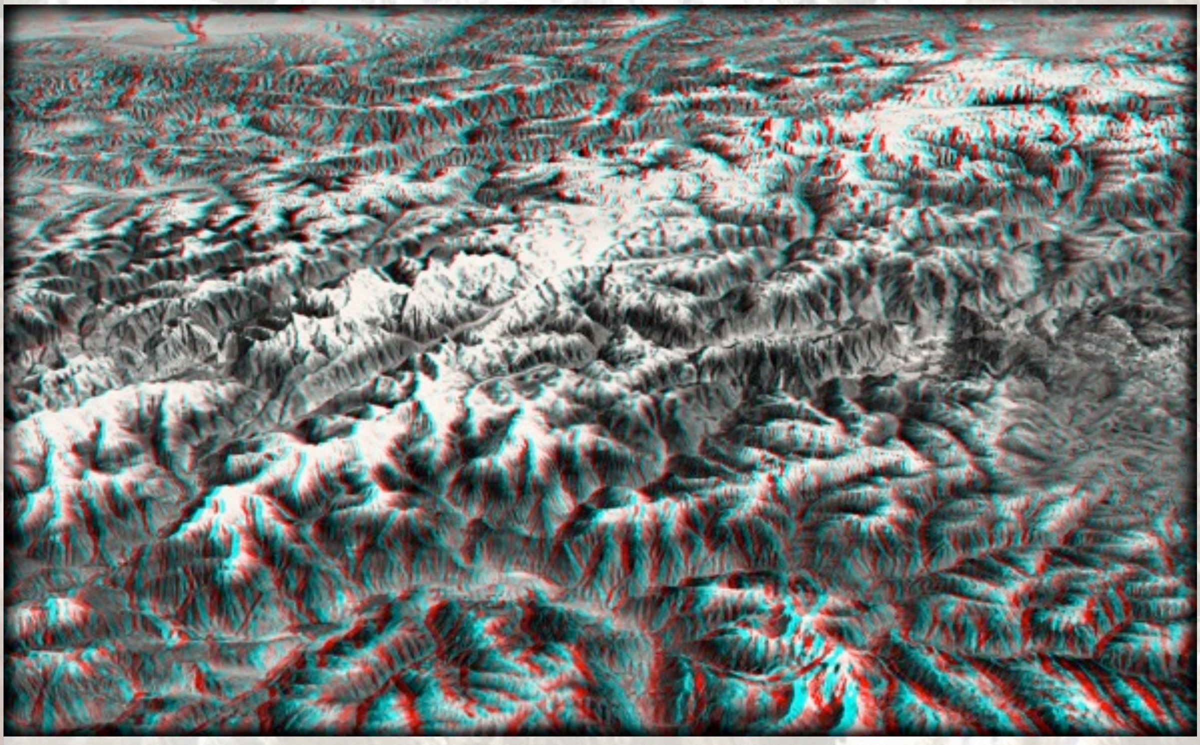
Karakoram Pamir Landscape

Water Resources

and

Climate Change Sensitivity

Analysis



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

By Nikolai Sindorf

August 2017

Sindorf N, *Karakoram Pamir 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:

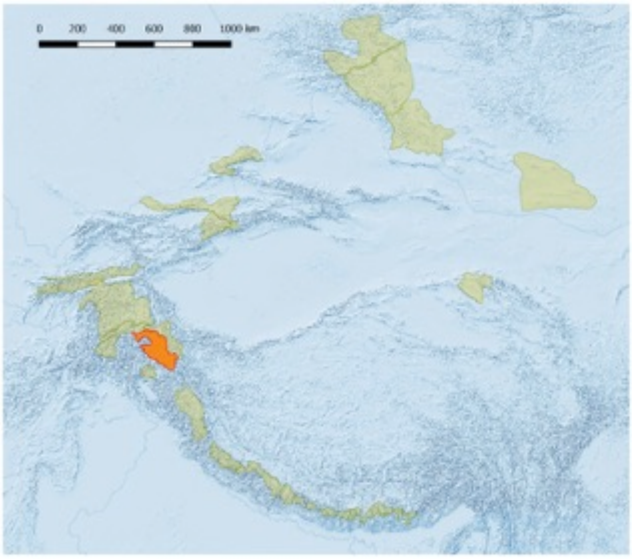
Ryan Bartlett, WWF-USA

Jessica Forrest, WWF-USA consultant

Corey Lesk, CCSR, Earth Institute, Columbia University

Danielle Peters, CCSR, Earth Institute, Columbia University

Karakoram-Pamir Landscape

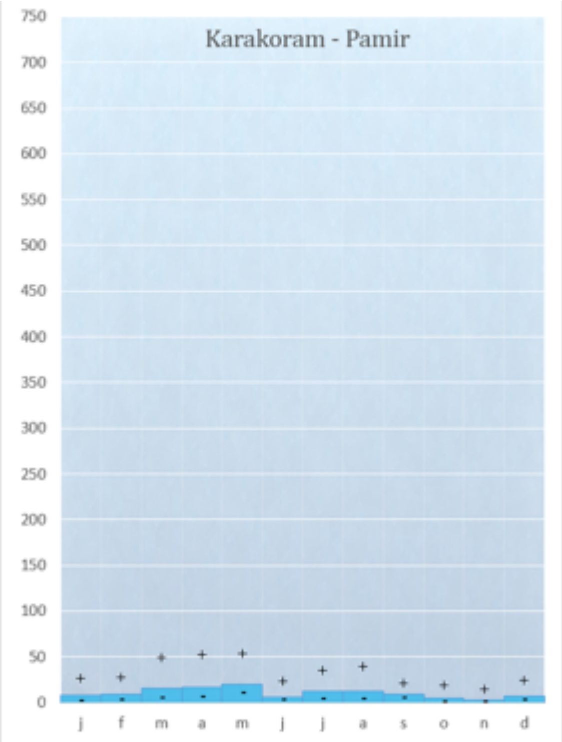


Country: Pakistan
Size: 25,500~km^2
Population: ~250,000 (WorldPop 2010)
Highest elevation: ~7,500 MSL
Lowest elevation: ~1,400 MSL

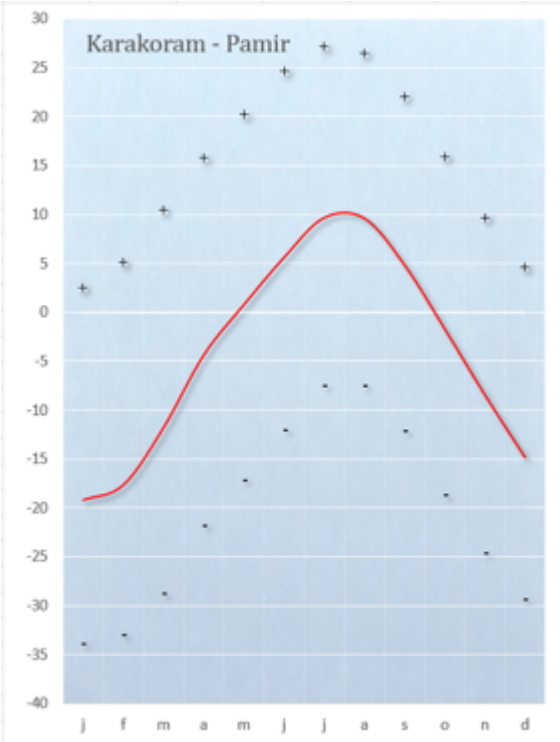
Connections:
North East: Tashikuerganyeshengdongwu (China)
North West: Wakhan (Afghanistan)

Overview

Basic climate



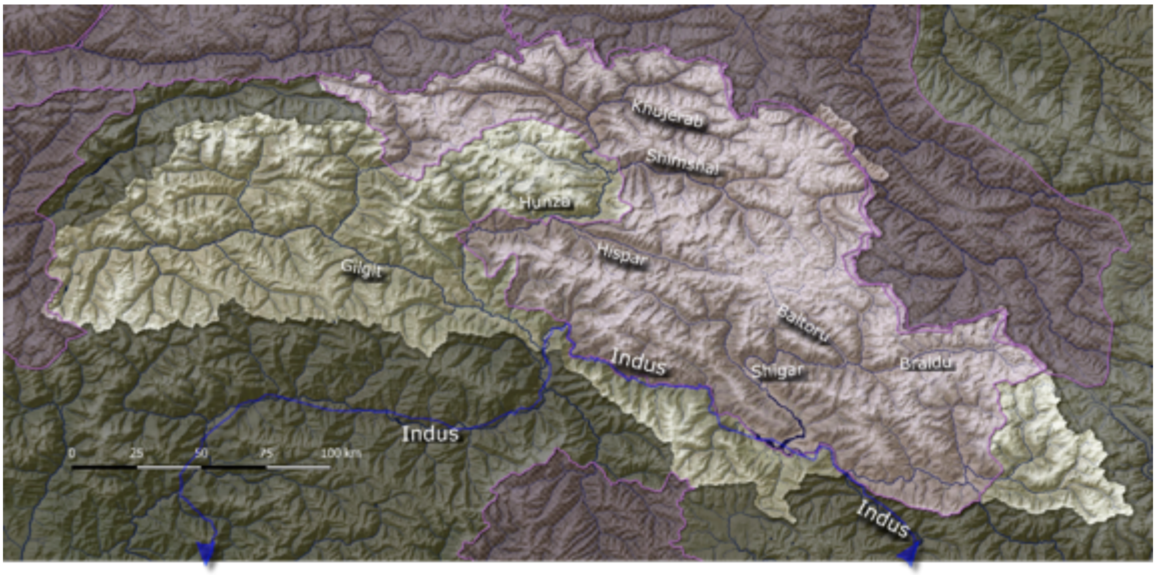
Historic monthly mean precipitation
in millimeters (WorldClim, 1950 -2000)
+ = highest mean of the landscape
- = lowest mean of the landscape



