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TECHNICAL REPORT 2017

GUARDIANS OF THE HEADWATERS II:

Biodiversity, water, and climate in six snow leopard landscapes

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Accompanying Reports

This full technical report is accompanied by a summary version, Guardians of the Headwaters II Summary Report: Mapping Biodiversity, Water, and Climate in Six Snow Leopard Landscapes. This map book follows a 2014 regional assessment, Guardians of the Headwaters I: Snow leopards, Water Provision, and Climate Vulnerability, Maps and Analysis. To download these reports and for more on methods, analyses, findings, and maps, please visit www.thirdpolegeolab.org or www.worldwildlife.org/ahm.

Authors

Jessica Forrest, Spatial Ecologist, based in New Hampshire, USA
Nikolai Sindorf, Environmental Specialist: water, development, nature, based in Lao PDR
Ryan Bartlett, Lead, Climate Risk Management, WWF-US, Washington, DC, USA

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Executive Summary

To advance climate-smart natural resources management planning in snow leopard habitats, we mapped and overlaid snow leopard habitat, current and potential human impacts, protected areas, selected water resources, and climate vulnerabilities in six priority snow leopard conservation landscapes in high Asia. The landscapes were: the Eastern Himalaya Landscape of Nepal (EHL/N), the Sikkim Landscape of India, the Bhutan Landscape, the Karakoram-Pamir Landscape of Pakistan (KKP), the Central Tien Shan Landscape of Kyrgzstan (CTS), and the South Gobi Landscape of Mongolia.

Snow leopard landscapes tend to have large habitat areas, though snow leopards require vast areas to survive. In the set of six landscapes that we studied, five landscapes had areas in the range of 3,000 km^2 to 8,000 km^2, with an average size of just under 6,000 km^2. The sixth landscape in the set, the South Gobi, has an estimated habitat area of over 68,000 km^2. These habitats ranged from extremely rugged, high alpine areas above treeline in the Himalaya and Karakoram Pamir Mountain ranges, to the high mountains and sweeping valleys of the Central Tien Shan, to harsh desert steppe punctuated by rugged, elevated mountains in the South Gobi. Three of the landscapes appear to have sufficient internal habitat connectivity, while two landscapes (the Eastern Himalaya and Bhutan) require habitats across the international border with China to maintain connectivity. Snow leopards have been observed to travel hundreds of kilometers, thus necessitating such large areas (McCarthy, et al., 2005; Government of Nepal and World Wildlife Fund, 2016).

Successful snow leopard conservation will require effective transboundary management. Habitats associated with all six landscapes in this series interface with international boundaries. This is required to ensure internal landscape connectivity in two landscapes (EHL and Bhutan). In all landscapes, cross-border habitats support connectivity to the broader snow leopard metapopulation. Snow leopards have been confirmed to travel long distances across international boundaries (Government of Nepal 2016). Effective snow leopard conservation will rely on effective transboundary collaborations between governments.

Snow leopard habitats tend to be well-protected, but all landscapes have critical gaps. Snow leopard habitats in the landscapes we studied range from 33% to 92% protected, with an average and median percent protected around 50%. However, each landscape has important gaps in the protected area and/or corridor system that omits crucial areas, particularly for securing habitat connectivity. Snow leopard habitat needs to be protected by a seamless network of protected areas, corridors, and multiple use zones that are snow leopard and prey-friendly.

Snow leopards and humans share landscapes, and the risk of habitat fragmentation tends to be a greater threat overall than habitat loss from direct human impacts. The landscapes of the eastern Himalayas tend to have the highest number of pinch points to habitat connectivity (5 to 9) from roads, population centers, and land use. The Karakoram-Pamir and the Central Tien Shan have fewer, but no less significant pinch points. The South Gobi does not appear to have any bottlenecks to habitat connectivity at this time, with low human population density and nomadic cultures. In all landscapes, livestock compete with prey for valuable grasslands. This can lead to habitat degradation in some cases, and spur human-wildlife conflict. Illegal hunting of snow leopards and prey is also an issue in most landscapes, and this risk can be higher along access routes. Snow-leopard friendly land-use zoning, management and smart infrastructure are effective approaches for maintaining connected and resilient landscapes.

Snow leopard landscapes provide certain ecosystem services, including water storage and regulation from snow and glacier melt, methane storage in permafrost, pasture for livestock grazing, aesthetic and biodiversity values for tourism, and medicinal plants. These landscapes do not tend to offer a significant water tower function in terms of direct runoff from precipitation to their surrounding sub-basins, with the exception of the Central Tien Shan. But, all landscapes, with the exception of the South Gobi, tend to offer a service to their surrounding basins from snowmelt, particularly at the driest times of year. The flows of water in four of the landscapes (the Himalayan landscapes and the Central Tien Shan) cross international boundaries. These water provisions are also linked to the seasonal patterns of downstream floods and droughts.

Global climate change will affect all landscapes. All landscapes are expected to become warmer. The amount of warming will range from about +2°C above average annual baseline temperatures by midcentury in the Eastern Himalayan landscapes (range = 1.7 °C to 2.5°C), to 3 or even 3.5°C above baseline temperatures (range = 1.9 °C to 3.6°C) in the landscapes to the north and west. All landscapes are also likely to experience modest to extreme increases in precipitation. The monsoon in the Eastern Himalayan landscapes is likely to become heavier, and there will likely be more snowfall in the Karakoram-Pamir. Precipitation increases in the Central Tien Shan and South Gobi are likely to be more modest, where the baseline precipitation is also close to zero (Peters et al. 2017).

Key climate change risks to snow leopards and their ecosystems vary by landscape, but will range from large scale ecosystem shifts, to more subtle ecological community changes, to habitat loss and degradation from permafrost melt, to land use changes and developments in response to new climates. The landscapes in the Eastern Himalayas may see 60 to 80% of existing snow leopard habitats transition from a climate zone favoring alpine grasslands to a climate zone favoring forest ecosystems. The Karakoram-Pamir may experience a more modest change from alpine to forest climate zone (12%), but with a fragmenting effect on key habitat areas. All landscapes will experience a decrease in the length of winter, ranging from one to three months. This will affect the timing of ecological processes, and ultimately change ecological community composition to species that prefer warmer climates and longer growing seasons. Climate suitability for crops is likely to increase within landscapes (in the case of the South Gobi and Central Tien Shan) and/or directly downstream (in the case of the Himalayan and Karaoram-Pamir landscapes). This may cause habitat conversion to croplands, or fragmentation if water resource development occurs within landscapes to regulate water availability for crops. All landscapes have permafrost (ranging from a few mountaintops in the South Gobi to 54% total coverage in the Central Tien Shan), and melting may lead to habitat loss and degradation.

Climate change in the landscapes will also have important impacts on human livelihoods, both within and downstream, indirectly affecting snow leopards and other biodiversity. Under changing climate, the water tower function of all landscapes may increase, though often to coincide with the monsoon in the Himalaya, which is the time of year when demand is lowest. Moreover, the timing of peak snowmelt may shift to coincide with the monsoon and increase flood risk. Water shortages may occur at dry times of year that have historically relied on snowmelt. Melting glaciers and ice increases the amount of water flowing downstream from the landscapes in the near term (except the South Gobi), but, as evidenced in all landscapes, also increases the size and/or volume of lakes (Pekel et al. 2016). Melting glaciers can increase the risk of glacial lake outburst floods (GLOFs). Melting ice and permafrost, coupled with heavier rains, can increase landslide risk. Melting permafrost will increase the release of greenhouse gases into the atmosphere, thus accelerating warming trends. These changes will make mountain livelihoods more difficult, potentially leading to significant new pressures on surrounding biodiversity, as communities seek alternative sources of income.

Monitoring of climate change impacts and adaptive management are critical in the face of uncertainty. While this analysis offers numerous new insights on how climate change affects high Asia, it is largely based on satellite data and models, in part due to how little observed historical data is available across the snow leopard range. A concerted effort is needed across high Asia to build and enhance data, monitoring, and research on climate change and its affects across the range.

Introduction

The Tibetan Plateau and the surrounding mountains ranges and deserts of northern Asia hold the largest store of permanent ice and permafrost outside the North and South Poles, earning the nickname the Third Pole. Home to the snow leopard, numerous traditional cultures, and the headwaters of Asia's mightiest rivers, the treasures of this region are shared by several countries. The vast stores of seasonal and permanent snow and ice provide vital ecosystem services: permafrost promotes habitat stability and stores greenhouse gases, and the melt from snow and glaciers provides water to the downstream during the driest times of year. The vast, open, often rugged land provides pasture for livestock, but also for wild ungulates that form the prey base for the iconic snow leopard. With a rapidly warming climate, these services are already undergoing significant changes that will only increase in the future, affecting the people and wildlife that depend on them (Smith, 2014).

In 2014, we conducted a regional mapping assessment to visualize the distribution of snow leopard habitats, water resources and climate vulnerabilities across the region (Sindorf, et al., 2014). From this work, certain themes emerged, such as the transboundary nature of habitats and water resources in this region. We also noted important geographic variations in the water resource value of high altitude alpine habitats across high Asia, demonstrating the relative importance of flows from the western edge of the snow leopard range, as well as important climate vulnerabilities like increasing aridity and shifting habitats due to warming temperatures. However, questions remained about the distribution of high alpine habitats and water resources at the landscape scale, and how to plan for these unique places under a changing climate.

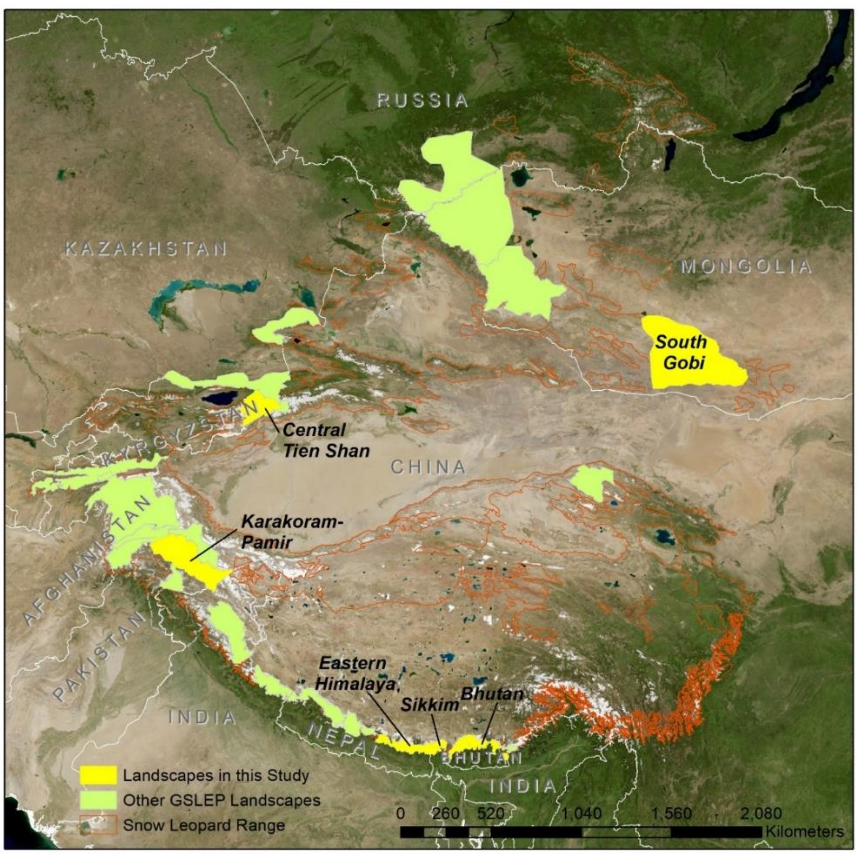
Here, we address these questions by conducting finer-resolution analysis and mapping of these values in six landscapes in northern and central Asia. Within these landscapes, we identify the most important areas of high alpine wildlife habitats for conservation, using snow leopards (*Panthera uncia*) as a focal species. We also look at the spatial distribution of selected water resources and services within these habitats and in the surrounding sub-basins. Finally, we map the distribution of potential climate change vulnerabilities of these habitats and water resources to better understand future risk. Several themes emerge that are consistent across all places, alongside others that show important distinctions. Our work here is meant to serve a practical purpose for government-led landscape management planning in the selected locations, with the intention of managing biodiversity and water resources under a changing climate while minimizing risks. At the same time, our work serves as a model for landscape planning at other sites in this region. More generally, and globally, we demonstrate how maps can be used to understand the relationships between biodiversity, ecosystem services, and climate vulnerabilities. They are essential for landscape management planning that explicitly addresses the impacts and risks of a changing climate.

We use the snow leopard here as a representative of alpine biodiversity across all the landscapes that we evaluated. The snow leopard is a feline predator endemic to northern Asia. It is charismatic, cryptic and iconic. It is highly threatened, and listed as Vulnerable on the Red List of Threatened Species (I.U.C.N., 2017), and it is included in CITES Appendix I (CITES, 2017). It is also a wide-ranging species, with its range encompassing that of many other species that share the same habitats. Thus, we argue that if we conserve the snow leopard, we will be able to save the habitats of many other species (Sanderson, et al., 2002). The snow leopard is also a species of common national concern: In 2013, twelve snow leopard range countries agreed to the Declaration on the Conservation of the Snow Leopard, and committed to secure snow leopards in 20 landscapes by the year 2020 (Snow Leopard Secretariat, 2013). This has led to a number of consistent conservation activities in the region, including management planning. Our work here supports the management planning activities in six of these landscapes, and serves as a model for others.

General approach and indicators

We conducted our work in six landscapes in the snow leopard range. These six landscapes represent a subset of the 23 snow leopard landscape identified by countries and the Global Snow Leopard and Ecosystem Protection Program (GSLEP) as priorities for conservation (See Figure 1). They are also priorities for the USAID-WWF project, *Conservation and Adaptation in Asia's High Mountains*, which has been implementing conservation and climate change adaptation activities since 2012. These landscapes are: the Eastern Himalaya Landscape of Nepal (EHL/N), the Sikkim Landscape of India, the Bhutan Landscape, the Karakoram-Pamir Landscape of Pakistan, the Central Tien Shan Landscape of Kyrgyzstan, and the South Gobi Landscape of Mongolia. They are distinct, but representative of the diversity of these places in terms of their topography, nationality, culture, climatic conditions, and location.

Figure 1. Six Landscapes included in this Study, as a Subset of the Priority GSLEP Landscapes



Data: Snow Leopard Range (ISLT, Panthera, SLN, WCS, Beijing GIS Workshop, 2008)
GSLEP = Global Snow Leopard and Ecosystem Protection Program
Note: The country boundaries shown on this map do not imply endorsement or acceptance

In these landscapes, we selected a core set of indictors for mapping, including snow leopard habitat, protected areas and corridors, vulnerability to direct human impacts, vulnerability to climate change, and vulnerability to human responses to climate change. We also mapped the distribution of key water services from each landscape, as well as their vulnerability under climate change. These included water towers (or sources of precipitation runoff), frozen ground (an indicator of winter duration and snowmelt timing), and open water (a water resource in itself, but also an indicator of climate change trends and vulnerabilities) (Sindorf 2017). We combined several of these indicators into summary maps to express the relationship between conservation priorities and potential impacts, and to demonstrate key vulnerabilities and opportunities. In the South Gobi, our selection of variables differed from the other landscapes due to its unique
climatic and hydrological conditions (i.e., very limited precipitation), as well as human use of the landscape (i.e., a very low density, nomadic population)

Snow leopards were chosen both as a focal species for mapping and management, but also as an umbrella species, with the notion that protecting their habitats will effectively protect many other species that share the same “home”. We created original, high resolution models of current snow leopard habitat in each landscape based on best available data, to indicate existing habitats and connectivity, as well as potential bottlenecks. Protected areas were mapped in order to identify gaps in the protected area system. We developed landscape-scale human footprint maps to demonstrate habitat vulnerability to direct human impacts (e.g., Sanderson, et al., 2002). The human footprint maps assume that areas that are more accessible to humans will have higher levels (or risk) of habitat loss, degradation and/or fragmentation, enable access for hunters, and potentially have higher rates of overgrazing of livestock.

Climate Risk

All focal landscapes are expected to experience warming temperatures, in the range of 1.7 to 3.6°C above baseline average annual temperatures by mid-century, depending on the place. These landscapes are also expected to experience changes in precipitation patterns, with variation in the amount of increase, the timing, and impacts (Peters et al. 2017). In the Himalaya and Karakoram-Pamir mountain ranges, we used projections on potential shifts in the forest and alpine zones to the year 2100 under three emissions scenarios (Forrest, et al., 2012). Indeed, as temperatures become warmer and wetter and the growing season lengthens, some alpine areas (with climates that inhibit tree growth) may begin to resemble the forest climate zones of baseline years. This could vastly change the ecological community compositions in these places.

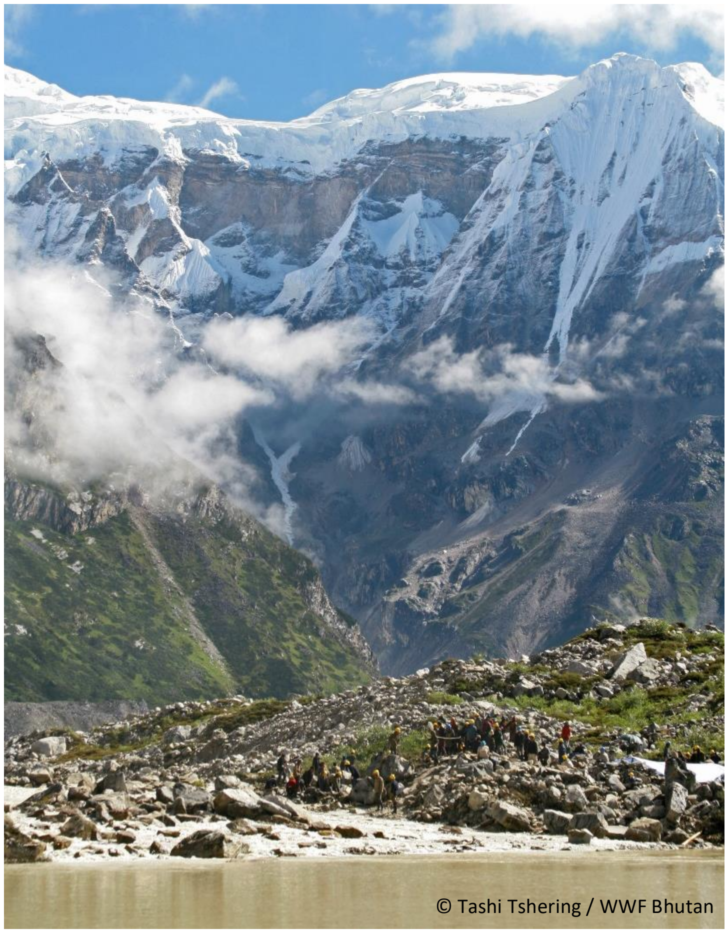
In the two northernmost landscapes, we used projections on the potential shift in snow leopard climate envelope under a high emissions scenario to the end of the century to demonstrate vulnerability to climate change (Sindorf, et al., 2014). Bioclimatic envelope models represent the suitable climate space for a given species, and when future climate projections are incorporated, they can give an indication of the potential resilience and vulnerability of this niche under climate change. Climate change can also influence how people use land and natural resources, and such changes may cause conflict with wildlife. One example of this is the likely change in climate suitability for croplands. We thus overlaid snow leopard habitats with potential change in suitability for cropland under changing climates (Sindorf, et al., 2014).

The hydrological indicators reviewed, including water towers, freeze line and frozen ground, and open water, have importance for people and biodiversity. To account for how these might change in the future, downscaled projections of temperature and precipitation were developed for two Intergovernmental Panel on Climate Change (IPCC) scenarios representing the most optimistic and extreme emissions trajectories and resulting changes, RCP 4.5 and RCP 8.5 (Peters D. , et al., Climate Change in the Snow Leopard Landscapes of Asia's High Mountains: Technical Report, 2017). These were then used to determine how freeze line, water towers, and open water all might change in the future.

Such changes can have complex implications: for example, an increase in water tower functionality towards increased run-off can have negative implications, depending on the time of year that precipitation increases. This can include an increased tendency towards flooding and landslides (Sindorf N. , Water Resources and Climate Change Sensitivity Analysis, 2017). Freeze line shifts are linked to the duration of winter. A shift towards shorter winters (as will inevitably occur in each landscape) would extend the length of the growing season. But, it could also lead to earlier snow melt (and water availability), delayed snow accumulation, and an increased rate of glacier and permafrost melt (Sindorf N. , Water Resources and Climate Change Sensitivity Analysis, 2017). Earlier springs can disrupt the timing of ecological processes (phenology), promoting ecological communities that favor warmer climates. This can cause results in shifts in ecological interactions up the food chain, to affect communities of grazing animals and predators. Shorter winters can thus ultimately mean, for example, a change in prey availability for snow leopards, or the rise of new competitors. Open water in landscapes represent an important service in terms of water availability, a landscape's internal connectivity, water storage, and regulation. It is also an easily detectable indicator of past and potential future trends (Pekel, Cottam, Gorelick, & Belward, 2016; Sindorf N. , Water Resources and Climate Change Sensitivity Analysis, 2017). Increases in open water can indicate increased rates of precipitation, melting of permanent ice stores, or infrastructure development. Depending on where shifts in open water occur, this can have implications for water availability and shortages, but also of floods (Sindorf, 2017).

We use the above variables to illustrate the key processes and trends for ecosystems and water resources in each of the six landscapes. Finally, we provide key findings and management implications to guide climate adaptive planning for snow leopards and people within and downstream of these focal landscapes.

I. Analysis and Mapping of Snow Leopard Habitat in the Bhutan Landscape



September 18, 2017

Jessica Forrest, Nikolai Sindorf, and Deki Wangmo

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Chapter 1 of 6 of the report:
Guardians of the Headwaters II:
Biodiversity, water, and climate in six snow leopard landscapes

Key Findings and Management Recommendations

- **The Bhutan Snow Leopard Landscape has nearly 6,500 km^2 of snow leopard habitat that is located in two large but discrete habitat patches connected via habitat in China.** The Bhutan landscape connects to at its western border to other priority habitats of the eastern Himalaya (in China, India and Nepal), and at its eastern boundary to habitat in India. **Transboundary management will be key to maintaining the snow leopard metapopulation in Bhutan and throughout the region.**

- **Protected areas cover over 90% of potential snow leopard habitat in Bhutan.** 531 km^2 of snow leopard habitat remains unprotected in the western part of the country between Jigme Khesar Strict Nature Reserve and Jigme Dorji National Park. This habitat forms a vital connection between the westernmost part of the Bhutan landscape and the vast areas of habitat in northern Bhutan. Bhutan has an impressive system of wildlife corridors, but this habitat falls outside the corridor system as well. Human presence is most heavily concentrated in the westernmost part of the landscape, so corridor zoning here may help to maintain habitat connectivity in this region.

- **Human impacts in snow leopard habitat are highest in the westernmost part of the landscape** both within and outside of protected areas. There is also an area of relatively high human impact in the Lhobrak river valley in the north of the country. These potential pinchpoints may require special management attention to maintain landscape connectivity.

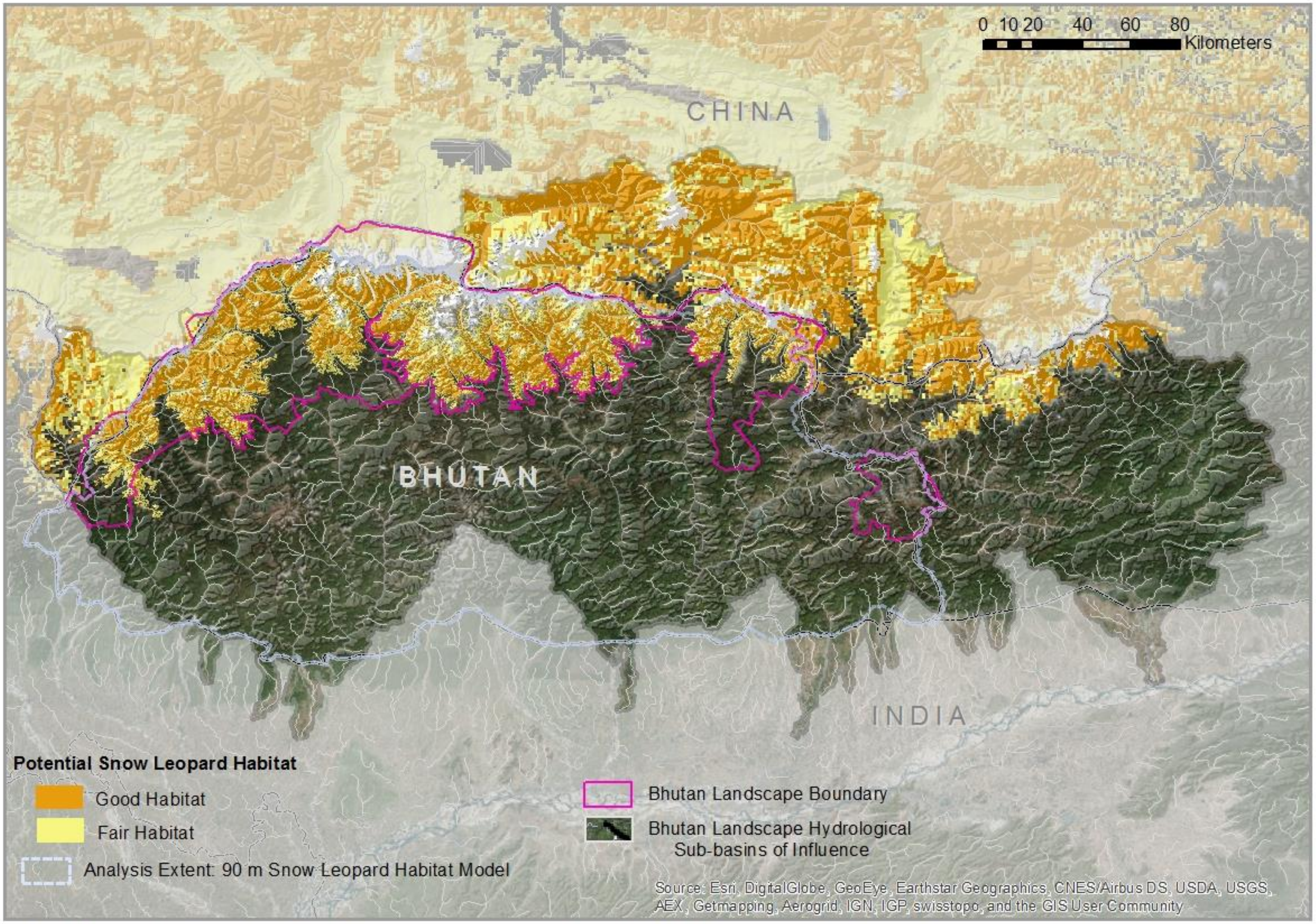
- **The snow leopard habitats in Bhutan are very vulnerable to climate change-driven ecosystem change, with a predicted loss of 60% of alpine habitats under a high emissions scenario**. Habitats in the eastern part of the country are most vulnerable to climate change, while habitats in the west may remain as refugia. Habitats in the west are currently subject to higher human impacts, so special management attention may be required to preserve habitat area and maintain connectivity.

- **The amount of arable land downstream of snow leopard habitat is likely to increase.** This may produce increased pressure on water originating in the snow leopard habitat, emphasizing the need for snow-leopard friendly water management practices and planning.

- **The length and severity of winter will decrease, with a range of ecosystem implications. Monitoring and adaptive management will be key to maintaining wildlife populations and ecosystem services.** Almost the entire landscape will experience a decrease of 1-2 months of winter, particularly at the lowest elevations. Loss of freeze months will occur throughout the winter, with most loss occuring in the transitional months of March to May, and in October. Impacts include permafrost loss, earlier springs - flowering and leaf out, changes in grassland community composition, and ungulate populations, as well as glacial melting and a higher risk of glacial lake outburst floods.

- **The landscape does not provide significant water tower services at this time.** Under a high-end precipitation scenario, monsoon rainfall may increase significantly by 2050, which will greatly increase the downstream risk of flooding and erosion.

Potential Snow Leopard Habitat of the Bhutan Landscape over Sub-basins of Influence



This map shows the local hydrological basins overlapping and immediately downstream of the Bhutan snow leopard landscape. *WWF 2017*

This map shows potential snow leopard habitat of the Bhutan Landscape over local hydrological sub-basins of influence. There is an estimated 6,490 km^2 of potential snow leopard habitat in Bhutan. Of this, 3,757 km^2 is classified as good habitat, and 2,733 km^2 is classified as fair habitat. 6,289 km^2 of habitat is within the Bhutan Landscape GSLEP boundary. The habitat is located in two discrete patches, separated by a river valley. These habitat patches are connected only by habitat located across the boundary in China. Good habitat ranges in elevation from 3,890 to 5,590 m, and fair habitats from 3,750 to 5,855 m.

Snow leopards have been confirmed to be present in the habitats of the western and central parts of the landscape, with an estimated population of 96 animals. The habitats in the eastern part of the country may be unoccupied, according to recent survey results (Bhutan DoFPS 2016a).

Methodology

Snow leopard potential niche was modeled at 90 m resolution in Bhutan, as a function of land cover, elevation, ruggedness, and snow leopard observations using MaxENT (Phillips et al. 2006). Our approach differs from other efforts (Bhutan DoFPS 2016a) in that only biophysical variables were selected for this model. This was in order to represent the entire potential niche for snow leopards in Bhutan, including occupied and unoccupied niche areas. We did not incorporate human variables into this model because we did not want to disregard currently unoccupied, though potentially restorable habitat areas. Human impacted areas were modeled separately and later overlaid on our map of potential snow leopard habitat.

We incorporated 212 snow leopard observations into the model, of which 170 were used for training, and 42 for testing (ISLT et al. 2008, Bhutan DoFPS 2016). The model was run in several iterations, testing alternative ruggedness models (the terrain ruggedness index and the vector ruggedness model) (Riley et al. 1999, Sappington et al. 2007), as well as some climate variables thought to be important drivers of alpine ecosystems. Climate variables tested included total summer precipitation, total precipitation as snow, number of months of frost, mean growing season temperature and percent of annual precipitation that occurs during the monsoon. Model sensitivity and output was tested systematically withdrawing certain variables. The resulting model based on land cover, elevation, and the vector ruggedness model had an Area under Curve (AUC) value of 0.928 and a test AUC of 0.918. This 3-variable model was selected as the best representation of current habitat at the 90 m scale.

The resulting logistic probability of occurrence (p) map was reclassified into good, fair and non-habitats based on p-thresholds. Good habitat was defined as areas where $p >= 0.4$. This threshold was selected through visual comparison between snow leopard observations and the probability of occurrence map. This selection was cross-checked with various statistic thresholds offered through the maxent output, and $p>0.4$ is more restrictive than statistical thresholds proposed by the Maxent output. Fair habitat was defined as $p>0.199$. Probability of occurrence (p) >0.199 represents a generous definition of habitat with a low omissions rate (training omissions rate < 0.035 and test omission rate < 0.071).

The habitat map was overlaid with an independent set of snow leopard observations from recent camera trap surveys (Bhutan DoFPS 2016b), and we found a false-negative rate of only 2.5%.

Data sources

Bhutan Snow Leopard Habitat Model:

- Land cover (Bhutan MoAF 2011)
- DEM, ruggedness (Lehner et al. 2008, Sappington et al. 2007)
- Snow leopard observations (ISLT, Panthera, SLN, WCS 2008; Bhutan DoFPS 2016a, DoFPS 2016c)

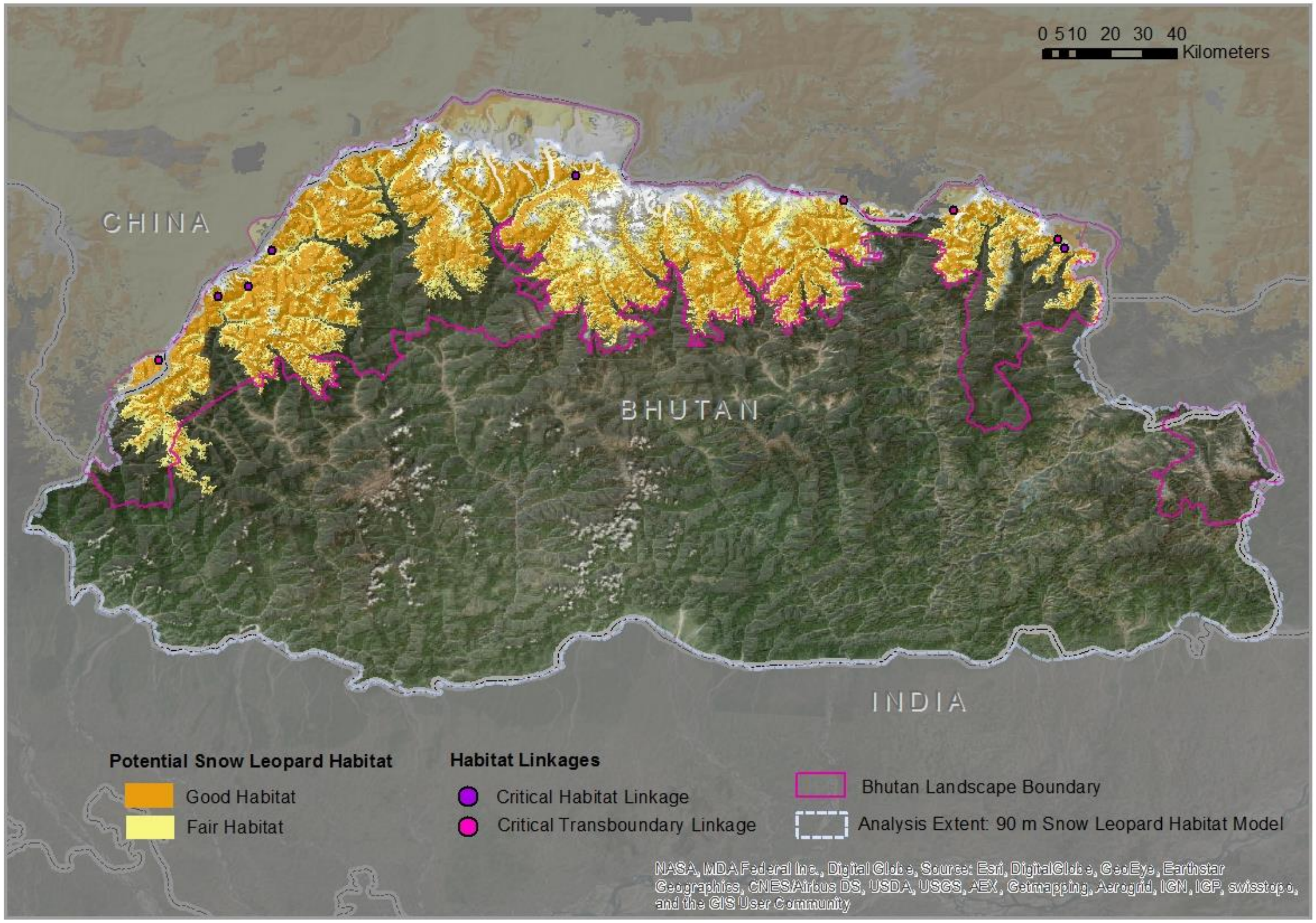
Regional Snow Leopard Habitat Model (outside pink box):

- Forrest et al. 2012

Other layers for display only:

- Glaciers (GLIMS & NSIDC 2016)
- Bhutan Landscape Boundary (Bhutan DoFPS, WWF & GSLEP 2016)
- Blue Marble Imagery (NASA, MDA Federal Inc., Digital Globe 2016)

Potential Snow Leopard Habitat and Critical Linkages in Bhutan



Potential snow leopard habitat and critical habitat linkages in the Bhutan Snow Leopard Landscape. *WWF 2017*

This map shows potential snow leopard habitat and critical linkages in the Bhutan Landscape.

