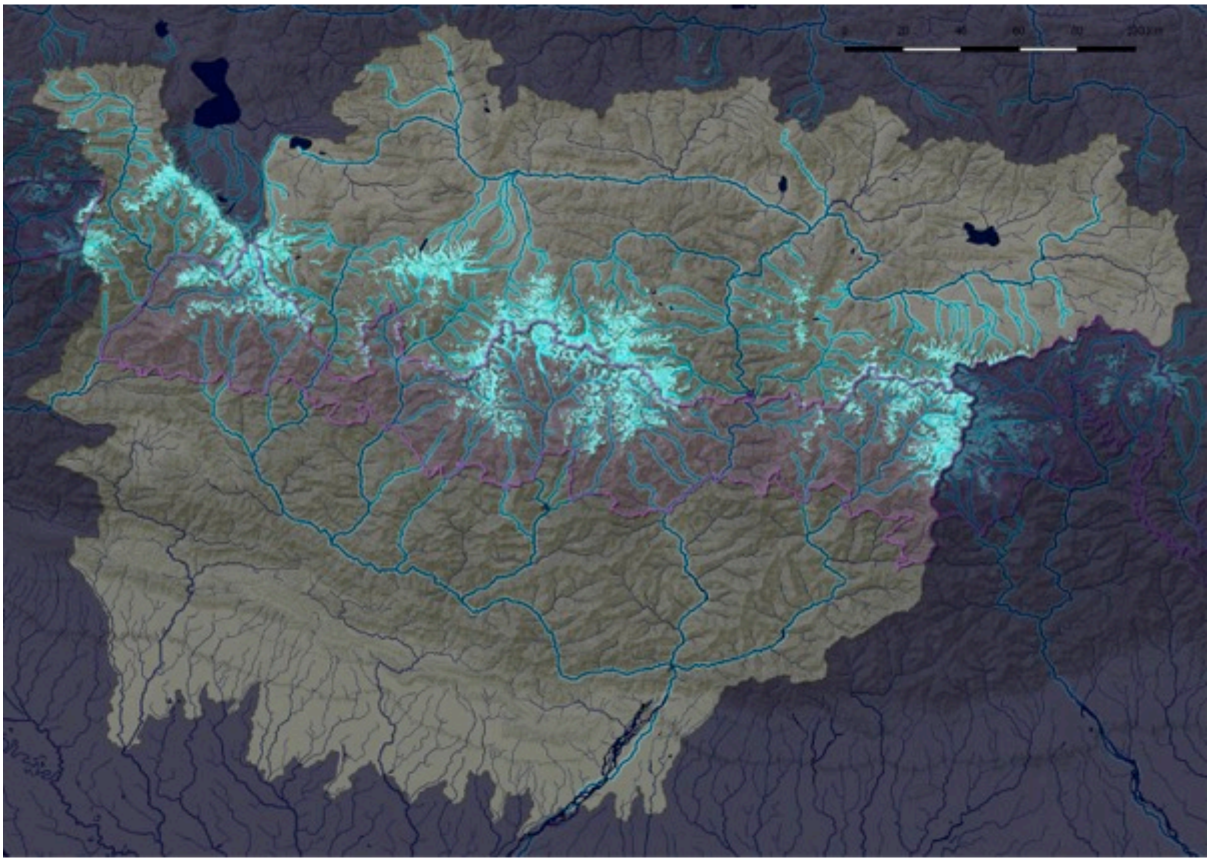
The mean snowmelt is then summarized in a GIS for each month by the selected HydroBASIN level 12 watersheds, and multiplied by each watershed area (in order to calculate quantities), both for the entire basin and the snow leopard landscape.

Data

NOAH-GLDAS V2.0, Monthly data on snowmelt from 2006-2015 at 0.25 degrees resolution
http://disc.sci.gsfc.nasa.gov/datareleases/gldas-version-2.0-data-sets

HydroBASINS, level 12, ~100 km^2 watershed outlines; Lehner, B., Grill G. (2013): Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. Hydrological Processes, 27(15): 2171–2186. Data is available at www.hydrosheds.org

Water provision functions; glaciers and glacial streams



Analysis

Subbasin context

Glaciers are important water sources because they can provide water to downstream throughout the year. Through regelation –pressure built up under thick layers of ice cause melting of the ice under the glacier- water keeps flowing from glaciers, regardless of the season. Therefore streams with glaciers in the headwaters do have different runoff pattern –as well as water chemistry- than streams with seasonal snowmelt in the headwaters.

Glaciers can continue to exist due to the imbalance between snowfall and snowmelt; where there is more snowfall than snowmelt, snow accumulates over the years and the layers get pressed into ice. This is a process that takes hundreds of years; that is how long it could take from initial snowfall to melt-off at the foot of a glacier. Ice melts off under high pressure under each glaciers, which makes glaciers slowly slide down, until it reaches elevations with seasonal thaw that melts-off the foot of the glacier. Under rising temperatures, this elevation gets higher and higher up the mountain, which could then escalate glacial melt off. In some cases, glaciers have pushed debris down the mountain, and under escalated melt-off, melt water is building up behind these walls of debris, creating risks for glacial lake outburst floods (GLOFS).

About half of the glacial coverage inside the subbasin lies outside the Eastern Nepal landscape; in Tibet. Hydrological connectivity to those glaciers in Tibet is provided by Arun river, that cuts through the landscape, and the Sun- and Tama Kosi rivers.

Though the map shows the spatial extent of the glaciers, it does not show the total volume of ice/water in each glacier. Each glacier has its own particularities that explains its existence, how it accumulates snow, and releases its water. To get a full understanding about the functioning of glacial water release would require detailed insights at the glacier level. Nepal et al (2014) describe how they used an hydrological model to understand the glacial dynamics of the Dudh Kosi headwaters; at their reference location, the basin (3712 km2) it contains 273 glaciers, with a total water volume of 53 km2, and 14% of the basin is covered by glaciers, with an estimated annual flow contribution of 17% of the total flow (Nepal et al, 2014). This study they assess that in April and May the flow contribution from glacier and snowmelt is 69% and 79% respectively.

Landscape context

An –estimated- fifth of the landscape's area is covered under glaciers, while all of its larger rivers and streams have glacial sources. The glaciated areas coincide with where the freeze line retreats to in summer.

Any landscape-based climate adaptation strategy that would combine snow leopard conservation with climate change impacts on glaciers would effectively capture all glaciers on the Nepal side of the subbasin, but would miss about percent of the subbasins glaciers –those located in Tibet. Moreover, some of the main rivers (Sun- and Tama-Kosi, Arun rivers) flowing through the landscape have significant glacial influence from the upstream in Tibet.