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

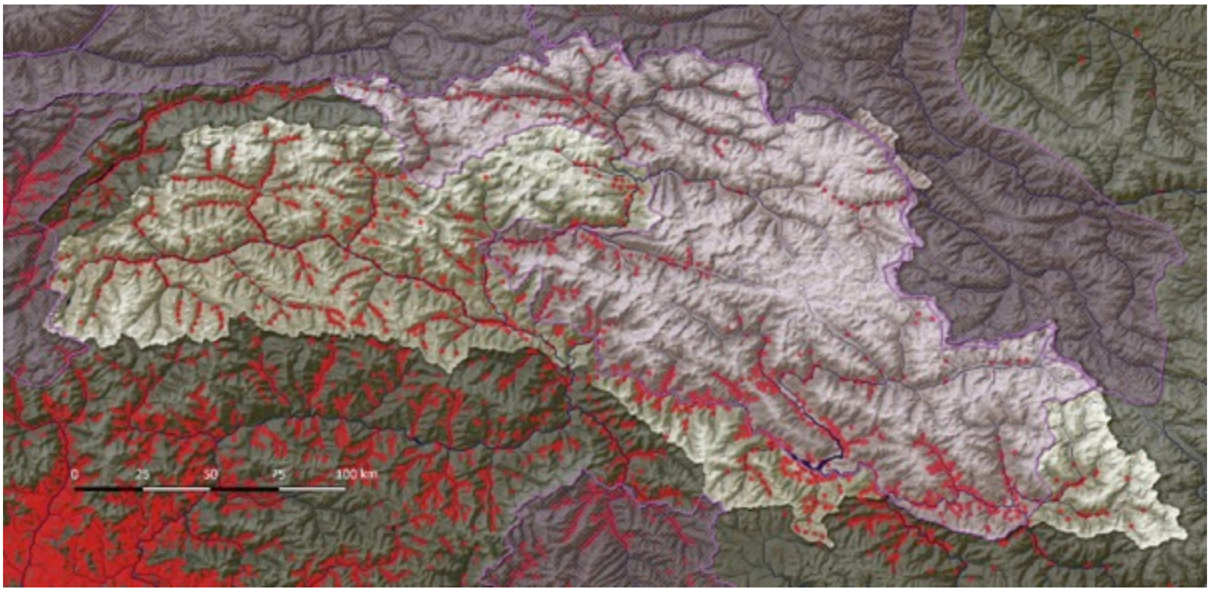
Throughout the year, there is little precipitation recorded throughout the landscape, on average less than 25 mm/month. The temperature range within the landscape is around 35 degrees throughout the year, which indicates a high variety of climatic zones inside the landscape.

Subbasin context; hydrography



The southern boundary of the landscape is the Indus river; the Indus river flows form its headwater in western direction towards the southwest. All rivers and streams of the landscape eventually drain into the Indus.

Subbasin context; human settlements

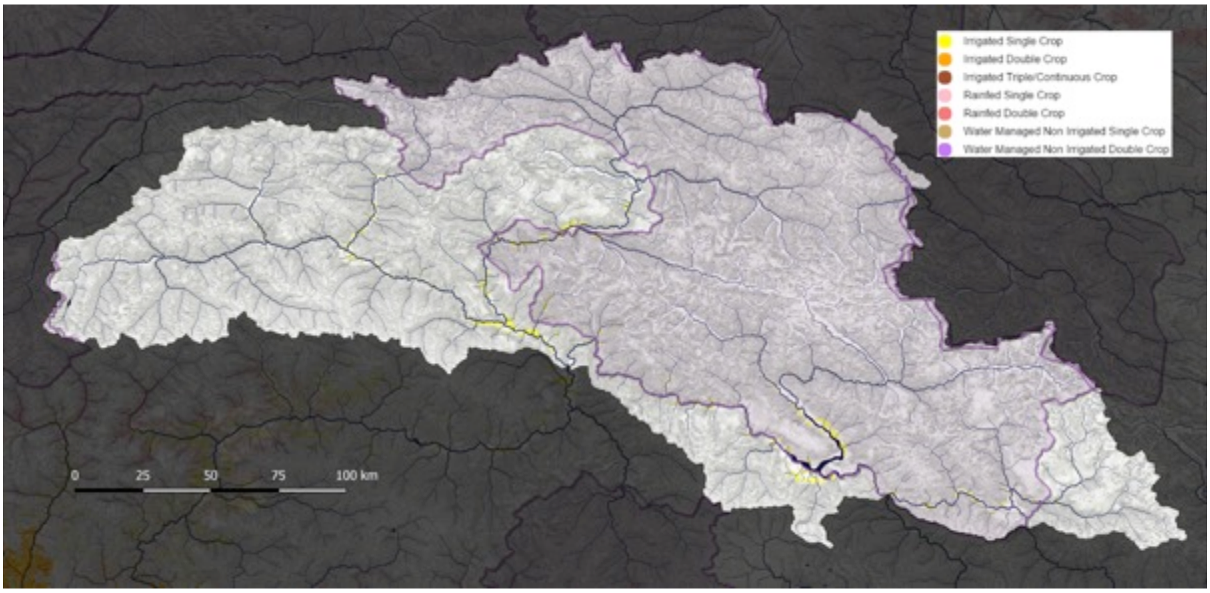


The settlement locations follow the river valleys inside and outside the landscape. There is a higher density of settlements along the banks of Indus river, following the southern boundary of the landscape. Downstrem of the subbasin, where the Indus plains are, there is a very high density of settlelements; so there seem to be a strong connection for water service provision. Settlement points are downloaded from geonames.org.

Subbasin context: population density (WorldPop)

The population density map shows a similar distribution as the settlement points map; the valleys are more densely populated, also inside the snowleopard landscape. The highest population densities can be found downstream of the subbasin, more outside of the mountains in the Indus plains. Water use in those areas will depend on water provided by this subbasin and further upstream in the Indus' headwaters.

Subbasin context: irrigated areas (IWMI, 2010)



Analysis

Some single-irrigated agriculture is taking place in the downstream valleys along the larger rivers, also inside the snowleopard landscape. The valleys would provide easier access to irrgation water as well as milder temperatures.

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/

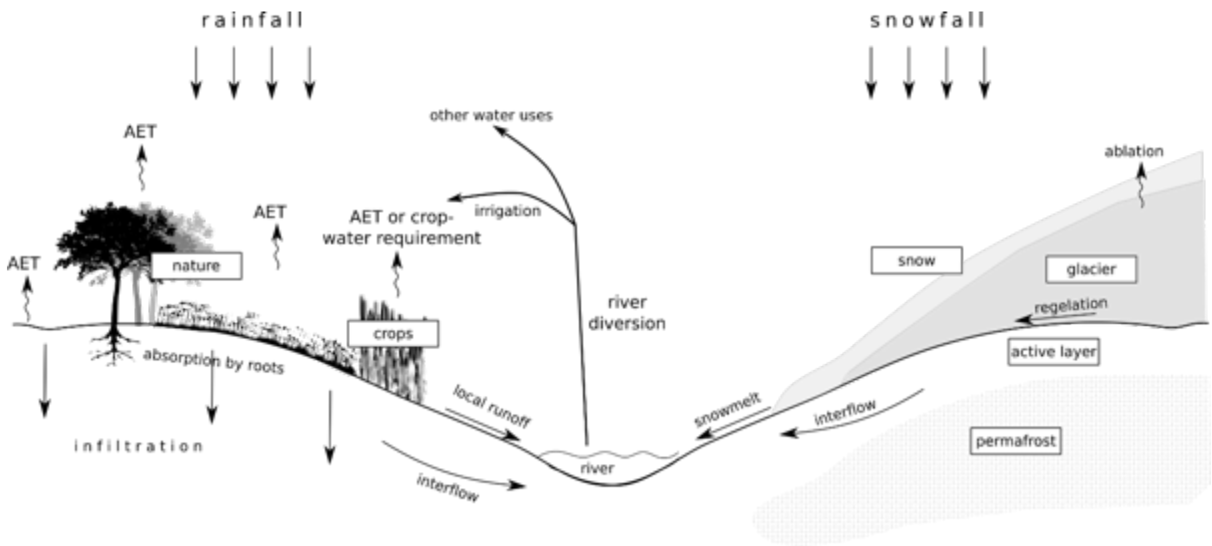
Water provision functions

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 changein groundwater interactions, but is is beyond the scope of this study to look further into this



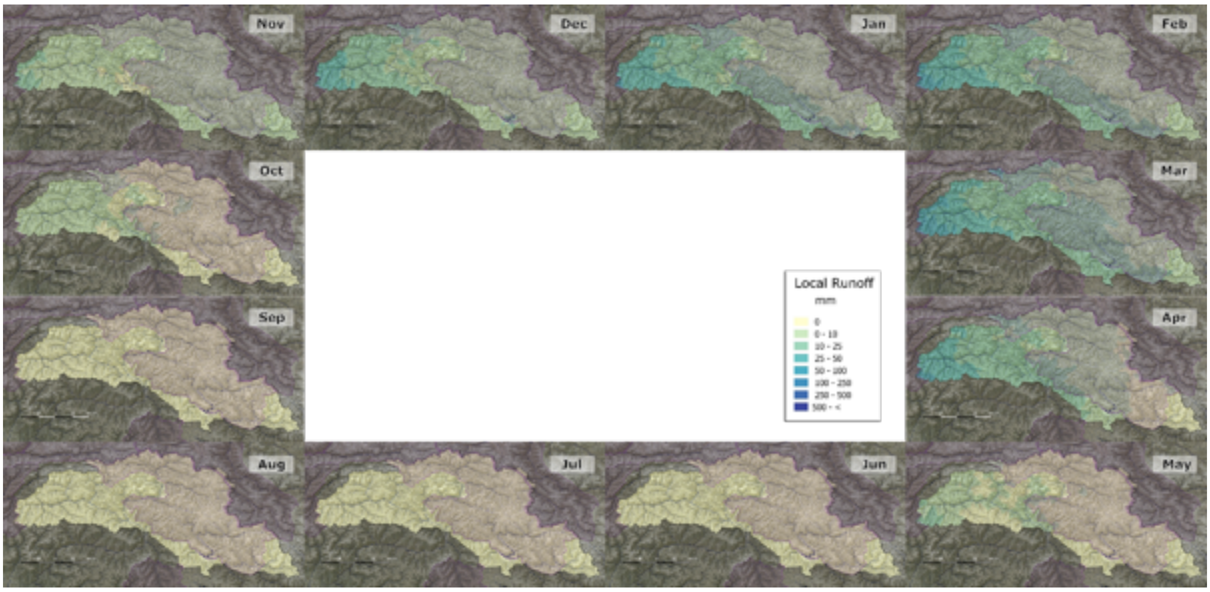
A simplified water balance including the components of rainfall, actual evapotranspiration, and local runoff. To the right: a simplified water balance of the cryosphere, including the components of snowfall, snowmelt, glaciers and permafrost.