Critical linkages were defined as areas that are currently narrow or potentially obstructed passages for snow leopards, or at-risk of becoming obstructed without special management. They include transboundary locations where snow leopards must cross into a neighboring country to remain in habitat, areas where good habitat is dissected by fair or non-habitat, and narrow habitat passages, near towns, roads, and or a cluster of settlements.

The methods used to produce the snow leopard habitat layer were described with the previous map.

Bhutan Snow Leopard Habitat Model:

- Land cover (Bhutan MoAF 2011)
- DEM, ruggedness (Lehner et al. 2008, Sappington et al. 2007)
- Snow leopard observations (ISLT, Panthera, SLN, WCS 2008; Bhutan DoFPS 2016)

Regional Snow Leopard Habitat Model: Forrest et al. 2012

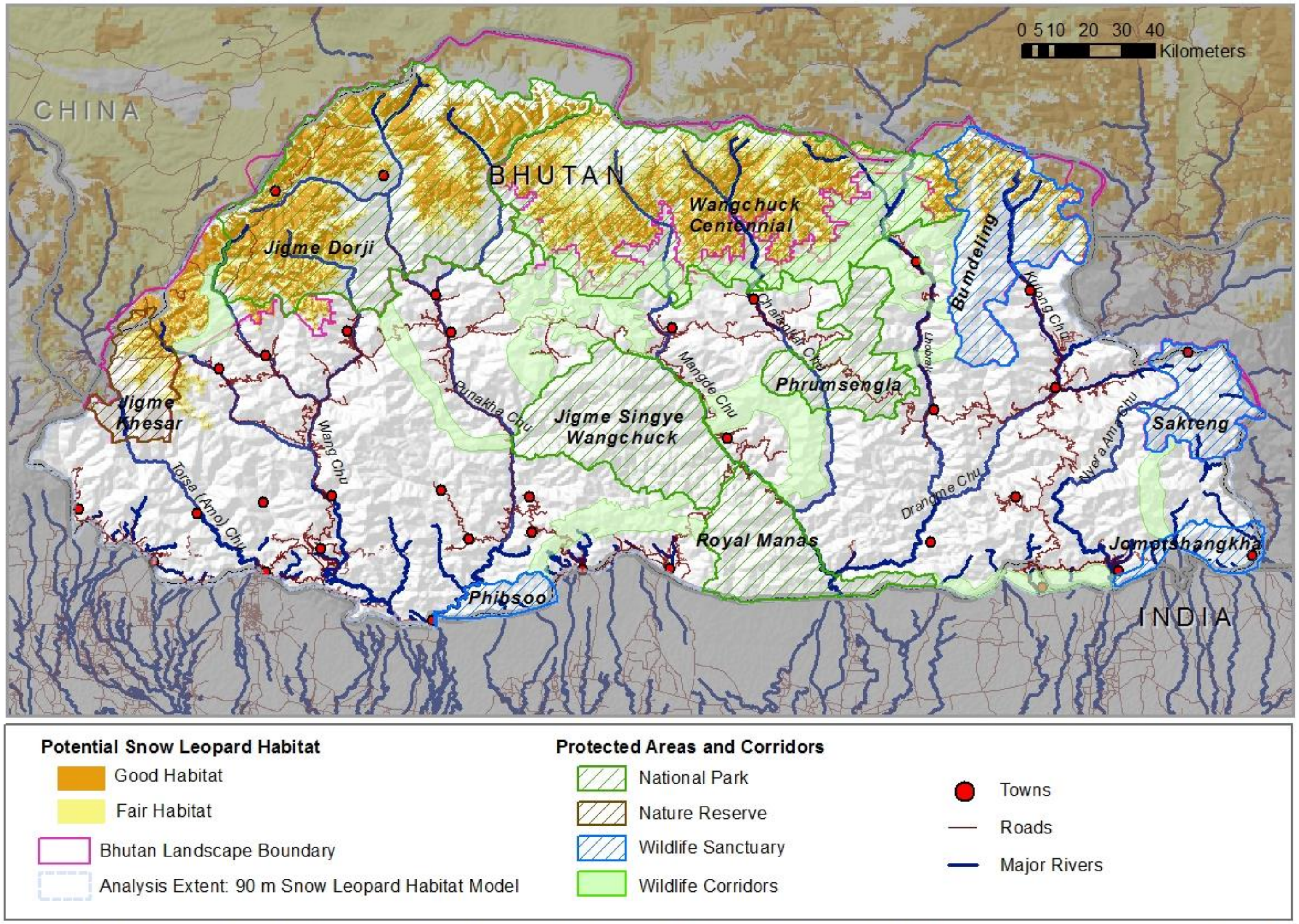
Critical Linkages:

- Roads (Bhutan NLC 2008)
- Settlements (Bhutan NLC 2016)
- Land cover (Bhutan MoAF 2011)
- Bhutan snow leopard habitat model (*this study*)

Other layers for display only:

- Glaciers: GLIMS & NSIDC 2016
- Bhutan Landscape Boundary (Bhutan DoFPS, WWF & GSLEP 2016)
- Blue Marble Imagery (NASA, MDA Federal Inc., Digital Globe

Protected Areas and Places of the Bhutan Landscape



Protected areas, roads, rivers, and major population centers of the Bhutan displayed with snow leopard habitat. *WWF 2017*

Protected areas cover over 5,950 km^2 or 91.8% of potential snow leopard habitat in Bhutan. As shown in Table 3.1, Wangchuck Centennial and Jigme Dorji National Parks have the most habitat among the protected areas, each with about 2,600 km^2 of protected snow leopard habitat. These areas also have the largest number of observed snow leopards, according to a recent survey (DoFPS 2016b). Jigme Khesar Strict Nature Reserve (JKSNR) also has a confirmed population of snow leopards (DoFPS 2016b). Though relatively small in area, JKSNR is significant for its connectivity to China and the rest of the Eastern Himalaya. Bumdeling Wildlife Sanctuary has a moderate amount of potential snow leopard habitat for the protected areas of northern Bhutan, and a blue sheep population. However, snow leopards are presumed to be extirpated from here, based on recent survey results. While habitats in Bumdeling WS may currently appropriate for snow leopard reintroduction (DoFPS 2016b), these habitats are also very vulnerable to climate change (as detailed later in the report).

Approximately 530 km^2 of snow leopard habitat remains unprotected in the western part of the country in the Paro Territorial Forest Division, which is located between Jigme Khesar Strict Nature Reserve and Jigme Dorji National Park. This habitat appears to form a vital connection between the westernmost part of the Bhutan landscape and the vast areas of habitat in northern Bhutan. Bhutan has an impressive system of wildlife corridors, but this habitat falls outside the corridor system as well. Snow leopards have been confirmed to use habitats in the PTFD and the neighboring protected areas, suggesting that rezoning this habitat as a snow leopard corridor or protected area may be reasonably justified (DoFPS 2016b).

Table 3.1. Protected Habitat Area in the Bhutan Landscape

Protected Area Name	Good Habitat (km2)	Fair Habitat (km2)	Total habitat (km2)
Bumdeling Wildlife Sanctuary	265	261	526
Jigme Dorji National Park	1675	922	2597
Jigme Khesar Strict Nature Reserve	90	124	214
Wangchuck Centennial National Park	1407	1216	2623
Total protected	**3437**	**2522**	**5959**

Bhutan Snow Leopard Habitat Model:

- Land cover (Bhutan MoAF 2011)
- DEM, ruggedness (Lehner et al. 2008, Sappington et al. 2007)
- Snow leopard observations (ISLT, Panthera, SLN, WCS 2008; Bhutan DoFPS 2016)

Regional Snow Leopard Habitat Model: Forrest et al. 2012

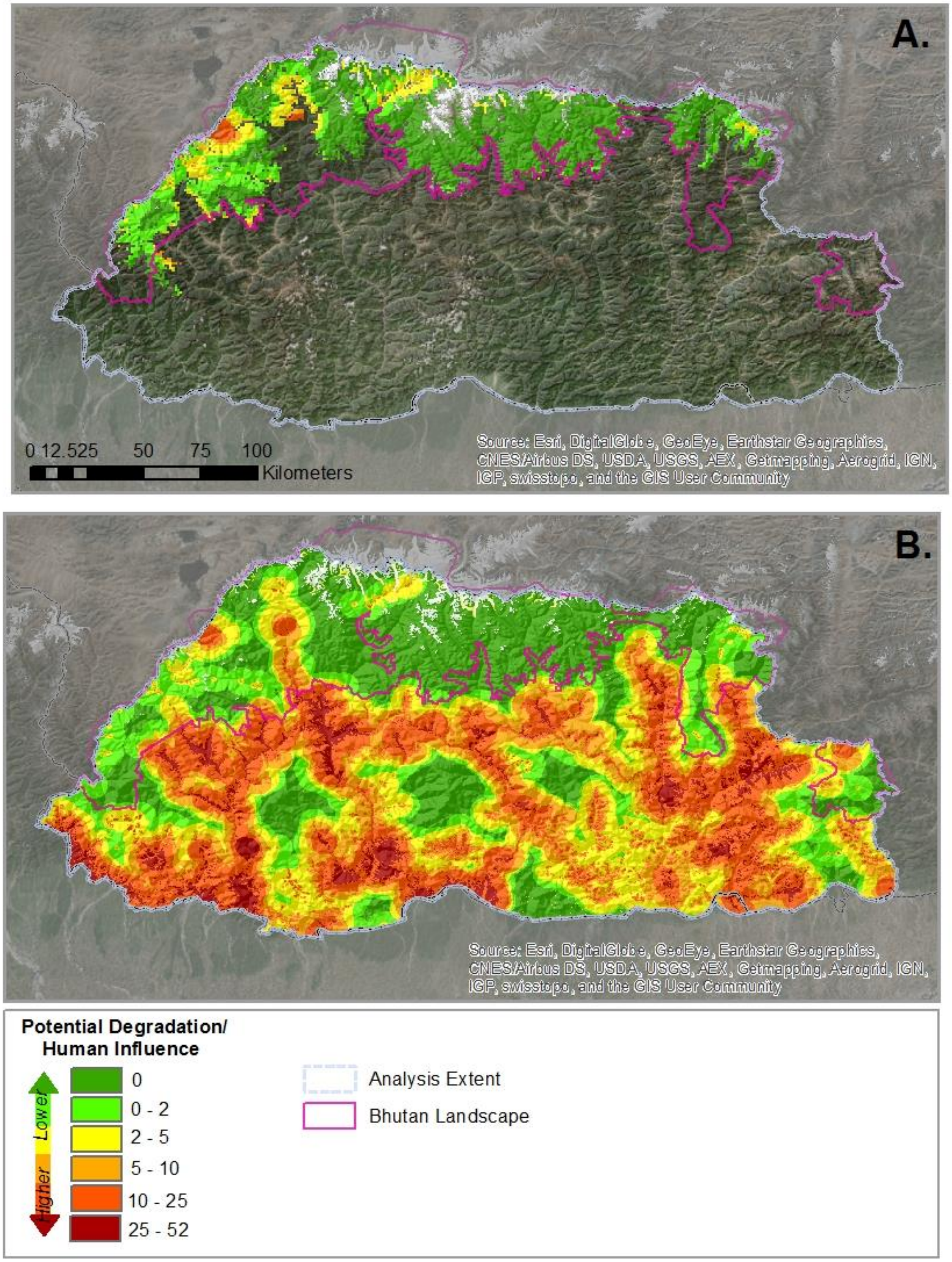
Human Landscape:

- Protected Areas and Corridors (DoFPS 2016c)
- Roads (Bhutan NLC 2008)
- Settlements (Bhutan NLC 2016)

Other Data:

- Glaciers (GLIMS & NSIDC 2016)
- Bhutan Landscape Boundary (Bhutan DoFPS, WWF & GSLEP 2016)

Potential for Degradation and Human Influence in Snow Leopard Habitat



Potential degradation and human influence of snow leopard habitat is represented by the relative amount of human activity and observed degradation. Map A shows human influence in snow leopard habitat, while Map B shows human influence across the country using the same model.

This map shows areas of potential degradation and human influence in the Bhutan Landscape. Human impacts are highest in the westernmost part of the landscape in Jigme Khesar Strict Nature Reserve and Jigme Dorji National Parks, and the unprotected habitats of the Paro Territorial Forest Division between. Human impact is also relatively high in the Lhobrak river valley, on the western side of Wangchuck Centennial National Park.

Snow leopards and their habitats are often directly affected by overgrazing and competition between livestock and prey, human wildlife conflict, direct hunting of snow leopard sand prey, tourism, and medicinal plant collection. We assume that degradation and threat drivers to snow leopards and their habitats are directly correlated with levels of human access via population centers, land use, roads and other infrastructure (Sanderson et al. 2002).

Methodology

Here, we represent human access through GIS layers on settlement density, land cover and land use, and distance to roads, settlements, mines and hydropower. Input layers were rescored according to Table 3.2 below and summed to produce a potential degradation and human influence layer according to methods developed by Sanderson et al. 2002. Scores represent the level of human impact relevant to snow leopards or large mammals with similar characteristics. A score of 0 represents no human impact, and 10 represents highest impact, across which snow leopards will not choose, or be unable, to move. This model was applied at the extent of Bhutan, both within and outside of snow leopard habitat. This was done so that the model could represent impacts to several species with similar wide-ranging characteristics. In all cases, the resulting human footprint data needs to be used in tandem with species habitat maps.

Table 3.2A. Land Cover Score for Human Footprint

Land cover	Potential Degradation Score
Conifer Forest	0
Broadleaf Forest	0
Shrubs	0
Meadows	0
Agriculture, Horticulture	8
Snow, glacier	0
Bare areas, degraded areas	5
Water bodies, marshy areas	0
Built-up areas	10
Non-Built up Areas	6

Table 3.2B. Distance to Populated Place Score for Human Footprint

Distance to Populated Place	Potential Degradation/Cost of Movement
Distance to Towns (m)	
0-3000	10
3000-5000	8
5000-10,000	3

10,000-12,000	1
>12,000	0
Distance to Settlements (Single dwellings) (m)	
0-90	10
90-270	8
270-450	4
450-1000	2
1000-5000	1
>5000	0

Table 3.2B. Settlement Kernel Density Scores for Human Footprint

Settlement density	Potential Degradation/Cost of Movement Score
0	0
0.0001-0.5	1
0.5-1	2
1-2	3
2-5	4
5-10	8
>10	10

Table 3.2C. Distance to Infrastructure Scores for Human Footprint

Distance to Infrastructure	Potential Degradation/Cost of Movement Score
Distance to Road (m)	
0-90	10
90-270	8
270-500	6
500-3000	3
3000-5000	2
>5000	0
Distance to Mines (m)	
0-500	10
500-1000	5
1000-2000	2
2000-3000	1
>3000	0
Distance to Hydropower	
0-90	10
90-270	6
270-500	4
500-2000	2
2000-3000	1
>3000	0

[1] almost all are paved roads. There are some unpaved roads, but these are in close proximity to the major roads.

Data sources:

Bhutan Snow Leopard Habitat Model:

- Land cover (Bhutan MoAF 2011)
- DEM, ruggedness (Lehner et al. 2008, Sappington et al. 2007)
- Snow leopard observations (ISLT, Panthera, SLN, WCS 2008; Bhutan DoFPS 2016)

Regional Snow Leopard Habitat Model: Forrest et al. 2012

Human Footprint

- Roads (Bhutan NLC 2008)
- Settlements (Bhutan NLC 2016)
- Mines (Bhutan DGM MoEA 1995)
- Hydropower (Bhutan DHMS MoEA 2014)
- Land cover (Bhutan MoAF 2011)

Other data:

- Glaciers (GLIMS & NSIDC 2016)
- Bhutan Landscape Boundary (Bhutan DoFPS, WWF & GSLEP 2016)
- Blue Marble Imagery (NASA, MDA Federal Inc., Digital Globe)

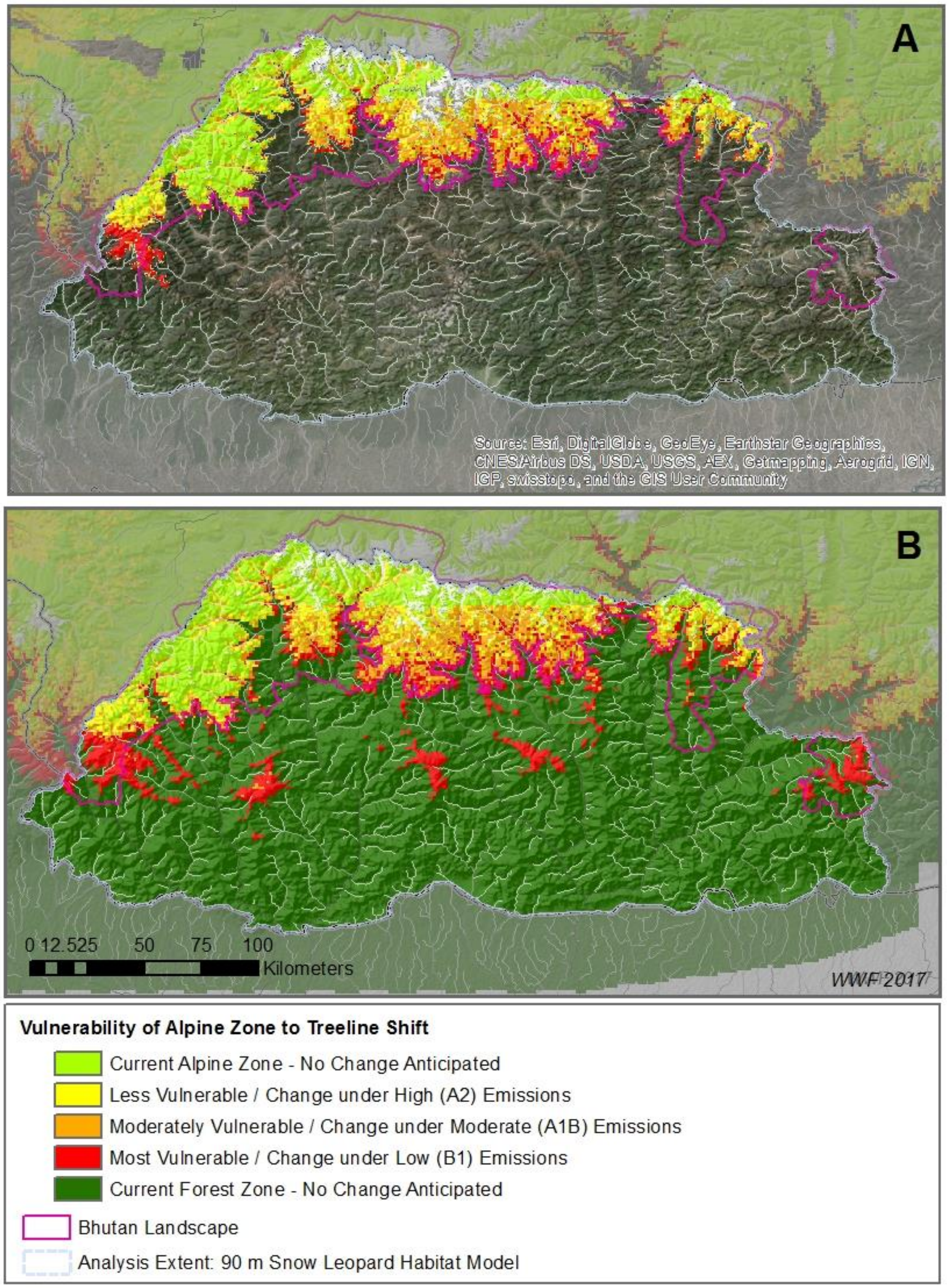
Potential Climate Change Impacts in the Bhutan Landscape

The Bhutan landscape is expected to experience an increase in average annual temperature of about +1.8˚C to 2.5˚C by the mid-century time frame of 2041-2070. The highest degree of warming will likely occur during the coldest months of the year. Warming temperatures during the January to April months can mean more precipitation as rain rather than as snow, earlier snow melt, and shorter winters (Peters et al. 2017).

Precipitation is also expected to increase in Bhutan, with the sharpest increases to occur during the monsoon season (+35-40% above baseline by mid-century) (Peters et al. 2017). Potential impacts of these climate changes include changes in ecological communities to those favoring shorter winters and longer growing seasons loss of alpine habitats from permafrost loss and treeline shift, changes in livestock grazing patterns, changes in the timing and quantity of available water, and increased risk of extreme events such as flooding and landslides, particularly during the monsoon (Climate Smart Snow Leopard Management Planning Workshop, April of 2016).

We selected a few indicators of climate change impacts for mapping in order to better understand the spatial distribution of climate risk for alpine wildlife and human communities. These included the distribution of treeline shift risk in the landscape (or the transition from a climate zone favouring alpine grassland to one favouring forest); potential change in the suitable climate envelope for cropland (indicating changing human habitability, but also human pressure on wildlife habitat); water towers (or water provision to the downstream from rainfall); winter duration (indicated by freeze-line, with implications on ecological functions as well as water availability for people); and change in open water availability (which is a good indicator of overall changes to a landscape). The latter three, and other hydrological functions, are covered in more depth by Sindorf 2017.

Vulnerability of Snow Leopard Habitat to Treeline Shift from Climate Change



Vulnerability of snow leopard habitat to climate-change induced treeline shift.
Map A shows projected change of snow leopard habitat to forest under climate change.
Map B shows projected change in the forest and alpine zones across the study area.

The snow leopard habitats in Bhutan are very vulnerable to climate change-driven ecosystem change, with a predicted loss of 60% of existing habitats under a high emissions scenario. There is a gradient in vulnerability from east to west and from low elevations to high, with habitats in the east and at lowest elevations as most vulnerable to potential treeline shift. Habitats in western Bhutan are most likely to remain as refugia, though these habitats will likely decrease in size and may become fragmented due to direct human impacts without proper management.

Treeline is expected to shift as temperatures become warmer and wetter, and the growing season in alpine areas becomes more hospitable (Forrest et al. 2012). Areas that become warmer, wetter, and more suitable for natural forests may also become more suitable for crops and livestock, encouraging human immigration. These indirect effects of climate change may also result in habitat loss. This model does not account for microrefugia that may exist currently and/or persist due to local climate conditions in this montane landscape (Thapa et al. 2016). However, snow leopards are wide-ranging species, so micro-refugia may not offer ample breeding or connectivity habitat for snow leopards.

Bhutan Snow Leopard Habitat:

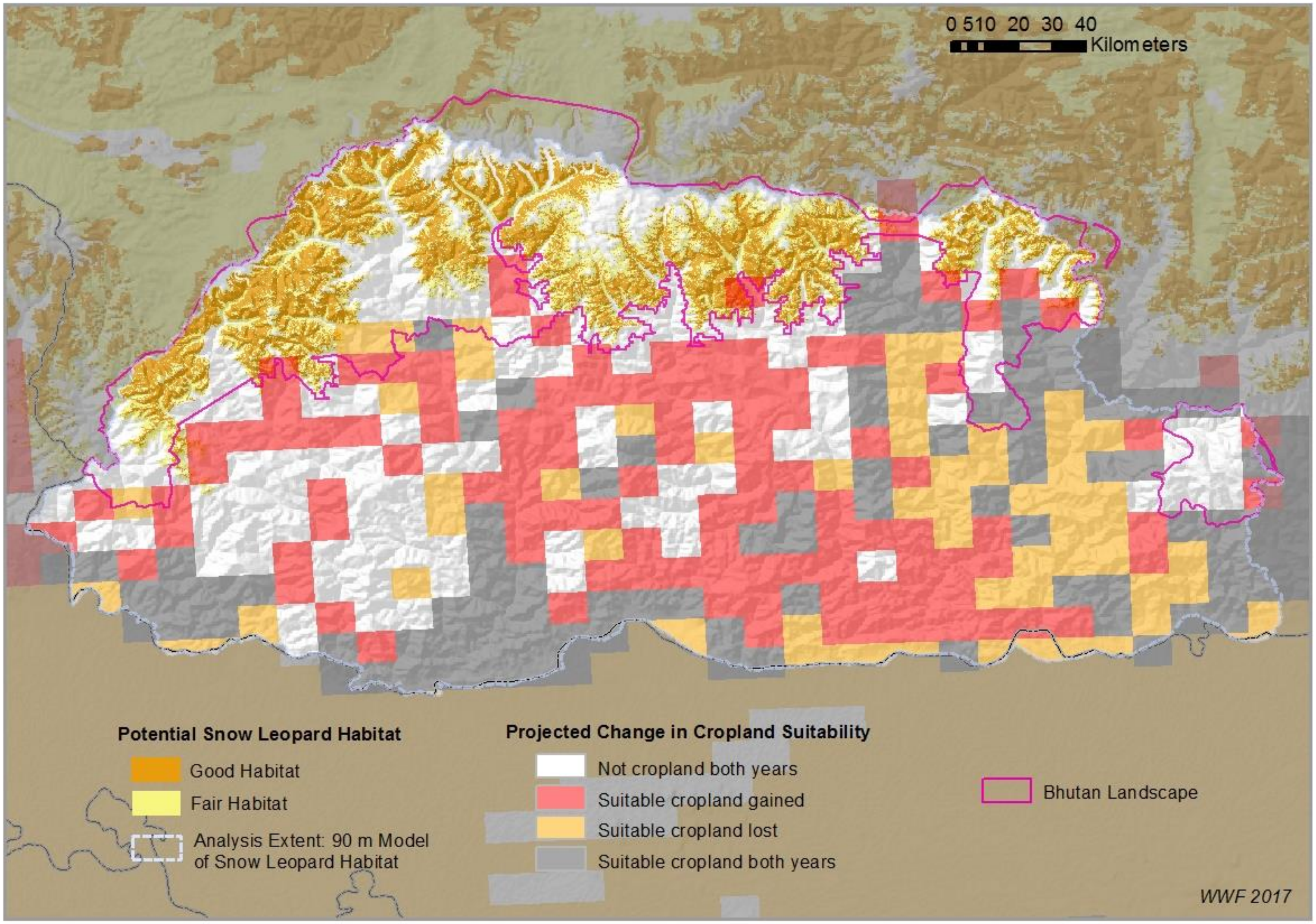
- Land cover (Bhutan MoAF 2011)
- DEM, ruggedness (Lehner et al. 2008, Sappington et al. 2007)
- Snow leopard observations (ISLT, Panthera, SLN, WCS 2008; Bhutan DoFPS 2016a)

Projected Change in Treeline under Climate Change: Forrest et al. 2012

Other layers for display only:

- Glaciers: GLIMS & NSIDC 2016
- Bhutan Landscape Boundary (Bhutan DoFPS, WWF & GSLEP 2015-16)

Projected Change in Cropland Suitability under Climate Change in Bhutan



This map shows how climate suitability for growing crops may shift under a high emissions (A2) scenario to the year 2100.

This map shows current climate niche and potential change in the extent of the arable land (or cropland) climate envelope after a high emissions climate change scenario. **The suitable climate envelope for arable land is likely to increase in western and central Bhutan-though generally at elevations below snow leopard habitat. Suitability for arable land is likely to decrease in eastern Bhutan.** While “encroachment” of arable land suitability into snow leopard habitat may not be a huge concern in this landscape, pressure on water originating in the snow leopard habitat of western and central Bhutan may increase. This emphasizes the need for snow-leopard friendly water management practices and planning.

The map of current climate suitability for arable land was projected using the Global Arable Lands database (Ramankutty et al. 2008) as observations, and 19 bioclimatic variables (Hijmans et al. 2005) as environmental layers. It was then projected under a high emission scenario (A2A) using the HADCM3 General Circulation Model to the year 2100 (Sindorf et al. 2014). This model extent includes the entire snow leopard range, though only the portion encompassing Bhutan is displayed here.

Bhutan Snow Leopard Habitat Model:

- Land cover (Bhutan MoAF 2011)
- DEM, ruggedness (Lehner et al. 2008, Sappington et al. 2007)
- Snow leopard observations (ISLT, Panthera, SLN, WCS 2008; Bhutan DoFPS 2016)

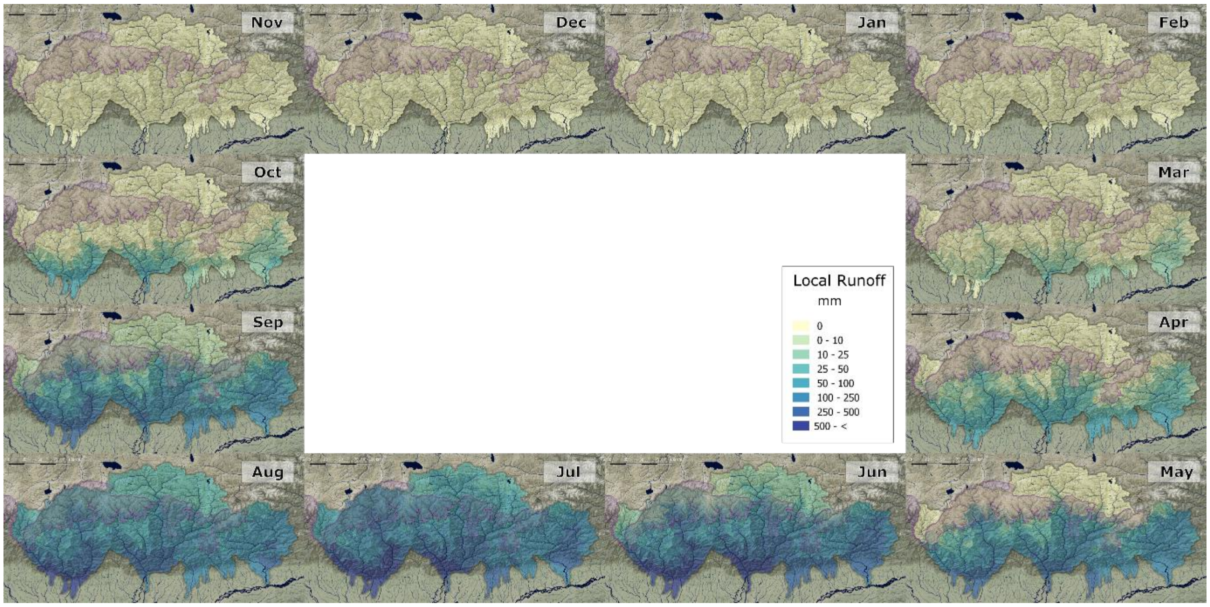
Regional Snow Leopard Habitat Model: Forrest et al. 2012

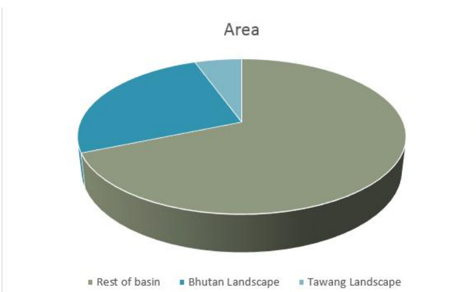
Projected Change in Cropland Suitability: Sindorf et al. 2014

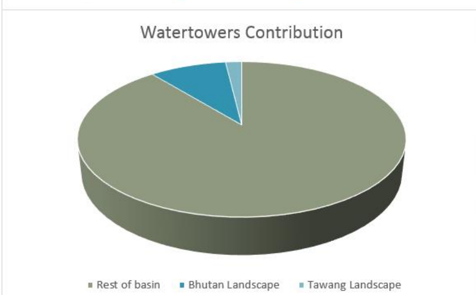
Other Data:

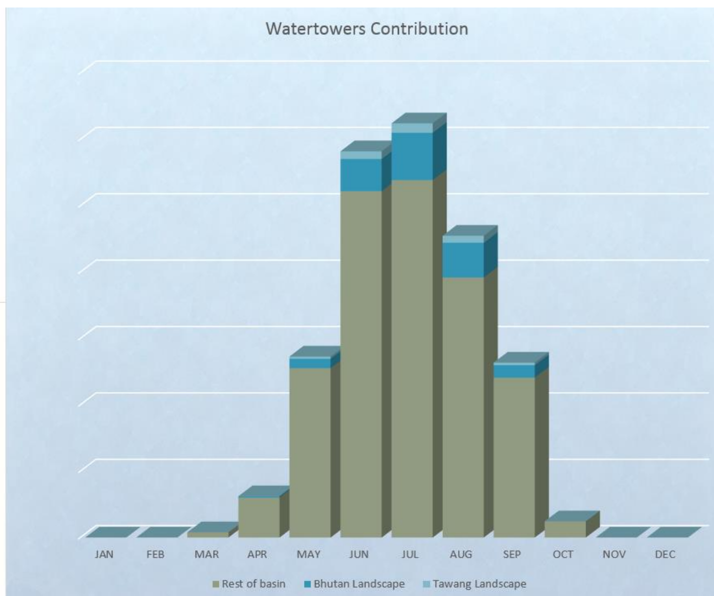
- Glaciers: GLIMS & NSIDC 2016
- Bhutan Landscape Boundary (Bhutan DoFPS, WWF & GSLEP 2016)

Water Towers (Local Runoff) in the Bhutan Landscape and Sub-basin









Water Towers/ Local Runoff	
Baseline Condition	The landscape is located entirely upstream of the Bhutan "water towers" and it represents the driest part of the basin. Throughout the dry season (October-May), when downstream water demand is highest, there is a clear mismatch between the landscape location and water provision areas in the sub-basin.
Projected Climate Change	Under a high precipitation scenario, precipitation and run-off would increase considerably. Annual runoff could increase by 81%, but concentrated during the monsoon season. This could lead to a vastly greater risk of monsoon-related floods downstream. While the low precipitation estimate predicts a 1% increase in annual runoff, the number of projections are skewed toward more run-off, implying a high likelihood of increased run-off under climate change.

Within the sub-basin, there is a distinctive North-South gradient in runoff generation from precipitation, which is entirely driven by the monsoon. The Bhutan Landscape sits just upstream of the water towers, and it is the driest part of the sub-basin. In fact, the landscape covers just over 25% of the sub-basin, but contributes to only 9% of its run-off. Throughout the dry season (October to May), when downstream water demand is highest, the landscape does not serve as a water tower from precipitation alone. During April and May, which is also the late dry season downstream, melting within the landscape helps to offset downstream water needs – though this is not represented in this particular model.

Within 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.

Figure 3.1 shows potential change in the water tower function of the landscape compared with the rest of the sub-basin under low and high precipitation projections to mid-century. The low-end estimate aligns well with the baseline scenario. Under a high-precipitation scenario, annual runoff could increase by 81%, but concentrated during the monsoon season (May to September). Accordingly, monsoon runoff could increase by 56.5% compared with the baseline, leading to a vastly increased risk of floods and landslides. The number of predictions are skewed towards more monsoon precipitation and run-off, implying that a high-end precipitation scenario is more likely than a future with baseline level precipitation.