Methodology

This is a map of the GLIMS database.

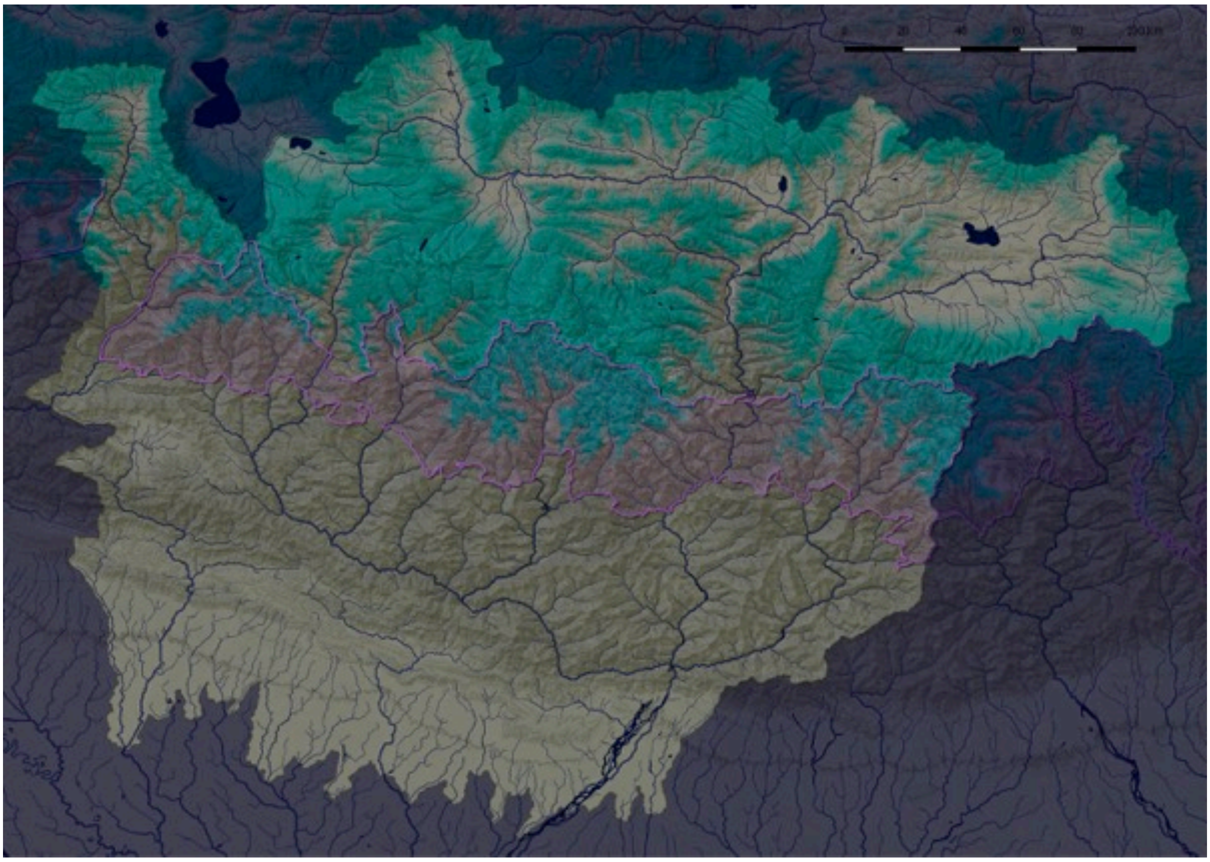
The glacial streams were created with HydroSHEDS 15s drainage directions. For that, the GLIMS polygons were converted to a 15s grid, and ran through a flow accumulation. A stream network was defined using HydroSHEDS 15s drainage direction, with the glacial flow accumulation attributed.

Data

GLIMS glacier database; GLIMS, and National Snow and Ice Data Center. 2005, updated 2012. GLIMS Glacier Database, Version 1. [polygons]. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi: http://dx.doi.org/10.7265/N5V98602. [April 2016].

HydroSHEDS 15s drainage directions; Lehner, B., Verdin, K., Jarvis, A. (2008): New global hydrography derived from spaceborne elevation data. Eos, Transactions, AGU, 89(10): 93-94. Data is available at www.hydrosheds.org

Water provision functions; permafrosts



Analysis

Subbasin context

The permafrost database is the work of Gruber (2012). It is a function of air temperature, ruggedness, and permafrost extents from earlier global assessments. The study acknowledges that the permafrost extents are mapped for consistent reference, but due to the lack of consistent information on permafrost, it is does not provide a reliable groundtruth (Gruber, 2012).

Overall, it provides a consistent and best-informed overview where permafrosts are located in the wider subbasin: i.e. on high elevations and on the Tibetan plateau, but not in the river valleys. So there is a component of being in the upstream source areas. Next to this, the permafrost maps shows strong similarity with the April and October freeze line maps, where it was concluded that the freeze line in those months would experience the largest change in spatial footprint under increased temperatures.

Though this map provides essential insight on the extent of permafrost, actually there are a wide range of permafrosts all with their specific seasonal impact on the landscapes in which they occur. The characteristic of each permafrost is essential to know in order to understand its role in landscape hydrology, or its vulnerability to climate change. At the moment, the map therefore illustrates the matter of uncertainty where permafrosts do occur; it depicts where changes are likely to happen under changing climate, but does not indicate how the landscape will change.

Possible changes already observed to coincide with permafrost degradation can be, but are not limited to:

- increased landslides, due to loss of permafrost slopes will lose their stability,
- decreased seasonal levels of groundwater, if permafrost dissolve or sink deeper, the active layer also sinks deeper, possible causing the disappearance of seasonal wetlands in alpine meadows, but also changes (or degradation) of surface vegetation,
- changed runoff patterns as sub-surface hydrology changes,
- release of greenhouse gasses that have been stored in permafrosts, and changes in runoff water chemistry.

These changes will become more dramatic at the frontier between permafrost and none-permafrost lands. This frontier runs throughout all the headwaters of this subbasin, and any climate change impacts on permafrosts will likely trigger unprecedented change at the subbasin level.

Landscape context

The permafrosts here are located at the highest elevations on the mountain slopes, surrounding the three mountains complexes (Langtang, Sagarmatha/Everest, Kanchenjunga), and upstream in the Sun- and Tama-Kosi and Arun rivers.

As inside the landscape, the permafrosts are mainly located on the mountain slopes, under increased temperatures the spatial footprint of any change will be minimal, yet small changes to slope stability will have dramatic local impacts.