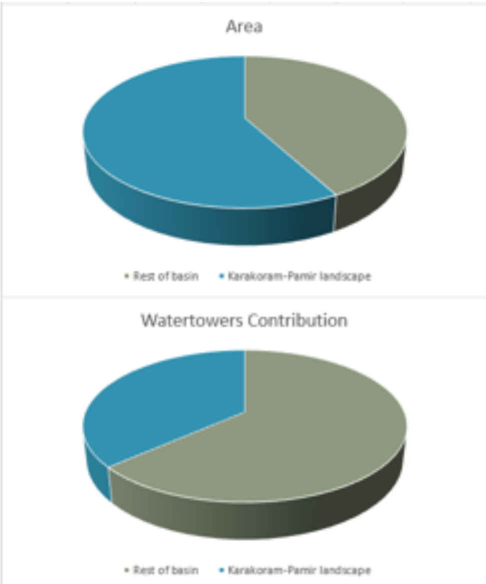
Summarized findings for the Karakoram-Pamir landscape

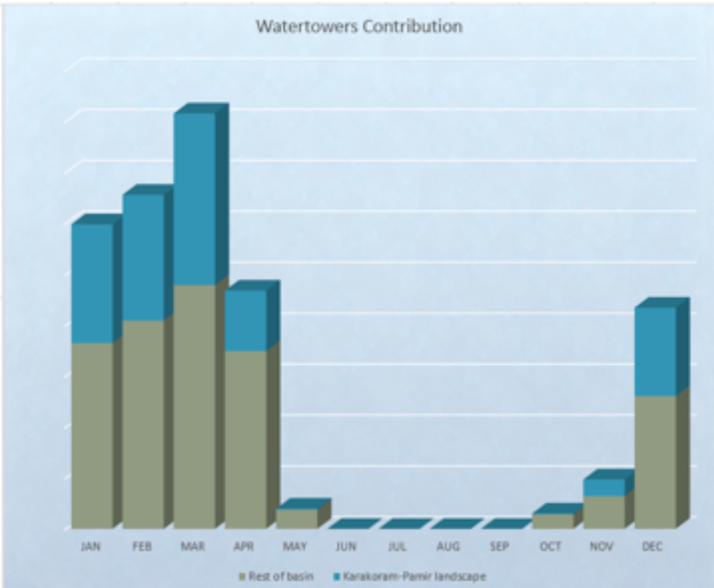
Water Towers/ Local Runoff	
Water provision	By area, the landscape covers 58 % of the subbasin, yet it only provides 36 % of the subbasin's local runoff. Hence the landscape's water towers does not form an argument for water provision as the landscape provides less water than its direct surroundings.
Projected Climate change	There are two projection for low- and high-precipitation; in the low-precipitation projections, not much is going to change landscape-wide; already precipitations are very low. Under the high-precipitation scenario an extra 35 % is expected, so, the projections are skewed towards increased precipitation (during the winter months). On the runoff water balance this creates uncertainty, but mainly over the winter months; so not in direct runoff but in snowfall accumulation.
Snowmelt	
Water provision	The landscape provides 58% of all snowmelt in the subbasin, which is in the exact proportion of the areas it covers; the landscape could therefore not be singled out as an area of *special* importance water provision by snowmelt.
Projected Climate change	Under projected climate change, snowmelt will be a function of the shifts in freeze line and changes to precipitation. There is likely to be more snowfall and higher temperature resulting in higher snow- and glacial melt. Snowmelt being the most imprtant component to the downstream Indus river, this will likely resutlt in increased floods, floods both in frequency and in intensity.
Aridity	
Water provision	Throughout the year, the landscape is more arid than its downstream areas, which implies that there are no water provision arguments for this function.
Projected Climate change	Of the two projections, only the high-precipitation projection would indicate a landscape-wide shift from arid to semi-arid conditions over the annual balance. This implies that soils and vegetation will partipitate more actively in the hydrological cycle, so some shifts are likely to take place in types of vegetation cover, towards a greener landcover.
River system layout	
Water provision	The subbasin is located in the relative upstream of the Indus basin, but there are parts of the Indus basin still more upstream, in the east.
Projected Climate change	The system layout indicates this as a source areas that contains much of snow- and ice-based landcover and soils. Under temperature rise, much of these characteritics will change the local hydrology and pose a high level of uncertainty towards its downstream.
Glaciers	
Water provision	The subbasin and landscape is dominated by the presence of glaciers. The monthly freeze line historically exposes most of the

	glaciers to thaw for at least three months (June-August). Historically this means that snowfall must have exceeded or balanced snowmelt for the glaciated areas; otherwise they would have melted off.
Projected Climate change	The high-precipitation projection indicates that more snow will fall during winter, this would probably feed the glaciers and extend their life expectancy under temperature rise. The freeze-line is contained in the landscape throughout the year; under increased temperatures this will shift upwards and increase glacial melt off. It is uncertain how the overall balance between extra snowfaal versus extra meltoff will change, it is likely that the differences will play out vey locally for each individual glacier.
Permafrost	
Water provision	The frontier between permafrosted and non-permafrosted lands runs throughout the entire subbasin, and any climate change impacts on permafrosts will likely trigger dramatic change at the subbasin level and towards its downstream. Not much is known about the types and characteristics of the permafrosts, it is recommended to collect more information that would help to classify the permafrosts.
Projected Climate change	A first recommendation would be to collect more data on the different typologies of permafrosts; as the typology would indicate to which extent the permafrost is temperature-rise resistent.
Snow cover and freeze line	
Water provision	The snow frontier is fragmented and shows a very long circumference throughout the year, such a layout means that changes to the snow frontier under temperature rise will have very significant impacts throughout the subbasin, the landscape, but also towards its downstream. But, the landscape is also very mountainous and therefore does not show many plateaus; impacts of shifts in the snow frontier will therefore be more lineair- than tipping point-based.
Projected Climate change	The freeze-line runs through the landscape during any month of the year; thus temperature rise will have direct impacts on the landscape at any month. Since the landscape is very mountainous, shifts in the freeze line will only be a few hundred meters, but since it surrounds historically snow-covered mountaintops in summer, even such shifts can mean dramatic change.
Lakes, wetlands and floodplains	
Water provision	The surface water database does not register a significant or systemic increase or change to the many small lakes in the landscape, though more in-depth study would lead to valuable insights. One recommendation would be to create a database of smaller lakes with names, simple characteristics (location, area, elevation, level) in order to systematically monitor patterns of change.
Projected Climate change	As snowfall is likely to increase in parallel with snowmelt, it is likely that the size and number of glacial lakes will increase

Water provision functions; water towers (local runoff)







Analysis

Since there are limited amounts of precipitation and temperatures are relatively high during summer, there is no local runoff generation during the summer months, when water demands (for people and crops) are at their highest. The curve shows relative distribution of local runoff, so winter runoff quantities are still very minimal; most of this would accummulate as snow in the landscape in winter. This has to be put in perspective of snowmelt quantities, which are likely to peak around the summer months. Though this database is not best in modelling snow cover and timing and amounts of snowmelt; these are considered in more detail in the other maps that are presented later.

By area, the landscape covers 58 % of the subbasin, yet it only provides 36 % of the subbasin's local runoff. Hence the landscape's water towers does not form an argument for water provision as the landscape provides less water than its direct surroundings.

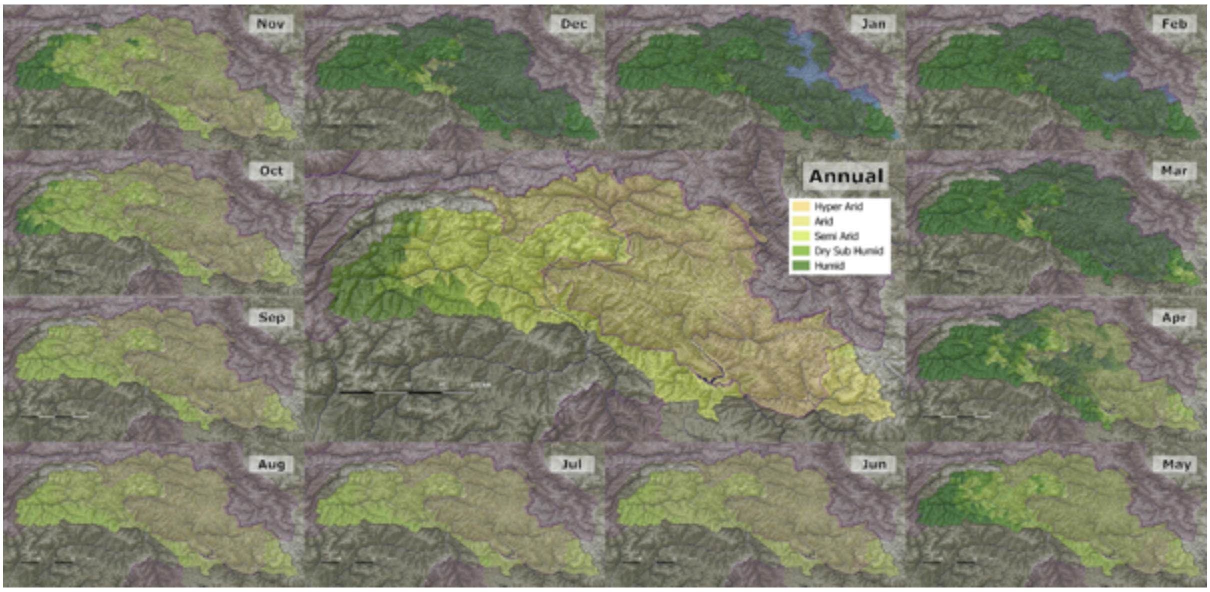
Data

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

Throughout the year, the landscape is more arid than its downstream areas, which implies that there are no water provision arguments for this function. For the months December-March, the maps show relative humidity throughout the subbasin; this is mainly due to the potential evapotranspiration being very low (due to low temperatures). In other words, the water demands by soil and vegetation are easily met, because soils and vegetation hardly have any water demands during these months while temperature is the limiting factor (and not precipitation). Under a changing climate, these areas could prove to become a volatile context; will temperatures increase and drive up soil-water demands? If so, will precipitation increase accordingly? In some cases, these areas might move towards desertification, in other cases these areas might cause extra floods downstream, the difference depends on the changing balance between temperature and precipitation.