Figure 3.1. Projected change in the relative water tower function of the Bhutan Landscape compared with the rest of the landscape under baseline and future precipitation scenarios

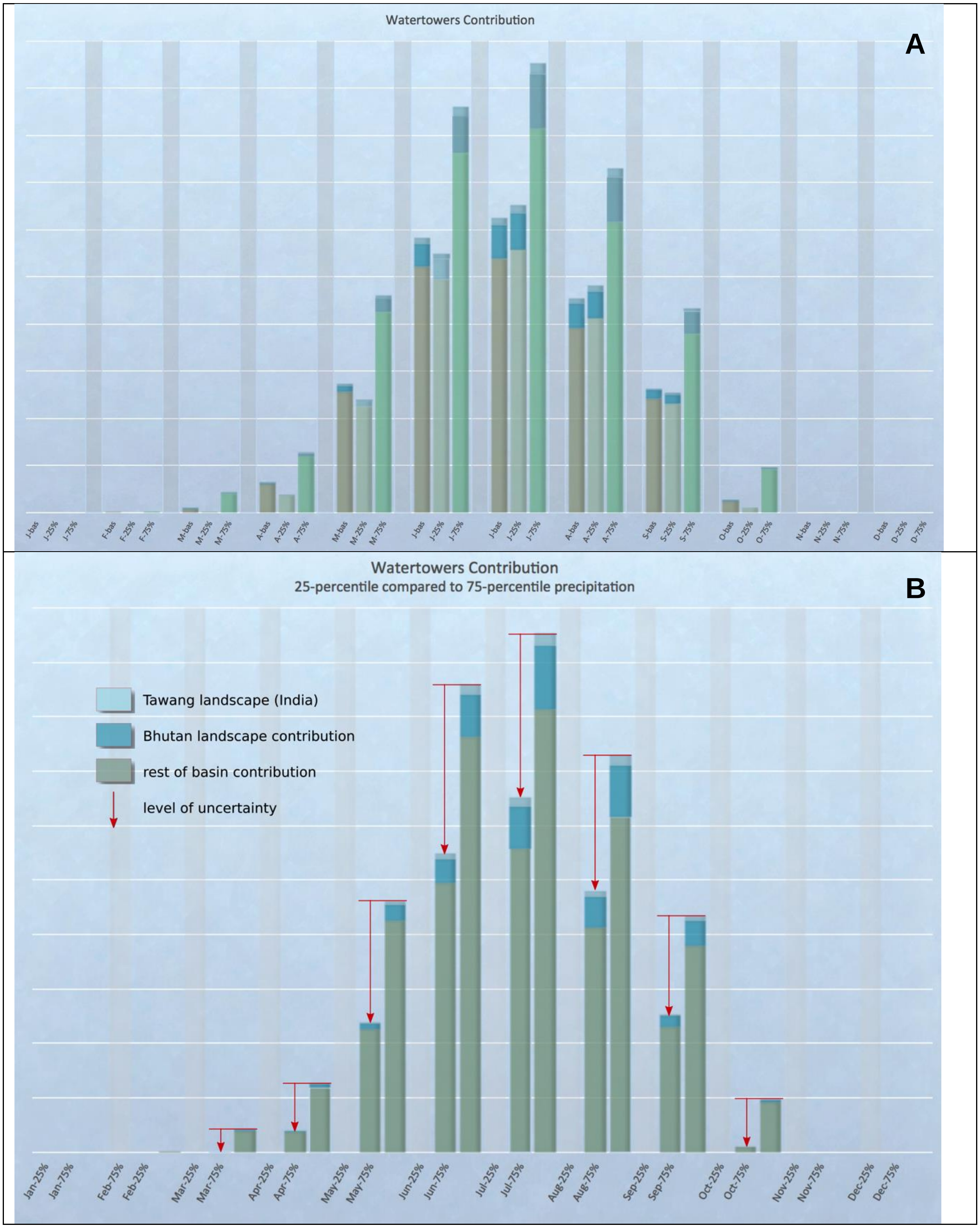
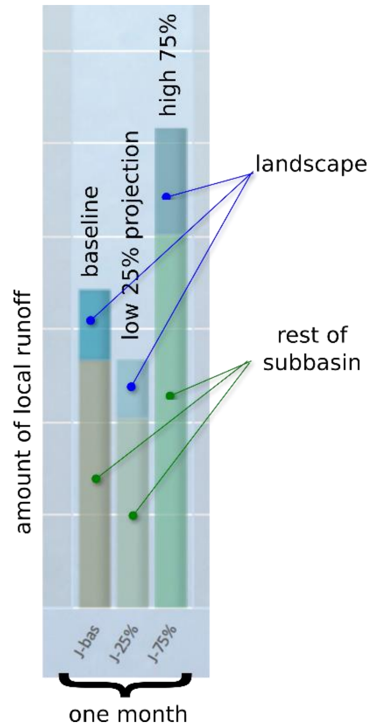


Figure 3.1A shows relative water tower contributions of the Bhutan Landscape compared with the rest of the sub-basin under baseline year and 25-percentile and 75-percentile mid-century precipitation projections (Peters et al. 2017, Sindorf 2017). Figure 3.1B compares the relative water tower contribution of the landscape with the rest of the sub-basin under low and high mid-century precipitation projections, and also expresses the range of uncertainty. Relative run-off from the landscape is represented by the blue color at the top of each bar, while run-off from the rest of the sub-basin is represented by the bottom portion of the bars. Red arrows show the range of changes in run-off based on the two projections, and therefore illustrates uncertainty in future climate impacts on runoff.



Methodology

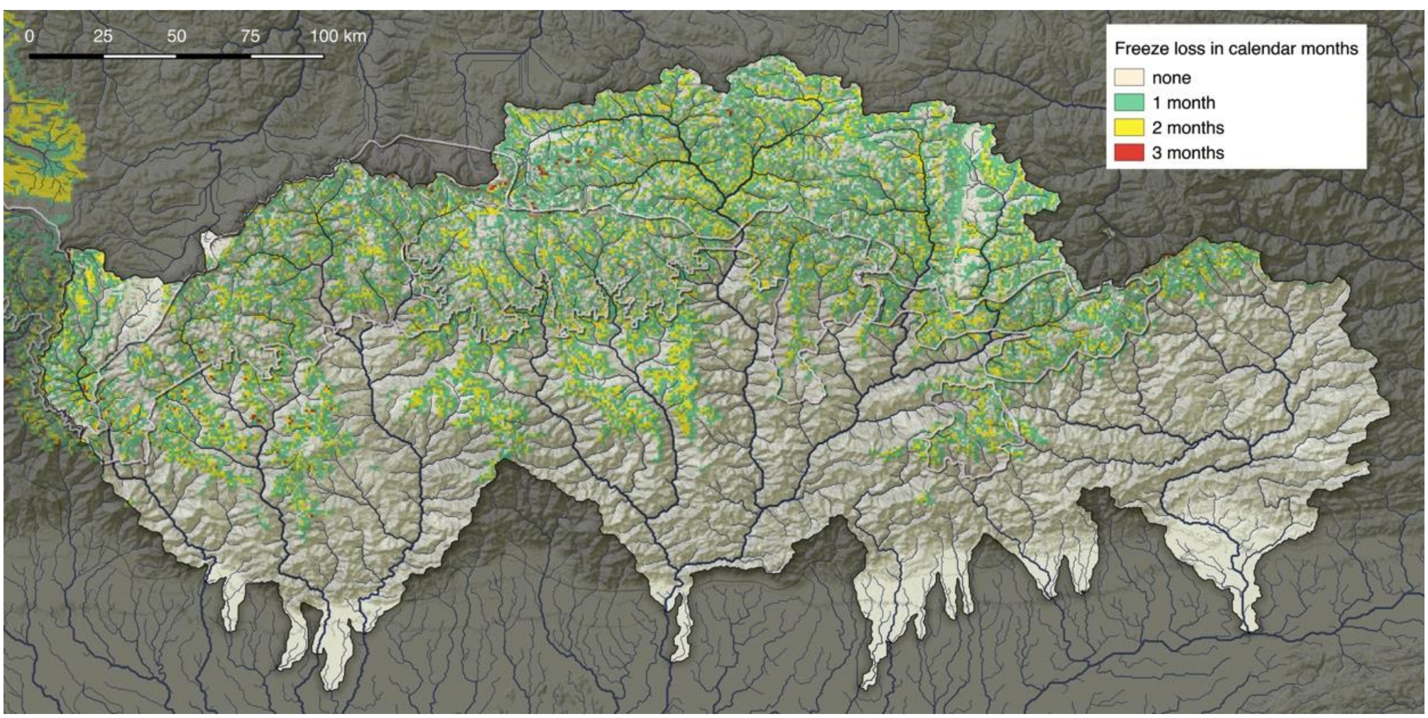
Local runoff is the difference between monthly precipitation (P) and actual evapotranspiration (AET). Monthly precipitation and AET are downloaded and, through a simple GIS command, summarized by their watershed 'mean', using HydroBASINS level 12 watersheds. The mean values were multiplied by each of the watershed areas in order to convert from millimetres to cubic meters. Next, mean actual evapotranspiration was subtracted from mean precipitation (P – AET) for each month. Local runoff values that were less than zero were displayed and flagged as being zero. Inside the sub-basin, those watersheds that drain the snow leopard landscape were also flagged to summarize run-off contribution from the landscape alone. For more information, see Sindorf 2017.

Data Sources

- Current Mean Monthly Precipitation, based on historic WorldClim, 30s resolution (Hijmans et al. 2005)
- Current Mean Monthly Actual Evapotranspiration, based on historic Global Soil-Water-Balance, CGIAR, 30s resolution (Trabucco and Zomer 2010)
- HydroBASINS, level 12, ~100 km^2 watershed outlines (Lehner and Grill 2013)
- Climate Projections on future temperatures and precipitation (Peters et al. 2017)

Decrease in Monthly Freeze Extent under Temperature Rise in the Bhutan Landscape Sub-basin

Calendar Months in Freeze Loss



Snow cover, Frozen Ground, and Freeze Line	
Baseline Condition	Frozen ground covers much of the landscape during the winter, and shifts upslope to only include dispersed mountaintops in the summer.
Projected Climate Change	A shift in freeze line under future climate change will be linear and closely follow the temperature gradients around the mountain ranges, from a few hundred meters to kilometers away from the baseline monthly position by mid-century. During the winter, the difference in the amount of frozen ground will be minimal compared with current conditions. During the summer, some of the 'eternal' mountaintop snowfields may experience melt. The Tibetan Plateau is unlikely to experience a change in patterns of frozen ground by mid-century.

The above maps illustrate for each month how the spatial footprint of the freeze frontier is expected to change under projected temperature rise to mid-century. The freeze line is an indicator of the average timing of snowfall and snow and ice-melt, subsequent water availability, and trends in glacier and permafrost coverage. It is also an indicator of phenological processes such as the timing of green-up and leaf-fall, breeding and birthing, and animal movements. Seasonal changes can selectively impact species, ultimately affecting the composition of vegetation and animal communities in the landscape.

During the winter months (November to March), the Tibetan plateau forms the core frozen area, and the freeze line is on the southern slopes of the Himalayas. In the summer and monsoon months (May to September), the freeze line shifts to surround some mountaintops, particularly near Masang Gang, which form small frozen islands in an otherwise warmer landscape. In the transitional months (April and October), the freeze line is on the Tibetan plateau and the valleys between the mountain complexes.

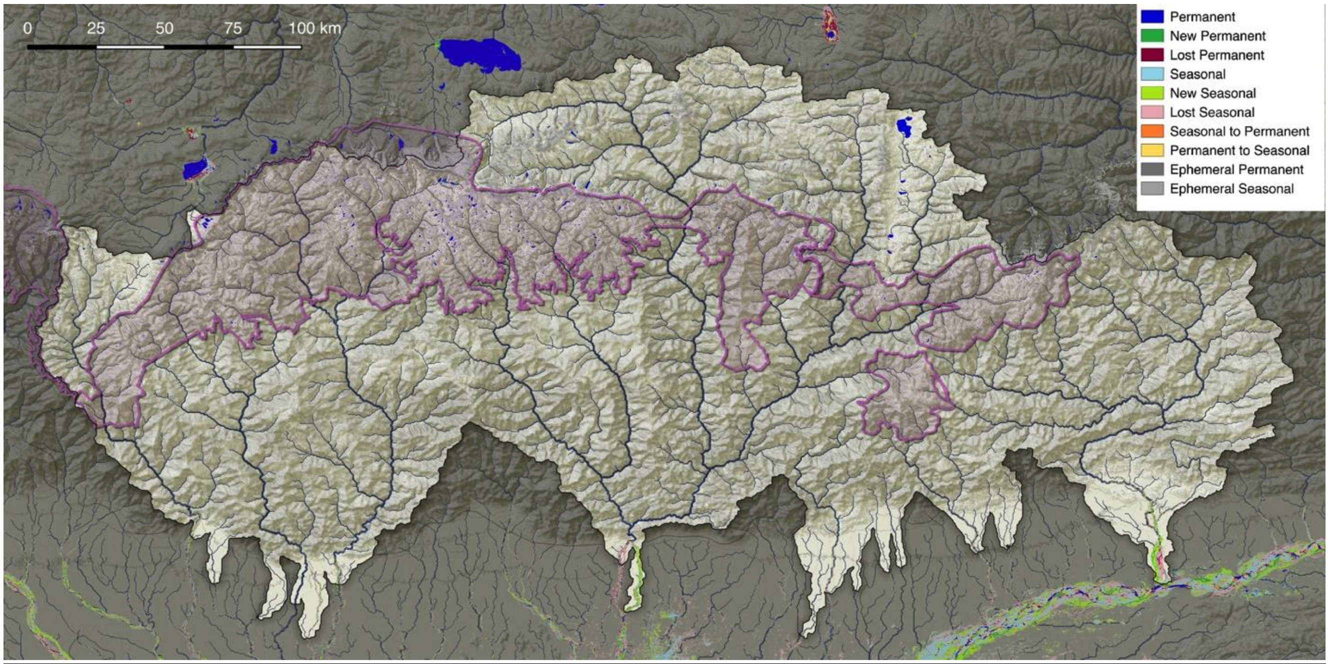
A shift in the freeze line under changing climate would be linear and closely follows the temperature gradients around the different mountain ranges. There is no signal that indicates a larger spatial footprint of change on the Tibetan Plateau. For the winter months, the difference in future freezeline will be minimal, but for the summer months a freezeline shift of a few hundred meters might severely impact the "eternal" snowfields around the mountaintops.

Data Sources:

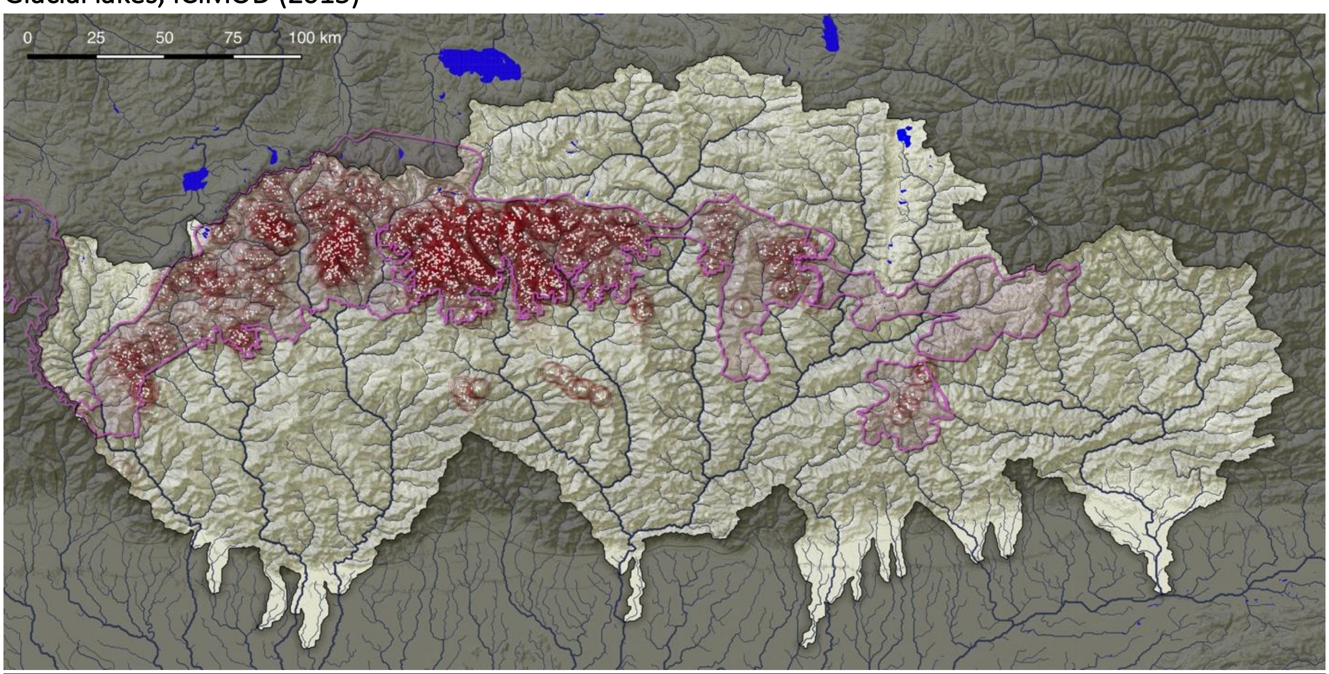
Current Mean Monthly Temperatures, based on historic WorldClim, 30s resolution (Hijmans et al. 2005)

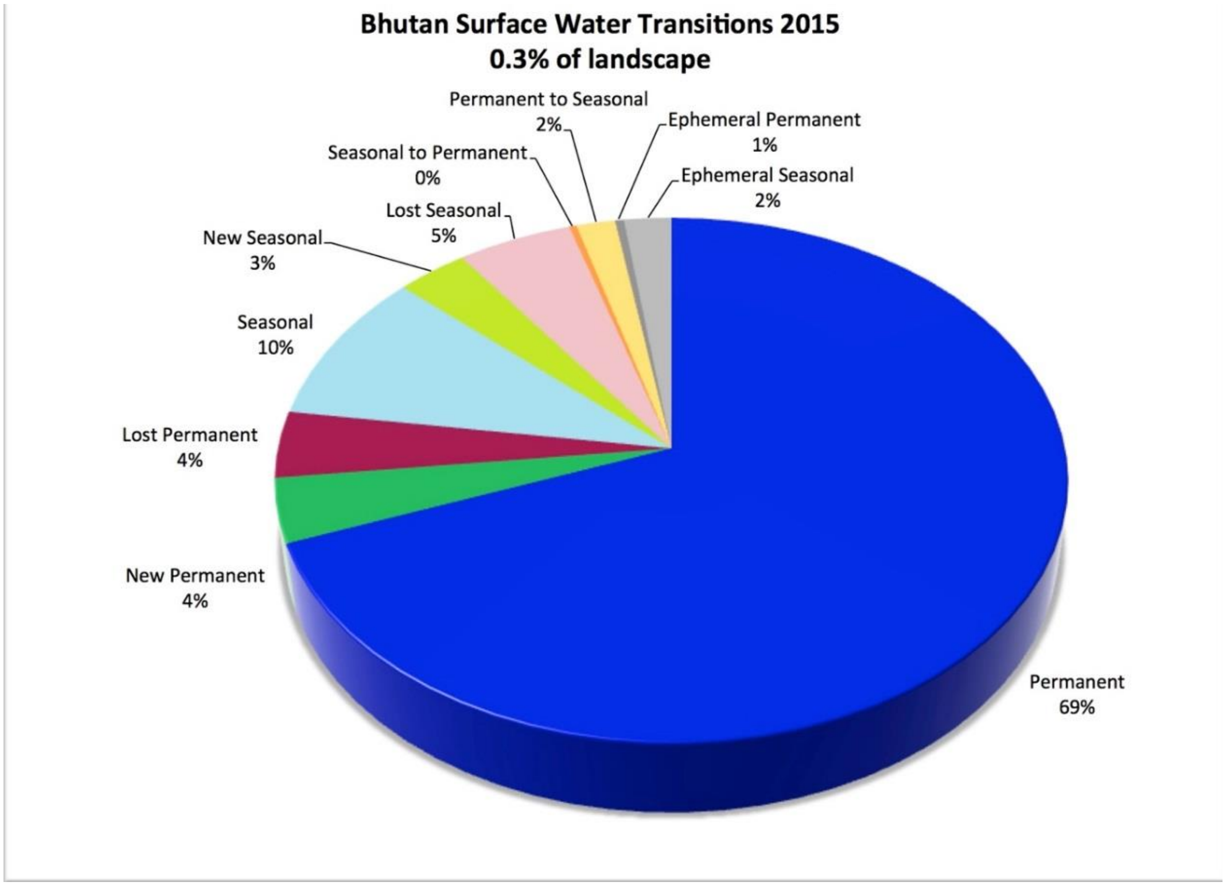
Climate Projections on future temperatures and precipitation (Peters et al. 2017)

Observed Surface Water Transitions (1984-2015) in the Bhutan Landscape Sub-basin



Glacial lakes, ICIMOD (2015)




Bhutan Surface Water Transitions 2015
0.3% of landscape
Permanent to Seasonal
2%
Ephemeral Permanent
1%
Seasonal to Permanent
0%
Ephemeral Seasonal
2%
Lost Seasonal
5%
New Seasonal
3%
Seasonal
10%
Lost Permanent
4%
New Permanent
4%
Permanent
69%

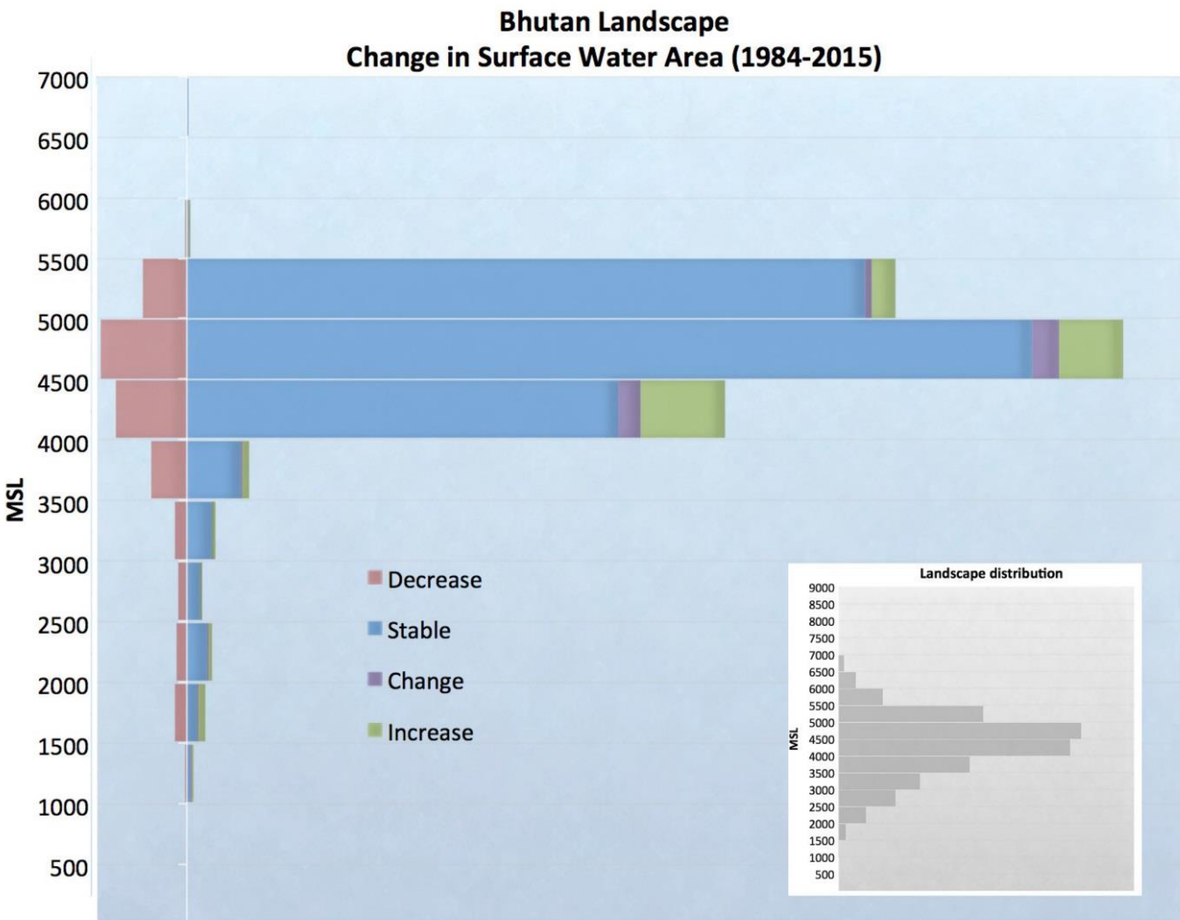
Lakes, wetlands and floodplains	
Baseline Condition	2674 glacial lakes have been identified in Bhutan (Mool 2001, ICIMOD 2015), the majority of which can be found inside the snow leopard landscape.
Observed Historic Change (1984-2015) and Projected Climate Change	The extent of open surface water has been relatively stable over the 1984-2015 period, though with significant dynamism at the elevations where glacial lakes are located. Changes in water storage, e.g. due to glacial melt, would not leave a large spatial footprint, since lakes in Bhutan in general have steep slopes. It is, however, likely that their water levels have increased over this period.

Inside the landscape, only 0.13% is classified as open surface water (Pekel et al. 2016). The following transitions occurred between 1984 and 2015:

- 82% of the open water surface was *stable* (permanent 69%, seasonal 10%, ephemeral 3%)
- 9% of the open water surface *disappeared* (permanent 4%, seasonal 5%)
- 7% was classified as *new* surface water (permanent 4%, seasonal 3%)
- while 2% of all open water surface *changed from permanent to seasonal*.

According to Figure 3.2, most of the open surface water is located at the elevation belt of 4,000 to 5,500 msl. These depict the glacial lakes directly downstream of the glaciers, and an independent assessment has identified 2674 such lakes (Mool 2001, ICIMOD 2015). The significant increases and decreases in open water surfaces at this elevation signal dynamism in lake coverage, but do not result in a huge amount of net change in surface extent. In this landscape, changes in water storage (e.g. due to glacial melt), would not leave a large spatial footprint, since lakes in Bhutan in general have steep slopes. It is, however, likely that their water levels have increased over this period. This surface water database would not detect such a change since it focuses on water surfaces and not volumes of water.

Figure 3.2. Change in Surface Water Area in the Bhutan Landscape



Methodology

This analysis was drawn from a map of global surface water and long-term changes (Pekel, 2016). It contains at least 6 different datasets, and the online version allows time-lapse analysis from 1984-2015. The dates coincide with Landsat coverage, which is the key dataset. For more information on methods, please also refer to Sindorf 2017.

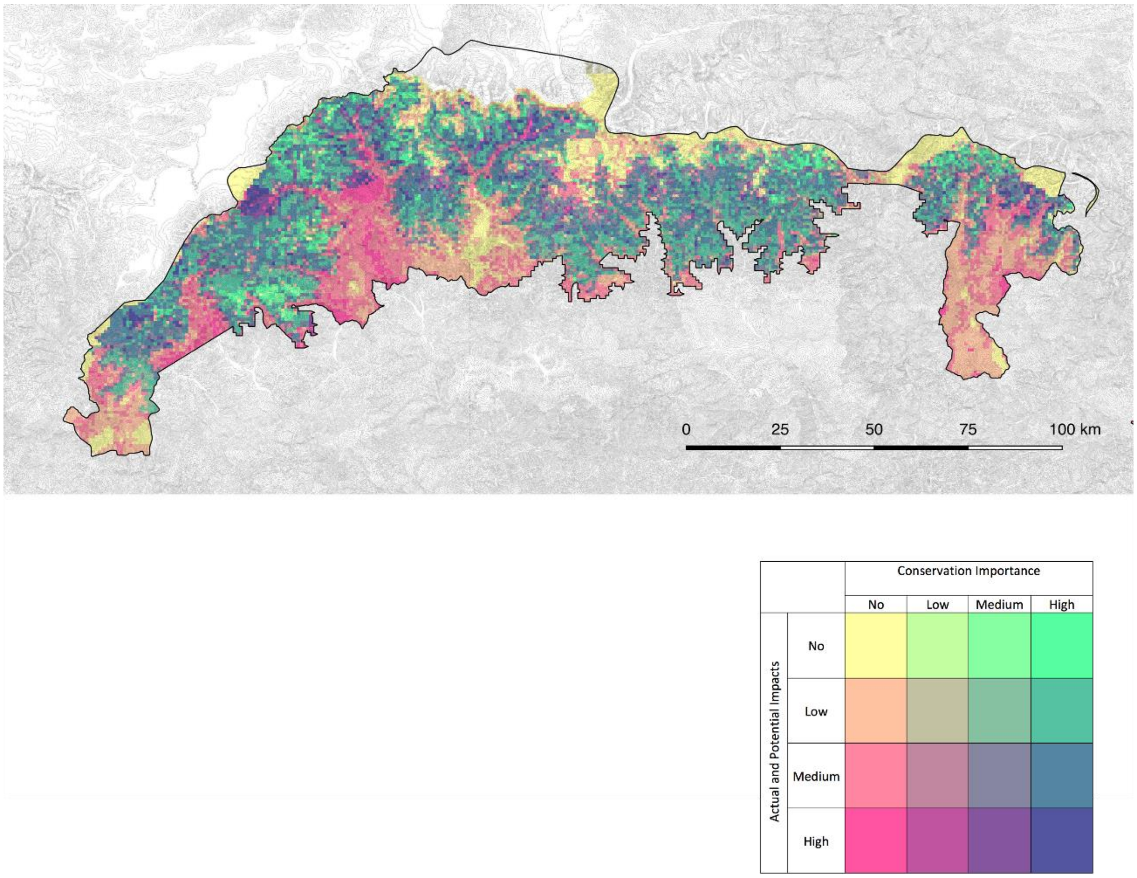
Data Sources

High-resolution mapping of global surface water and its long-term changes (Pekel et al. 2016)

Inventory of glaciers, glacial lakes and glacial lake outburst floods: monitoring and early warning systems in the Hindu Kush-Himalayan region, Bhutan (Mool et al. 2001)

Glacier and glacial lakes database of Bhutan (ICIMOD 2015)

Summary of Conservation Importance and Potential Impacts in the Bhutan Landscapes



This map displays the landscape according to conservation importance and actual and potential impacts. Conservation importance is represented by snow leopard habitat suitability, and actual and potential impacts are represented by climate vulnerability and direct human impacts. Results indicate that much of the important habitat of the landscape is under high risk of impact (dark blue). This is particularly evident in the southern and western side of the landscape as well as the far eastern edge, where human access is relatively high. The habitats of high conservation importance in the central part of the landscape are subject to slightly lower cumulative risk (medium blue and green) and may be more resilient in the long term. Areas of important habitat at low risk (bright green) are located on isolated mountain tops. These low risk areas tend to be fragmented by habitats at higher risk, requiring management across threat levels to maintain habitat and metapopulation connectivity.

Methodology

This map was created to display conservation importance and actual and potential impacts. Conservation importance was represented by data on snow leopard habitat suitability. Actual and potential impacts from climate change vulnerability are represented by potential treeline shift and number of months of winter expected to be lost. Impacts from humans are represented by the human footprint. For each of these layers, scores representing value (in the case of conservation importance) or severity (in the case of impacts) were developed in collaboration with field experts, and assigned as presented in Table 3.3. A score of 0 indicates the lowest score possible, and a score of 8 indicates the highest. Protected areas were not included, since most habitat in the landscape is under protected status. The values in the tables correspond with the 'raw' values of each input GIS data layer. The qualitative scores of conservation importance and impacts were summed with others in their class, then combined into a single map with 16 different combinations.

Table 3.3A. Conservation Importance

Score	Habitat Suitability
0	0
1	
2	
3	
4	
5	
6	3
7	2
8	1

Table 3.3B. Actual and Potential Impacts

Score	Treeline shift	Months of freeze loss	Human Footprint
0	0, 4	0	0
1	3		
2		1	1-5
3	2		
4		2	6-10
5	1		
6		3	
7			
8			>11

Combined scores: No: 0; Low: 1-3; Medium: 4-7; High: >8

II. Analysis and Mapping of Snow Leopard Habitat in the Sikkim Landscape, India

September 8, 2017

Partha Ghose, Jessica Forrest, Nikolai Sindorf, Areendran Gopala

World Wildlife Fund, with funding from the

United States Agency for International Development (USAID)

Chapter 2 of 6 of the report:

Guardians of the Headwaters II:
Biodiversity, water, and climate in six snow leopard landscapes

Key Findings and Management Recommendations

- **The Sikkim landscape offers a relatively small but rich habitat for snow leopards, critical to metapopulation connectivity in the Himalayan mountain range.** The landscape is located at the heart of the eastern Himalaya, connecting the habitats of China and Bhutan in the east to Nepal in the west. It offers over 1,000 km^2 of breeding habitats and nearly 2,000 km^2 of good dispersal habitats. Currently, all habitat in the landscape is connected. Recently concluded camera trap surveys in the plateau regions and adjacent areas of North Sikkim indicate that there may be 12 snow leopards in the landscape.

- **Transboundary management is key.** Recent monitoring of radio-collared snow leopards in Nepal establishes clearly that the species require vast areas to survive, and that there is cross-border movement of the species between Sikkim and Nepal. It is necessary to establish transboundary management cooperation with Nepal, Bhutan and China to ensure effective conservation of the metapopulation.

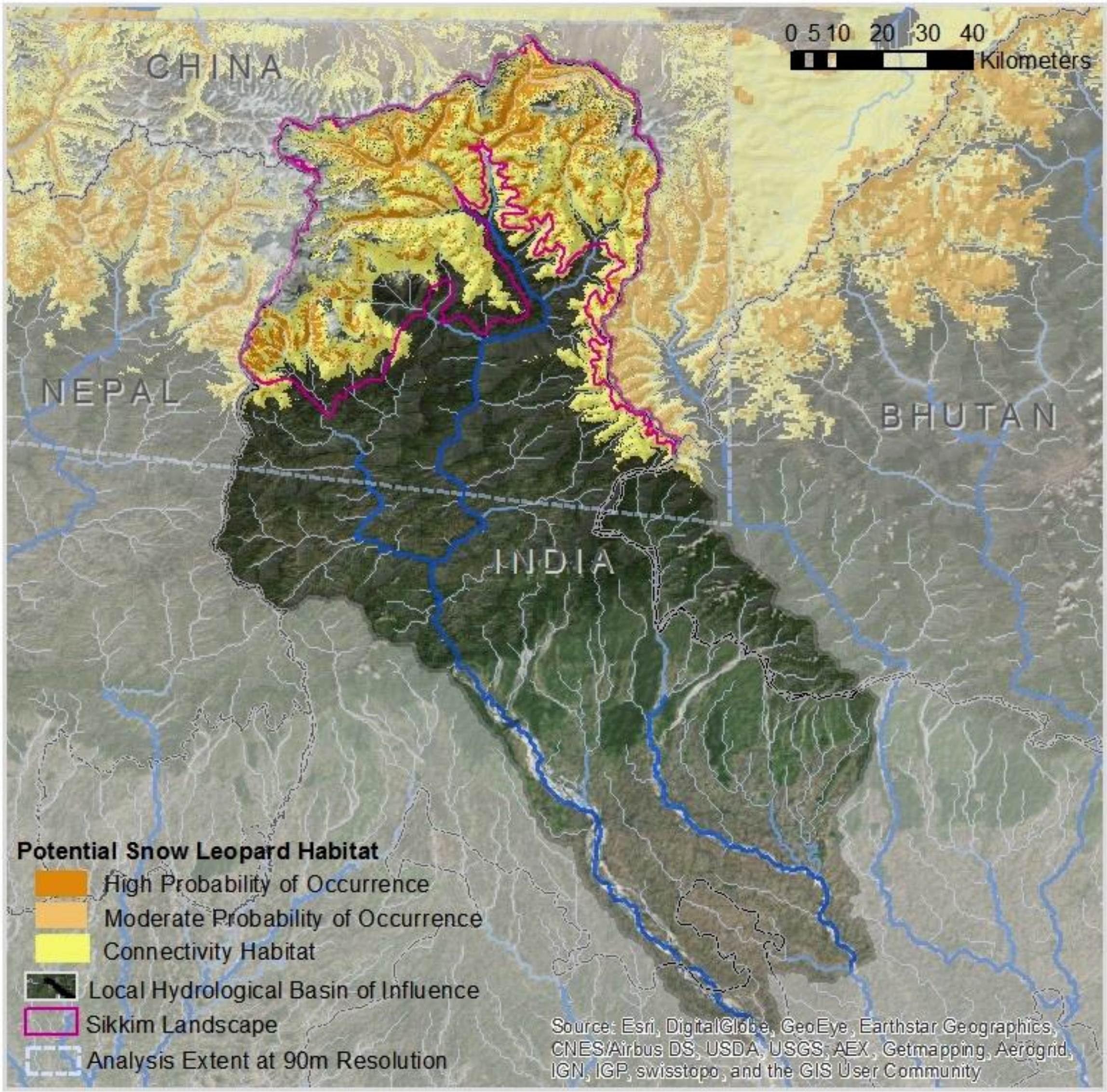
- **The western portion of the landscape is well-protected by Khangchendzonga National Park.** The area east of the Teetsa River, however, is not protected and may require more management attention.