Methodology

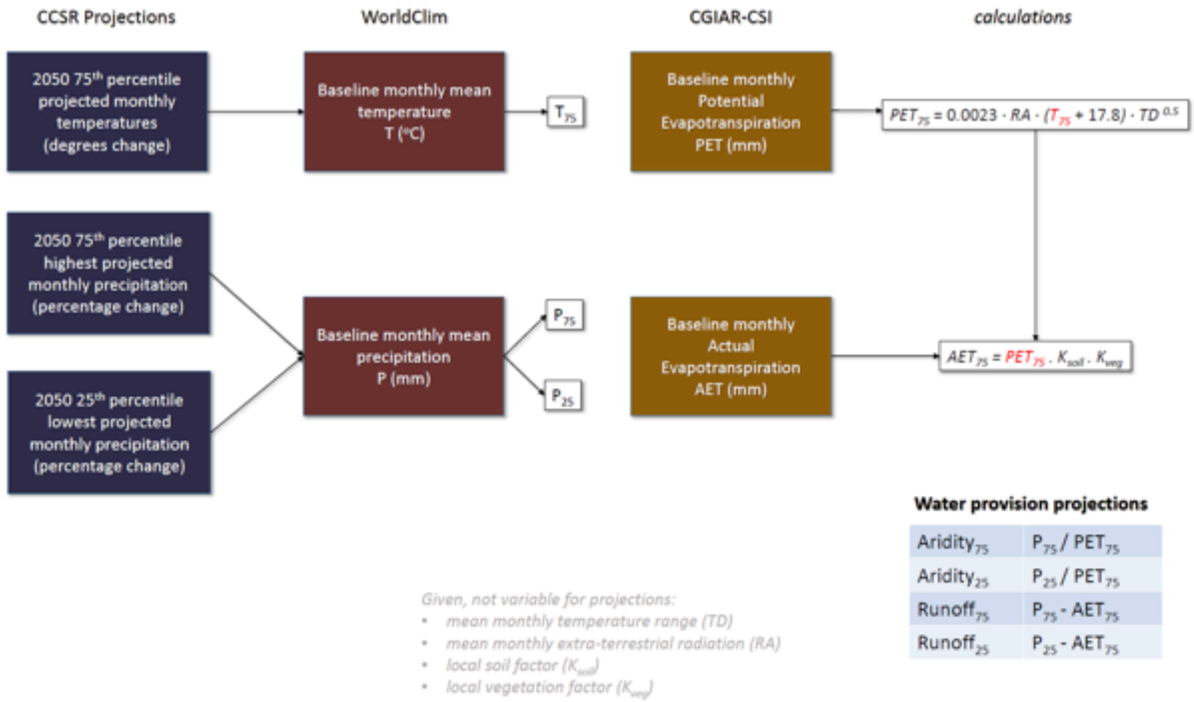
This is a map of the PZI database.

Data

Global permafrost database, Permafrost Zonation Index (PZI); Gruber, S.: *Derivation and analysis of a high-resolution estimate of global permafrost zonation*, The Cryosphere, 6, 221-233, doi:10.5194/tc-6-221-2012, 2012. http://www.geo.uzh.ch/microsite/cryodata/pf_global/

Eastern Nepal Climate Projections

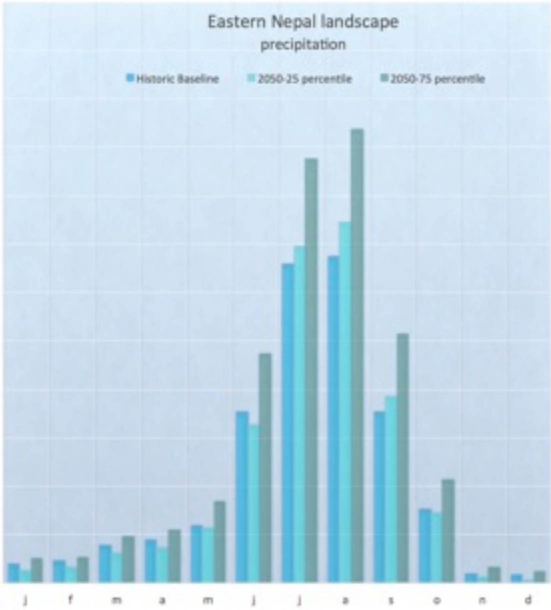
This section discusses how sensitive the different water provision functions are to different projections of climate change. It makes use of the same datasets as were being used for the water provision functions and applies the projections produced by the Center for Climate Systems Research, under the ADVANCE partnership with the WWF (CCSR, 2016)



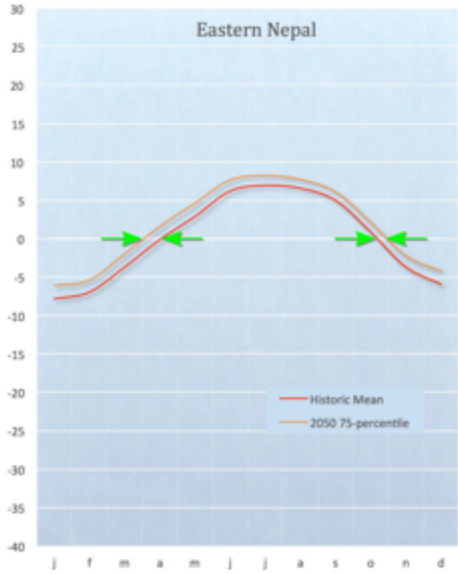
- CSSR Projections are calculated at 0.25 degree resolution; WorldClim and CGIAR-CSI datasets are at 1 km^2 resolution
- Calculations are upscaled/downscaled to HydroSHEDS level 12 (~100 km^2) watersheds, both for the snowleopard landscape and their larger subbasins
- The results are presented as graphs, this is in order to communicate *relative* changes to seasonality and to identify uncertainties in the projections; hence the water balances are not presented in millimetres of change
- In the annex, one quantitative example is given of a single (watershed) entry, representative for the snow leopard landscape; this quantitative example provides an insight in why certain graphs show the variability and uncertainty.

These projections are based on bias-corrected output from 21 General Circulation Models run under 2 scenarios of future emissions (moderate-emissions RCP 4.5 and high-emissions RCP 8.5), for a total of 42 projections. Projections for 2050 reflect average climate over 2041-2070. A most likely range of future climate change is defined from the 25th to the 75th percentiles of the suite of projections for precipitation. For temperature, a single higher-end estimate (75th percentile) is used for simplicity. While changes within this range are most likely, changes outside the range are also possible based on the full suite of projections.

Precipitation and temperature projections



Historic precipitation compared to the low end of the range of climate projections (25th percentile) and the high end of the range of climate projections (75th percentile) in the 2050s, horizontal axis crosses at 0 mm.