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

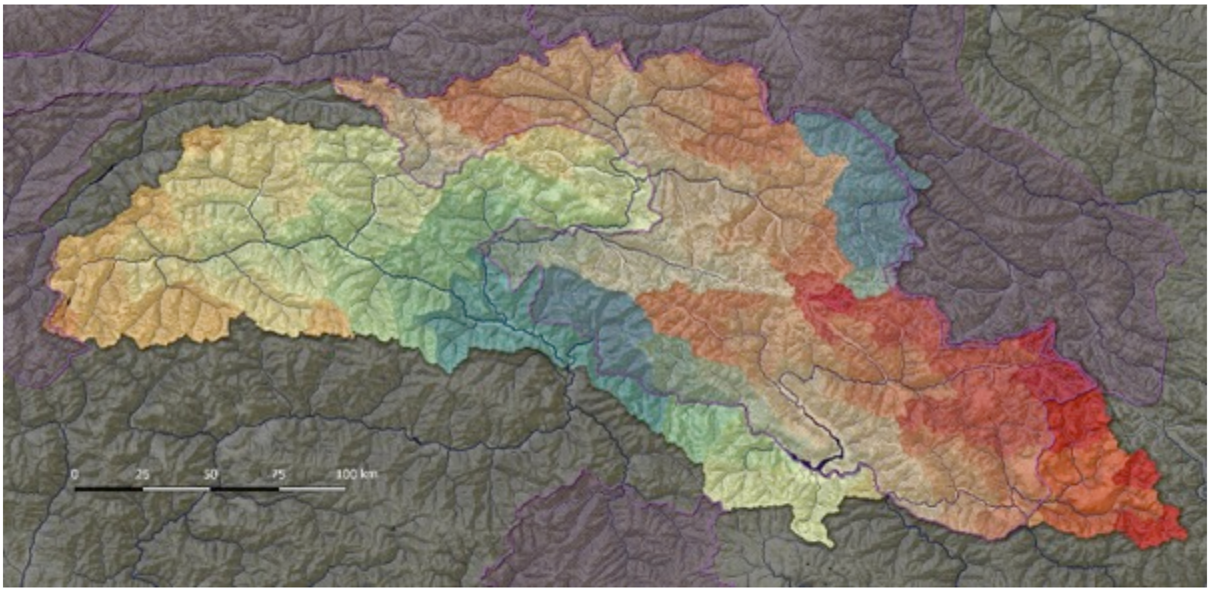
Data

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

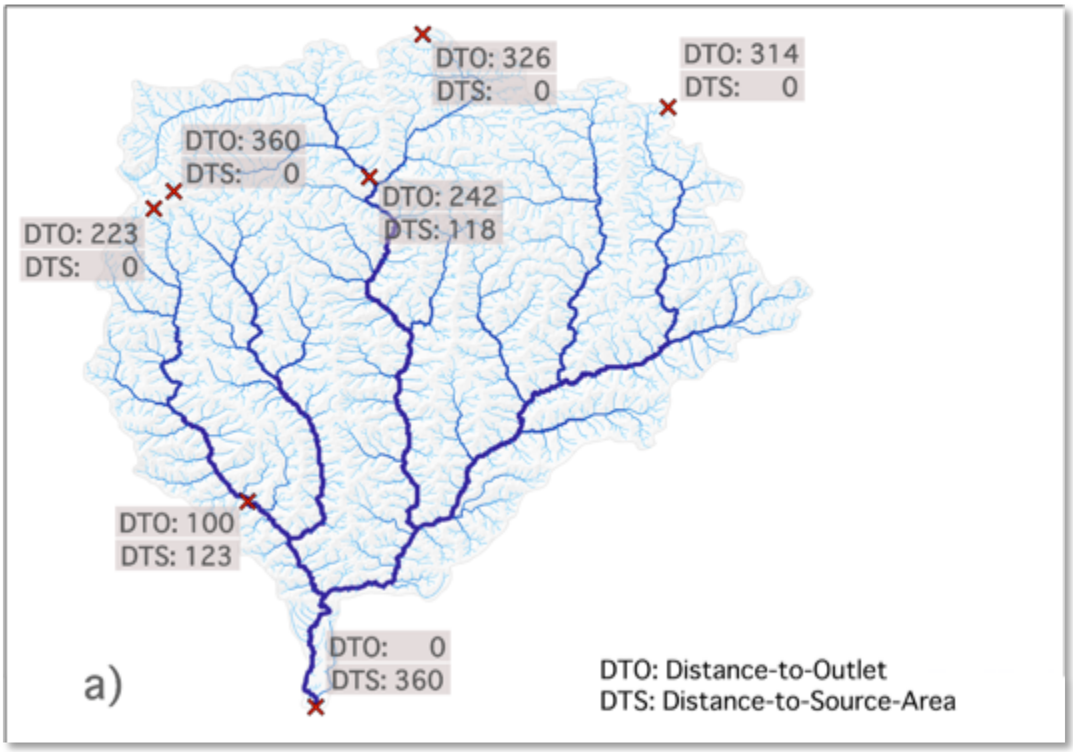
In terms of being in the upstream, the entire landscape and subbasin is tributary to the Indus river. The subbasin is located in the relative upstream of the Indus basin, but there are parts of the Indus basin still more upstream in the east.

Concerning layout, the upstream parts in in Gilgit river –outside the landscape, covering the western parts of the entire sub basin- provide the same level of functionality as the landscape.

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:

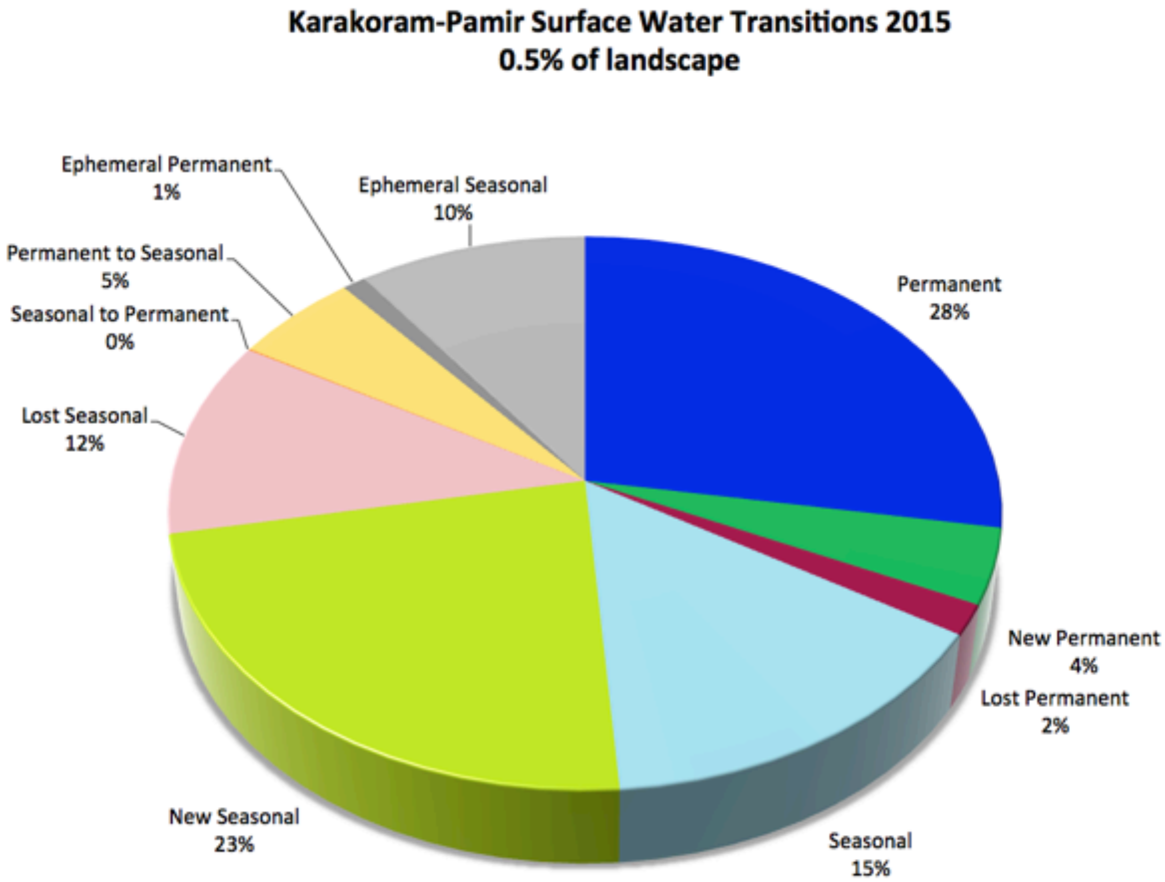
$$headwater\ function\ = \frac{DTO}{longest\ stream} \times \frac{DTO}{DTO + DTS}$$

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)



Overview

Inside the landscape; according to the most recent map of global surface water (Pekel, 2016) only 0.5% is classified as open surface water; it can therefore hardly be identified in the above map. The following transitions occurred between 1984 and 2015:

- 54% of the open water surface was *stable* (permanent 28 %, seasonal 15 %, ephemeral 11 %)
- 14 % of the open water surface *disappeared* (permanent 2%, seasonal 12 %)
- 27 % classified as *new* surface water (permanent 4 %, seasonal 23 %)
- while 5 % of all open water surface *changed from permanent to seasonal*.

These shifts can be explained because most of the open surface waters are located around the very active Indus and Shigar floodplains that are fed mainly by snow and glacial melt.

The global HydroLAKES database (Messager, 2016) detects four smaller lakes inside the landscape:

Name of the Lake	Surface Area (km^2)	Shoreline (km)	Volume (10^6 m^3)	Average Depth (m)	Elevation (m)	Upstream Area (km^2)
Barah	0.18	2.09	1.6	8.9	4512	9.3
Jarbazoo	0.17	2.63	0.72	4.3	2202	1.1
Karambar	2.54	7.15	32.66	12.9	4286	23.9
Not seen on Google Earth	0.68	5.07	6.34	9.3	3475	686.5

In both the surface water database and Google Earth, many smaller lakes can be identified, often snow- or glacial melt-based, and many of these pose a risk of GLOFS. The surface water database does not register a significant or systemic increase or change to these lakes, though more in-depth study would lead to valuable insights. One recommendation would be to create a database of smaller lakes with names, simple characteristics (location, area, elevation) in order to systematically monitor patterns of change.