- **The eastern portion of the landscape (comprising part of the North and East Districts) is subject to higher human impacts from settlements and roads than the western part of the landscape.** Pinchpoints to east-west connectivity exist in particular along the Teetsa/Lachen Chu and Lachung Chu (Rivers), and at the borders with China and Nepal. It may be necessary to actively manage these specific pinchpoints through zoning, corridor implementation, or human-wildlife conflict management to ensure metapopulation connectivity.

- **The Sikkim landscape is predicted to become warmer and wetter under a changing climate, with severe impacts to snow leopard habitat. Indeed, approximately 80% of snow leopard habitat in Sikkim is expected to transition from a climate niche favoring alpine grasslands to one favoring forest ecosystems.** The largest area of climate resilient, contiguous habitat may remain in the northeastern and eastern portion of the landscape, which is the area also subject to higher fragmentation and degradation risk from humans. These climate resilient areas should be managed for long term sustainability, as they are most likely to offer suitable climate space in the future. The resilient habitats of the east and northeast also connect to resilient habitats across the Chinese border to the east; thus, this transboundary connection should also be maintained.

- **Habitats that are considered resilient to full ecosystem shifts (from treeline) will likely experience effects of climate change resulting from shorter winters.** Associated impacts on snow leopards and their habitats could affect the arrival of spring and first blooms (and thus grassland composition); invasive species; the presence and composition of prey populations; the timing of snow leopard breeding, movements and birthing; patterns of species interactions (particularly increased competition with species favoring shorter winters); glacial and permafrost melting and water regulation, increased risk of glacial outburst floods (GLOFs) and landslides. Since the impacts of climate change area are unpredicatable, monitoring and adaptive management can help to adjust management strategies to observed changes.

Sikkim Snow Leopard Landscape Sub-basin of Influence



Potential snow leopard habitat of the Sikkim snow leopard landscape, shown with its local sub-basin of influence. *WWF 2017*

Potential snow leopard habitat of the Sikkim Landscape, with local hydrological sub-basins of influence. There is nearly 3,000 km^2 of potential snow leopard habitat in Sikkim, India. Of this, 740 km^2 (25%) is classified as good habitat having a high probability of snow leopard occurrence, and 330 km^2 (11%) is classified as having a moderate probability of snow leopard occurrence. Habitat important for maintaining connectivity occupies about 1,925 km^2 (64%) of the landscape. Good and moderate habitats in Sikkim range in elevation from 3600 m and 5800 m, with almost 75% of these habitats ranging between 4470 m and 5700 m. Only 0.1% of good and moderate habitats projected by the model are >5700m.

Methodology

The map of snow leopard habitat is an aggregation of two models: The first model projects the best patches of habitat for snow leopards, particularly during the summer months when water sources may influence the distribution of snow leopards and their prey. These habitat patches are described in the maps as high and moderate probability of occurrence. The second model was used to map areas of presumed connectivity between the best habitat patches. Snow leopards may reside in connective habitat for longer periods of time during the winter months, when water is more evenly distributed throughout the landscape in the form of snow. The models are described in detail as follows.

Model #1: Mapping Habitat Patches with High and Moderate Probability of Occurrence and Summer Habitats

Habitats with high and moderate probability of occurrence of snow leopards in Sikkim, India and the neighbouring Kanchenjunga Conservation Area (KCA) in Nepal was modelled as a function of four habitat correlates, viz. DEM, slope, land use and distance from nearby water sources (mainly streams) and 44 snow leopard occurrence points, using Maxent v. 3.3.3 (Phillips et al. 2006). The snow leopard observation points came from sign survey information, camera trap captures and radio-telemetry data (ISLT; SLN; Panthera; WCS 2008; Government of Nepal 2016; WWF-India 2016, unpublished). Prior to running the actual model with four variables, a pre-run was conducted using the 44 occurrence points and five habitat correlates (viz. DEM, slope, land use, terrain ruggedness index and distance from nearby water sources) to evaluate their contributions. The pre-run indicated that the terrain ruggedness information (Sappington et al. 2007) did not contribute substantially to the model. Therefore, it was excluded from any further analysis.

Four models were run and the programme was made to withhold 20%, 30%, 40% and 50% of the presence locations during the first, second, third and fourth runs respectively, to test the performance of each model. Fifteen replicates were produced for individual models. Thus, 60 models were calibrated for potential snow leopard habitat. The potential snow leopard habitat (probability of occurrence) across the landscape was predicted as a mean across the 60 models. The model qualities were evaluated based on the Area under Curve (AUC) value. High AUC value indicates a high capacity of models to discriminate presence and absence. The models were graded as: poor ($AUC<0.8$), fair ($0.8<AUC<0.9$), good ($0.9<AUC<0.95$) and very good ($0.95<AUC<1.00$). For all model runs we used the default settings for regularization and selecting the feature classes after Phillips et al. (2006). Five thousand iterations of the programme were run. The convergence threshold was set to 0.0001, regularization multiplier to 1 and the algorithm parameters to auto. The maximum background points were set to 10,000. A "logistic" output format was selected for the results. The inferences on AUC and predictor importance are based on their average estimates of the four models.

Overall area under curve (AUC) values for both training and test datasets were 0.92 ± 0.00 and 0.90 ± 0.01, which indicated that the model is highly informative and has high discriminating capacity. A comparative evaluation of AUC values across 20%, 30%, 40% and 50% models showed that the training AUC values ranged from 0.91 - 0.92 and test AUC ranged from 0.89 – 0.92 (Figure 2). This suggested that the models were highly informative individually and there was no significant difference in the AUC values across the four models. Among the environmental correlates used to model the potential snow leopard habitat, DEM came forth as the most important variable in terms of variable and permutation contribution. The omission rate across different threshold levels varied between 0.02 and 0.25 with an average of 0.08. The logistic threshold values varied between 0.015 and 0.39, with a mean of 0.22, across the different threshold selection methods. However, potential snow leopard areas were considered as those where logistic threshold value was >0.06 (in this case that of "Balance training omission, predicted area and threshold value") and altitudinal range of 3300 – 5700 m. Areas that had threshold value <0.06 were deemed unsuitable. The potential habitat was classified into two categories: moderately suitable areas ($0.06 >= p > 0.85$), and highly suitable areas ($0.85 >= p > 1.00$).

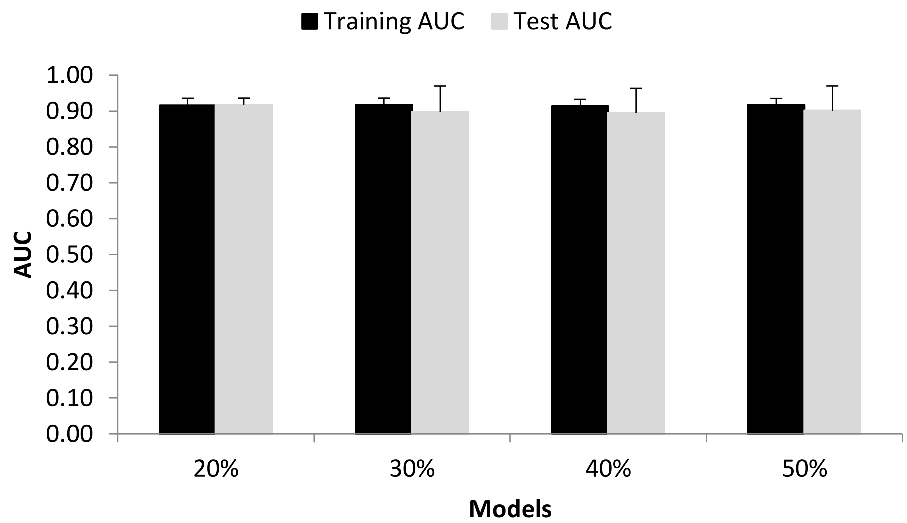


Figure 2. Training and test AUC for the individual models

Model #2: Mapping Connectivity and Winter Habitats

Snow leopard habitat that is important for maintaining connectivity was modeled at 90 m resolution across Sikkim and Eastern Nepal as a function of land cover, elevation, slope, ruggedness, and snow leopard observations (see data sources below for full reference). Snow leopard observations came from camera trap surveys, DNA testing of signs, and radio collaring of an individual. Radio collar points were randomly pruned to reduce sampling bias compared with the other survey methods. A Maxent model was run using 74 snow leopard observation points from across the analysis extent (with 54 points used to train the model and 20 used for testing), and the 4 environmental variables (Phillips et al. 2006). The model was run in several iterations, testing alternative ruggedness models (the terrain ruggedness index and the vector ruggedness model), as well as some climate variables thought to be important drivers of alpine ecosystems (including total summer precipitation, total precipitation as snow, number of months above frostline, mean growing season temperature and percent of annual precipitation that occurs during monsoon). Model sensitivity and output was tested by systematically withdrawing certain variables. The resulting model based on land cover, elevation, slope and terrain ruggedness had an AUC value of 0.832 and a test AUC of 0.792. The 4-variable model was selected as the best representation of current habitat at the 90 m scale.

The resulting logistic probability of occurrence (p) map was reclassified into habitat and non-habitats based on a p-thresholds, and refined with elevation data. Habitat was defined as areas where $p >= 0.29$ and elevation < 6000 m. The value of 6000 m was selected as a maximum elevation threshold since snow leopards have not been observed above this threshold in Nepal (R. Shrestha, personal communication, August 29, 2016). The *P*-value 0.29 is equivalent to the 10th percentile training point presence.

Accuracy

The map of snow leopard habitats was overlaid with snow leopard observations. Approximately 70% (n = 31) of the points are located in high probability of occurrence habitat, 21% (n = 9) are located in moderate probability of occurrence habitats and about 9% (n = 4) of the points are located in connective habitats.

Data sources

High and Moderate Probability of Occurrence Habitats (Model #1):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, slope, stream network (Lehner et al. 2008)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008. WWF India)

Connectivity Habitat (Model #2):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, ruggedness, slope (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008)

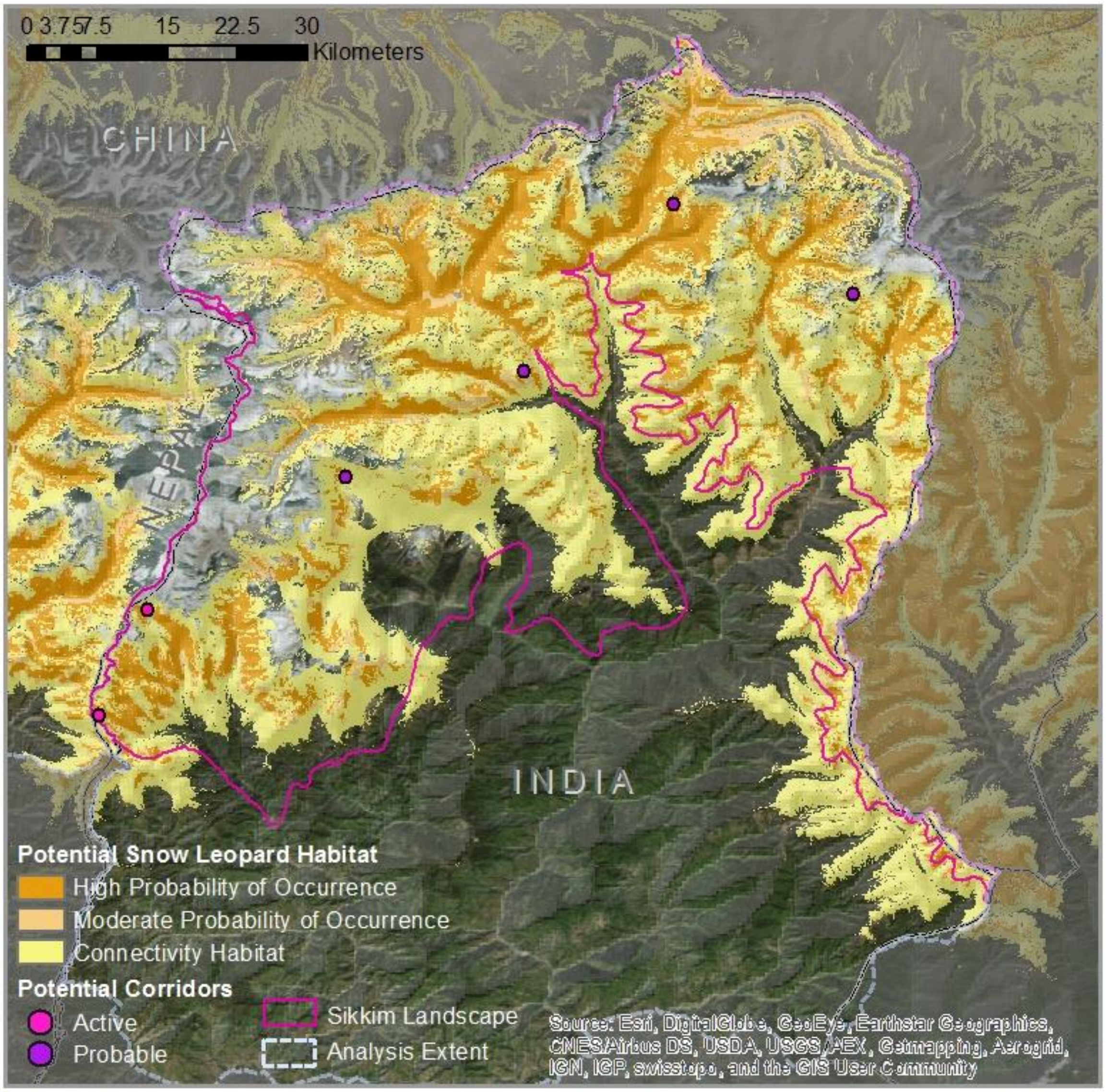
Data sources for 500 m habitat model (outside pink box):

- Forrest et al. 2012

Other layers for display only:

- Sikkim Landscape Boundary (Government of India, WWF & GSLEP 2016)
- Blue Marble Imagery (NASA, MDA Federal Inc., Digital Globe 2016)

Potential Snow Leopard Habitat in Sikkim, India



Potential snow leopard habitat and corridors in Sikkim, India. *WWF 2017*

Potential snow leopard habitat describes areas where snow leopards live, breed, and move. **Potential corridors** were defined as important areas where snow leopards move across the landscape, perhaps necessitating special management. **Transboundary corridors were confirmed through the use of** data from radio-collared snow leopards documenting their path between Nepal and India (Government of Nepal, 2015). Other potential corridors were identified through visual assessment of the model outputs. The methods used to produce the snow leopard habitat layer were described along with the previous map.

Data sources

High and Moderate Probability of Occurrence Habitats (Model #1):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, slope, stream network (Lehner et al. 2008)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008. WWF India)

Connectivity Habitat (Model #2):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, ruggedness, slope (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008)

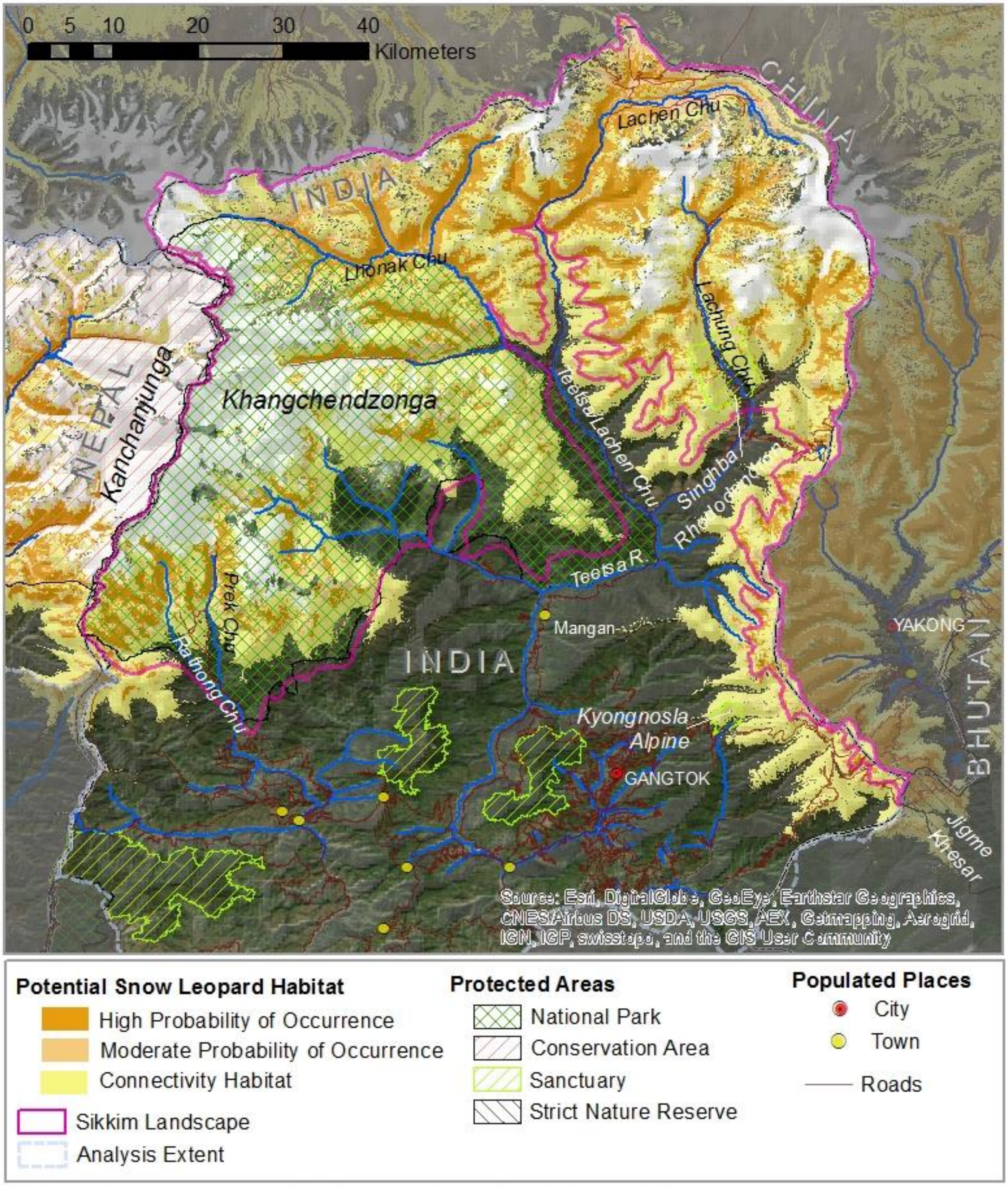
Data sources for probable corridors:

- 90 m snow leopard habitat suitability model (this study)

Other layers for display only:

- Sikkim Landscape Boundary (Government of India, WWF & GSLEP 2016)
- Blue Marble Imagery (NASA, MDA Federal Inc., Digital Globe 2016)

Protected Areas and Places of the Sikkim Landscape



Protected areas, roads, major rivers, and populated places of the Sikkim Landscape.

WWF 2017

Protected areas cover over 1120 km^2 or 37% of potential snow leopard habitat in Sikkim. 1873 km^2 of habitat remains unprotected, particularly along the northern and eastern parts of the State that forms a connection to habitats in China and Bhutan. Human presence in the landscape is mainly concentrated in a few river valleys, particularly the Teetsa/Lachen Chu and Lachung Chu.

As shown in the table below, Khangchendzonga National Park covers the largest extent of the habitat among the protected areas, with 1080 km^2 of total habitat area. Singhba Rhododendron Sanctuary also has a small amount of habitat, mainly connectivity habitat (Table 2.1).

Table 2.1. Protected Habitat Area in the Sikkim Landscape

Protected Area Name	Snow Leopard Habitat			
	High Probability	Moderate Probability	Connectivity	Total
Khangchendzonga National Park	238	107	735	**1080**
Kyongnosla Alpine Sanctuary	0	0	6	**6**
Singhba Rhododendron Sanctuary	2	3	30	**35**
Total Protected[1]	**240**	**110**	**771**	**1121**

1. Values are in kilometers^2

Data sources

High and Moderate Probability of Occurrence Habitats (Model #1):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, slope, stream network (Lehner et al. 2008)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008. WWF India)

Connectivity Habitat (Model #2):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, ruggedness, slope (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008)

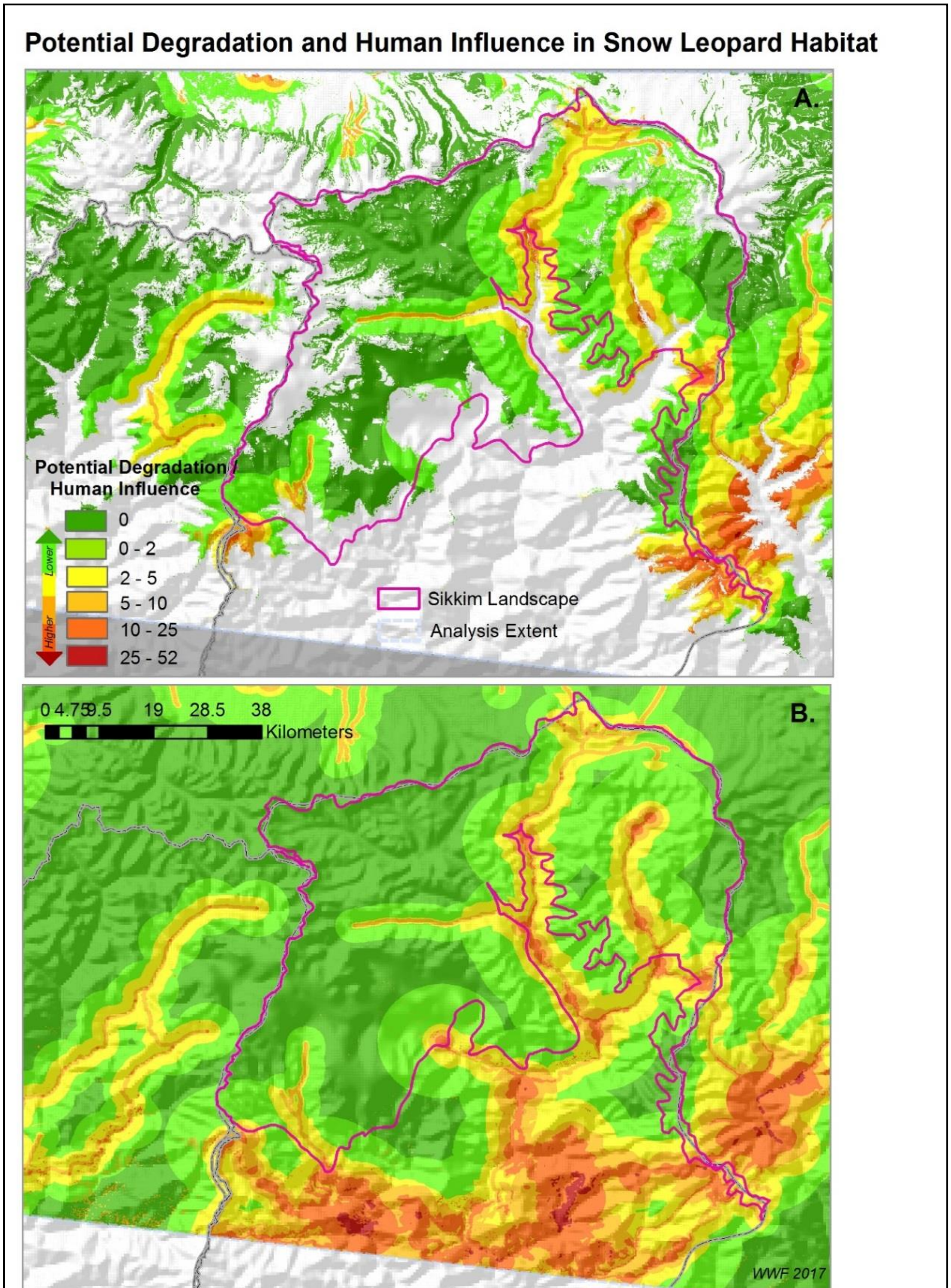
Human and Natural Landscape:

- Protected Areas (ICIMOD 2007)
- Roads, Populated Places, Waterways (OpenStreetMap 2016)

Other layers for display only:

- Sikkim Landscape Boundary (Government of India, WWF & GSLEP 2016)
- Glaciers (GLIMS and NSIDC 2016)

- Blue Marble Imagery (NASA, MDA Federal Inc., Digital Globe 2016)



Potential degradation and human influence in snow leopard habitat is a function of the distance to roads, distance to settlements, and land cover and land use. Map A shows human footprint in current snow leopard habitat only, while Map B shows the human footprint across the analysis extent.

This map represents existing and potential human threats to snow leopards, their habitats, and their prey from sources such as hunting of snow leopards and prey, human wildlife conflict, and habitat loss and degradation. The most significant human presence in the landscape is along the Teetsa/Lachen and Lachung Chu river valleys, where these rivers bisect the landscape from north to south. There is also human presence in the southwest corner of the landscape near the Nepal border, and at the southeast corner near the border with China. These may affect transboundary connectivity unless managed properly.

Methodology

The model is based on measures of human accessibility that include distance to roads, distance to population centers, and landcover using methods developed by Sanderson et al. (2002). Values in the three layers were rescored to represent cost of movement or degradation. As such, a score of 0 represents no degradation or cost of movement, and 10 represents the highest cost of movement or level of habitat degradation (i.e., a score of 0 represents a fully permeable area of habitat, while a score of 10 represents nearly impermeable). Rescored layers were summed to produce a potential degradation and human influence layer (Tables 2.2 A-C).

Table 2.2A. Land Cover Class Scores for Human Footprint

Land cover[1]	Potential Degradation/Cost of Movement
Needleleaved Forest	0
Broadleaved Forest	0
Shrubland	0
Alpine Meadow	0
Agriculture	8
Fallow land	6
Snow, glacier	0
Barrenland	0
Water	0
Built-up	10

[1] Land cover prepared with WWF 2015, Hansen et al. 2013, GLIMS & NSIDC 2016

Table 2.2B. Distance to Population Center Scores for Human Footprint

Distance to Cities (m)[2]	Potential Degradation/Cost of Movement
0-3000	10
3000-5000	8
5000-10,000	3
10,000-12,000	1
>12,000	0
Distance to Settlements, Villages and Towns (m)[2]	**Potential Degradation/Cost of Movement**
0-1000	10
1000-2000	6
2000-3000	3
3000-5000	2
5000-10,000	1
>10,000	0
Distance to Hamlets and Isolated Dwellings (m)[2]	**Potential Degradation/Cost of Movement**
0-90	10
90-270	8
270-500	2
500-5000	1
>5000	0

Table 2.2C. Distance to Road Scores for Human Footprint

Distance to Major Road (m)[2, 3]	Potential Degradation/Cost of Movement
0-90	10
90-270	8

[2] OpenStreetMap 2017
[3] primary and trunk roads; Note that there were none in this extent

270-500	6
500-3000	3
3000-5000	2
>5000	0
Distance to Secondary Roads and Paths[2,4]	**Potential Degradation/Cost of Movement**
0-90	8
90-270	6
270-500	4
500-2000	2
2000-3000	1
>3000	0

Data sources

High and Moderate Probability of Occurrence Habitats (Model #1):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, slope, stream network (Lehner et al. 2008)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008. WWF India)

Connectivity Habitat (Model #2):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, ruggedness, slope (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008)

Human Footprint:

- Roads, Places (Open Street Map 2013)
- Land cover (WWF 2015, Hansen et al. 2013, GLIMS & NSIDC 2016)

Other layers for display only:

- Sikkim Landscape Boundary (Government of India, WWF & GSLEP 2016)
- Blue Marble Imagery (NASA, MDA Federal Inc., Digital Globe)

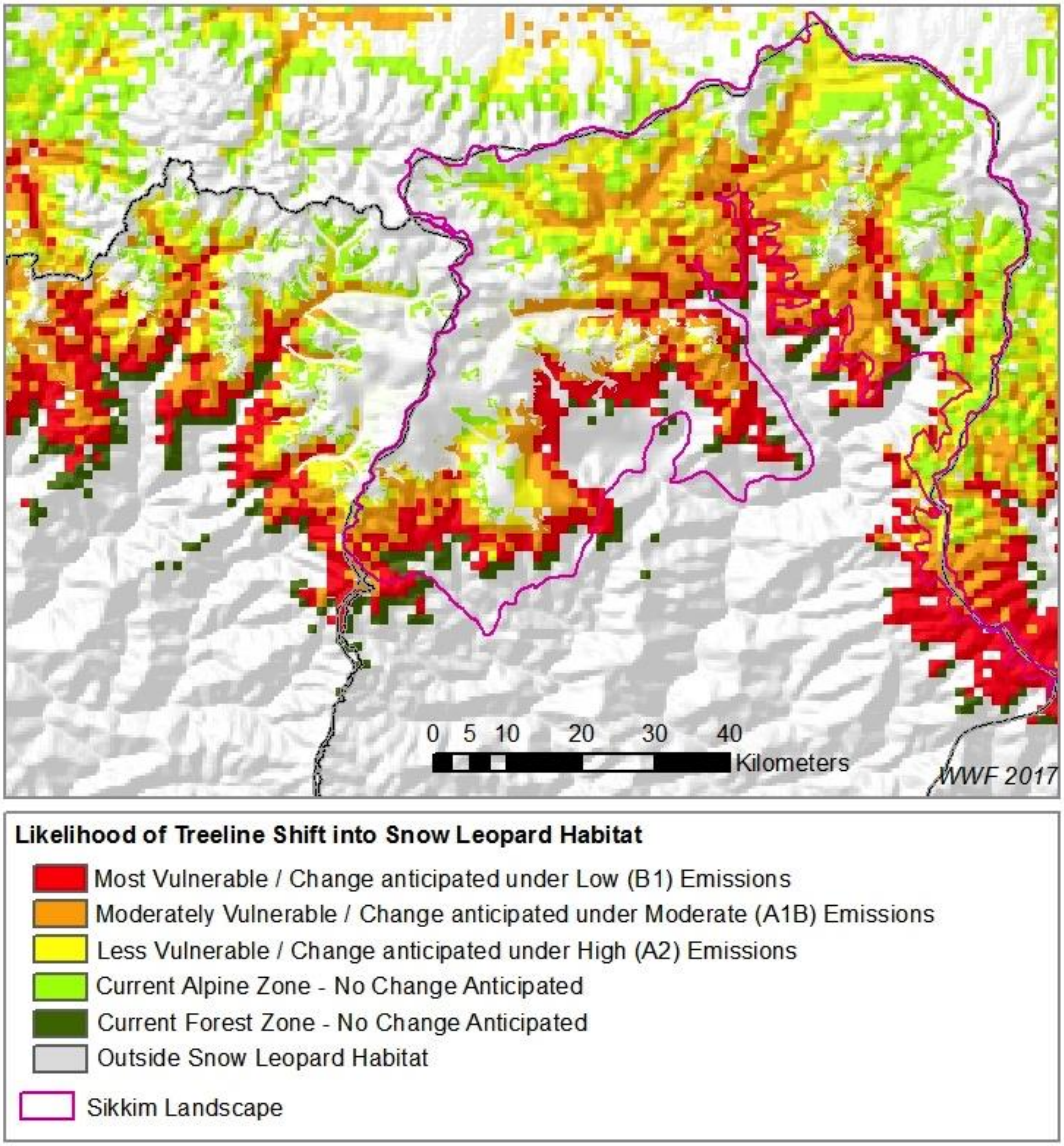
[4] living street, residential, road, secondary, service, unclassified, construction, path, footway, bridleway, tertiary, and track

Climate Change Vulnerability in the Sikkim Landscape

The Sikkim landscape is expected to experience a substantial increase in average annual temperature (+1.7˚C to 2.5˚C by the mid-century time frame of 2041-2070). The highest degree of warming will likely occur during the coldest months of the year, from January to March, which could affect the freeze-thaw cycle and the timing of snow melt. Precipitation is also expected to increase, particularly during the monsoon, when rainfall is already high (Peters et al. 2017). Potential impacts of these climate changes include changes to vegetation patterns, permafrost cover, and location of major ecosystem types – with implications for habitat quality and availability; cropland availability – with implications for people and pressure on wildlife resources; patterns and timing of livestock grazing, and flooding and landslide risk, particularly during the monsoon (Climate Smart Snow Leopard Management Planning Workshop, April of 2016).

We selected a few indicators of climate change impacts for mapping, in order to better understand the spatial distribution of climate risk for alpine wildlife and human communities. These included the distribution of treeline shift risk in the landscape (or the transition from a climate zone favouring alpine grassland to one favouring forest); potential change in the suitable climate envelope for cropland (indicating changing human habitability, but also human pressure on wildlife habitat); water towers (or water provision to the downstream from precipitation); winter duration (indicated by freeze-line, with implications on ecological functions as well as water availability for people); and change in open water availability (which is a good indicator of overall changes to a landscape). The latter three, and other hydrological functions, are covered in more depth by Sindorf 2017.

Potential Vulnerability of Snow Leopard Habitat to Climate Change



This map represents the vulnerability of current snow leopard habitat to climate change induced treeline shift. There is a gradient in vulnerability from south to north and from low elevations to high, with habitats in the south and at lowest elevations most vulnerable to potential treeline shift. Under a high emissions scenario, about 80% of habitat is vulnerable to loss, all but the ring near 5500 m, the highest elevations of current habitat. The best remaining contiguous piece of habitat is in the far east and northeast of the landscape.

Treeline is expected to shift as temperatures become warmer and wetter, and the growing season in alpine areas becomes more hospitable (Forrest et al. 2012). Areas that become warmer, wetter, and more suitable for natural forests may also become more suitable for crops and livestock, encouraging human immigration. These indirect effects of climate change may also result in habitat loss. This model does not account for microrefugia that may exist currently and/or persist due to local climate conditions in this montane landscape (Thapa et al. 2016). However, snow leopards are wide-ranging species, so micro-refugia may not offer ample breeding or connectivity habitat for snow leopards.