Historic temperature compared to the maximum projection (75th percentile) of 2050 (reference to CCSR-report, 2016). Arrows denote projected future loss of frost season duration. Note that this figure only depicts the higher end of the most likely range of future temperatures

Observations:

- From July to September, both the high- and the low-ends of the most likely range of projected changes show an increase in precipitation compared to the baseline; this coincides with the peak monsoon, so it is likely that monsoon floodings will increase in severity
- In the high-end-projection, there will be annually 28.5 % extra precipitation, in the low end projection there will be 3.7 % less precipitation annually
- The largest difference in amounts of precipitation between high- and low end projection occurs in July and August, and the low-projection is about 25% lower than the high-projection; this is a measure of uncertainty in the projections
- Due to increased temperatures, there is an approximate one month decrease in freeze/winter season; about 3 weeks in March/April, and about 1 week in October, indicated by the green arrows in the temperature chart

Data

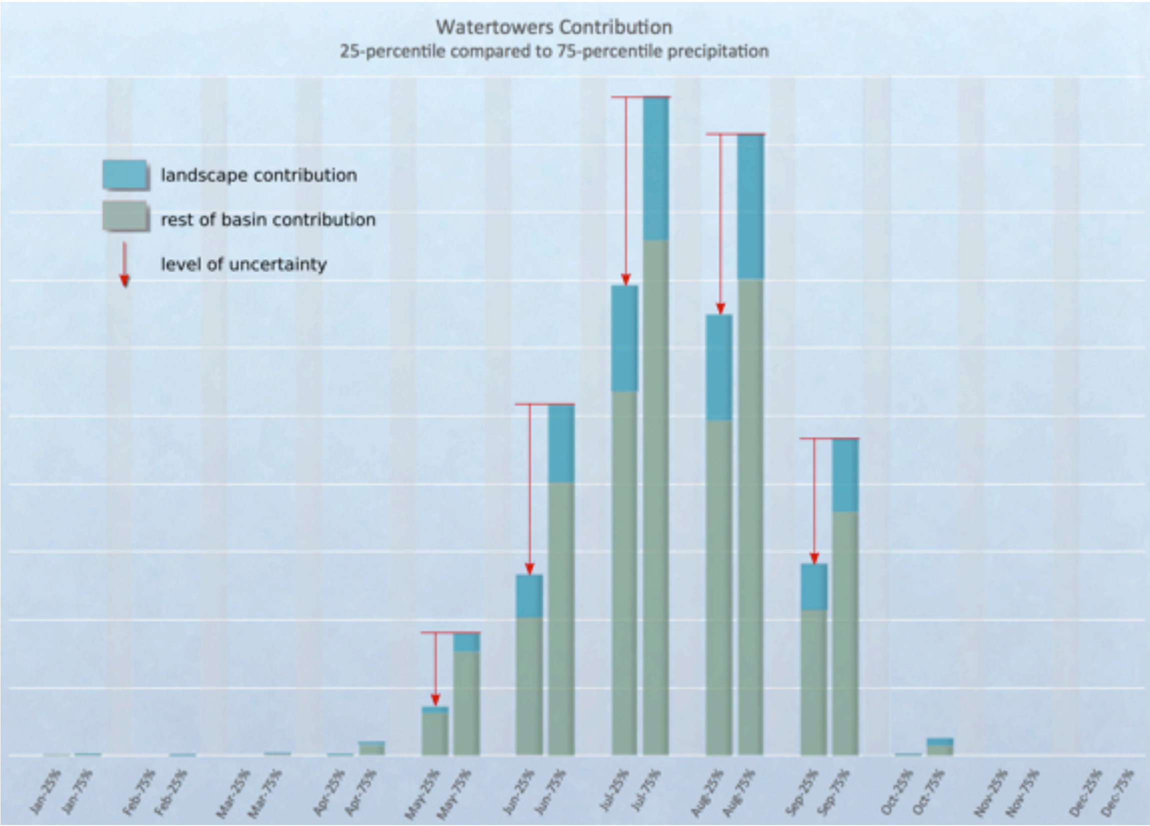
Current Mean Monthly Precipitation, based on historic WorldClim, 30s resolution; Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978. www.worldclim.org

Current Mean Monthly Temperatures, based on historic WorldClim, 30s resolution; Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high resolution interpolated climate

surfaces for global land areas. International Journal of Climatology 25: 1965-1978. www.worldclim.org

Climate Projections on future temperatures and precipitation by Center for Climate Systems Research, Earth Institute, Columbia University, under the ADVANCE partnership, 2016.

Watertower projections



Analysis

This graph shows how much water will locally runoff based on two 2050 estimates, one with the low 25 percentile precipitation and one with the high 75 percentile precipitation. Red arrows show the range of changes in runoff based on the range of climate changes, and therefore illustrate uncertainty in future climate impacts on runoff. The figure compares the overall sub-basin runoff (green colors under at the bottom of the bar chart) to the runoff specific to the snow leopard landscape (blue colors at the top of the bar chart). The horizontal axis crosses at 0 mm.

This graph would help to identify if the role of the snow leopard landscape in water provision would change under the climate projections. But there is certain proportionality in changes to the landscape versus the rest of the subbasin; if the subbasin gets drier, so would the landscape; if the subbasin would get wetter, so would the landscape. So it is not expected that the relative role of the landscape in water provision would change much.

In the annex, a graph shows the same range of projections in comparison with the historic baseline. That graph shows that the low-end estimate is more closely related to the baseline than the high-end estimate.