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:

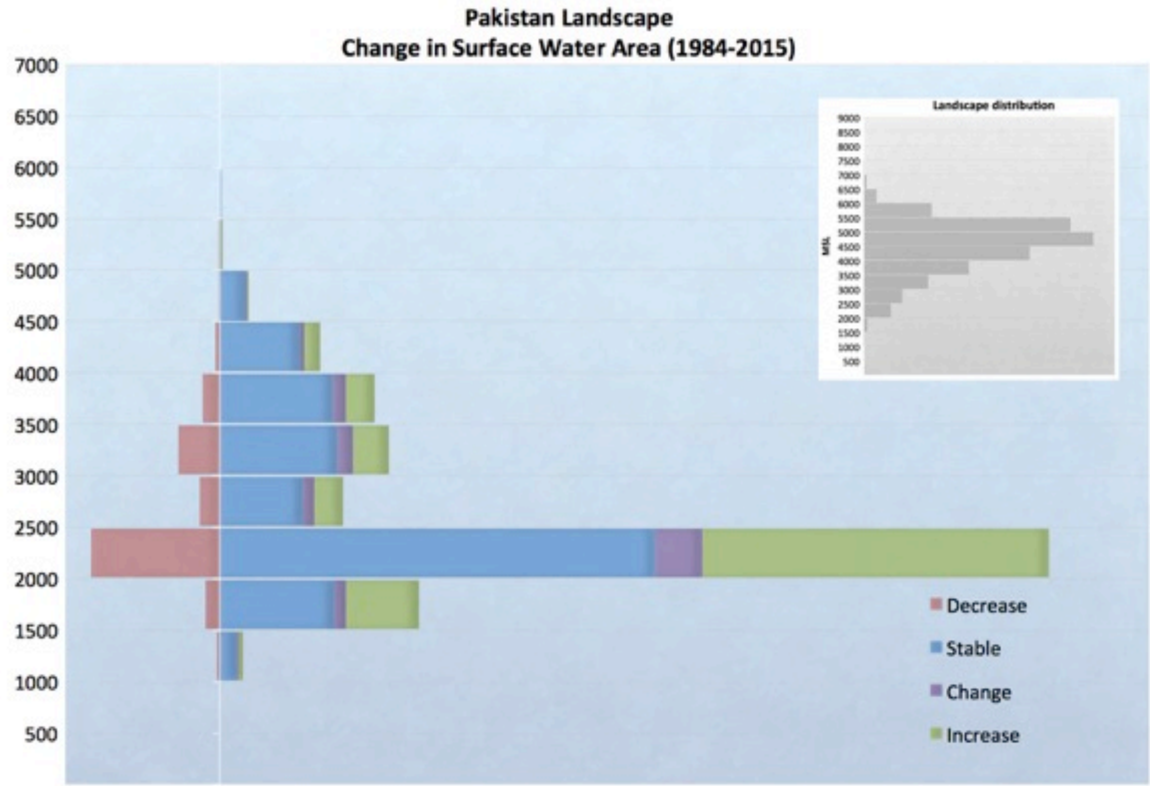
"The Water Transitions map documents changes in water state between the first year and the last year of observation. It documents:

- *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 lakes in the HydroLAKES database originate from the Global Lakes and Wetland Database. Since none of the lakes have names attributed to them, each record has been checked on Google Earth (2017) for names.



With the surface water transitions plotted against elevation, it becomes evident that the 2,000-2,500 msl elevation band contains the largest amount of surface water area. This is disproportionate to the overall landscape distribution of elevations, see the inset. It is very likely that these are the floodplains of the tributaries that feed into the Indus, with large glaciated areas in the direct upstream. The transitions at this elevations are dramatic, which might be related to dynamic shift in river courses over these floodplains under sporadic and intense flooding regimes. Here, the increase in surface water area exceeds the decrease, which can point to different processes:

- River channels have become more shallow, taking more place in the landscape

- Extra water is coming in from the upstream, which might be by glacial meltoff or increased precipitation
- A dam has been constructed and the reservoir been filled in the period 1984-2015

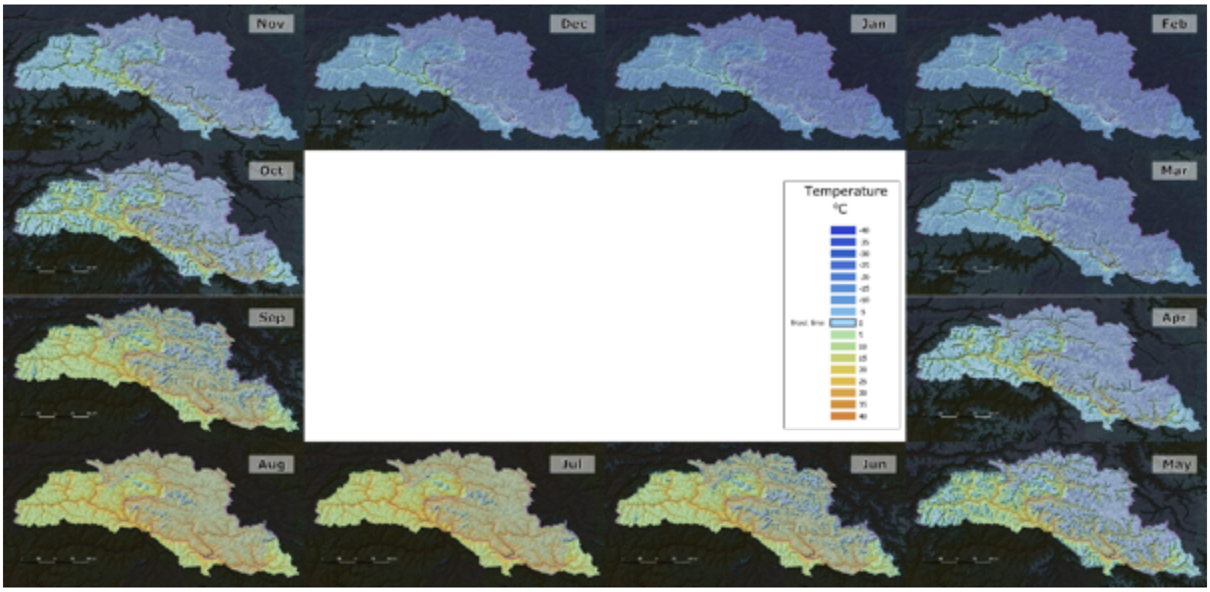
At the higher elevations –above 2,500- the increase is much more balanced with decreased surface water areas, which might indicate a shift of location in the landscape, but not necessary in amounts of water. It is important to stress that the graph depicts surface water *areas*, and *not volumes* of 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.

Water provision functions; freeze line



Analysis

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.

Throughtout the year, the deep valleys temperatures remain above zero; yet from October to May the majority of the subbasin area is below freezing point. The southern extent of the freeze line in winter extents far outside of the subbasin, and does not show on these maps, apart from the Indus valley.

In the summer months of July and August, some of the mountain ranges, central in the subbasin, remain below zero around the snow-capped mountain ranges.

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 on flatter areas (plateaus) has a bigger spatial footprint than a shift at steeper areas. The subbasin here is very mountainous and does not show many plateaus; impacts of shifts in the snow frontier will therefore be more lineair- than tipping point-based.

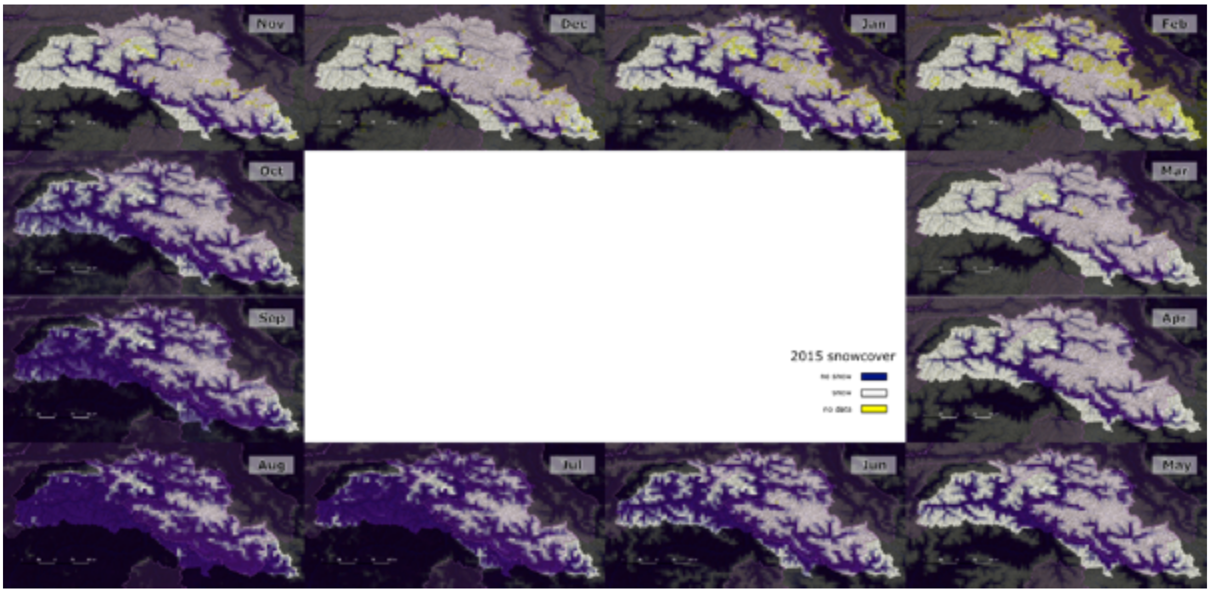
Methodology

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

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 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.

The valleys remain without snow throughtout the year, where snow accumulates on the mountaintops. Even throughout the summer months, the mountainstops remain covered with snow; it is a very prominent landcover throughout the year. The snow frontier is fragmented and shows a very long circumference throughout the year, such a layout means that changes to the snow frontier under temperature rise will have very significant impacts throughout the subbasin, the landscape, but also towards its downstream.