Data Sources

High and Moderate Probability of Occurrence Habitats (Model #1):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, slope, stream network (Lehner et al. 2008)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008. WWF India)

Connectivity Habitat (Model #2):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, ruggedness, slope (Lehner et al. 2008, Riley et al. 1999)

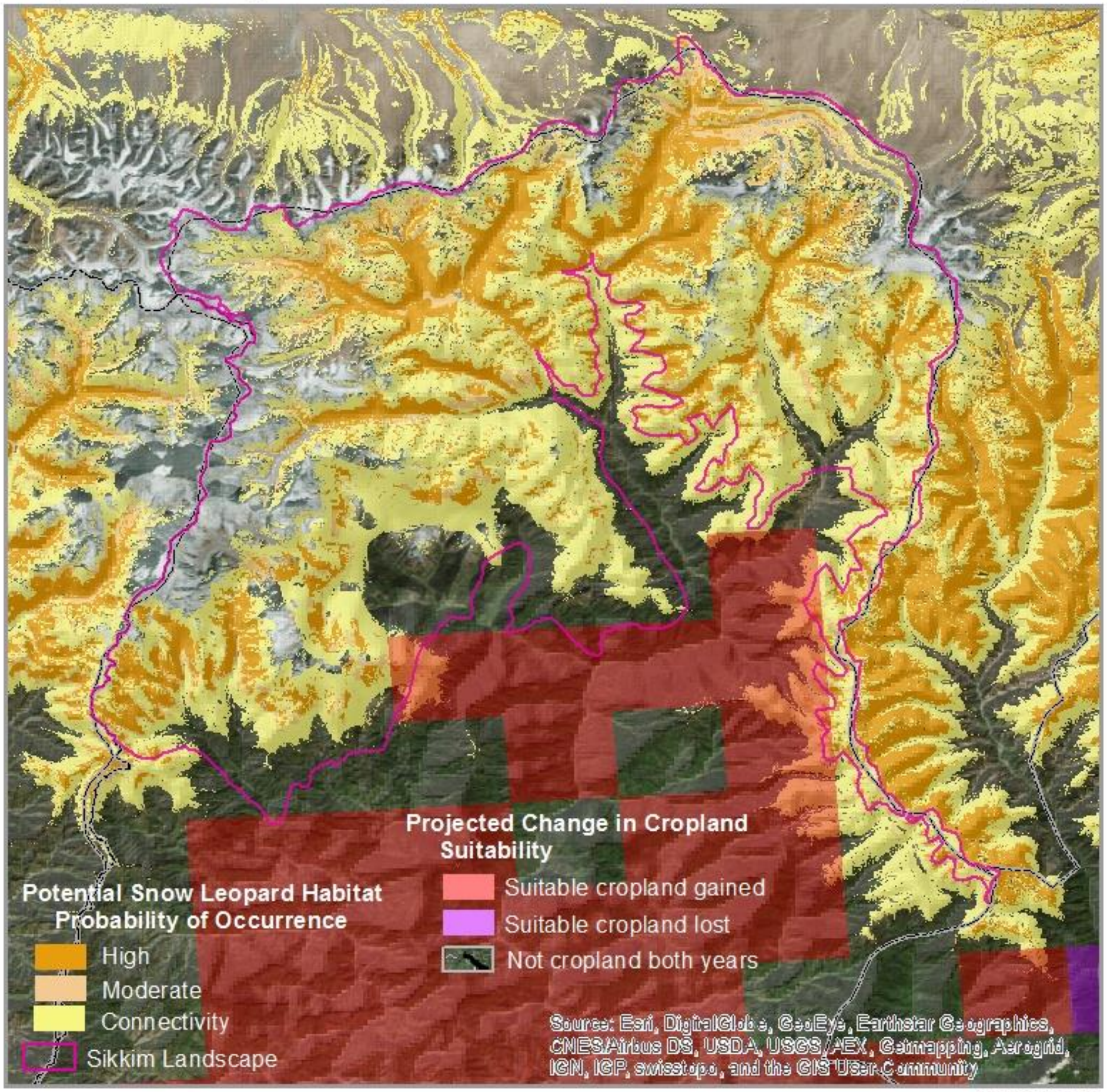
Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008)

Projected Change in Treeline under Climate Change: Forrest et al. 2012

Other layers for display only:

- Glaciers: GLIMS & NSIDC 2016
- Eastern Sikkim Landscape Boundary (Government of India, WWF, & GSLEP 2015-16)

Projected Change in Cropland Suitability under Climate Change in Sikkim



Projected change in climate suitability for agricultural crops under a high emissions (A2) scenario to the year 2100 according to a regional model. The model also projected areas of no change in cropland suitability: Non-arable areas in the current and future time splices are displayed here as null, or background color. The model did not project any areas of arable land in both years in this extent.

WWF 2017

This map shows projections of current climate envelope for arable land (or cropland), and potential change under a high emissions climate change scenario. The model shown is based on the Global Arable Lands database (Ramankutty et al. 2008) and 19 bioclimatic variables (Hijmans et al. 2005). These inputs were used to produce climate envelope projections for the current time period and the 2080's under a high emission scenario (A2A) using the HADCM3 General Circulation Model (see Sindorf et al. 2014).

These results suggest that in this landscape, snow leopard habitats at the lowest elevations in the East and North Districts may experience increased conversion pressure to cropland. More important, however, is that vast areas just below the snow leopard range may become more suitable for crops, which may increase dependence and pressure on water originating in the snow leopard range. This scenario emphasizes the need for snow-leopard friendly management planning.

Data Sources

High and Moderate Probability of Occurrence Habitats (Model #1):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, slope, stream network (Lehner et al. 2008)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008. WWF India)

Connectivity Habitat (Model #2):

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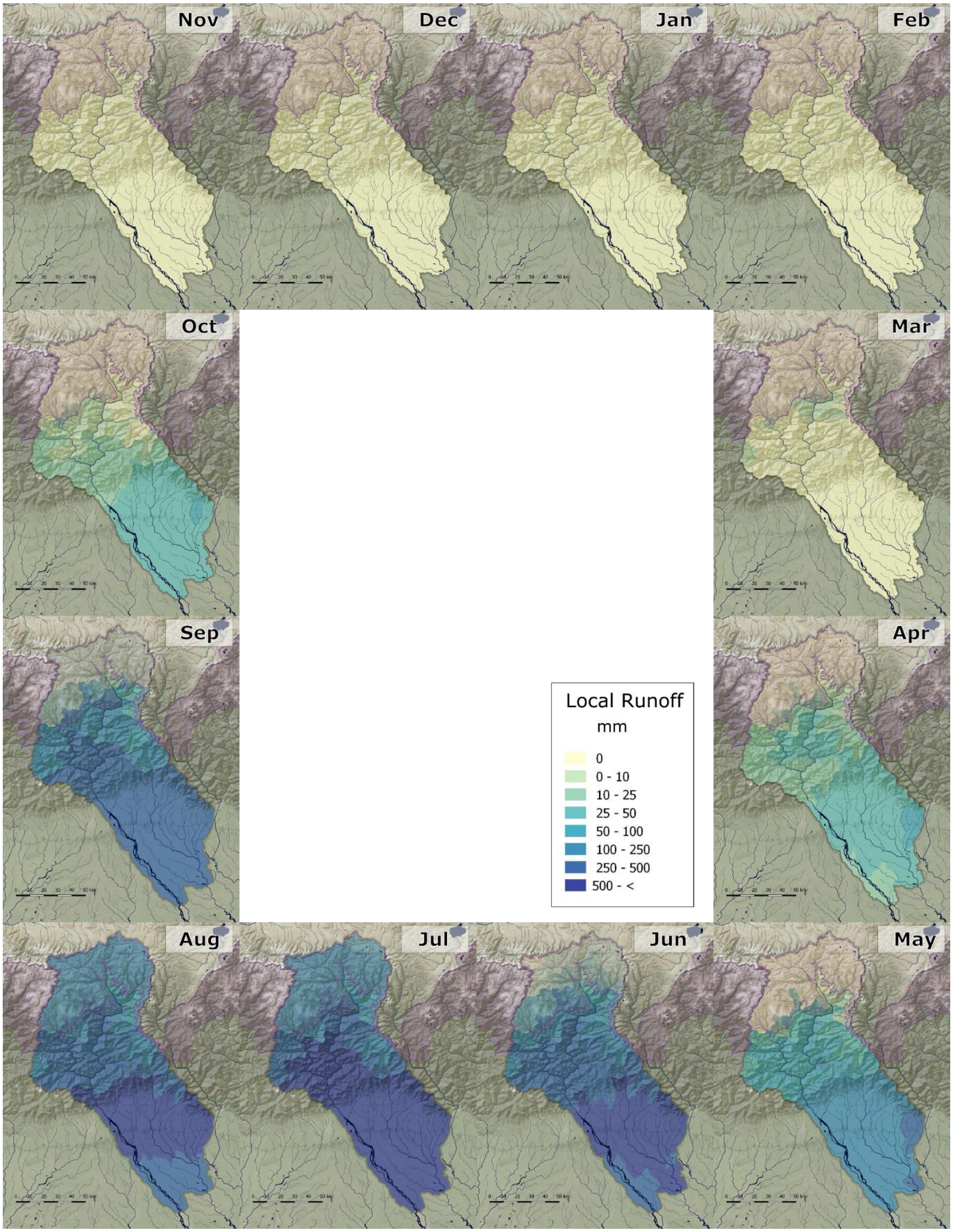
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008)

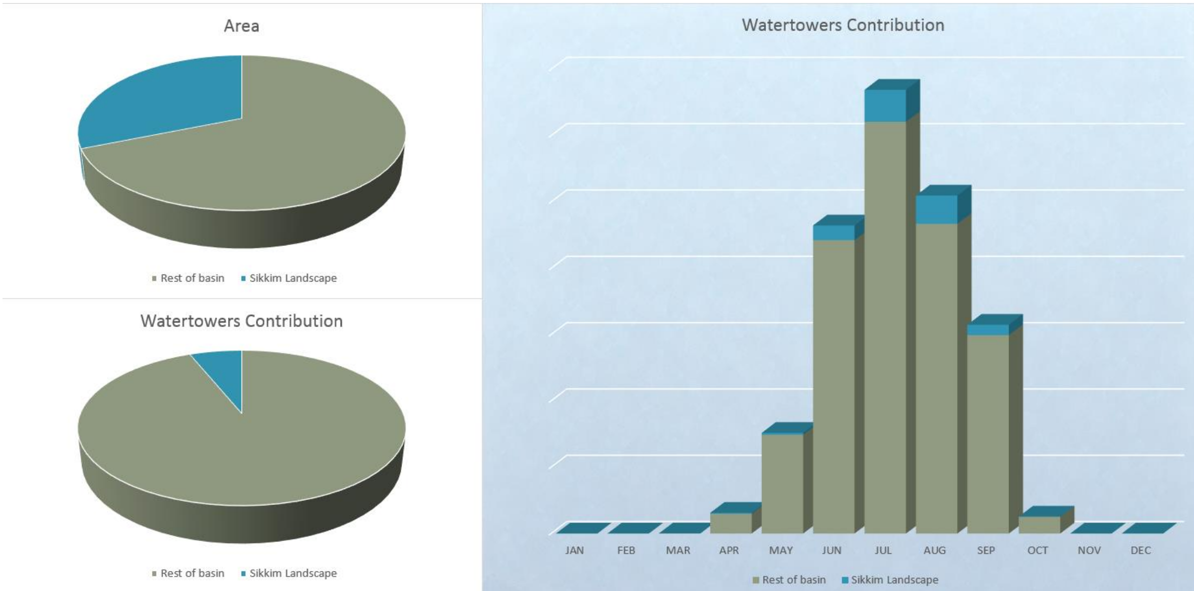
Projected Change in Cropland Suitability: Sindorf et al. 2014

Other layers for display only:

- Glaciers: GLIMS & NSIDC 2016
- Sikkim Landscape Boundary (Government of India, WWF & GSLEP 2016)

Water towers (Local Runoff) in the Sikkim Landscape Sub-basin





Water Towers/ Local Runoff	
Baseline Scenario	The area downstream of the Sikkim landscape receives much more water throughout the year compared with the snow leopard landscape. The Sikkim landscape is the driest part of the basin.
Projected Climate Change	Future precipitation projections range from low to high. Under a low precipitation change estimate, there would be little change to the baseline water tower contribution of the landscape. Under a high-precipitation estimate, the landscape would generate relatively more run-off during the monsoon, which would indefinitely result in in extra floods towards the downstream.

Within the sub-basin, there is a distinctive North-South gradient in 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. The Sikkim landscape itself is the driest part of the basin.

Within the landscape, and in every month, there is a gradient in local runoff that decreases from south to north, from lower to higher elevations, and downstream to upstream.

When comparing the annual local runoff that is 'generated' inside the Sikkim snow leopard landscape with the rest of the subbasin, it becomes evident that the landscape is located entirely upstream of the so-called "water towers." As such, the landscape cover 30% of the entire sub-basin, but only contributes to 6% of its runoff from rainfall.

Throughout the dry season (October-May), when water demand is highest, the landscape provides little to no rainfall run-off to the downstream (See Figure 2.1A). It is important to note that this analysis only shows relative run-off potential from rain and not from snow or ice-melt.

Figure 2.1. Projected change in the relative water tower function of the Sikkim Landscape compared with the rest of the landscape under baseline and future precipitation scenarios.

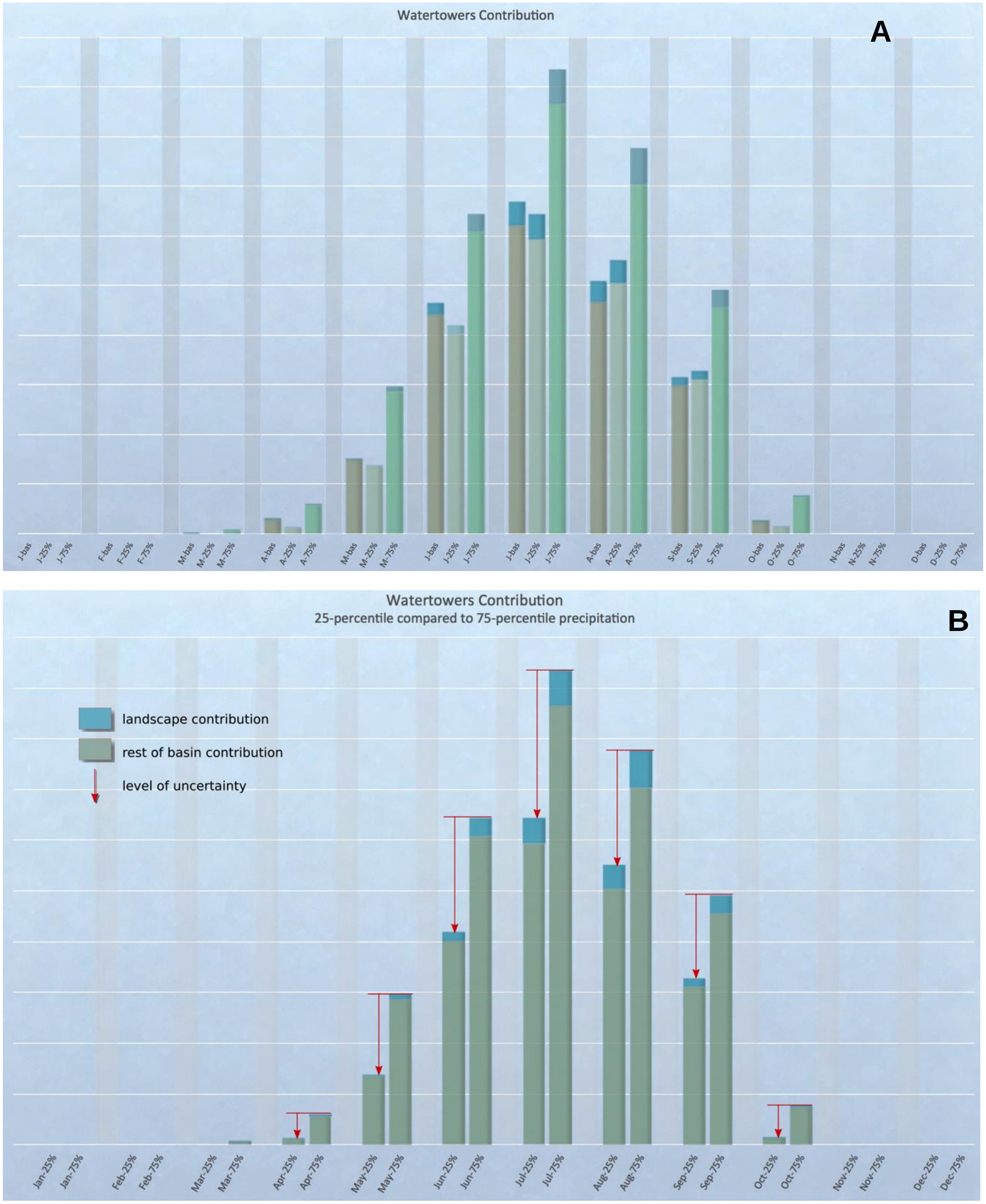
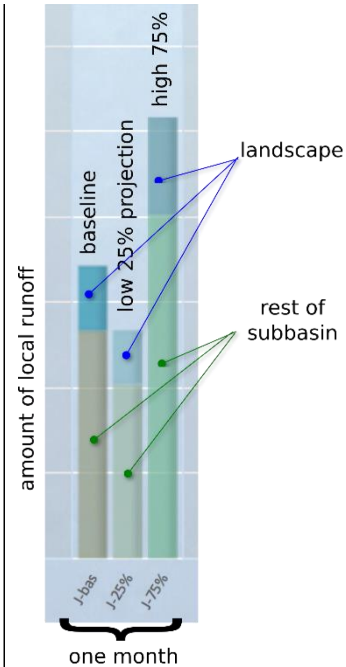


Figure 2.1A shows relative water tower contributions of the Sikkim Landscape compared with the rest of the sub-basin under baseline year and 25-percentile and 75-percentile mid-century precipitation projects (Peters et al. 2017, Sindorf 2017). Figure 2.1B compares the relative water tower contribution of the landscape with the rest of the sub-basin under low and high mid-century precipitation projections, and also expresses the range of uncertainty. Relative run-off from the landscape is represented by the blue color at the top of each bar, while run-off from the rest of the sub-basin is represented by the bottom portion of the bars. Red arrows show the range of changes in runoff based on the low- and high-projections, and therefore illustrate uncertainty in future climate projections on local runoff. The graph shows that the vast majority of the run-off in the sub-basin is generated outside of the landscape. Very little change from the baseline is represented in the low future precipitation projection. A high precipitation future would result in a vastly wetter monsoon season, with slightly more run-off generation from the landscape at mid-century compared with the baseline.



Methodology

Local runoff is the difference between monthly precipitation (P) and actual evapotranspiration (AET). Monthly precipitation and AET were downloaded and, through a simple GIS command, summarized by their watershed 'mean', using HydroBASINS level 12 watersheds. The mean values were multiplied by each of the watershed areas in order to convert from millimeters to cubic meters. Next, mean actual evapotranspiration was subtracted from mean precipitation (P – AET) for each month. Local runoff values that were less than zero were displayed and flagged as zero. Inside the sub-basin, those watersheds that drain the snow leopard landscape were also flagged. See download links below.

Data sources

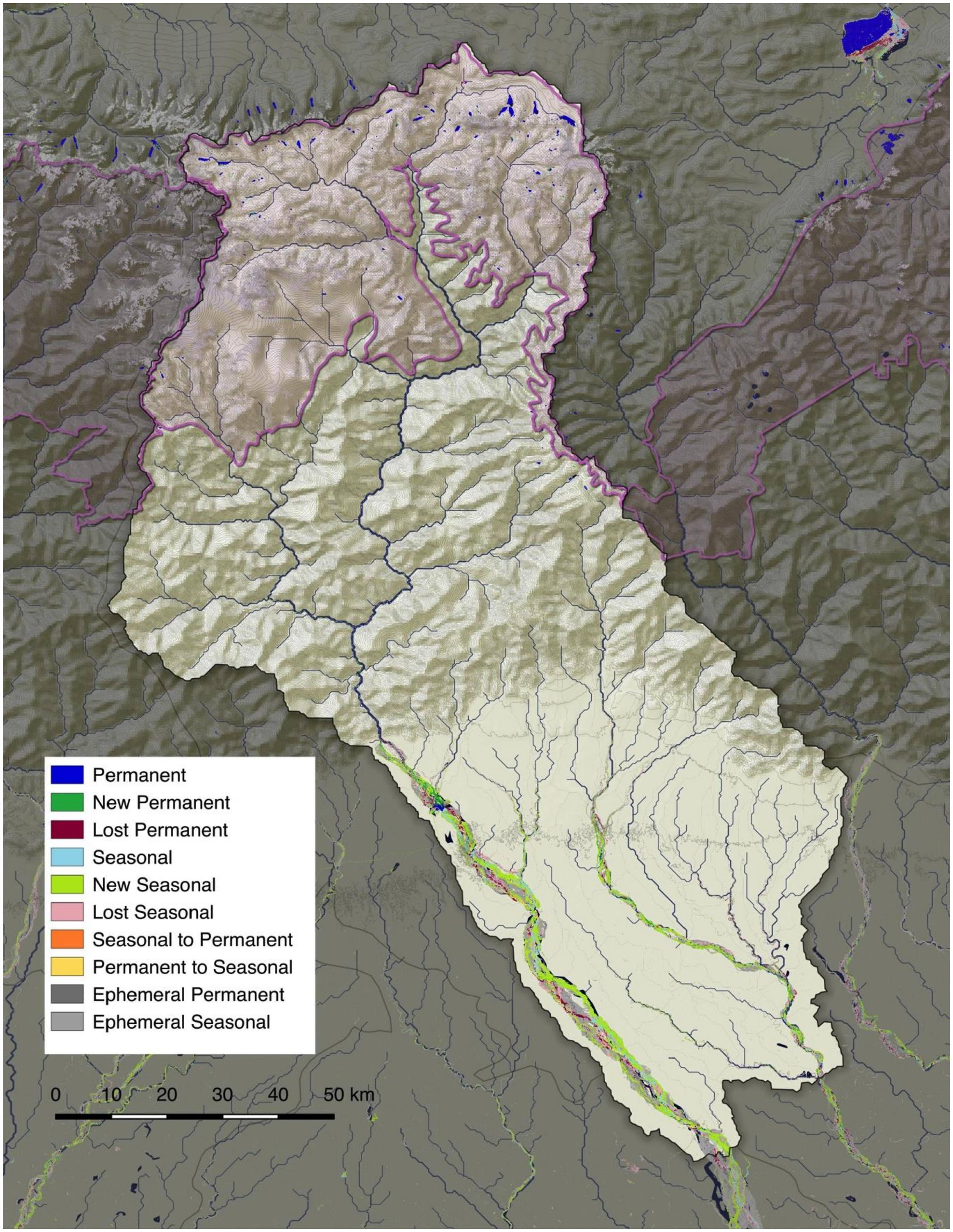
Current Mean Monthly Precipitation, based on historic WorldClim, 30s resolution (Hijmans et al. 2005)

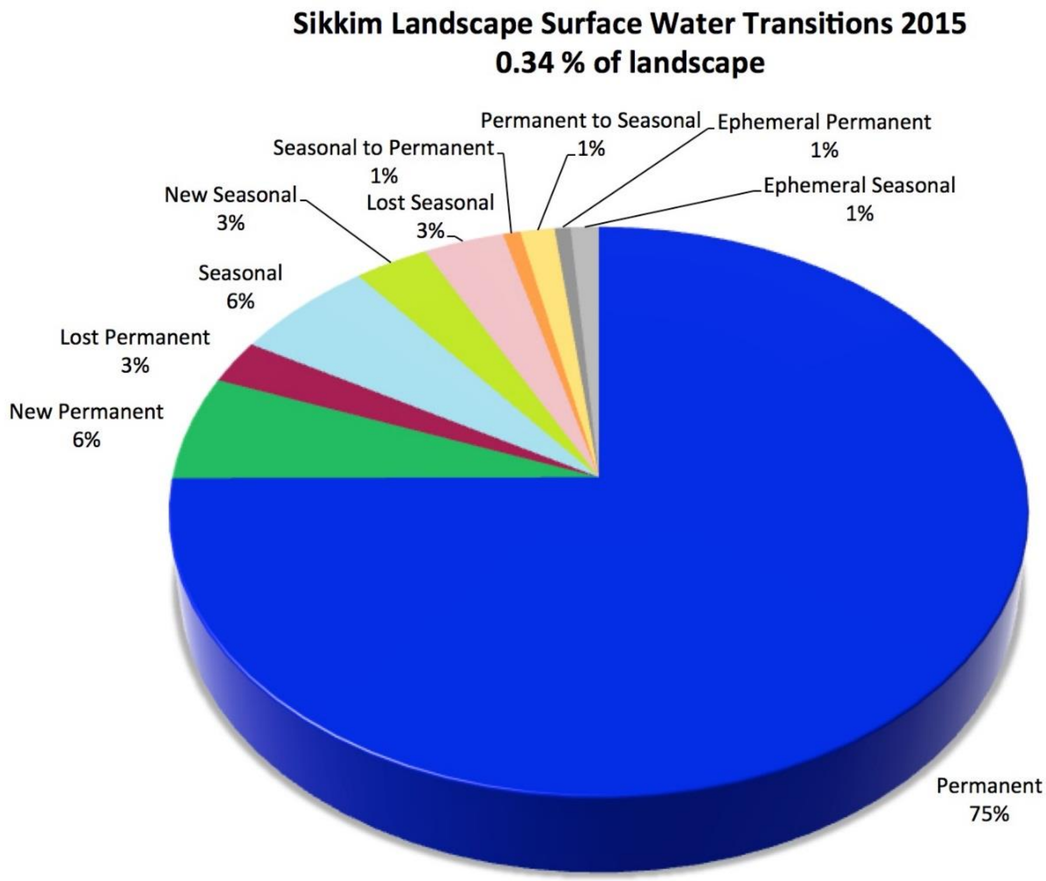
Current Mean Monthly Actual Evapotranspiration, based on historic Global Soil-Water-Balance, CGIAR, 30s resolution (Trabucco and Zomer 2010).

HydroBASINS, level 12, ~100 km^2 watershed outlines (Lehner and Grill 2013).

Climate Projections on future temperatures and precipitation (Peters et al. 2017).

Observed Surface water transitions (1984-2015) in the Sikkim Landscape Sub-basin





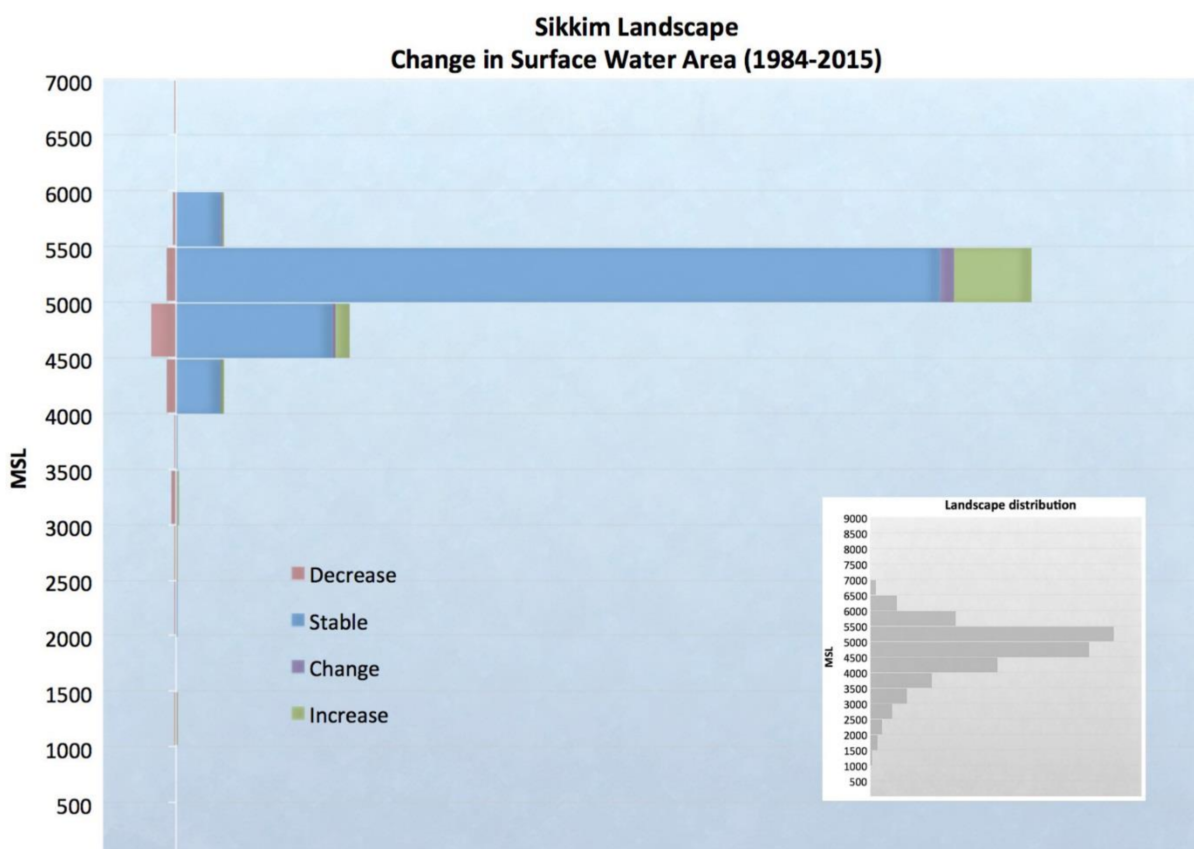
Lakes, wetlands and floodplains	
Baseline Condition	There are approximately 50 glacial lakes detected in the landscape (Worni, 2012). These may play a role in local water management, but eight of them also pose a risk for glacial lake outburst floods (GLOFS). Compared to other Indian Himalaya landscapes, Sikkim's glacial lakes are relatively large. Floodplains exist directly downstream of the landscape. There, floods are recurring and devastating.
Observed Historic Change (1984-2015) and Anticipated Climate Impacts	It is likely that the observed melting of the glaciers would result in increased sizes of glacial lakes. Yet, a global assessment on changing water surfaces (Pekel et al. 2016) shows that surface water areas in the Sikkim landscape have been relatively stable for the period 1984-2015. This might be because of the sloping geography. Thus, any possible increase in the volume of lake water would result in a relatively low spatial footprint, but a larger degree in water storage.

Inside the landscape, only 0.34% is classified as open surface water (Pekel et al. 2016). Thus, historic change is not easily seen in the above map. The following transitions occurred between 1984 and 2015:

- 83% of the open water surface was *stable* (permanent 75 %, seasonal 6 %, ephemeral 2 %)
- 6% of the open water surface *disappeared* (permanent 3 %, seasonal 3 %)
- 9% classified as *new* surface water (permanent 6 %, seasonal 3 %)
- 2% of all open water surface *changed from permanent to seasonal and vice versa*.

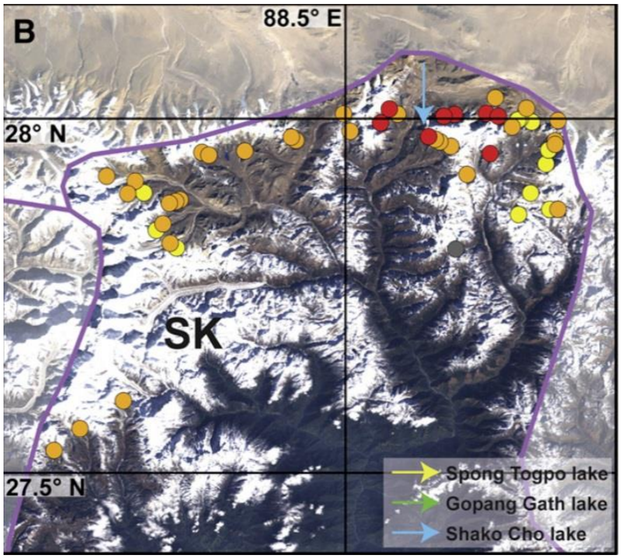
Figure 2.2 indicates that a single elevation belt (5,000-5,500 msl) contains most of the surface water entities in the Sikkim landscape. This is closely related to the presence of the glacial lakes directly downstream of the glaciers. In the period 1984-2015, there was an increase in open water surface area at this elevation, which might indicate the melting off of glaciers. This increase in surface water extent may in fact underestimate the increase in water volume of these glacial lakes due to the sloping topography. An improved assessment of water storage in the landscape would include records of any change in lake depths as well.

Fig. 2.2



Worni et al (2012) from their assessment on glacial lakes in the Indian Himalayas, detect around 50 glacial lakes in Sikkim, of which 8 are classified as critically at risk of an outburst flood (Figure 2.3). Sikkim's glacial lakes are relatively large compared to other Indian Himalaya landscapes.

Figure 2.3. Glacial Lakes in the Sikkim Landscape and Level of Risk of GLOF (Worni et al. 2012)



Methodology

This analysis was drawn from a map of global surface water and long-term changes (Pekel, 2016). It contains at least 6 different datasets, and the online version allows time-lapse analysis from 1984-2015. The dates coincide with Landsat coverage, which is the key dataset.