Data

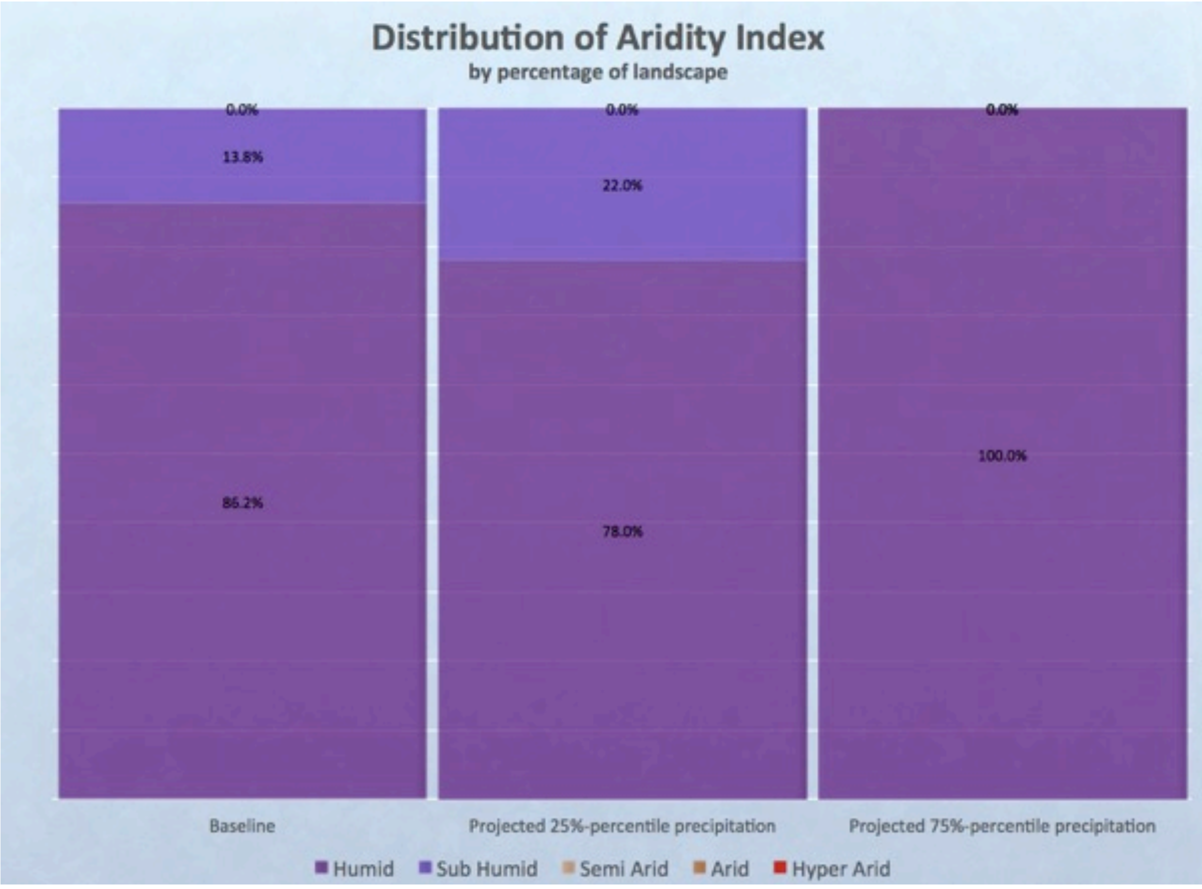
Current Mean Monthly Precipitation, based on historic WorldClim, 30s resolution; Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978. www.worldclim.org

Current Mean Monthly Actual Evapotranspiration, based on historic Global Soil-Water-Balance, CGIAR, 30s resolution; Trabucco, A., and Zomer, R.J. 2010. Global Soil Water Balance Geospatial Database. CGIAR Consortium for Spatial Information. Published online, available from the CGIAR-CSI GeoPortal at: http://www.cgiar-csi.org

HydroBASINS, level 12, ~100 km^2 watershed outlines; Lehner, B., Grill G. (2013): Global river hydrography and network routing: baseline data and new approaches to study the world's large river systems. Hydrological Processes, 27(15): 2171–2186. Data is available at www.hydrosheds.org

Climate Projections on future temperatures and precipitation by Center for Climate Systems Research, Earth Institute, Columbia University, under the ADVANCE partnership, 2016

Projected change in aridity index inside the landscape (annual)



These graphs compare the current (baseline) situation of aridity versus humidity to the high and low ends of the range of projected climate change defined from the 25th percentile of projected change in precipitation for 2050 (in this case, drier) to the 75th percentile projected of change in precipitation for 2050 (in this case, wetter) among 42 climate model runs. The range between the low and high estimates represents the most likely range future changes, and therefore illustrates a measure of uncertainty.

The classification of aridity versus humidity is a measure to which extent the precipitation is a limiting factor in vegetation growth; more arid landscape will have more drought resistant vegetation. The aridity puts this in perpective of other climatic parameters, such as temperature or solar radiation.

In the annual balance, most of the seasonality is balanced-out. Since the index is quantity-based, this means that the monsoon rainfall is attibuted over the entire year, and therefore, on the overall balance, the Eastern Nepal landscape relatively wet; the majority of the landscap classifies as "Humid", while the low-end estimate shows a small shift from humid to sub-humid, the high-end estimate shows the landscape completley shifts to humid conditions.

The difference between to low and high ends of the most likely range of future precipitation in this context is not very significant in terms of water provision. For this, the graph that illustrates the monthly distributions of change in aridity (see annex) provides essential insights on the changing durations in dry season.

The graph in the annex shows that the largest change in humidity and aridity is expected to take place directly after the monsoon; the low-end estimate predicts a drier start of the dry season, for which the effects will mainly be felt at the end of the dry season. The high-end estimate show a slightly longer wet season, which coincides with the flood season after the monsoon. The difference between both estimates indicate a high level of uncertainty.

Data

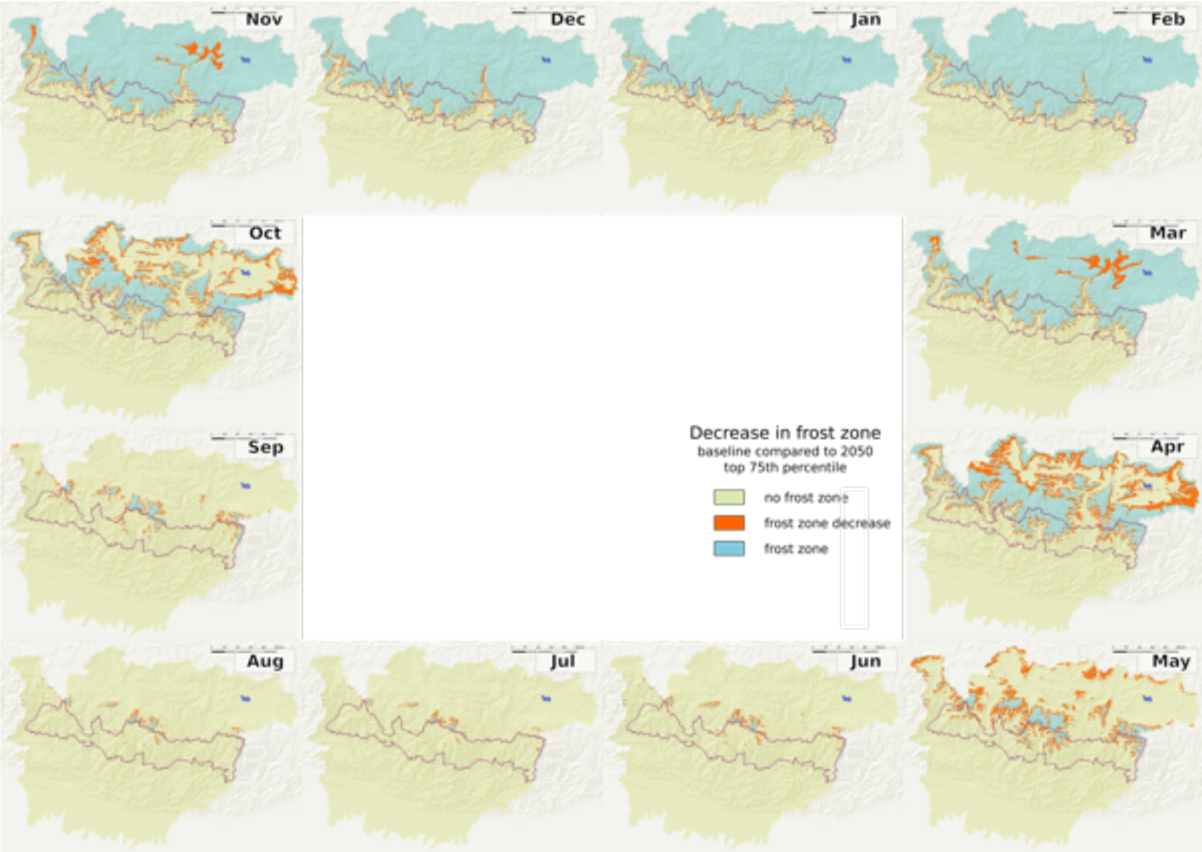
Current Mean Monthly Precipitation, based on historic WorldClim, 30s resolution; Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978. www.worldclim.org