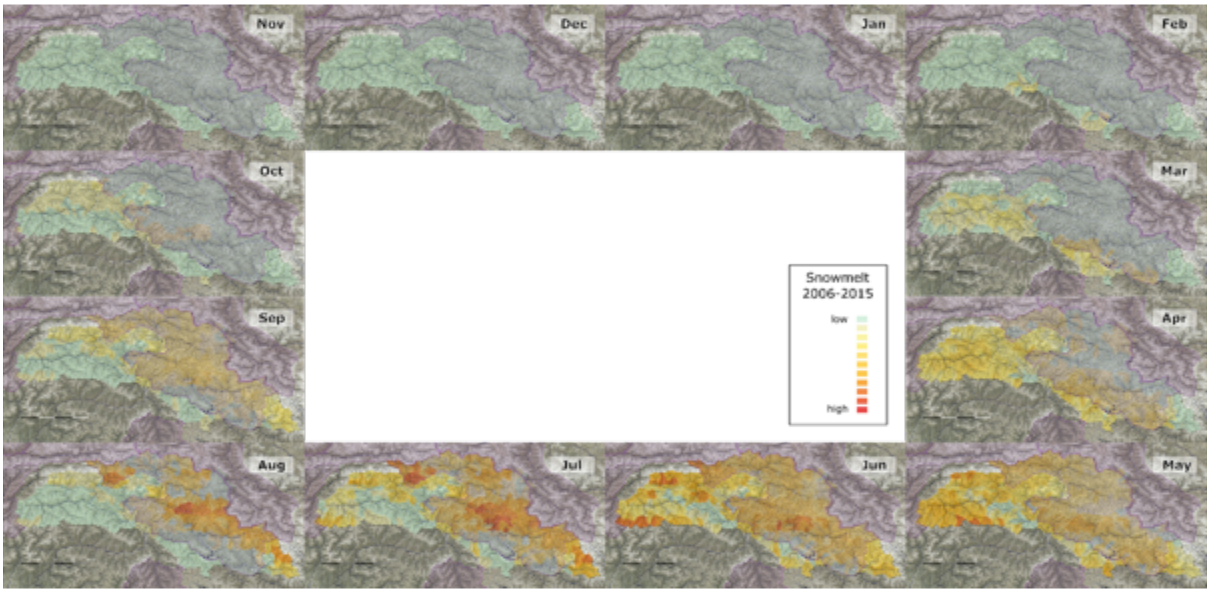
Methodology

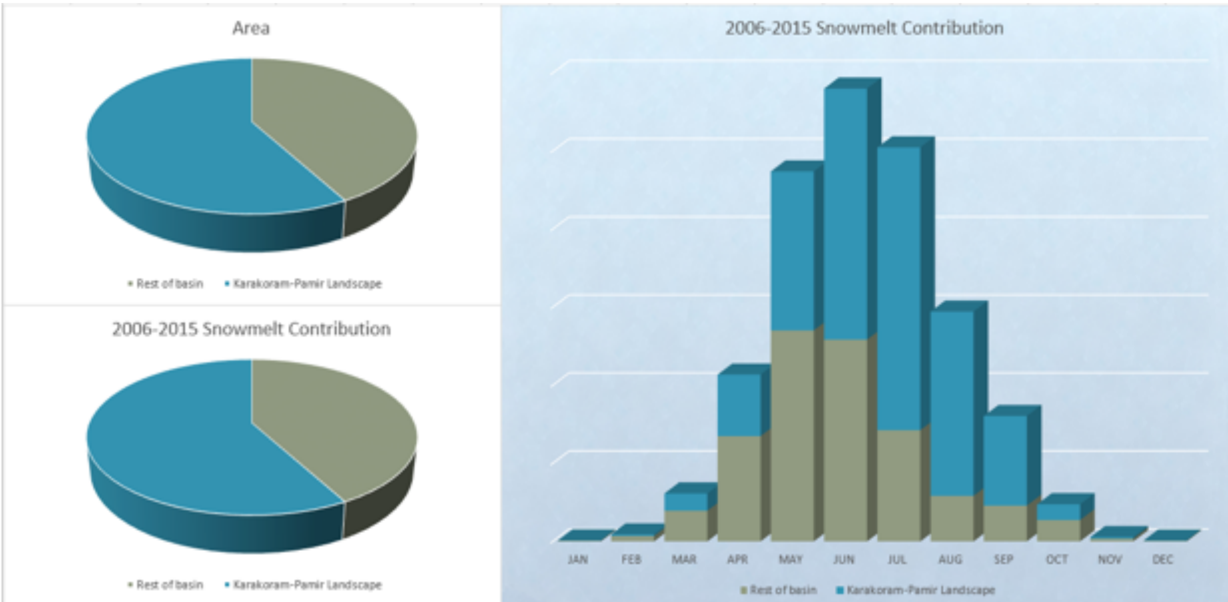
This is a map of MODIS/TERRA snow cover at 0.05 degree resolution with no additional processing required.

Data

MODIS/TERRA Montly Snowcover L3 at 5km (0.05 degree) resolution; 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

The landscape provides 58% of all snowmelt in the subbasin, which is in the exact proportion of the areas it covers; the landscape could therefore not be singled out as an area of *special* importance water provision by snowmelt. Yet overall, snowmelt is the most important component to the Indus river; Bookhagen (2010), reports a 65.7 % of snowfall contribution to the total discharge of the river.

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.

Increasing temperatures will have two direct consequences regarding snowmelt;

- historically, there is an amount of precipitation that falls as snow in fall (September-November) 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; this could cause extra floods in the downstream at the end of the wet season. This trend will be taking place at the lowest elevations of snow accumulation, but throughout the entire basins, because the snow frontier here is following the valleys that cut through the entire subbasin, including the landscape.
- in spring, higher temperatures means that the more snow will start to melt off earlier in the year. 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. The subbasin here is very mountainous and does not show many plateaus; impacts of shifts in the snow frontier will therefore be more lineair- than tipping point-based.

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.

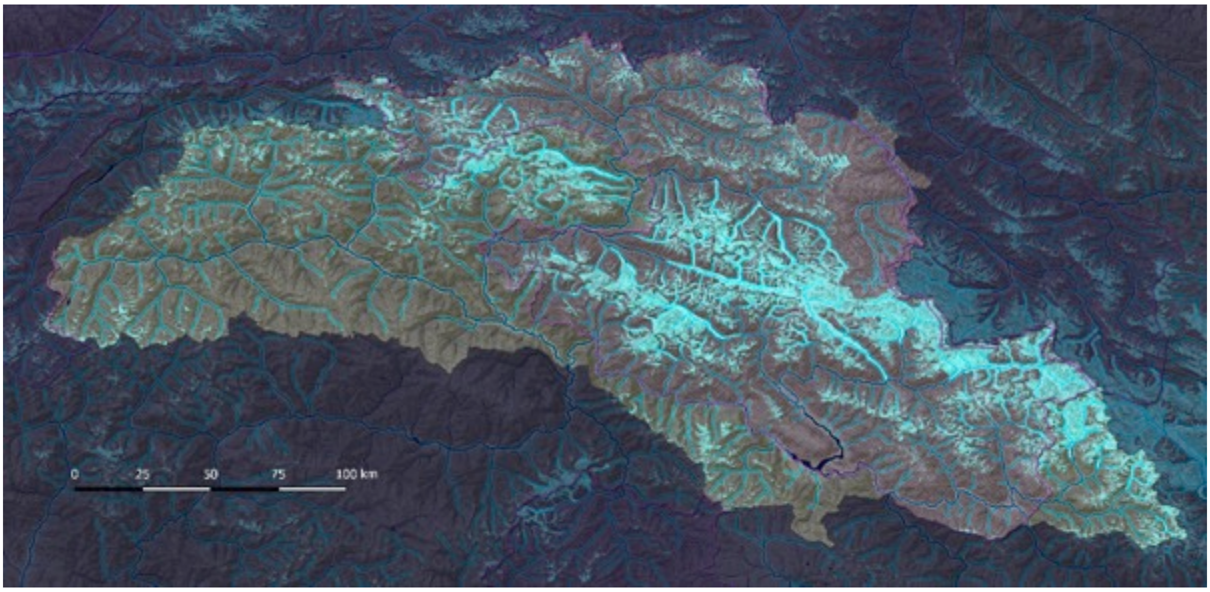
Data

Bookhagen, B; Burbank, DW (2010) '*Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge*.' Journal of Geophysical Research 115:10.1029/2009JF001426

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

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).

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.

The subbasin and landscape is dominated by the presence of glaciers. The monthly freeze line historically exposes most of the glaciers to thaw for at least three months (June-August). Historically this means that snowfall must have exceeded or balanced snowmelt for the glaciated areas; otherwise they would have melted off.

The high-precipitation projection indicates that more snow will fall during winter, this would probably feed the glaciers and extend their life expectancy under temperature rise. The freeze-line is contained in the landscape throughout the year; under increased temperatures this will shift upwards and increase glacial melt off. It is uncertain how the overall balance between extra snowfaal versus extra meltoff will change, it is likely that the differences will play out vey locally for each individual glacier.

Increasing temperatures will result in increasing glacial melt-off and increased flows to the downstream, as well as built-up of lakes at the foot of the glaciers, with risks of GLOFS. Since all streams in the subbasin and landscape have glacial sources, these impacts will be wide-spread and be cummulative towards the downstream.

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

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). It is recommended to collect more information that would help to classify the permfrosts.

Overall, it provides a consistent and best-informed overview where permafrosts are located in the wider subbasin: i.e. aount the mountaintops, but not in the river valleys. So there is a component of being in the upstream source areas.

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. Since the permafrosts consistently occur in the source areas of every river in the subbasin and landscape; it illustrates an alarming picture of what might happen when temperature rise will cause uncertain changes to these permafrosts.

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 the entire subbasin, and any climate change impacts on permafrosts will likely trigger unprecedented change at the subbasin level and towards its downstream.

Methodology

This is a map of the PZI database. From the website:

"The Permafrost Zonation Index (PZI) or a corresponding map color indicates, to what degree permafrost exists only in the most favorable conditions … or nearly everywhere ... These local conditions affecting permafrost occurrence will partly exhibit regional trends (e.g. mean snow cover characteristics or continentality), partly vary over typical distances on the order of several km (e.g. shaded or sun-exposed side of a mountain), and partly over tens to hundreds of meters (e.g. snow drift, vegetation, ground material). These conditions need to be assessed during interpretation, depending on the intended purpose of using the PZI map. This product is likely to be most valuable in remote regions where only sparse reliable information exists.The accompanying publication points to the importance of heterogeneity and uncertainty in the derivation and use of such permafrost zonation maps."

And from the paper (Gruber, 2012);

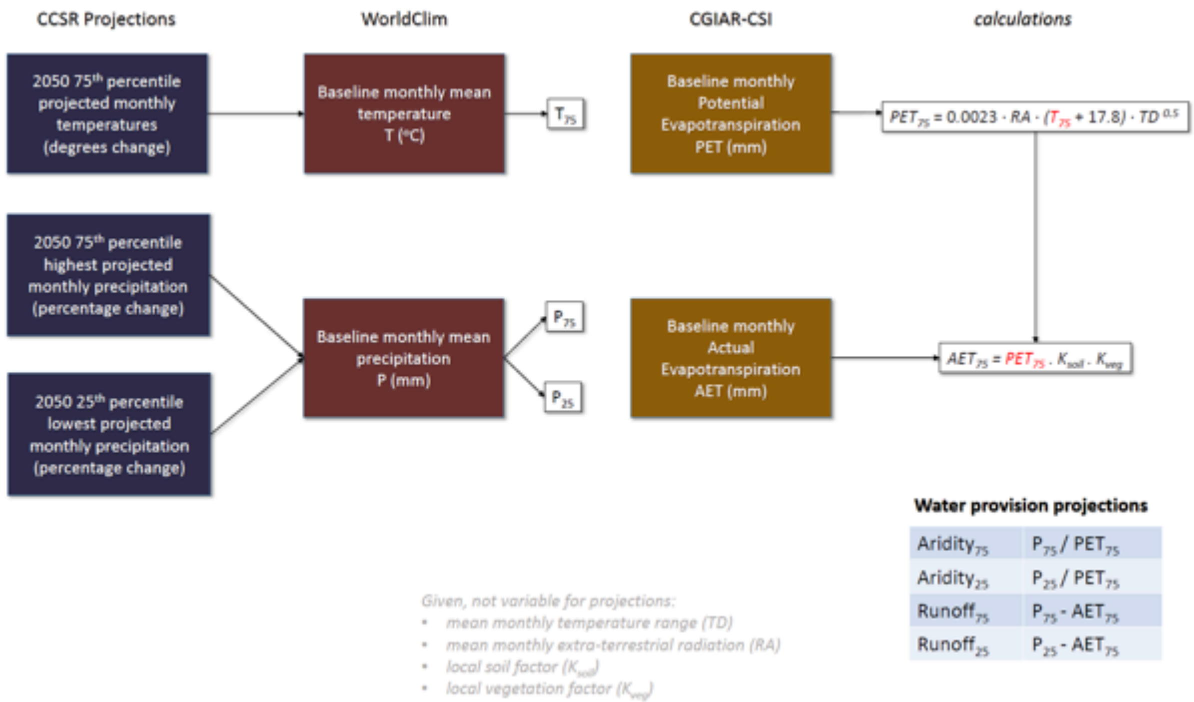
"*Established relationships between air temperature and the occurrence of permafrost are re-formulated into a model that is parametrized using published estimates. It is run with a high-resolution (<1 km) global elevation data and air temperatures based on the NCAR-NCEP reanalysis and CRU TS 2.0. The resulting data provide more spatial detail and a consistent extrapolation to remote regions, while aggregated values resemble previous studies. The estimated uncertainties affect regional patterns and aggregate number, and provide interesting insight. The permafrost area, i.e. the actual surface area underlain by permafrost, north of 60S is estimated to be 13–18106 km^2 or 9–14% of the exposed land surface. The global permafrost area including Antarctic and sub-sea permafrost is estimated to be 16–21 x 10^6 km^2. The global permafrost region, i.e. the exposed land surface below which some permafrost can be expected, is estimated to be 22±3 x 10^6 km^2. A large proportion of this exhibits considerable topography and spatially-discontinuous permafrost, underscoring the importance of attention to scaling issues and heterogeneity in large-area models."*