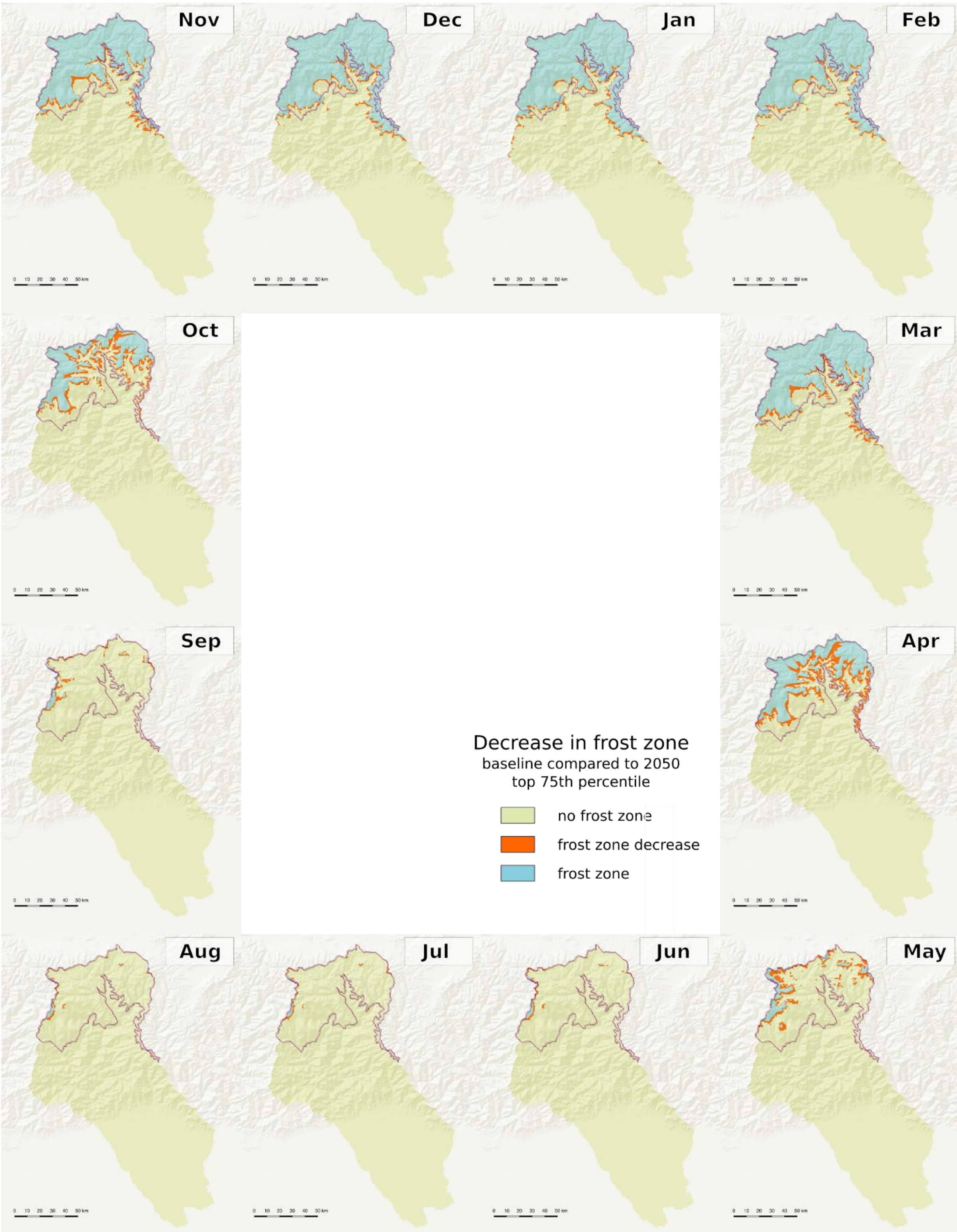
Data sources

Open surface water (Pekel et al. 2016)

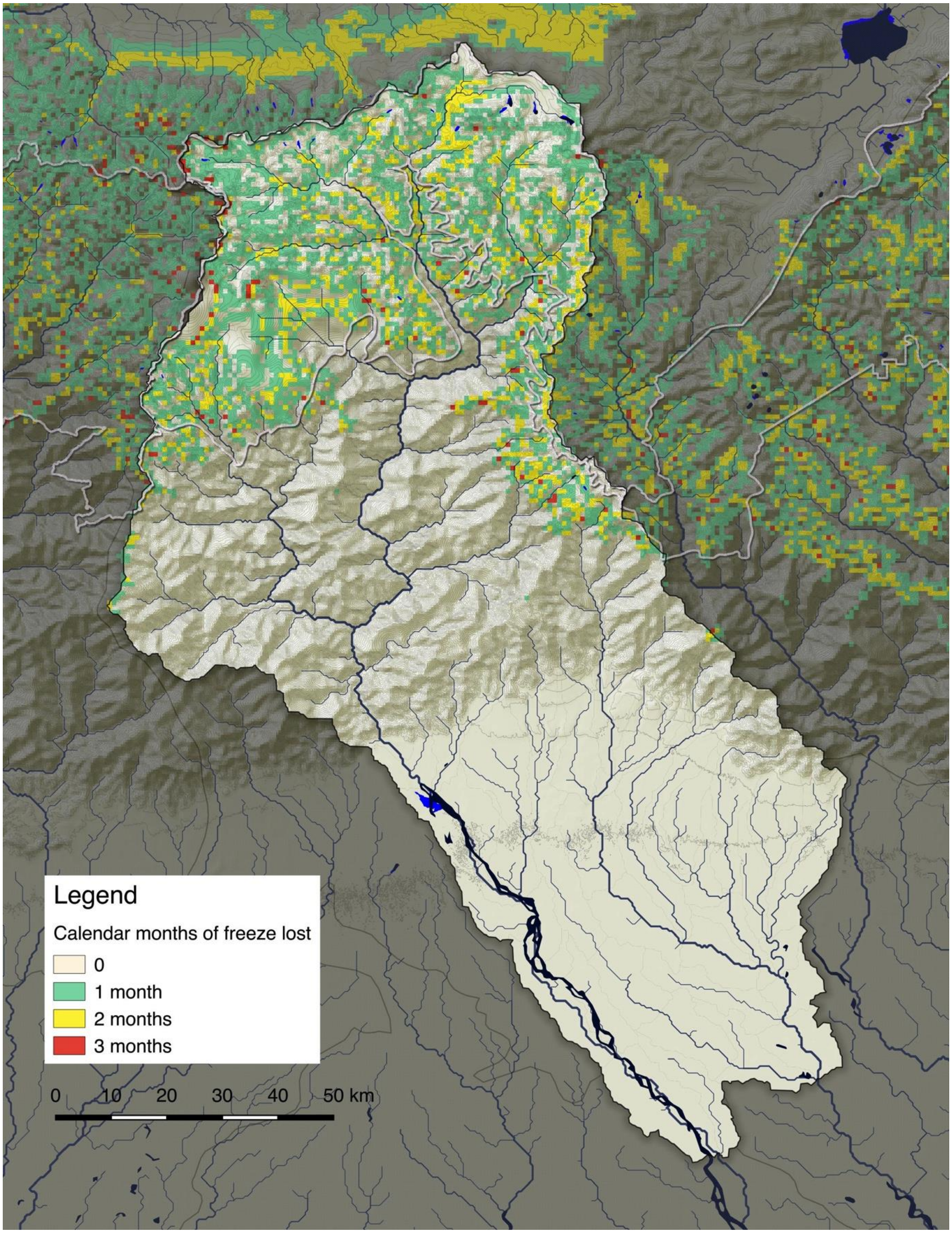
Volume and age of water stored in global lakes (Messager et al. 2016)

Glacial lakes in the Indian Himalayas — inventory and risk assessment (Worni et al. 2012)

Decrease in Monthly Freeze Extent under Temperature Rise in the Sikkim Landscape Sub-basin



Calendar Months of Freeze-loss



Snow Cover, Frozen Ground, and Freeze Line	
Baseline Conditions	The Sikkim landscape encompasses the entire subbasin's freeze area throughout the year. Hence, the landscape covers the seasonal fluctuation of minimum and maximum freeze and snow extent, and therefore provides an essential role in the generation of snowmelt and other cryospheric interactions (glacial run-off, permafrost, etc.)
Projected Climate Change	The cryosphere here is historically exposed to a 4-5 month summer period. Despite this summer, many important cryospheric features occur in the headwaters (glaciers, permafrosts). It is likely that a decrease in freeze duration under rising temperatures will have direct and immediate impacts on the extent of glaciers, permafrost, snow and ice extent, periods of melting, and other cryospheric features.

The above maps illustrate the monthly projected change in 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 that of other cryosphere features (e.g. glaciers, permafrost).

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

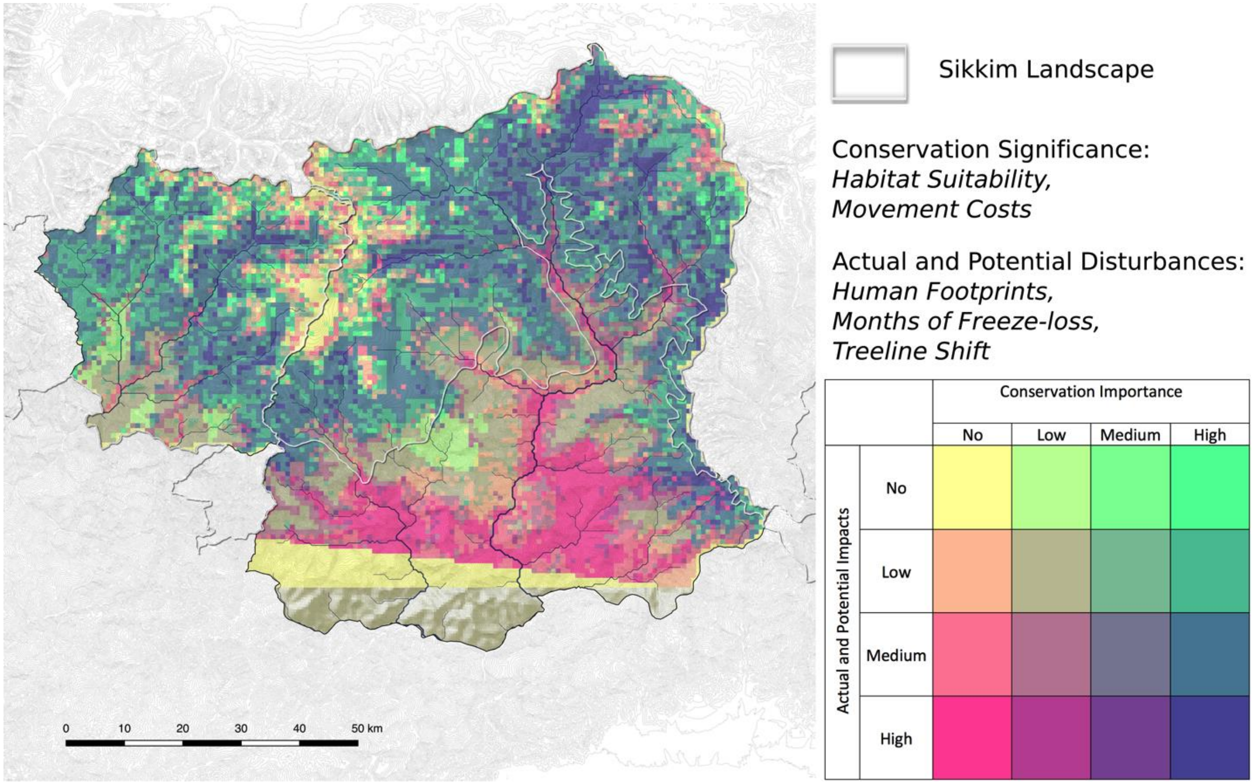
- In winter (November to March), the freeze extent is on the slopes. Any increase in temperature will result in a minimal shift in freeze extent. In this season, the temperatures on top of the mountain ranges are too low to be influenced in freeze extent from warming temperatures by mid-century.
- In April and October, the historic seasonal temperatures change between seasons. Increases in these temperatures will therefore result in a more substantially reduced freeze extent. This can result in an earlier spring, and a later fall, with transitions to ecological communities that favor shorter winters.
- In the summer months (May and June to September) the spatial footprint of the freeze extent is already limited, but surrounds important mountaintops. These mountaintops have historically accumulated 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 accumulate and more precipitation and snow will melt off directly, in coincidence with the monsoon. This will very likely result in a dramatic increase in the size and timing of downstream floods.

Data sources

Current Mean Monthly Temperatures, based on historic WorldClim, 30s resolution (Hijmans et al. 2005).

Climate Projections on future temperatures and precipitation (Peters et al. 2017).

Summary of Conservation Importance and Potential Impacts in the Sikkim Landscape



This map displays the landscape according to conservation importance and actual and potential impacts. Conservation importance is represented by snow leopard habitat suitability, and actual and potential impacts are represented by climate vulnerability and direct human impacts. Results indicate that much of the important habitat of the landscape is under high risk of impact (dark blue). This is particularly evident in the eastern side of the landscape, where human access is higher. The habitats of high conservation importance in the western part of the landscape are subject to slightly lower cumulative risk (medium blue and green) and may be more resilient in the long term. Areas of important habitat at low risk (bright green) are located in a narrow band along the northern edge of habitat, but these areas are fragmented by high risk areas. Managing all habitat for resilience and connectivity is critical to ensure snow leopard metapopulation persistence.

Methodology

This map was created to display conservation importance and actual and potential impacts. Conservation importance was represented by data on snow leopard habitat suitability. Actual and potential impacts from climate change vulnerability are represented by potential treeline shift and number of months of winter expected to be lost. Impacts from humans are represented by the human footprint. For each of these layers, scores representing value (in the case of conservation importance) or severity (in the case of impacts) were developed in collaboration with field experts, and assigned as presented in Table 2.3. A score of 0 indicates the lowest score possible, and a score of 8 indicates the highest. Protected areas were not included, since most habitat in the landscape is under protected status. The values in the tables correspond with the 'raw' values of each input GIS data layer. The qualitative scores of conservation importance and impacts were summed with others in their class, then combined into a single map with 16 different combinations.

Table 2.3A. Conservation Importance

Score	Habitat Suitability	Movement costs
0	0	>15
1		
2		10-14
3		
4		5-9
5		
6	3	1-4
7	2	
8	1	

Table 2.3B. Actual and Potential Impacts

Score	Treeline shift	Months of freeze loss	Human Footprint
0	0, 4	0	0
1	3		
2		1	1-5
3	2		
4		2	6-10
5	1		
6		3	
7			
8			>11

Combined scores: No: 0; Low: 1-3; Medium: 4-7; High: >8

III. Analysis and Mapping of Snow Leopard Habitat in the Eastern Himalaya Landscape, Nepal

Jessica Forrest, Rinjan Shrestha, Nikolai Sindorf, and Ryan Bartlett

World Wildlife Fund, with funding from the
United States Agency for International Development

Chapter 3 of 6 of the report:
Guardians of the Headwaters, Volume 2:
Biodiversity, Water, and Climate
in Six Snow Leopard Landscapes

Key Findings and Management Recommendations

- **The Eastern Himalaya Landscape, Nepal (EHL/N) has over 5,800 km2 of snow leopard habitat located in four discrete habitat blocks.** These blocks are effectively connected by adjacent habitat across the international boundary with China. Snow leopards have been confirmed to use habitats on both sides of the international border, indicating both structural and functional connectivity of the greater EHL/N landscape when it is considered in tandem with habitat in southern China.

- **Protect key unprotected habitat areas.** Approximately 86% of habitat in the landscape is under some form of protection. However, the habitat that is unprotected (most of which is between Kanchenjunga Conservation Area and the Chinese border) serves a vital connectivity, and perhaps breeding habitat function. There is an additional area of unprotected habitat south of Kanchenjunga near the India border. All key habitat areas should be under some form of snow leopard management.

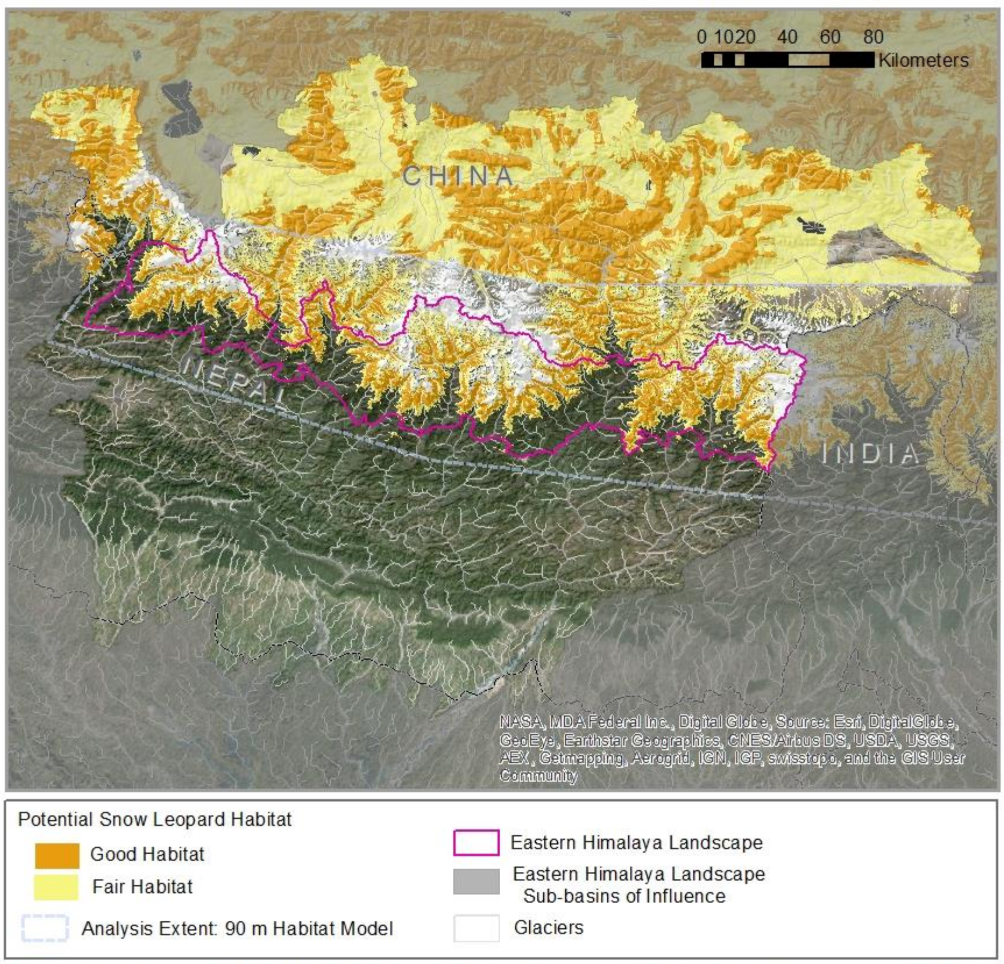
- **Transboundary Management.** The snow leopard habitat of the EHL/N is only intact when considered alongside adjacent habitat across the international border with China. The EHL/N also connects to the greater snow leopard metapopulation at its international boundary with India at its easternmost end, and with China at its northwestern corner. Radio-collared snow leopards have been observed moving hundreds of kilometers between Nepal and China, and Nepal and India. Nine transboundary crossings have been indentified in need of management attention. Successful conservation of the Eastern Himalaya snow leopard population will involve collaboration between Nepal, China and India.

- **Snow leopards and humans coexist in the EHL/N, and management activities can help to minimize risk of habitat loss and fragmentation in key areas. Priorities for conservation include 11 Critical Conservation Sites and 14 Potential Corridors.** Critical Conservation Sites are important habitat areas also subject to high levels of human impact and/or poor protection. Corridors are areas that are vital for maintaining habitat and population connectivity. In general, risks from human activities are more severe in the western part of the landscape than in the east, though pinchpoints are distributed throughout. These priorities should be assessed on a regular (~decadal) basis in light of potentially changing climate suitability.

- **Snow leopard habitat in the EHL/N is likely to be severely impacted by climate change, particularly in the east and at low elevations. To mitigate these effects, long-term conservation efforts should seek to protect and restore macrorefugia and habitat connectivity.** Our model predicts nearly 60% of snow leopard habitat in the landscape may be lost due as the climate zone shifts to one favoring forest ecosystems over alpine grasslands. Snow leopard habitat may in the future compress to the north, west and upslope within its current habitat area. This is despite the fact that the best snow leopard population in this landscape is currently in the east. It will be necessary to focus long-term conservation efforts on climate refugia in the western part of the landscape and at the higher elevations by managing human impacts and maintaining habitat connectivity.

- **Habitats that are considered resilient to full ecosystem shifts will likely experience effects of climate change resulting from shorter winters. Monitoring and adaptive management will be key to determine the nature of these changes and make smart management adjustments.** Almost the entire landscape will experience a shorter winter, and some areas may experience up to 2 – 3 months loss. The loss of frost months will likely occur in the transitional months of March to May and October. Spring over most of the landscape will arrive in April by the year 2050, while it used to arrive by May. This could mean earlier flowering and leaf out, but also changes to grassland and wildlife community composition to species that favor shorter winters. Shorter winters will also result in increasing rates of permafrost and glacial melt, with effects on habitat loss in lost permafrost areas, increasing amounts of run-off during the warmer months of the year (with increased potential for floods), and an increased risk of glacial lake outburst floods (GLOFs).

Potential Snow Leopard Habitat of the Eastern Himalaya Landscape, Nepal



Potential snow leopard habitat of the Eastern Himalaya Landscape, Nepal, over its local hydrological sub-basin of influence. *WWF 2017*

Potential snow leopard habitat of the Eastern Himalaya Landscape, Nepal (EHL/N) with local hydrological sub-basins of influence. There is more than 5,800 km^2 of snow leopard habitat in the EHL/N. Of this, 2,743 km^2 is classified as good habitat, and 3,084 is classified as fair habitat. The habitat is arranged in four discrete habitat patches, requiring habitat across international borders to maintain connectivity. Good habitat ranges in elevation from 3500-5200 m, and fair habitat from 3500-6000 m.

Methodology

Snow leopard habitat displayed in these maps was modeled at 90 m resolution as a function of land cover, elevation, slope, ruggedness, and snow leopard observations (see data sources below for full reference). Snow leopard observations came from camera trap surveys, DNA testing of signs, and radio collaring of an individual. Radio collar points were randomly pruned to reduce sampling bias compared with the other survey methods. A Maxent model was run using 74 snow leopard observation points from across the analysis extent (with 54 points used to train the model and 20 used for testing), and the 4 environmental variables (Phillips et al. 2006). The model was run in several iterations, testing alternative ruggedness models (the terrain ruggedness index and the vector ruggedness model), as well as some climate variables thought to be important drivers of alpine ecosystems (including total summer precipitation, total precipitation as snow, number of months of frost, mean growing season temperature and percent of annual precipitation that occurs during monsoon). Model sensitivity and output was tested systematically by withdrawing certain variables. The resulting model based on land cover, elevation, slope and terrain ruggedness had an Area under Curve (AUC) value of 0.832 and a test AUC of 0.792. The 4-variable model was selected as the best representation of current habitat at the 90 m scale.

The resulting logistic probability of occurrence (*p*) map was reclassified into good, fair and non-habitats based on *p*-thresholds, and refined with elevation data. Good habitat was defined as areas where *p* >= 0.5 and elevation < 5200 m. The logistic p-value > 0.5 was selected as a restrictive statistical definition of habitat, in this case, the "Maximum of training sensitivity plus specificity". The value of 5200 m was selected as a maximum elevation threshold of good habitat based on expert opinion (R. Shrestha, personal communication, August 29, 2016) and snow leopard collar data (Government of Nepal & WWF 2016). Fair habitat was defined at elevations < 5200 m as areas where *p* >0.29 and <0.5. At elevations between 5200 and 6000 m, fair habitat was defined as *p*>0.29 (reclassifying "good" habitat at these elevations to "fair"). *p*-value 0.29 represents a generous definition of habitat, in this case, the 10th percentile training presence.

The elevation thresholds were adopted because snow leopards are rarely observed between elevations of 5,200-6,000 m, and have not been observed at elevations > 6,000 m in Nepal (R. Shrestha, personal communication, August 29, 2016). Radio collar evidence from a male snow leopard (Government of Nepal & WWF 2016) corroborates this opinion: the leopard spent 92% of the time below 5200 m, 7.7% of his time at elevations 5,200-6,000m, and 0.27% of the time at DEM values> 6000m. The observations > 6,000m were located in India on the northeast side of Kanchenjunga mountain, and are uncertain due to potential inaccuracies in the DEM in this particular location resulting from very steep terrain. Data gaps here are void-filled using an algorithm, and a slight shift in the DEM with respect to point locations in steep terrain can result on large discrepancies between reported and actual elevation.

The map of good, fair, and non-habitat was overlaid with snow leopard observations. We noted that among 62 snow leopard observations in the landscape, 72.6% of snow leopard observations were found in good habitat, 21.0% in fair habitat, and 6.6% in non-habitat. This corresponds with the proportional use of the three habitat classes by snow leopards, and a 6.6% omission error. Data from two radio collared snow leopards corroborated this evidence. Together, the two snow leopards visited good habitat 74.8% of the time, fair habitat 23.5% of the time, and non-habitat 1.6% of the time. Both traveled more than 100 km: the female was captured in Kanchenjunga Conservation Area and moved north into southern China. The male was also captured in Kanchenjunga and moved east into Sikkim, India (Government of Nepal & WWF 2016).

It is important to note that while snow leopards may use areas described as non-habitat infrequently (1.6-6.6% of the time), some non-habitat sites represent highly important linkages for connecting snow leopard populations and movement (R. Shrestha, personal communication, September 2, 2016). Thus, narrow passages of non-habitat between large habitat patches should not be written off from conservation efforts and should be managed for their connectivity benefits.

Data Sources

EHL/N Snow Leopard Habitat Model (90 m):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, ruggedness, slope (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008)

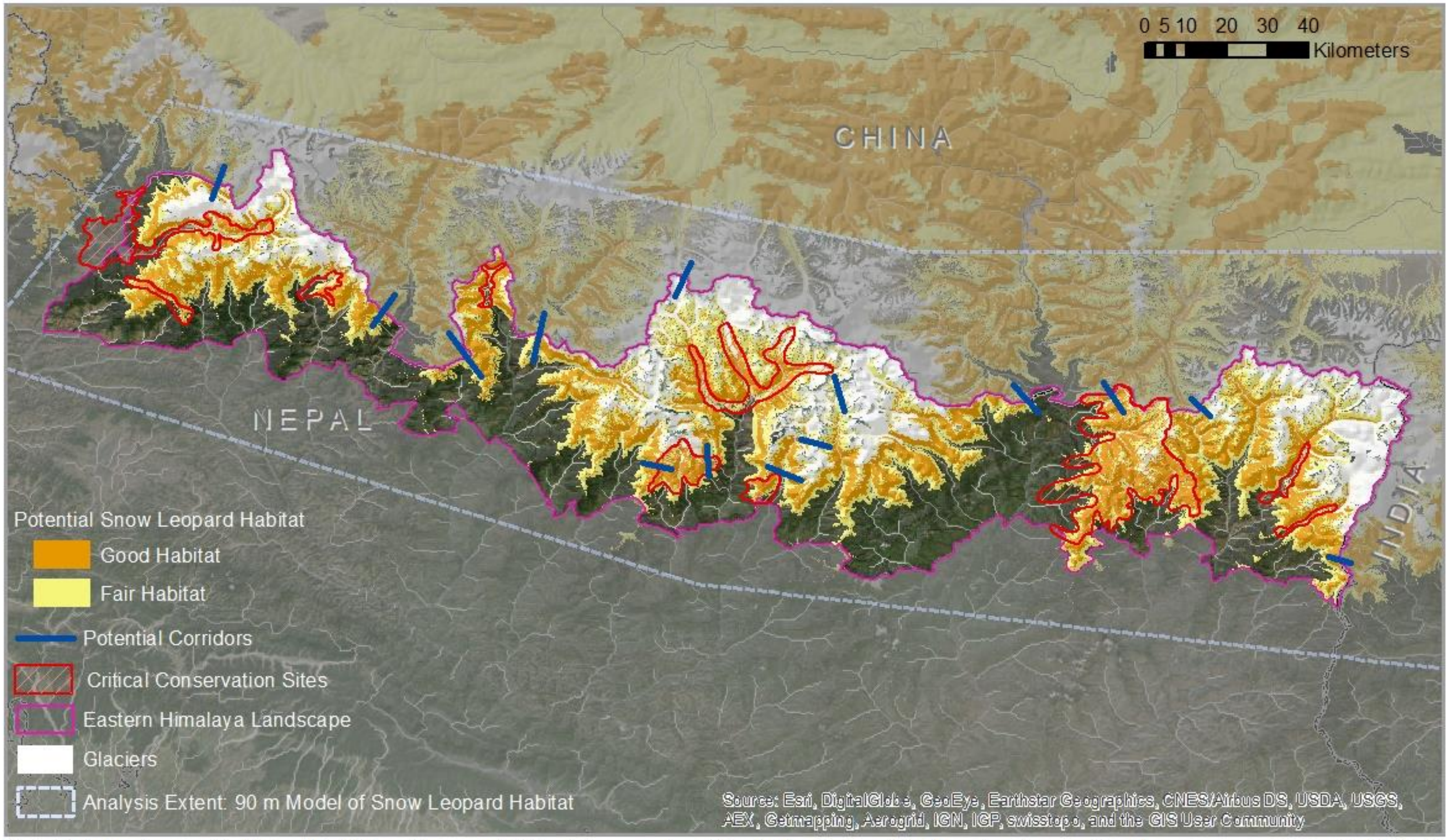
Regional Snow Leopard Habitat Model (500 m):

- Forrest et al. 2012

Other layers for display only:

- Glaciers (GLIMS & NSIDC 2016)
- EHL/N Boundary (Government of Nepal & GSLEP 2015-6)
- Blue Marble Imagery (NASA, MDA Federal Inc., Digital Globe 2016

Potential Snow Leopard Habitat, Corridors, and Critical Conservation Areas of Eastern Nepal



Potential snow leopard habitat, potential corridors, and Critical Conservation Sites in the Eastern Himalaya Landscape, Nepal. Potential corridors indicate important or at-risk habitat crossings. Critical Conservation Sites are important habitat areas that may be at-risk due to unprotected status or proximity to human dominated zones. *WWF 2017*

This map shows snow leopard habitat, Critical Conservation Sites, and Potential Corridors in the EHL/N. There are 11 Critical Conservation Sites and 14 Potential Corridors (nine of which are transboundary).

Snow leopard habitat indicates where snow leopards are most likely to hunt, live and breed. Critical Conservation Sites represent important areas of snow leopard habitat that are at-risk due to high human activity and/or lack of adequate protection. Potential Corridors represent the most likely path for snow leopards to travel between two habitat patches or across marginal or narrow habitat. Corridors may represent places where snow leopards need to move across, or in close proximity to features such as mountain peaks, human dominated landscapes, or extensive forests patches caused by depressions.

Methodology

Potential corridors were drawn with reference to maps of snow leopard habitat and a cost of movement raster developed for this study using ArcGIS 10.3 Spatial Analyst (ESRI, Redlands, CA), according to methods first described by Beier et al. 2007, 2008. Specific input layers to the cost raster included: the inverse of snow leopard probability of occurrence rescaled to a scale of 0-10, distance to major roads, distance to secondary and tertiary roads, land cover, distance to hamlets and isolated dwellings, distance to settlements, villages and towns, and distance to cities. All classes in all layers were assigned cost scored on a scale of 0-10, with 0 as the lowest cost of movement, and 10 as the highest (see Table 1.1). A score of 10 does not mean the land is uncrossable, it is just highest cost of movement on a relative scale. The cost grid was produced by summing all the of the input layers.

Critical Conservation Sites were drawn in conjunction with data on snow leopard habitat, the human footprint (methods described later in this report), and protected areas. For more information, see Government of Nepal 2017.

Table 1.1. Cost of Movement Scores in the EHL/N

Original Data	Cost of Movement Score
Snow leopard habitat suitability	
Habitat suitability (0-100 scale)	(100-suitable habitat)/10 = Cost
Land cover	
Needleleaved Forest	5
Broadleaved Forest[1]	7
Shrubland	4
Alpine Meadow	0
Agriculture	3
Fallow land	2
Snow, glacier	7
Barrenland	2
Water	10
Built-up	10
Distance to Population Centers	
Distance to Settlements, Villages and Towns (m)	
0-180	10
180-450	4
>450	0
Distance to Hamlets and Isolated Dwellings (m)	
0-90	10
90-180	2
>180	0

Distance to Roads	
Distance to Major Road[2] (m)	
0-90	8
90-270	3
270-450	1
>450	0
Distance to Secondary Roads and Paths[2]	
0-270	3
270-450	1
>450	0

1. Presumed in this extent to be low to mid-elevation forest type such as *Schima-Castonopsis,* 2. primary and trunk roads; Note that there were none in this extent, 3. living street, residential, road, secondary, service, unclassified, construction, path, footway, bridleway, tertiary, and track

Data Sources

EHL/N Snow Leopard Habitat Model (90 m):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, ruggedness, slope (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008)

Regional Snow Leopard Habitat Model (500 m):

- Forrest et al. 2012

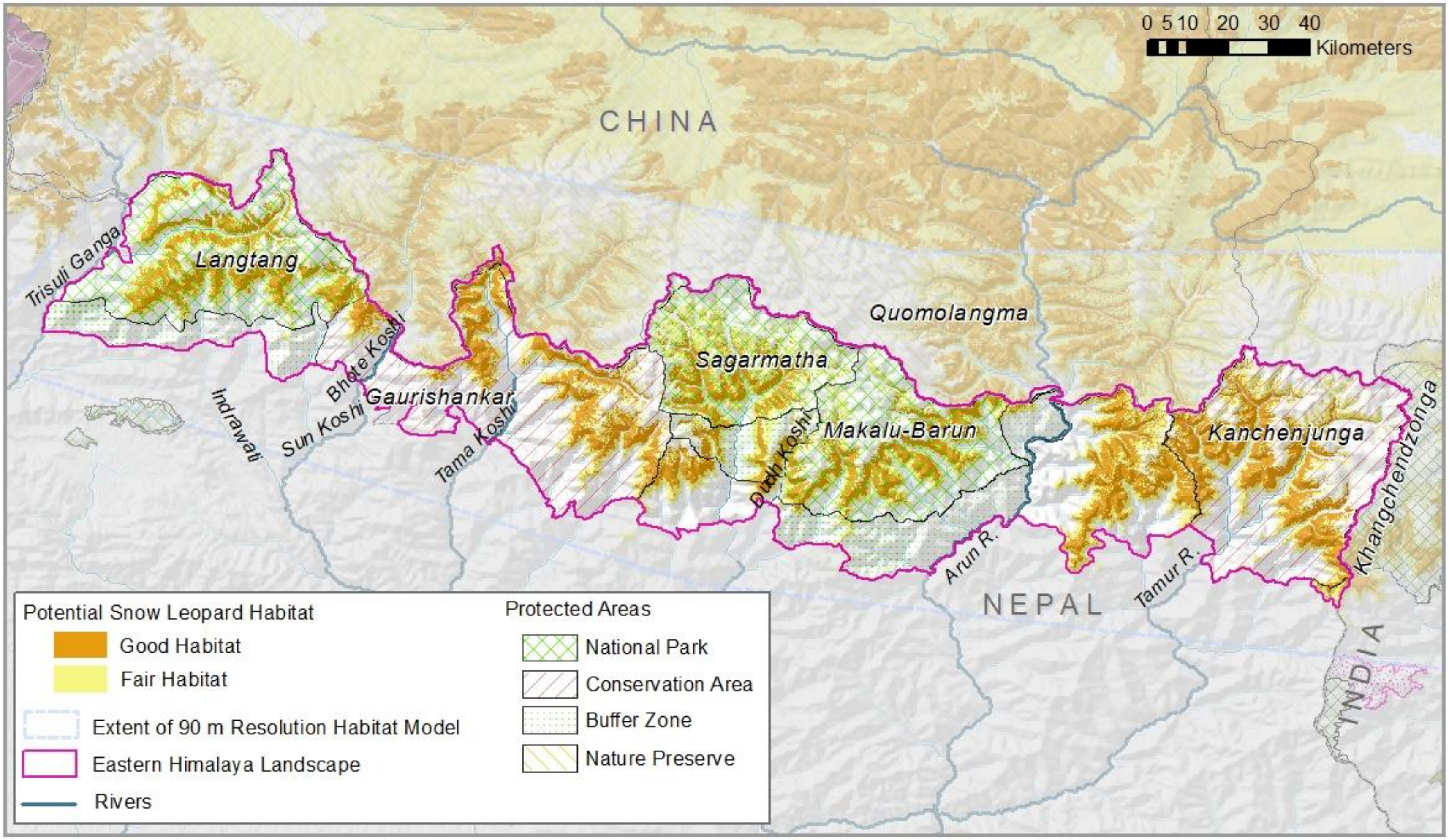
Cost of Movement Model:

- Roads, Places (OpenStreetMap 2016)
- Land cover (WWF 2015, Hansen et al. 2013, GLIMS & NSIDC 2016)
- EHL/N Snow Leopard Habitat Suitability Model (this study)

Other layers for display only:

- Glaciers: GLIMS & NSIDC 2016
- EHL/N Boundary (Government of Nepal & WWF 2015-16)
- Blue Marble Imagery (NASA, MDA Federal Inc., Digital Globe)

Protected Areas and Snow Leopard Habitat in and near the Eastern Himalaya Landscape



Protected areas, major rivers, and snow leopard habitat in and near the Eastern Himalaya Landscape.