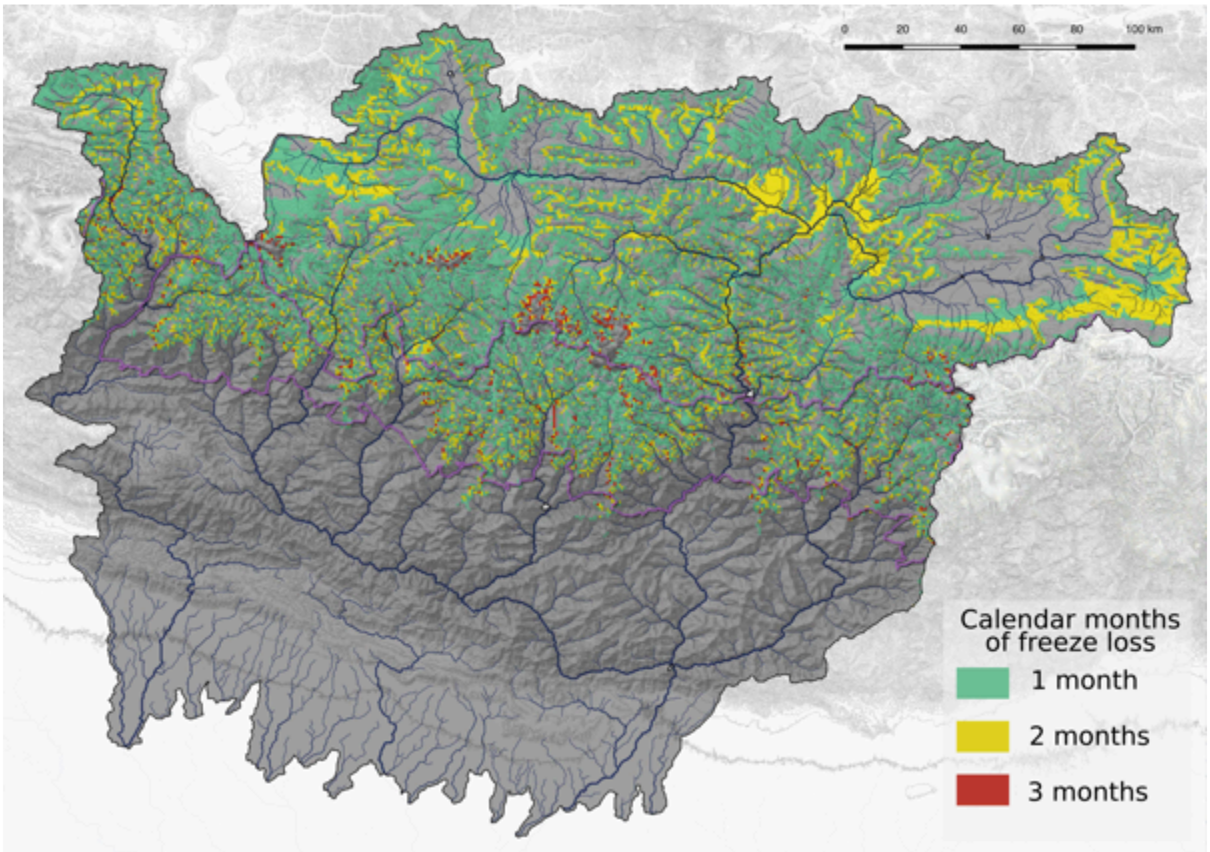
Current Mean Monthly Actual Evapotranspiration, based on historic Global Soil-Water-Balance, CGIAR, 30s resolution; Zomer RJ, Trabucco A, Bossio DA, van Straaten O, Verchot LV, 2008. Climate Change Mitigation: A Spatial Analysis of Global Land Suitability for Clean Development Mechanism Afforestation and Reforestation. Agric. Ecosystems and Envir. 126: 67-80.

Current Mean Monthly Temperatures, based on historic WorldClim, 30s resolution; Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978. www.worldclim.org

Climate Projections on future temperatures and precipitation by Center for Climate Systems Research, Earth Institute, Columbia University, under the ADVANCE partnership, 2016