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/

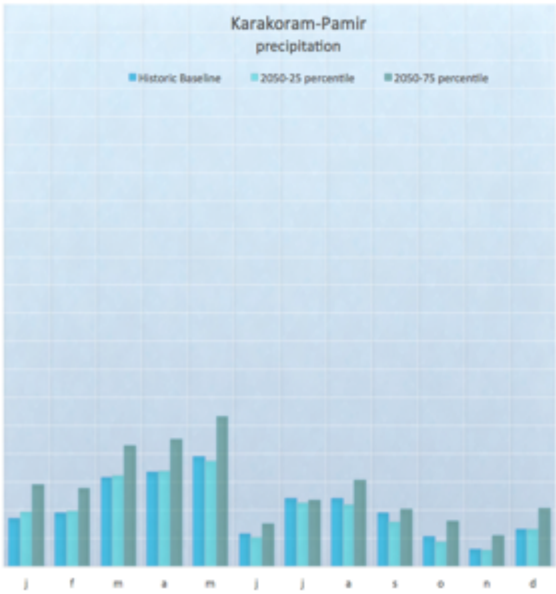
Karakoram-Pamir Climate Projections

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)

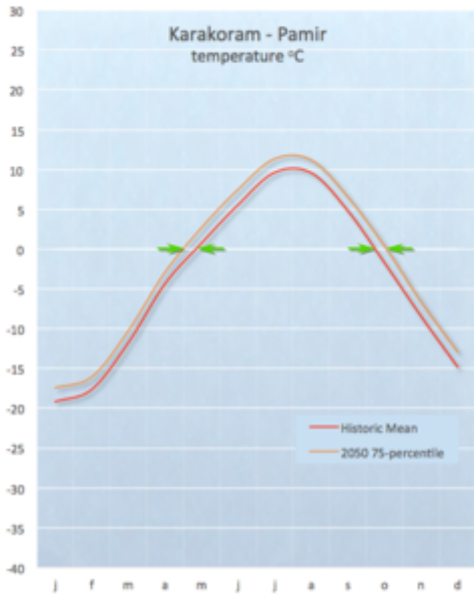


- CSSR Projections are calculated at 0.25 degree resolution; WorldClim and CGIAR-CSI datasets are at 1km^2 resolution
- Calculations are upscaled/downscaled to HydroSHEDS level 12 (~100 km^2) watersheds, both for the snowleopard landscape and their larger subbasins
- The results are presented as graphs, 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.

Precipitation and temperature projections



Historic precipitation compared to two projections, the minimum (25th percentile) and maximum (75th percentile) of 2050, horizontal axis crosses at 0 mm.



Historic temperature compared to the maximum projection (75th percentile) of 2050 (reference to CCSR-report, 2016)

Observations:

- In the high-projection, there will be annually about 35% extra precipitation, in the low-projection there will be around 3% less precipitation annually.
- The largest difference in amounts of precipitation between high- and low- projection occurs in May, and the low-projection is about 30% lower than the high-projection; this is a measure of uncertainty in the projections.
- Due to increased temperatures, there is an approximate 3-4 week decrease in freeze/winter season; about 2 weeks in April, and about 1.5 weeks in October, indicated by the green arrows in the temperature chart.

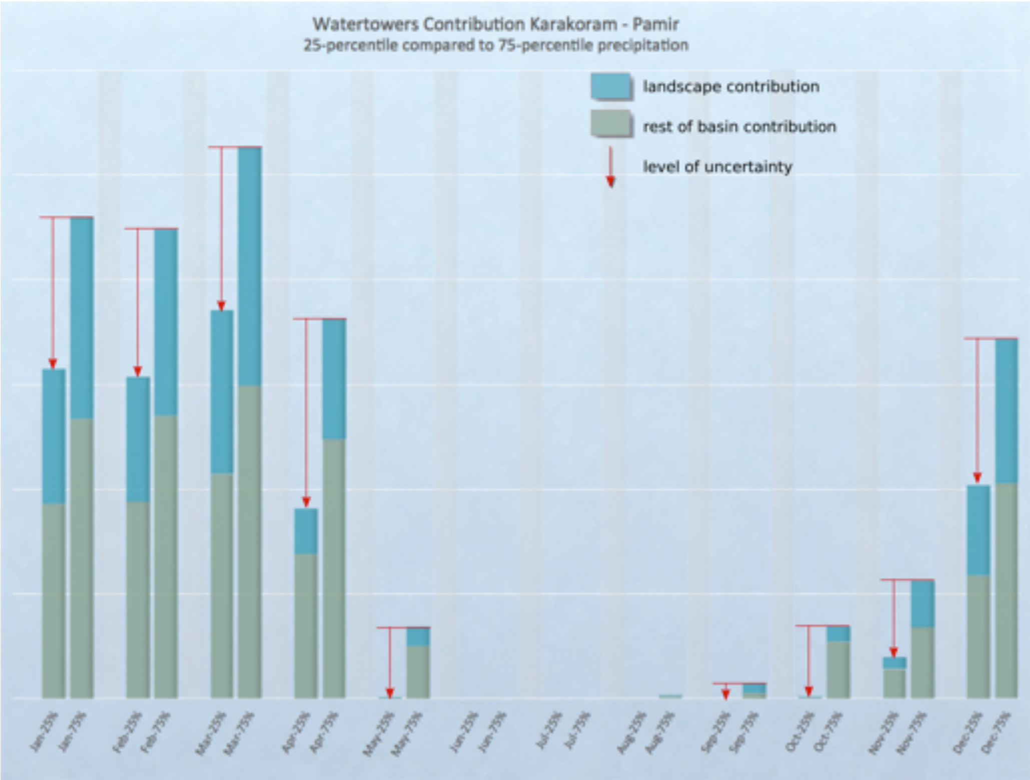
Data

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 scenarios, one with the low 25 percentile precipitation and one with the high 75 percentile precipitation. It 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. In the annex, a graph shows the same two projections in compirison with the historic baseline.

During winter month, most of the contribution will fall as snow and will accummulate untill spring, when it melts off as snowmelt. In the spring and summer months, when downstream water demands are at its highest, the difference between these two projections show a very high difference, e.g. from almost zero to the highest annual value in May. This indicates a severe measure of uncertainty on what might actually happen to local runoff under climate change in the spring/summer months.

This graph would help to identify if the role of the snow leopard landscape in water provision would change under the climate projections.

There is a 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 he landscape. So it is not expected that the relative role of the landscape in water provision would change much.

Though from July to September, the role of the landscape in water provision might increase somewhat –under the high-precipitation projection. Yet the uncertainty here is much higher as well, so it is very difficult to assess what might happen; this would require more specific insights.

Data

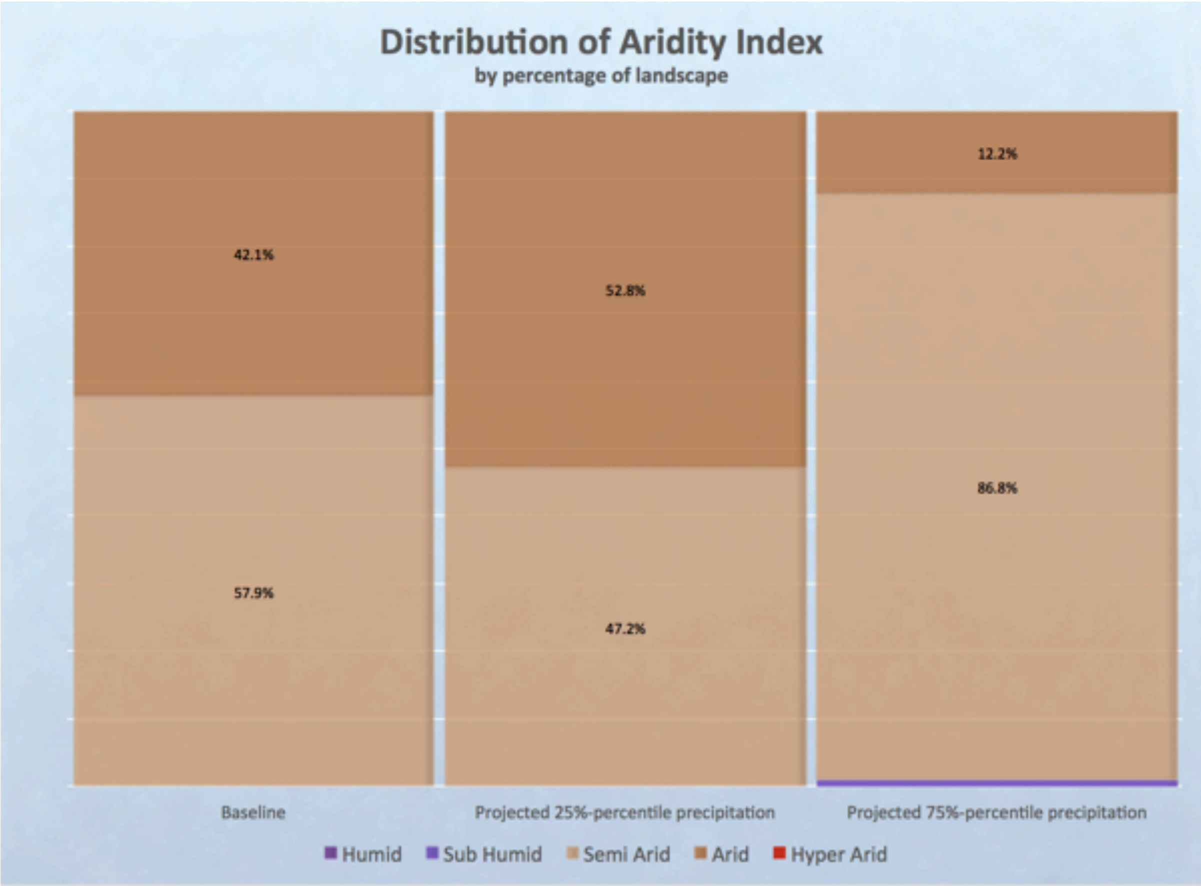
Current Mean Monthly Precipitation, based on historic WorldClim, 30s resolution; Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978. www.worldclim.org