WWF 2017

Protected areas cover over 5,000 km^2 or 86% of potential habitat in the Eastern Himalayas Landscape, Nepal. 826 km^2 of habitat remains unprotected, most of it located west of Kanchenjunga Conservation Area. This habitat forms a vital connection between Kanchenjunga and Quomolangma Nature Preserve in China, and through this, habitats of the rest of the EHL/N. There is a smaller area of unprotected habitat at the southeast corner of Kanchenjunga, adjacent to the Nepal-India border.

As shown in Table 1.2, Kanchenjunga Conservation Area has the most snow leopard habitat among the protected areas, with more than 1,200 km^2 of total habitat area. Langtang National Park, Gaurishankar Conservation Area, Makalu Barun National Park, and Sagarmatha National Park also have substantial amounts of habitat.

Table 1.2. Protected Habitat Area in the Eastern Himalaya Landscape, Nepal

Protected Area Name	Snow Leopard Habitat (km2)		
	Good	Fair	Total
Gaurishankar Conservation Area	458	447	905
Kanchenjunga Conservation Area	574	636	1210
Langtang National Park	497	512	1009
Langtang National Park-Buffer Zone	0	4	4
Makalu Barun National Park	373	433	806
Makalu Barun National Park-Buffer Zone	9	37	46
Sagarmatha National Park	302	516	819
Sagarmatha National Park- Buffer Zone	89	114	202
Total Protected	**2,302**	**2,698**	**5,001**

Data Sources

EHL/N Snow Leopard Habitat Model (90 m):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, ruggedness, slope (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008)

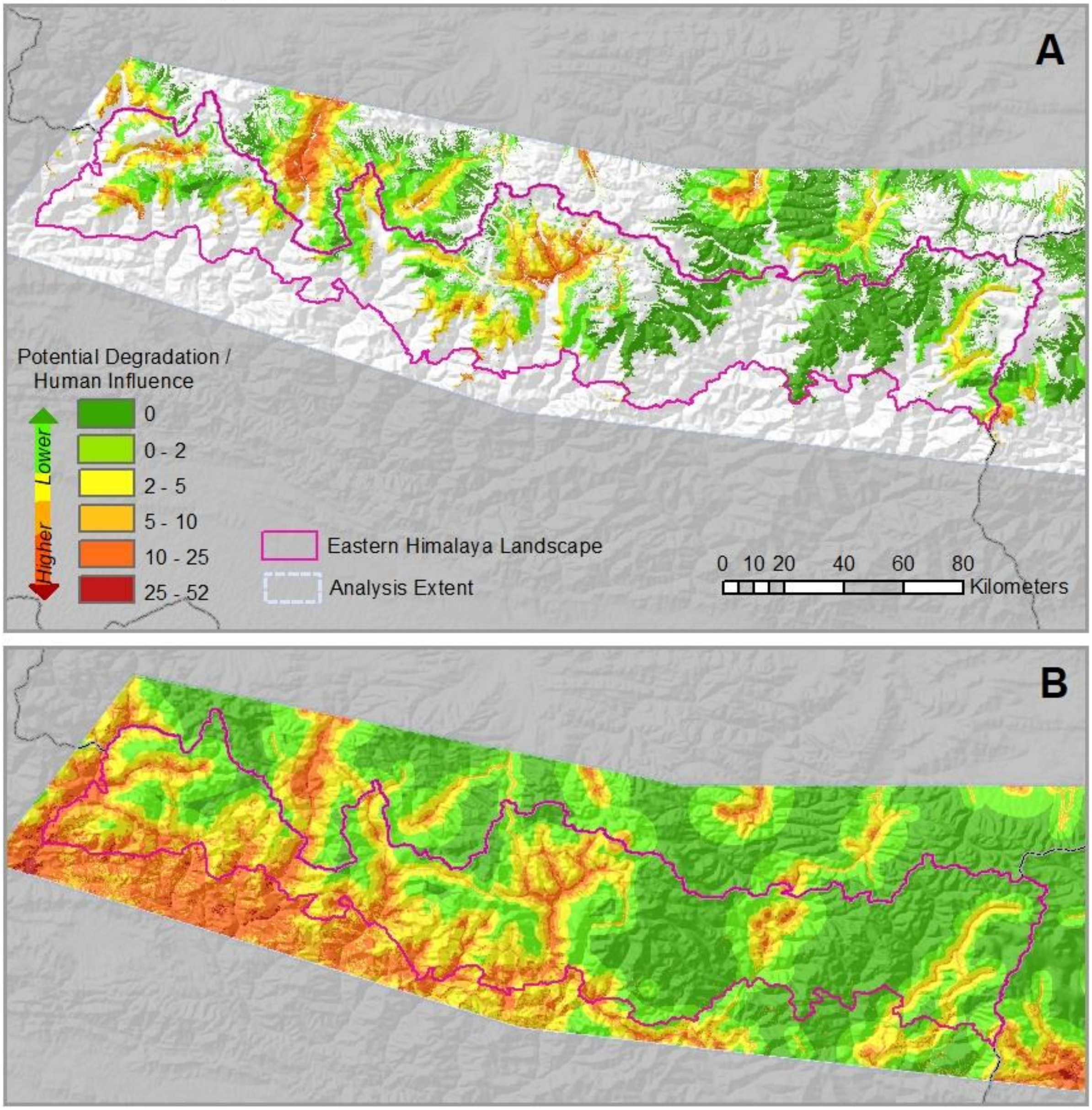
Regional Snow Leopard Habitat Model (500 m):

- Forrest et al. 2012

Human Landscape:

- Protected Areas (Government of Nepal 2016)
- Rivers (OpenStreetMap 2016)
- EHL/N Boundary (Government of Nepal & WWF 2015-16)

Potential for Degradation and Human Influence in Snow Leopard Habitat



Potential degradation and human influence of snow leopard habitat is represented by the relative amount of human activity and observed degradation. It is a function of the distance to roads, distance to settlements, and land cover and land use. Map A shows potential degradation and human influence in snow leopard habitat, and Map B shows potential degradation and human influence across the analysis extent.

WWF 2017

This map represents existing and potential future degradation and human threats to the snow leopards, their habitats, and their prey, from sources such as hunting, human wildlife conflict, infrastructure, and land use. It is based on measures of human accessibility that include distance to roads, distance to population centers, and land cover and land use. Human impact and potential degradation is higher on the western side of the landscape compared with the east due to a higher human population and more roads. As indicated in Table 1.3, 83% of habitat has a low level of human footprint that is generally suitable for snow leopards. Fourteen percent of habitat has a moderate human presence (with some infrastructure, potential degradation from grazing, and human-snow leopard conflict) but that snow leopards can generally move across. Approximately 2% of habitat has a high human footprint that is not suitable for snow leopard movement. These areas may have built infrastructure, dense population and/or intensive human use zones.

Table 1.3. The Distribution of the Human Footprint across Snow Leopard Habitat in the EHL/N.

Human Footprint Level	Total Area (km^2)	Percent of Total Habitat (km^2)
Low (<=4)	4880.4	83.8
Medium (>4 and <=12)	813.6	14.0
High (>12)	133.1	2.3

Methodology

The model is based on measures of human accessibility that include distance to roads, distance to population centers, and landcover using methods developed by Sanderson et al. (2002). Values in the three layers were rescored to represent cost of movement or degradation (Table 1.4). As such, a score of 0 represents no degradation or cost of movement, and 10 represents the highest cost of movement or level of habitat degradation (i.e., a score of 0 represents a fully permeable area of habitat, while a score of 10 represents nearly impermeable). Rescored layers were summed to produce a potential degradation and human influence layer.

To characterize snow leopard habitat by level of potential human impact, the resulting human footprint was reclassified into three human footprint classes (low, medium, and high). Thresholds were based on the putative response of snow leopard to human presence and associated threat. Low human footprint describes areas generally suitable for snow leopards (HF <=4). Medium human footprint describes areas that have human presence high enough to cause some problems for snow leopards, but where snow leopards will generally able to move between habitat patches (HF > 4 and <=12). These areas may have a moderate level of human presence with some infrastructure, potential habitat degradation from grazing, and human-snow leopard conflict. High human footprint describes areas that are presumably not suitable for snow leopards to move across (HF>12). These areas may be characterized by fragmentation from built infrastructure, dense population, or other types of intensive human-use zones.

Table 1.4A. Land Cover Class Scores for Human Footprint

Land cover	Potential Degradation/Human Impact Score
Needleleaved Forest	0
Broadleaved Forest	0
Shrubland	0
Alpine Meadow	0
Agriculture	8
Fallow land	6

Snow, glacier	0
Barrenland	0
Water	0
Built-up	10

Table 1.4B. Distance to Population Center Scores for Human Footprint

Distance to Cities (m)	Potential Degradation Score
0-3000	10
3000-5000	8
5000-10,000	3
10,000-12,000	1
>12,000	0
Distance to Settlements, Villages and Towns (m)	**Potential Degradation Score**
0-1000	10
1000-2000	6
2000-3000	3
3000-5000	2
5000-10,000	1
>10,000	0
Distance to Hamlets and Isolated Dwellings (m)	**Potential Degradation Score**
0-90	10
90-270	8
270-500	2
500-5000	1
>5000	0

Table 1.4C. Distance to Roads Scores for Human Footprint

Distance to Major Road[1] (m)	Potential Degradation Score
0-90	10
90-270	8
270-500	6
500-3000	3
3000-5000	2
>5000	0
Distance to Secondary Roads and Paths[2]	**Potential Degradation Score**
0-90	8
90-270	6
270-500	4
500-2000	2
2000-3000	1
>3000	0

[1] primary and trunk roads; Note that there were none in this extent, [2.] living street, residential, road, secondary, service, unclassified, construction, path, footway, bridleway, tertiary, and track

Data Sources

EHL/N Snow Leopard Habitat Model (90 m):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, ruggedness, slope (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008)

Regional Snow Leopard Habitat Model (500 m):

- Forrest et al. 2012

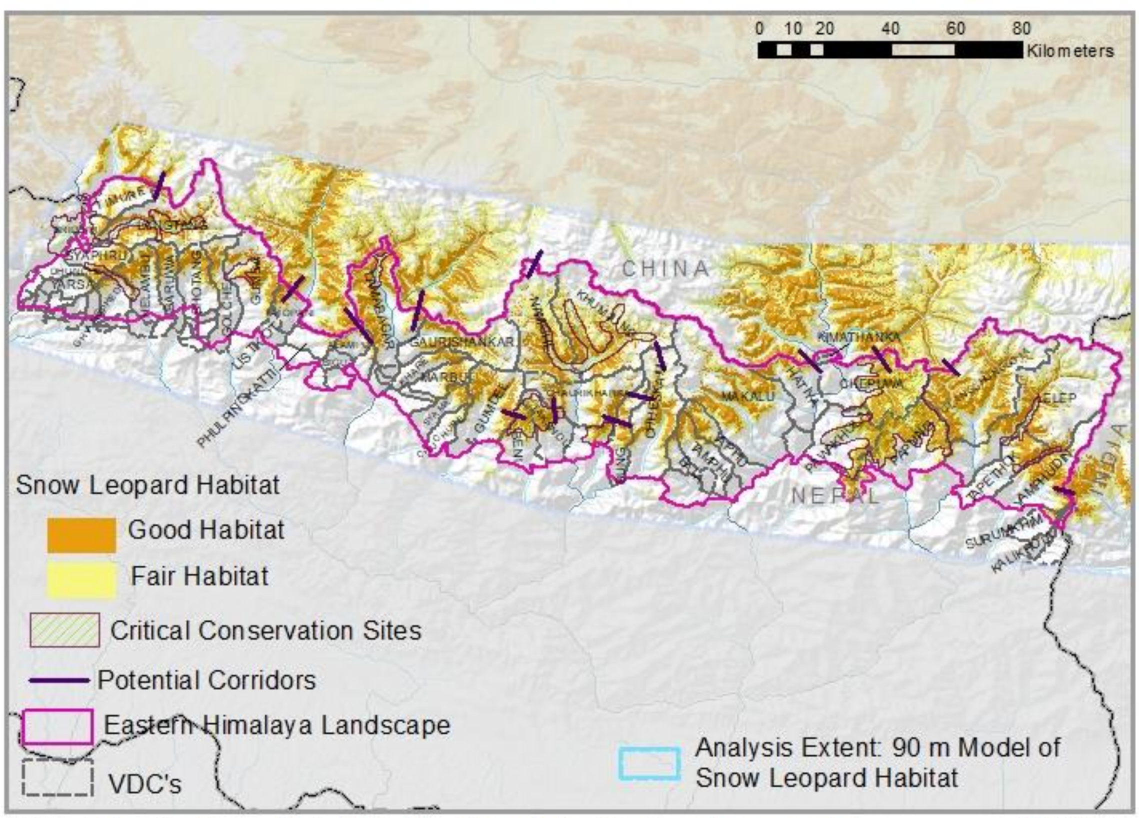
Human Footprint/Potential Degradation:

- Roads, Places (Open Street Map 2016)
- Land cover (WWF 2015, Hansen et al. 2013, GLIMS & NSIDC 2016)

Other layers for display only:

- Glaciers (GLIMS & NSIDC 2016)
- EHL/N Boundary (Government of Nepal & WWF 2015-16)
- Blue Marble Imagery (NASA, MDA Federal Inc., Digital Globe)

VDC's of the Eastern Himalaya Landscape, Nepal



VDC's (Municipal Level Administrative Boundaries) that overlap potential snow leopard habitat.

WWF 2017

Data Sources

EHL/N Snow Leopard Habitat Model (90 m):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, ruggedness, slope (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008)

Regional Snow Leopard Habitat Model (500 m):

- Forrest et al. 2012

Human Landscape:

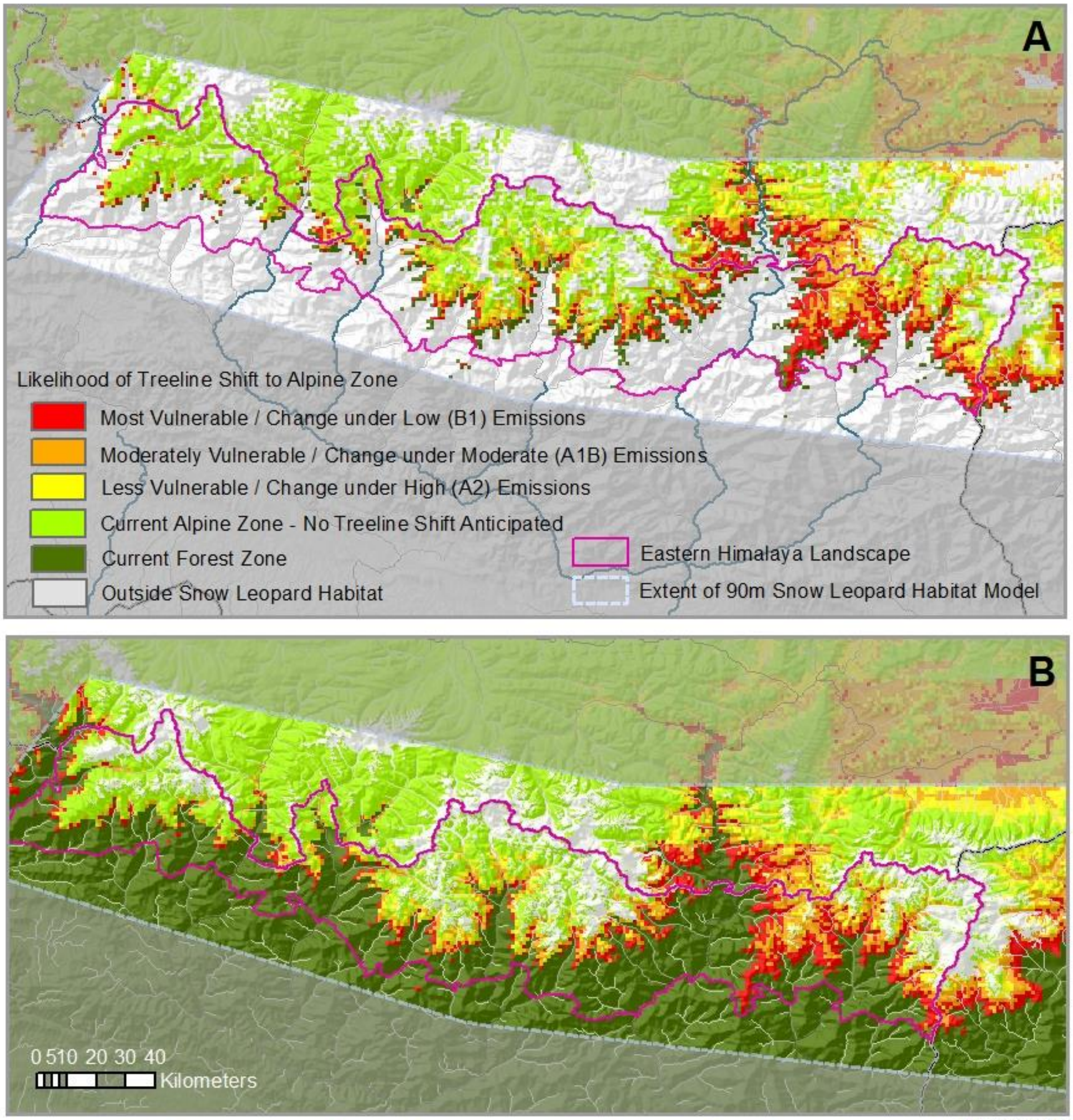
- VDC boundaries (Department of Survey, Government of Nepal 2013)
- EHL/N Boundary (Government of Nepal & WWF 2015-16)

Climate Change Vulnerability in the Eastern Himalaya Landscape, Nepal

The EHL/N is expected to experience a substantial increase in average annual temperature (+1.9˚C to 2.6˚C by the mid-century time frame of 2041-2070). The highest degree of warming will likely occur during the winter months, particularly March. This could affect the freeze-thaw cycle and the timing of snow melt, lead to earlier snow melt and flooding conditions, and the arrival of spring. Precipitation is also expected to increase, particularly during the monsoon, when rainfall is already high (Peters et al. 2017). Potential impacts of these climate changes include changes to vegetation patterns, permafrost cover, and location of major ecosystem types – with implications for habitat quality and availability; cropland availability – with implications for people and pressure on wildlife resources; patterns and timing of livestock grazing, and flooding and landslide risk, particularly during the monsoon (Climate Smart Snow Leopard Management Planning Workshop, April of 2016).

We selected a few indicators of climate change impacts for mapping, in order to better understand the spatial distribution of climate risk for alpine wildlife and human communities. These included the distribution of treeline shift risk in the landscape (or the transition from a climate zone favouring alpine grassland to one favouring forest); potential change in the suitable climate envelope for cropland (indicating changing human habitability, but also human pressure on wildlife habitat); water towers (or water provision to the downstream from precipitation); winter duration (indicated by freeze-line, with implications on ecological functions as well as water availability for people); and change in open water availability (which is a good indicator of overall changes to a landscape). The latter three, and other hydrological functions, are covered in more depth by Sindorf 2017.

Vulnerability of Snow Leopard Habitat to Treeline Shift from Climate Change



Vulnerability of snow leopard habitat to climate-change induced treeline shift. Map A shows projected change of snow leopard habitat to forest under climate change scenarios. Map B shows projected change in the forest and alpine zones across the study area.

WWF 2017

This map represents the vulnerability of current snow leopard habitat to climate change-induced treeline shift. There is a gradient in vulnerability from southeast to northwest and from low elevations to high, with habitats in the southeast and lowest elevations most vulnerable to potential treeline shift. This model predicts that 58% of current snow leopard habitat could resemble the forest climatic zone by the year 2100, as opposed to the baseline climate that has historically favored alpine grasslands. This map suggests that a long-term strategy could be to maintain habitat connectivity throughout the landscape, focusing in particular on maintaining and restoring macrorefugia in the west.

Treeline is expected to shift as temperatures become warmer and wetter, and the growing season in alpine areas becomes more hospitable (Forrest et al. 2012). Areas that become warmer, wetter, and more suitable for natural forests may also become more suitable for crops and livestock, encouraging human immigration. These indirect effects of climate change may also result in habitat loss. This model does not account for microrefugia that may exist currently and/or persist due to local climate conditions in this montane landscape (Thapa et al. 2016). However, snow leopards are wide-ranging species, so micro-refugia may not offer ample breeding or connectivity habitat for snow leopards.

Data Sources

EHL/N Snow Leopard Habitat Model (90 m):

- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, ruggedness, slope (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008)

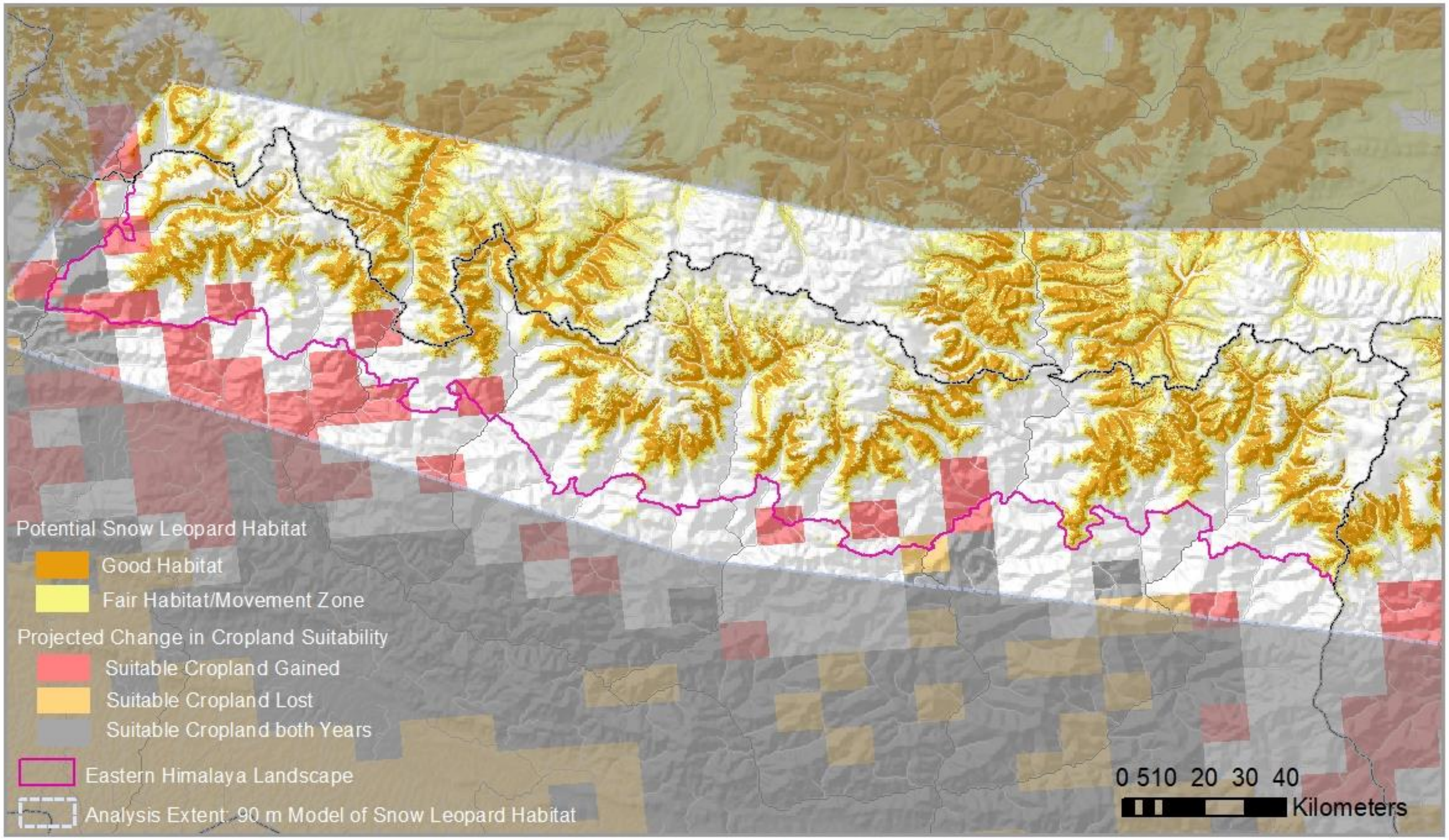
Regional Snow Leopard Habitat Model (500 m):

- Forrest et al. 2012

Projected Change in Treeline under Climate Change: Forrest et al. 2012

EHL/N Boundary: Government of Nepal & WWF 2015-16

Projected Change in Cropland Suitability under Changing Climate



This represents a model of how climate suitability for growing crops may shift under a high emissions (A2) scenario to the year 2100. *WWF 2017*

This map shows projections of current climate envelope for arable land (or cropland), and potential change under a high emissions climate change scenario. These results suggest that in this landscape, “encroachment” of the climate envelope for arable land into the snow leopard range may not be a major concern. However, there may be an increase in arable land in the sub-basins that receive water originating in the snow leopard range. This could effectively increase the pressure on water resources from these habitats and emphasize the need for snow-leopard friendly management.

The model shown is based on the Global Arable Lands database (Ramankutty et al. 2008) and 19 bioclimatic variables (Hijmans et al. 2005). These inputs were used to produce climate envelope projections for the current time period and the 2080’s under a high emissions scenario (A2A) using the HADCM3 General Circulation Model (see Sindorf et al. 2014).

Data Sources

EHL/N Snow Leopard Habitat Model (90 m):

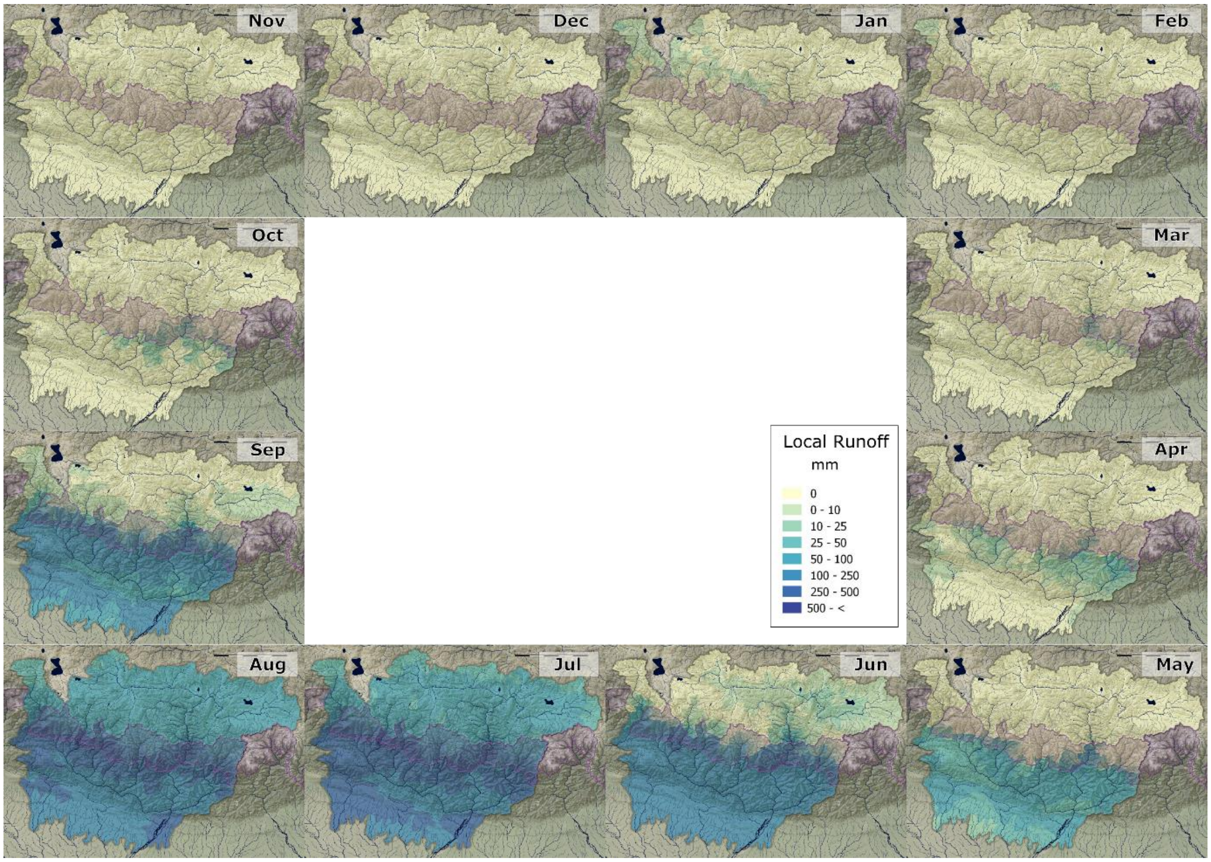
- Land cover (WWF 2015, Hansen et al. 2013, Liu and Guo 2014)
- DEM, ruggedness, slope (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (Government of Nepal & WWF 2015-16; ISLT, Panthera, SLN, WCS 2008)

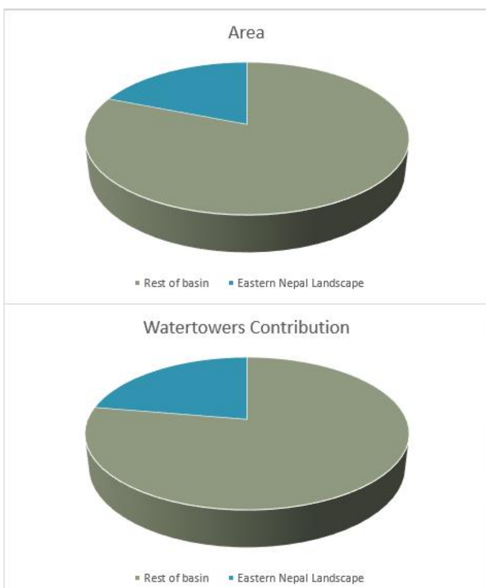
Regional Snow Leopard Habitat Model (500 m): Forrest et al. 2012

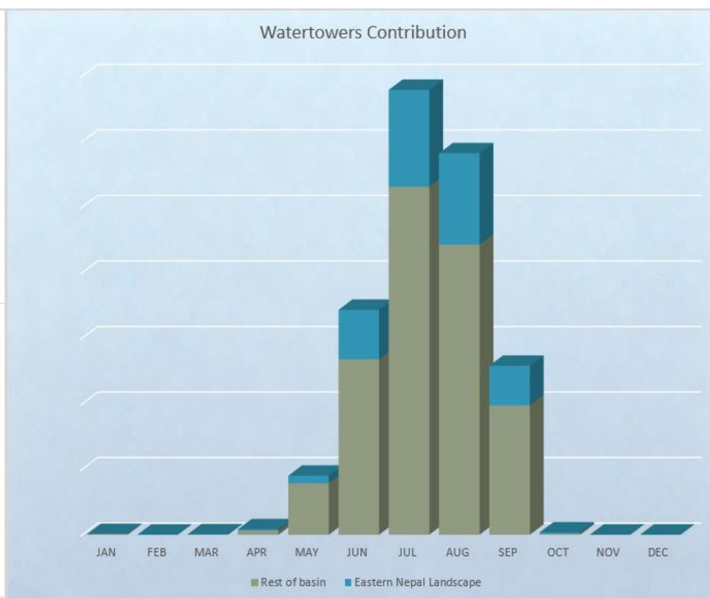
Projected Change in Cropland Suitability: Sindorf et al. 2014

EHL/N Boundary: Government of Nepal & WWF 2015-16

Water towers (local runoff) in the Eastern Himalayas Landscape Sub-basin







Water Towers/ Local Runoff	
Baseline Conditions	The EHL/N is located just upstream of the wettest part of the sub-basin, and does not provide a significant water tower service to the downstream. Local runoff from precipitation occurs mainly during the monsoon season, when downstream needs are already saturated. At this time of year, runoff from the landscape can contribute to floods downstream.
Projected Climate Change	The relative role of the landscape in water provision is not expected to change under changing climate. In a low precipitation future scenario, the landscape would become much drier in proportion with the rest of the basin. Under wetter conditions, the landscape and surrounding sub-basin would both get wetter.

Within the sub-basin, there is a distinctive North-South gradient in runoff generation from precipitation. The landscape is in the transition zone between the dry and the wet parts of the basin, and it sits just above the wettest part of the sub-basin. While annual averages show that the landscape covers 19% of the sub-basin, but provides 22% of its runoff, the water tower value is not significant due to the timing of peak run-off during the monsoon (June-September). At this time of year, precipitation is high throughout the sub-basin, and demand is low. In fact, at this time of year, run-off from the landscape can contribute to floods downstream. Throughout the dry season (October-May), when downstream water demand is highest, the landscape does not serve as a water tower from precipitation alone- though snow and ice melt from the landscape helps to address significant downstream needs during the late dry season (April-May). The timing of snow and ice melt is not represented in the model.

Within the landscape, and in every month, there is a gradient in local runoff that decreases from south to north, lower to higher elevations, and from downstream to upstream. The Arun river valley -that cuts through the landscape from north to south- shows a local runoff pattern that is associated with its lower elevation; it therefore stands out inside the landscape as having higher runoff quantities. Annual runoff from the landscape is expected to increase from 3.3% to 57.6% compared with the baseline, based on low to high precipitation models. The timing of this increase coincides with the monsoon; so it is expected to increase floods downstream.