Decrease in monthly freeze extent under temperature rise





Analysis

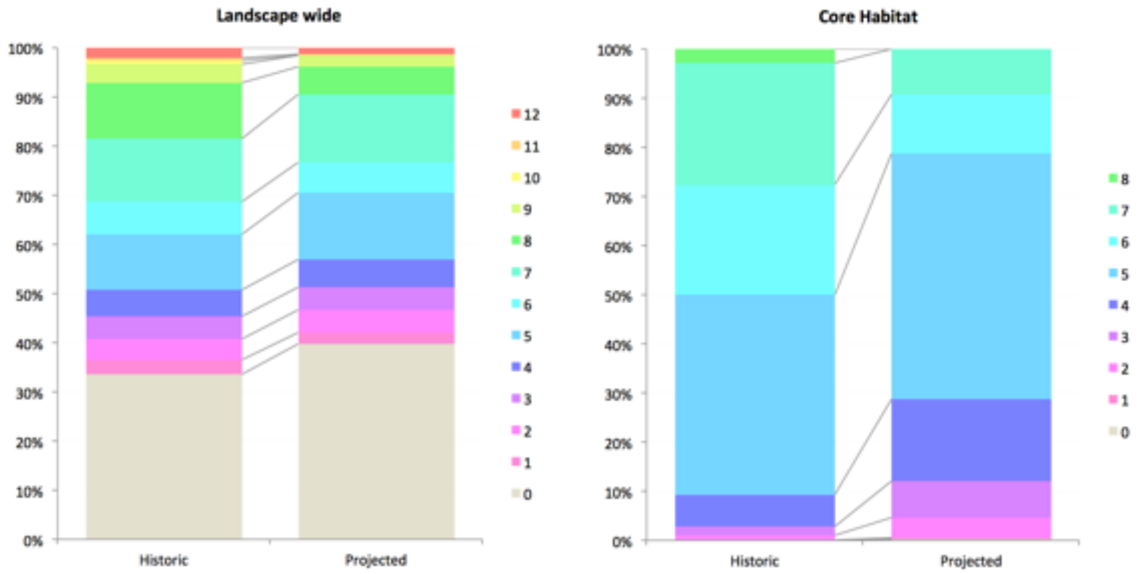
This mapset illustrates for each month what the spatial footprint would be on the freeze frontier under projected temperature rise. The baseline freeze extent guides a landscape's freeze and thaw cycles, and any change to this will result in different patterns of snowfall and snowmelt, and other cryosphere interactions (e.g. glaciers, permafrost).

In order to visualize those interactions, the online version of this mapset would allow for each monthly map to be overlaid with the baseline snowfall, snowmelt, glacier and permafrost maps. In such a way it could be visualized how the timing and spatial footprint of the freeze/thaw cycle would change under projected temperature rise.

There are three clear patterns emerging from the projected temperature change inside the landscape and the wider sub-basin;

- In winter (December to March), the freeze extent is on the southern slopes (Himalayas) of the Tibetan Plateau. Any increase in temperature will leave a minimal shift in the extent, while the temperatures on top of the plateau are too low to be influenced
- On the shoulders of the winter season (October, November, March, April/May), the freeze lin is on the plateau, and any shift will leave a large spatial footprint; these months are also incredibly important for the accummulation and meltoff of seasonal snow. There will be a major change in the timing and quantities of snowmelt. This is mainly driven by the large spatial footprint of the change, as on the plateau itself there is no large accummulation of snow.
- In the summer months (May/June to September) the spatial footprint is limited but surrounding important mountaintops. These mountaintops would historically accummulate the largest amount of snow during the monsoon season due to the combination of relatively large amounts of precipitation and freezing temperatures. Under changing temperatures, less snow will accummulate, more snow will melt off directly, this in coincidence with the monsoon; this will very likely result in a dramatic increase in the size and timing of downstream floodings.

Overall duration of historic winter versus projected (Columbia-CCSR projection 2050 top percentile).



One thing these graphs shows is that the core snowleopard habitat does not contain areas with more than 8 months of winter (while this covers ~25% of the landscape)

Another thing these show is that the core habitat does not contain any areas that do not experience winter months (this area covers just over 30% of the landscape)

Under projected change in temperature, the core habitat will overall experience dramatic decrease in winter duration, but will stay within the historic upper and lower limits... Yet, the main change here is not only the direct link to number of freeze months, but how this transition will impact the landscape; snowfall/melt, glacial melt, permafrost coverage and depths.

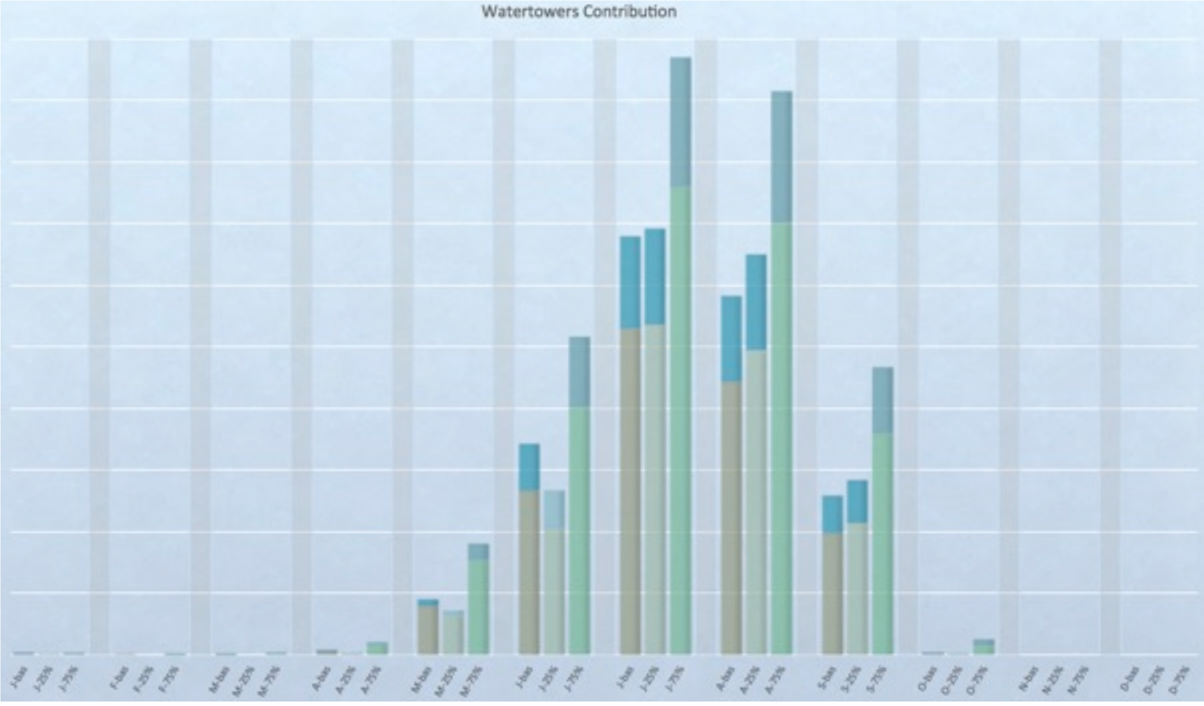
Data

Current Mean Monthly Temperatures, based on historic WorldClim, 30s resolution; Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978. www.worldclim.org