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 two projections; one the gives the lowest percentile of change in precipitation for 2050 (whether it gets drier) and one that giver the projected highest percetile of change in precipitation for 2050 (where it gets wetter). Both projections are equally valid -or likely to happen-, the dfference between the projections 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, the seasonality -which showed in the baseline maps- is balanced-out. Under the low-precipitation projection, the semi-arid extent would more than triple at the expense of humid areas; humid areas will shift to sub-humid, and sub-humid to semi-arid. Under the high-precipitation projection, the semi-arid areas will disappear and turn more towards sub-humid, and even humid.

Also here, the low-precipitation projection is close to the historic baseline, while the high=precipitation projection would mean a significant landscape change from arid to semi-arid.

Data

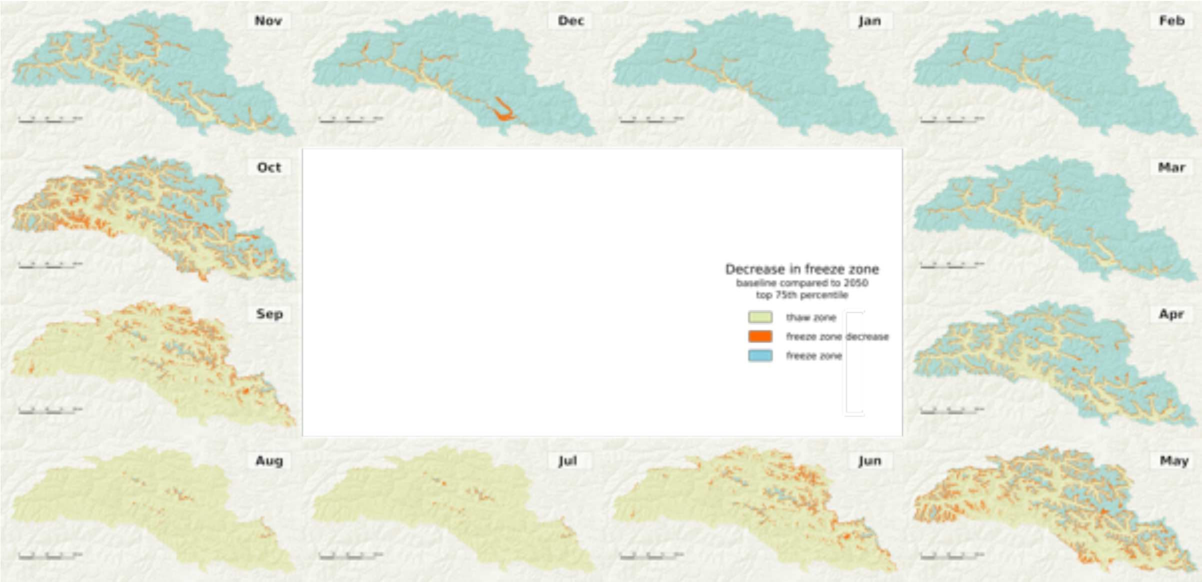
Current Mean Monthly Precipitation, based on historic WorldClim, 30s resolution; Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005. Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology 25: 1965-1978. www.worldclim.org

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



Calendar months of freeze-loss

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.

In general, the decrease in freeze extent closely follows the baseline freeze frontier, and changes are within the range of a few hundred meters to a few kilometres. Yet for mountaintop snow cover and glaciers, such an impact might be dramatic (May to October).

In May and October, the maps also show that that southwest corner of the subbasin (but outside the landscape), would experience a disproportiate amount of loss in freezing conditions; those areas show up more red than their surroundings. These areas are low in glacial cover, but do show high levels of seasonal snowcover and snowmelt. Any significant changes to the historical conditions might upset the local hydrological balances there.

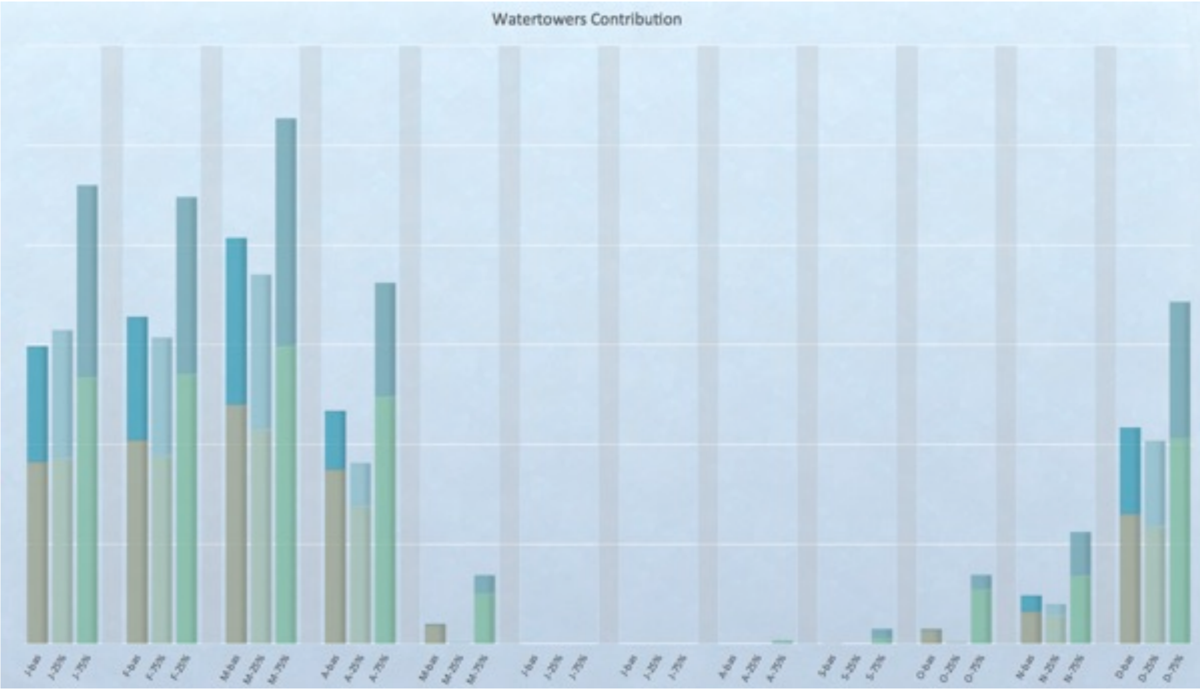
Data

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)



Analysis

The graph illustrates that the low-precipitation proejection does not deviate too much from the historic baseline, while the high-precipitation projection would cause changes to the overall water balance. It is important to notice that these changes are only projected to take place during the winter months; so most of the precipitation would fall as snow, remain in the landscape over winter, only to melt off during spring and summer.

Quantitative example

Basin ID: 9315	area_km^2:	117.6	lat:	36.300	lon:	75.435								
Karakoram-Pamir Landscape			jan	feb	mar	apr	may	jun	jul	aug	sep	oct	nov	dec
baseline														
temperature	°C		-20.43	-18.88	-12.96	-5.49	-0.36	4.48	8.61	8.56	3.73	-2.83	-9.61	-16.02
precipitation	mm		6.53	7.20	12.99	14.24	17.62	5.25	11.47	11.45	8.78	4.45	2.79	5.26
AET	mm		0.02	0.30	2.93	10.88	21.18	26.64	28.32	21.86	12.46	5.54	1.59	0.00
PET	mm		0.77	2.05	11.51	33.67	62.53	86.43	108.70	99.16	65.48	34.77	12.79	3.20
runoff	mm x km^2		765.10	810.60	1182.30	394.80	0.00	0.00	0.00	0.00	0.00	0.00	141.40	618.80
2050_25 percentile														
precipitation change	%		113.04	104.15	105.85	98.21	97.71	89.42	98.44	83.88	97.86	87.41	93.87	105.46
precipitation$_{25}$	mm		7.38	7.50	13.75	13.98	17.22	4.69	11.29	9.61	8.59	3.89	2.62	5.55
runoff$_{25\ (T75)}$	mm		867.07	881.46	1162.07	211.62	0.00	0.00	0.00	0.00	0.00	0.00	79.24	652.59
2050_75 percentile														
temperature change	°C		1.72	1.56	1.54	1.47	1.97	1.89	1.82	1.60	1.82	2.03	1.84	1.88
temperature$_{75}$	°C		-18.71	-17.32	-11.42	-4.01	1.61	6.37	10.42	10.16	5.55	-0.80	-7.77	-14.14
precipitation change	%		174.63	157.49	136.31	136.61	140.85	137.19	21.19	142.86	27.68	150.28	187.95	161.96
precipitation$_{75}$	mm		11.40	11.33	17.70	19.45	24.82	7.20	2.43	16.36	2.43	6.69	5.25	8.52
AET$_{75}$	mm		0.01	0.00	3.87	12.18	23.57	28.91	30.27	23.18	13.51	6.29	1.95	0.00
PET$_{75}$	mm		0.27	0.00	15.17	37.70	69.58	93.79	116.17	105.16	71.01	39.48	15.67	6.58
runoff$_{75}$	mm x km^2		1340.00	1332.85	1627.30	854.70	146.19	0.00	0.00	0.00	0.00	46.96	388.10	1002.24

These numbers are presented as reference to the different graphs; they will explain why certain values occur.

Again, the baseline runoff completeley coincides with the freezing temperatures and will mainly fall as snow and melt off during the summer months. There seems to be a minimal shift in spring under the high-precipitation projection; May no longer has a mean temperature below zero, and some new runoff will occur during this month.

Overall, the local runoff (precipitation minus AET) has relatively low values in this context; small changes to precipitation or AET might therefore lead to larger changes over the water balance.