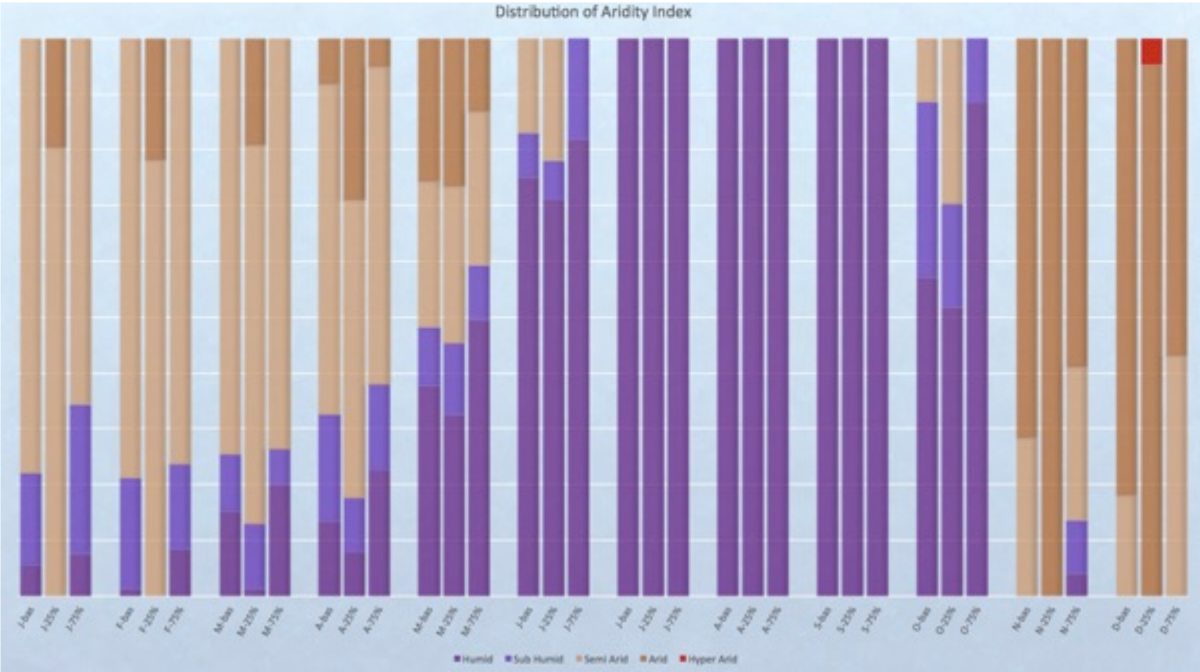
Climate Projections on future temperatures and precipitation by Center for Climate Systems Research, Earth Institute, Columbia University, under the ADVANCE partnership, 2016

Annexes

Watertower contributions (baseline vs 25-percentile vs 75-percentile)



Projected change in aridity index inside the landscape (monthly)



The montlhy distribution of aridity index show to which extent the landscape is changing towards a drier or wetter landscape. In terms of water use, this would imply to which extent crops could depend on precipitation or require additional irrigation.

In general, under drier conditions the dry season (January to May) will become slightly drier, and under wetter conditions, the dry season will become slighly wetter. Overall, the difference between low end and high end estimates does imply a certain level of certainty on this water provision function. This implies that temperature rise and change in precipitation are reasonably in balance inside the landscape and no specific tipping points are reached that would completely disturb the local water balance with regard to humidty and aridity.

The biggest, and probably most dramatic change is in the aftermath of the monsoon (October-December), there the difference between the low and high-end estimates are of more importance. A more humid landscape directly after the monsoon could indicate an increased length in the flood season, while a much drier start of the dry season would result in more drought-related problems at the end of the dry season. Here, the difference between the estimates would indicate a relevant uncertainty; will the flood season be prolonged, or will there be a much drier dry season?

Quantitative example

Basin ID: 2180	area_km^2:	155.4	lat:	27.800	lon:	86.950								
Eastern Nepal Landscape			jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
baseline														
temperature	°C		-12.50	-11.70	-8.61	-4.86	-1.42	2.39	3.20	2.76	0.98	-3.72	-8.35	-10.39
precipitation	mm		7.28	6.14	8.74	10.85	10.76	38.50	105.48	117.29	47.31	23.83	1.96	3.00
AET	mm		8.82	10.58	20.43	29.78	36.41	38.21	41.64	48.40	43.78	30.69	16.54	11.53
PET	mm		13.67	16.44	32.43	50.65	69.64	79.26	75.29	69.80	58.47	42.57	24.71	18.44
runoff	mm x km^2		0.00	0.00	0.00	0.00	0.00	45.04	9920.08	10705.33	548.78	0.00	0.00	0.00
2050_25 percentile														
precipitation change	%		63.78	73.82	78.51	83.45	98.18	93.15	102.73	112.28	107.65	96.03	67.09	23.44
precipitation$_{25}$	mm		4.64	4.54	6.86	9.05	10.57	35.87	108.36	131.68	50.93	22.88	1.31	0.70
runoff$_{25\ (T75)}$	mm		0.00	0.00	0.00	0.00	0.00	0.00	9977.37	12525.16	707.77	0.00	0.00	0.00
2050_75 percentile														
temperature change	°C		1.76	1.59	1.77	1.75	1.81	1.47	1.27	1.14	1.11	1.23	1.42	1.67
temperature$_{75}$	°C		-10.75	-10.12	-6.85	-3.10	0.38	3.86	4.47	3.90	2.09	-2.48	-6.93	-8.72
precipitation change	%		131.03	118.06	113.74	116.35	141.14	131.89	132.27	137.63	144.63	139.08	180.80	160.36
precipitation$_{75}$	mm		9.53	7.25	9.95	12.62	15.19	50.78	139.51	161.42	68.42	33.14	3.54	4.81
AET$_{75}$	mm		11.75	13.34	24.36	33.82	40.42	40.99	44.15	51.08	46.38	33.38	19.01	14.12
PET$_{75}$	mm		18.20	20.72	38.66	57.51	77.32	85.01	79.84	73.68	61.94	46.29	28.41	22.60
runoff$_{75}$	mm x km^2		0.00	0.00	0.00	0.00	0.00	1522.40	14818.93	17146.16	3426.13	0.00	0.00	0.00

These numbers are presented as reference to the different graphs; they will explain why certain values occur in a randomly selected watershed inside the Eastern Nepal landscape.

From the numbers it becomes clear that the monsoon precipitation is driving runoff values; in the baseline and high-end estimate there are 4 months of *some* flow, in the low end estimate there are 3 months.

In the baseline there are 8 months of sub-zero temperature, under temperature rise there would be 7 months; this occurs on this location specifically because the mean montlhy temperature is really close to zero for many of the summer months, but similar changes are observed throughout the landscape.