Figure 1.1. Projected change in the relative water tower function of the Eastern Himalayas Landscape, Nepal compared with the rest of the landscape under baseline and future precipitation scenarios

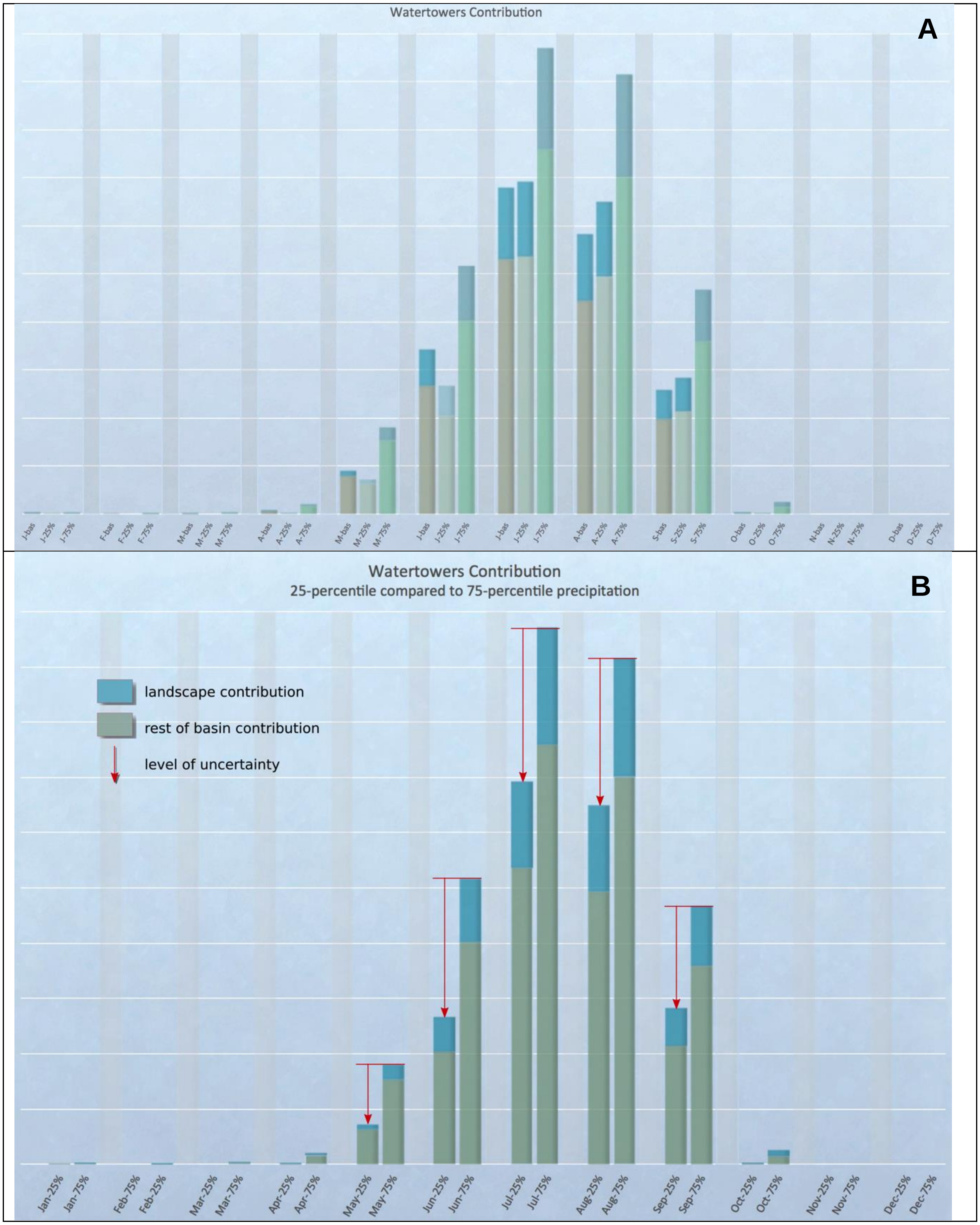


Figure 1.1A shows relative water tower contributions of the Eastern Himalayas Landscape, Nepal compared with the rest of the sub-basin under baseline year and 25-percentile and 75-percentile mid-century precipitation projections (Peters et al. 2017, Sindorf 2017). Figure 1.1B compares the relative water tower contribution of the landscape with the rest of the sub-basin under low and high mid-century precipitation projections, and also expresses the range of uncertainty. Relative run-off from the landscape is represented by the blue color at the top of each bar, while run-off from the rest of the sub-basin is represented by the bottom portion of the bars. Red arrows show the range of changes in runoff based on the two projections, and therefore illustrates uncertainty in future climate impacts on runoff.

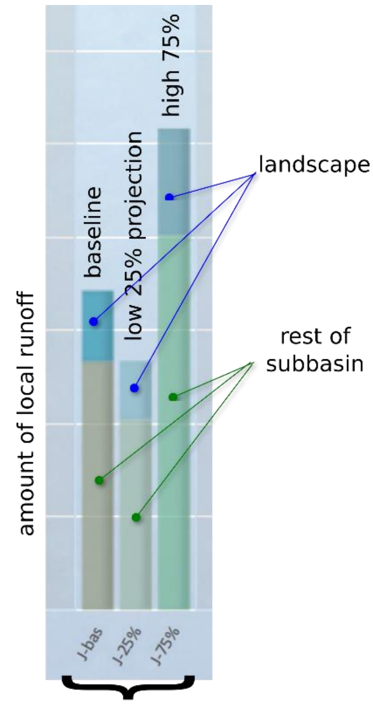


Figure 1.1 indicates that the water tower role of the landscape relative to the rest of the sub-basin is not likely to change drastically with climate change by mid-century. Under low precipitation scenarios, the landscape would get drier in proportion with the rest of the sub-basin. Under high precipitation scenarios, the landscape would become proportionally wetter.

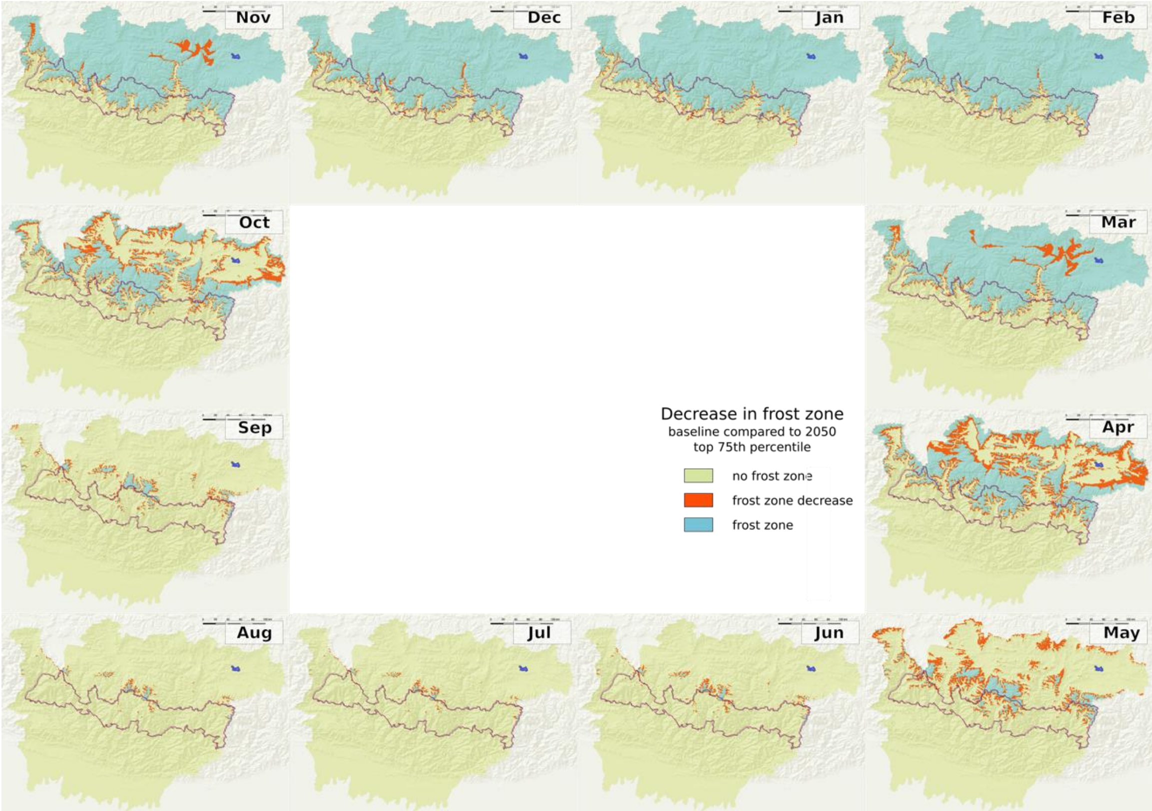
Methodology

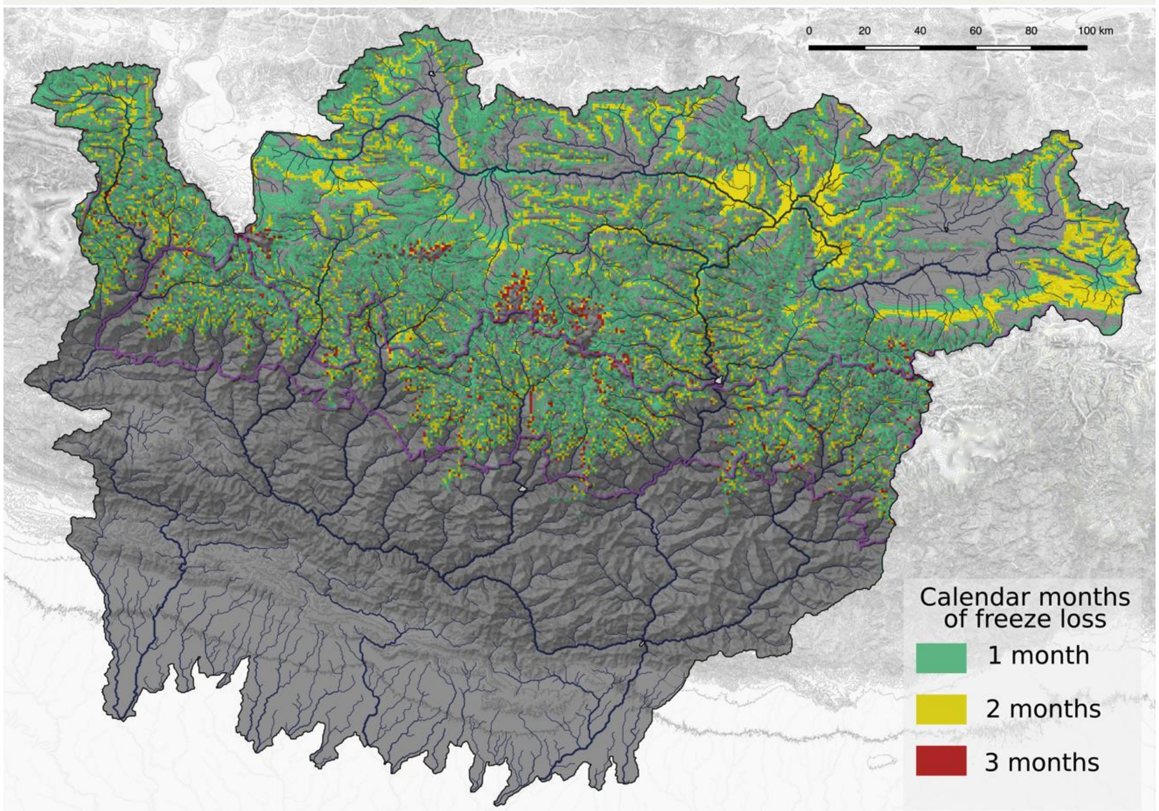
Local runoff is the difference between monthly precipitation (P) and actual evapotranspiration (AET). Monthly precipitation and AET are downloaded and, through a simple GIS command, summarized by their watershed 'mean', using HydroBASINS level 12 watersheds. The mean values were multiplied by each of the watershed areas in order to convert from millimetres to cubic meters. Next, mean actual evapotranspiration was subtracted from mean precipitation (P – AET) for each month. Local runoff values that were less than zero were displayed and flagged as being zero. Inside the sub-basin, those watersheds that drain the snow leopard landscape were also flagged to summarize run-off contribution from the landscape alone. For more information, see Sindorf 2017.

Data Sources

- Current Mean Monthly Precipitation, based on historic WorldClim, 30s resolution (Hijmans et al. 2005)
- Current Mean Monthly Actual Evapotranspiration, based on historic Global Soil-Water-Balance, CGIAR, 30s resolution (Trabucco and Zomer 2010)
- HydroBASINS, level 12, ~100 km^2 watershed outlines (Lehner and Grill 2013)
- Climate Projections on future temperatures and precipitation (Peters et al. 2017)

Decrease in Monthly Freeze Extent under Temperature Rise in the Eastern Himalayas Landscape, Nepal Sub-basin





Snow Cover, Frozen Ground, and Freeze Line	
Baseline Conditions	The freeze line coincides with the southern landscape boundary in winter, and with the northern landscape boundary near the mountaintops in summer. Since the landscape covers the seasonal fluctuation of minimum and maximum freeze and snow extent, it provides an essential role in the generation of snowmelt and other cryosphere interactions.
Projected Climate Change	A warming climate is expected to result in a dramatic shift in freeze line and the duration of winter. This will affect the timing of snow and ice melt, which will affect downstream water flows. Downstream areas could be more vulnerable to floods during the wet season, and water shortages during dry times of year that have typically relied on snow-melt.

The above maps illustrate for each month how the spatial footprint of the freeze frontier is expected to change under projected temperature rise to mid-century. The freeze line is an indicator of the average timing of snowfall and snowmelt, glacial melt, permafrost coverage and depths, and subsequent water availability. It is also an indicator of phenological processes such as the timing of green-up and leaf-fall, breeding and birthing, and animal movements. Seasonal changes can selectively impact some species, ultimately affecting the composition of vegetation and animal communities in the landscape.

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. Increasing temperatures to mid-century would result in a minimal shift in the extent of freezeline, while the temperatures on top of the plateau are too low to be influenced
- During the transitional months of October and November and March to May, the freeze line is on the plateau, and warming temperatures would result in a large spatial footprint of change. These months are incredibly important for the accumulation and melt-off of seasonal snow, and there will be a major change in the timing and quantities of snowmelt.
- In the summer months (May/June to September) the spatial footprint of the freeze line is limited, but includes important mountaintops. These mountaintops would historically accumulate 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 accumulate, and more will melt off directly. In coincidence with the monsoon, this will likely result in a dramatic increase in the size and timing of downstream floods.

Figure 1.2. Overall Duration of Historic Winter versus that Projected under Changing Climate

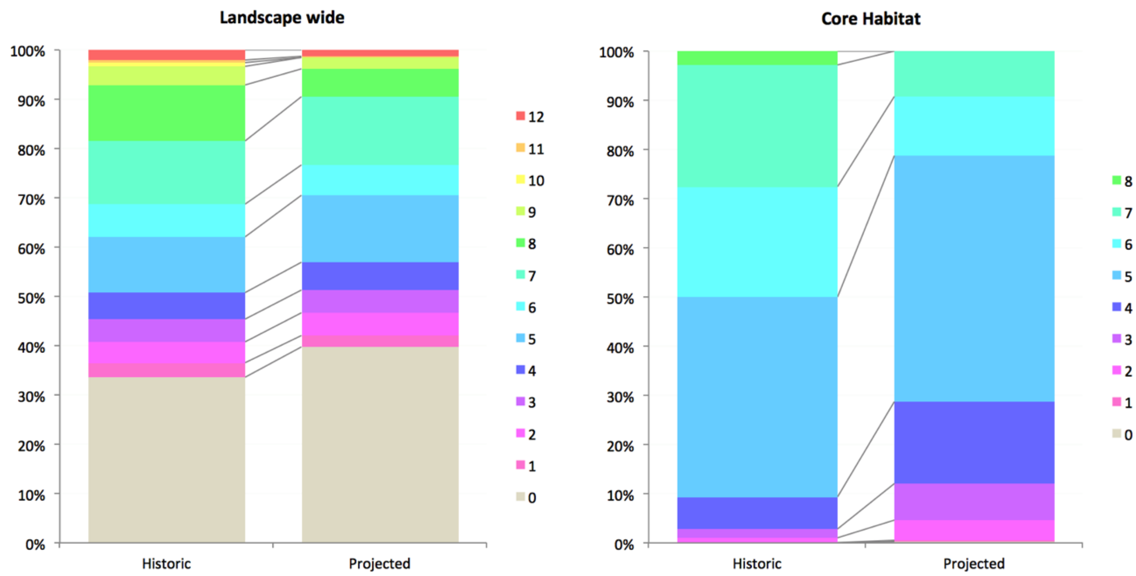


Figure 1.2 shows is that snow leopard habitat does not contain areas with more than 8 months of winter, though this area covers approximately 25% of the landscape. Snow leopard habitat also does not contain any areas that do not experience any winter months, though this area covers just over 30% of the landscape.

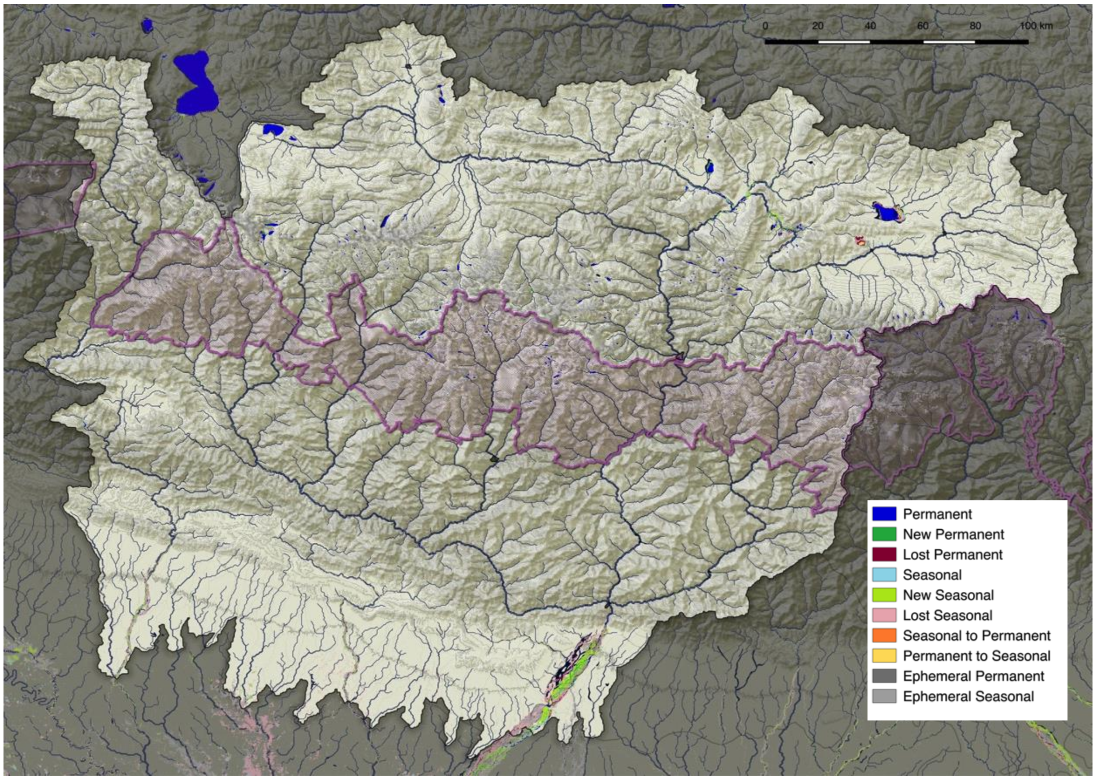
Under projected temperature change, the core habitat will experience a dramatic decrease in winter duration, but will stay within the historic upper and lower limits. These transitions, however, will have important impacts on hydrological and phenological processes in the landscape, such as the patterns and timing of snowfall and snowmelt, glacial melt, permafrost coverage and depths, and ecological community composition.

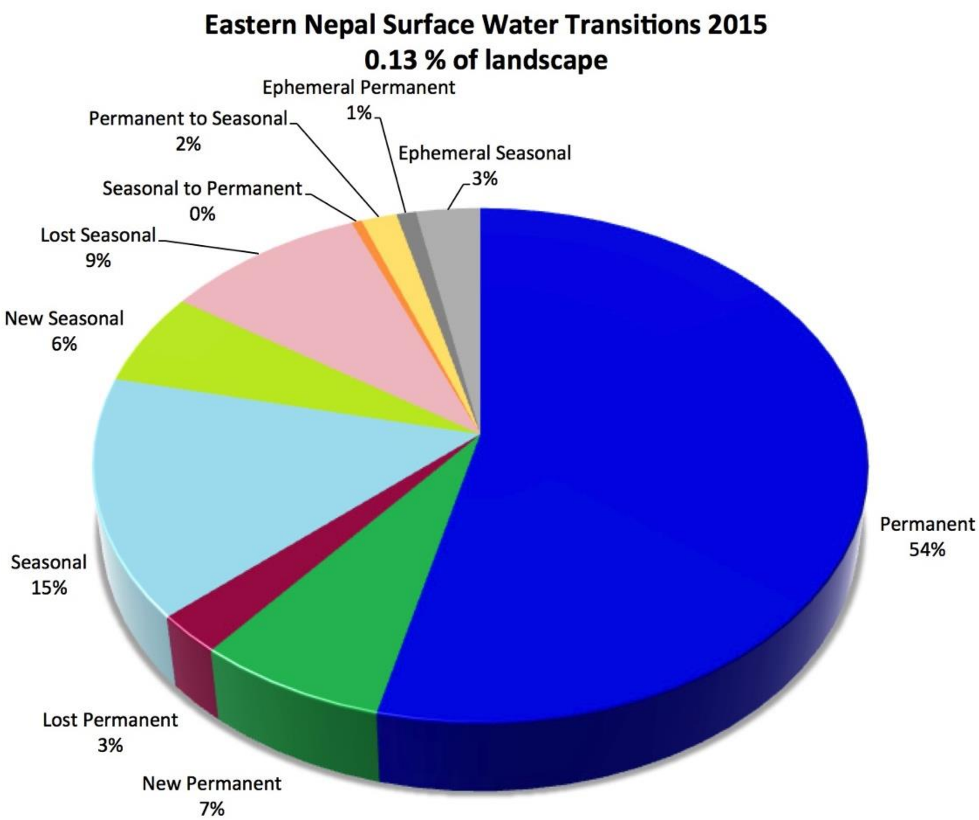
Data Sources

Current Mean Monthly Temperatures, based on historic WorldClim, 30s resolution (Hijmans et al. 2005)

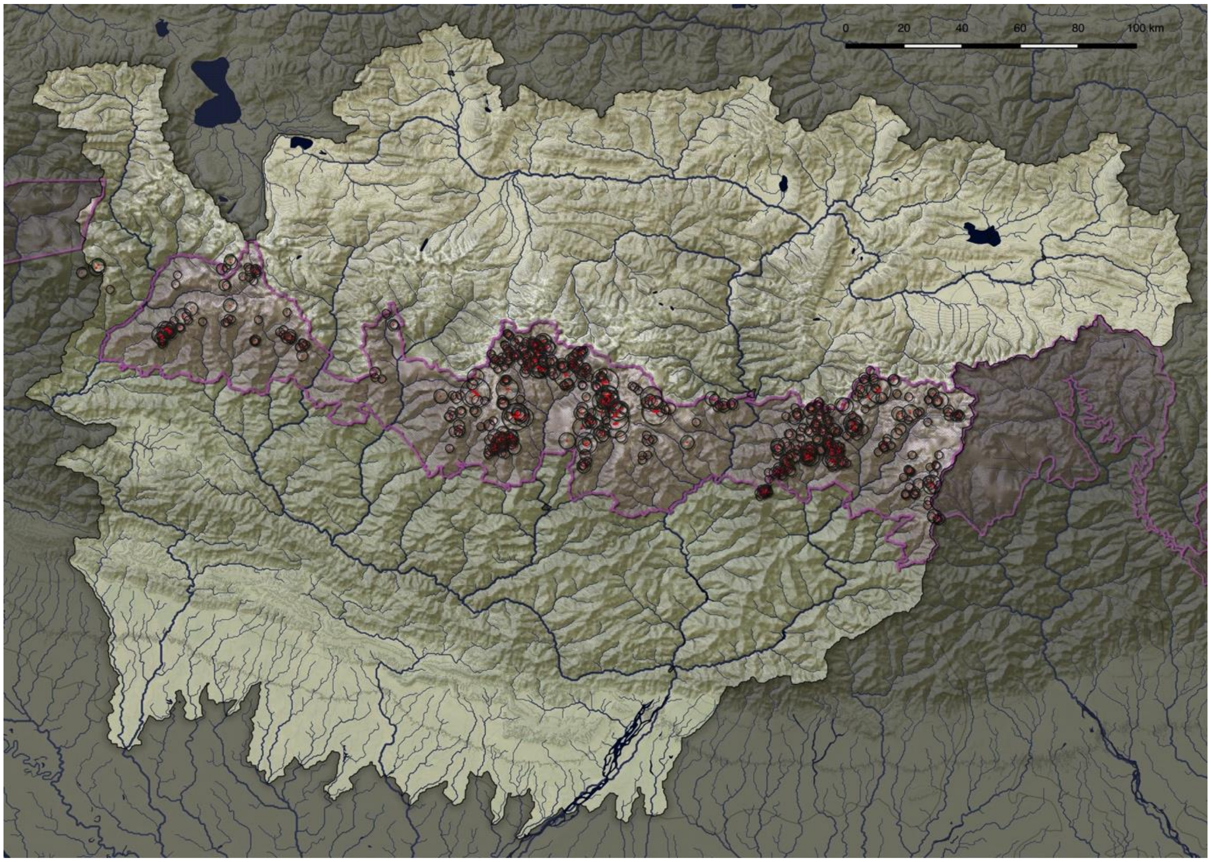
Climate Projections on future temperatures and precipitation (Peters et al. 2017)

Observed Surface water transitions (1984-2015) in the EHL/N Sub-basin





Location and Size of Glacial Lakes (ICIMOD, 2011)



Lakes, Wetlands and Floodplains	
Baseline Condition	There are many small glacial lakes in the landscape. These serve an important function, but also are a risk for glacial lake outburst floods (GLOFS). Floodplains exist mainly where the Arun river cuts through the landscape. Downstream of the landscape, in the Ganges river tributary floodplains in particular, floods are recurring and devastating.
Observed Historic Change (1984-2015) and Anticipated Climate Impacts	Over the 1984-2015 study period, there was an observed increase in the size and number of glacial lakes inside the landscape. With a change in the timing of snow and glacial melt, it is very likely that this trend will continue, which poses serious threats to people living downstream.

Inside the landscape, only 0.13% is classified as open surface water (Pekel, 2016). 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*.

The largest changes in surface water extents occurred around some of the active floodplains and rivers inside the landscape, accompanied by an increase in the number and size of glacial lakes (ICIMOD 2011, Messager et al. 2016, Pekel et al. 2016).

Figure 1.3. Change in Surface Water Area in the Eastern Himalayas Landscape, Nepal

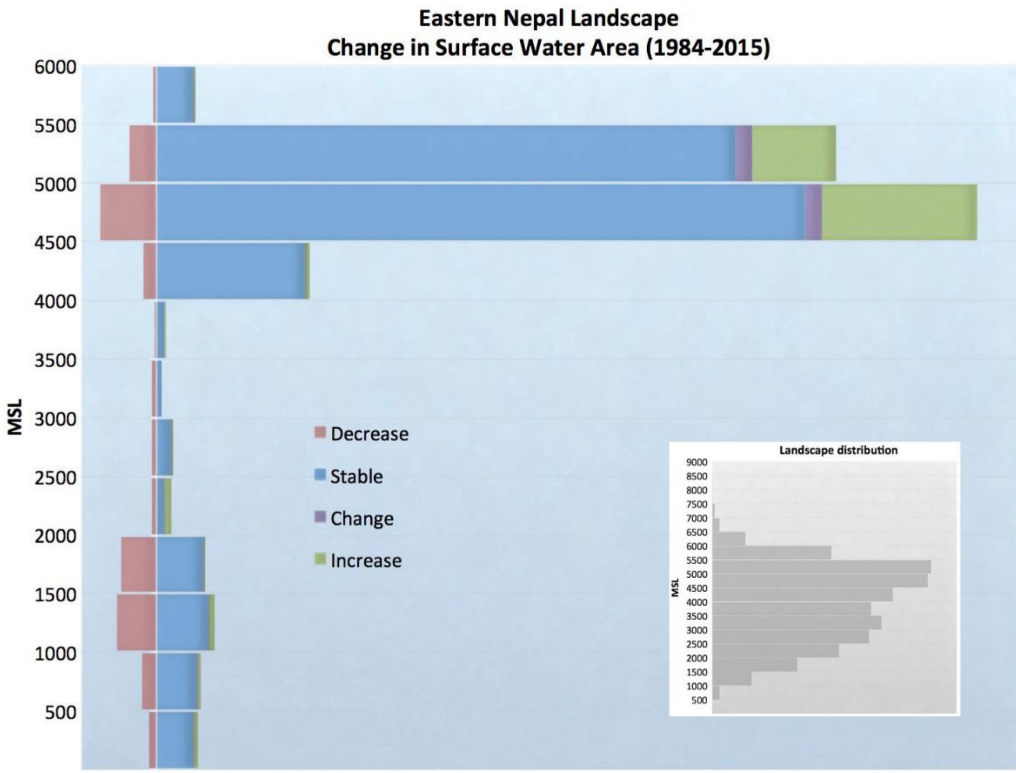


Figure 1.3 shows surface water transitions distributed by elevation. The 4,500-5,500 MSL zone contains the largest open water surfaces, even though the landscape is more gradually distributed by elevation (see inset). This zone is directly downstream of glaciers, and are therefore *mainly* glacier-fed. The open water surfaces in this zone have **increased dramatically** from 1984-2015, indicating that glaciers might have been melting off. At lower elevations (below 2,000 MSL), the overall surface water extent is much lower, and these areas have also experienced dramatic **loss** in coverage. This indicates possible development in the floodplains of those rivers. It is important to note that this analysis describes ***surfaces*** *and* ***not volumes*** of water.

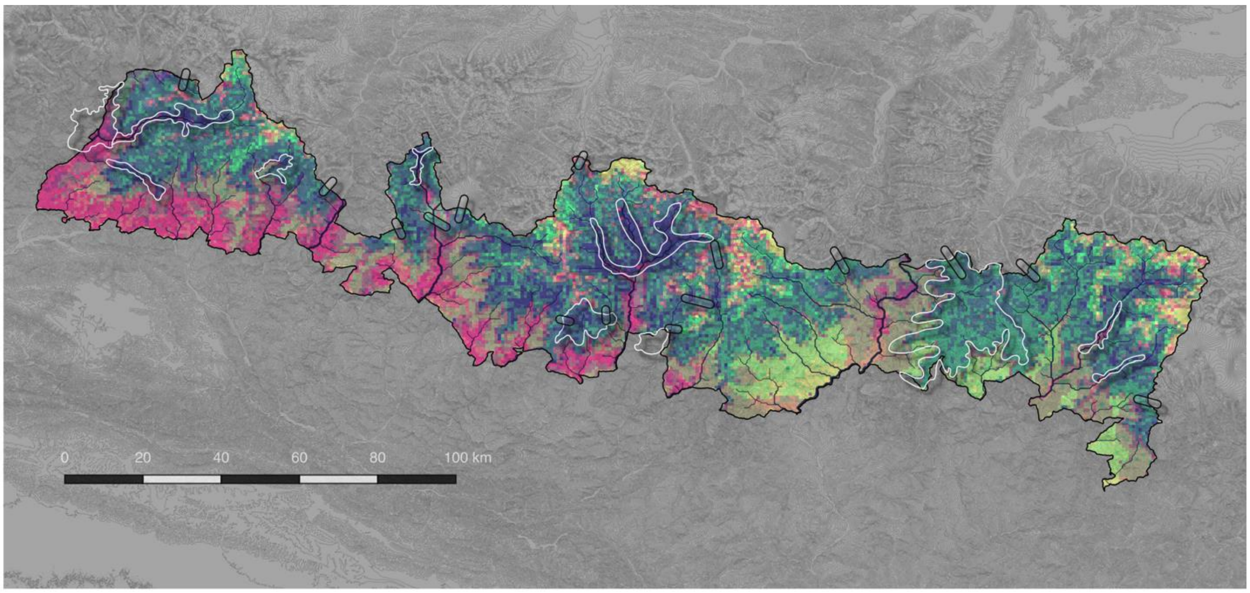
Methodology

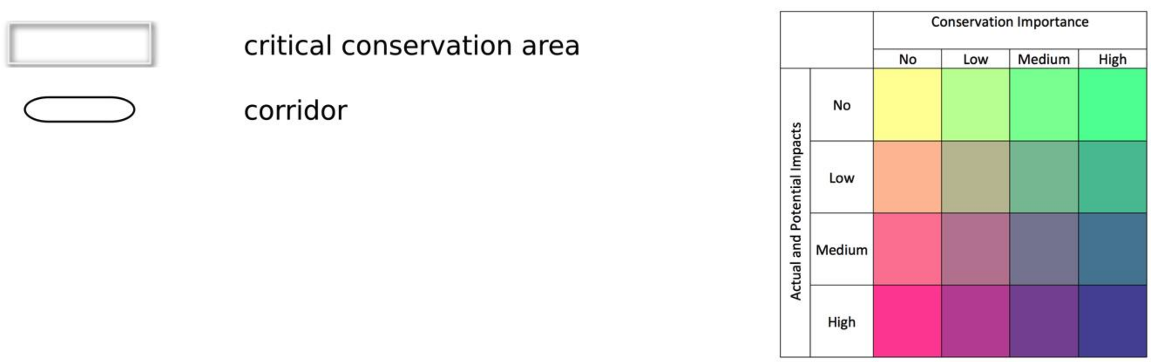
This analysis was drawn from a map of global surface water and long-term changes (Pekel, 2016). It contains at least 6 different datasets, and the online version allows time-lapse analysis from 1984-2015. The dates coincide with Landsat coverage, which is the key dataset. For more information on methods, please also refer to Sindorf 2017.

Data Sources

- Open surface water (Pekel et al. 2016)
- HydroSHEDS 15s void-filled elevations (Lehner et al. 2008)
- Glacial lakes and glacial lake outburst floods in Nepal (ICIMOD 2011)

Summary of Conservation Importance and Potential Impacts in the EHL/N Landscape





This map displays the EHL/N according to conservation importance and actual and potential impacts. Results indicate that much of the important habitat of the landscape is under high risk (dark blue). This is particularly evident in the western half of the landscape, where human access is higher. The habitats in the east-central part of the landscape are under moderate risk (medium blue-green), where human impacts are low and and climate risk is also relatively low. The far eastern side of the EHL/N has high risk due to climate vulnerability.. Areas of important habitat at low risk (bright green) are rare and quite fragmented by higher risk areas. These areas tend to be at the highest elevations of snow leopard habitat. Minimizing direct human impacts and managing the landscape for connectivity will help to maintain climate resilience and ensure snow leopard metapopulation persistence.

Methodology

This map was created to display conservation importance and actual and potential impacts. Conservation importance was represented by data on snow leopard habitat suitability, movement costs, and potential corridors. Protected areas were not included in the conservation importance layer because most of the landscape is under protected status. Critical Conservation Areas were also not incorporated into this layer because they are redundant with the human footprint and snow leopard habitat suitability.

Actual and potential impacts from climate change vulnerability are represented by potential treeline shift and number of months of winter expected to be lost. Impacts from humans are represented by the human footprint. For each of these layers, scores representing value (in the case of conservation importance) or severity (in the case of impacts) were developed in collaboration with field experts, and assigned as presented in Table 1.5. A score of 0 indicates the lowest score possible, and a score of 8 indicates the highest. The values in the tables correspond with the 'raw' values of each input GIS data layer. The qualitative scores of conservation importance and impacts were summed with others in their class, then combined into a single map with 16 different combinations.

Table 1.5A. Conservation Importance

Score	Habitat Suitability	Corridor	Movement costs	Protected or Critical Area
0	0	0	>15	0
1				
2			10-14	
3				
4			5-9	
5				
6	2	1	1-4	
7				
8	1			

Table 1.5B. Actual and Potential Impacts

Score	Treeline shift	Months of freeze loss	Human Footprint
0	0, 4	0	0
1	3		
2		1	1-5
3	2		
4		2	6-10
5	1		
6		3	
7			
8			>11

Combined scores: No: 0; Low: 1-3; Medium: 4-7; High: >8

IV. Analysis and Mapping of Snow Leopard Habitat in the Central Tien Shan Landscape, Kyrgyzstan

Jessica Forrest[1], Nikolai Sindorf[1], Yash Veer Bhatnagar[2], Koustubh Sharma[2]

World Wildlife Fund[1], Snow Leopard Trust[2], and the Snow Leopard Secretariat[3], with Funding from the U.S. Agency for International Development

Chapter 4 of 6 of the report:

Guardians of the Headwaters, Volume 2:
Conservation, Water, and Climate
in Six Snow Leopard Landscapes

Key Findings and Management Implications

- **The Central Tien Shan landscape of eastern Kyrgzstan has over 6,630 km^2 of snow leopard habitat located predominantly in one contiguous block.** The best habitat areas are in the central and southern parts of the landscape. Habitat in this landscape connects at its southern boundary to habitat in China and through that, to southern Kyrgzstan. There is also structural habitat connectivity to the North Tien Shan landscape of Kazakhstan to the northeast.

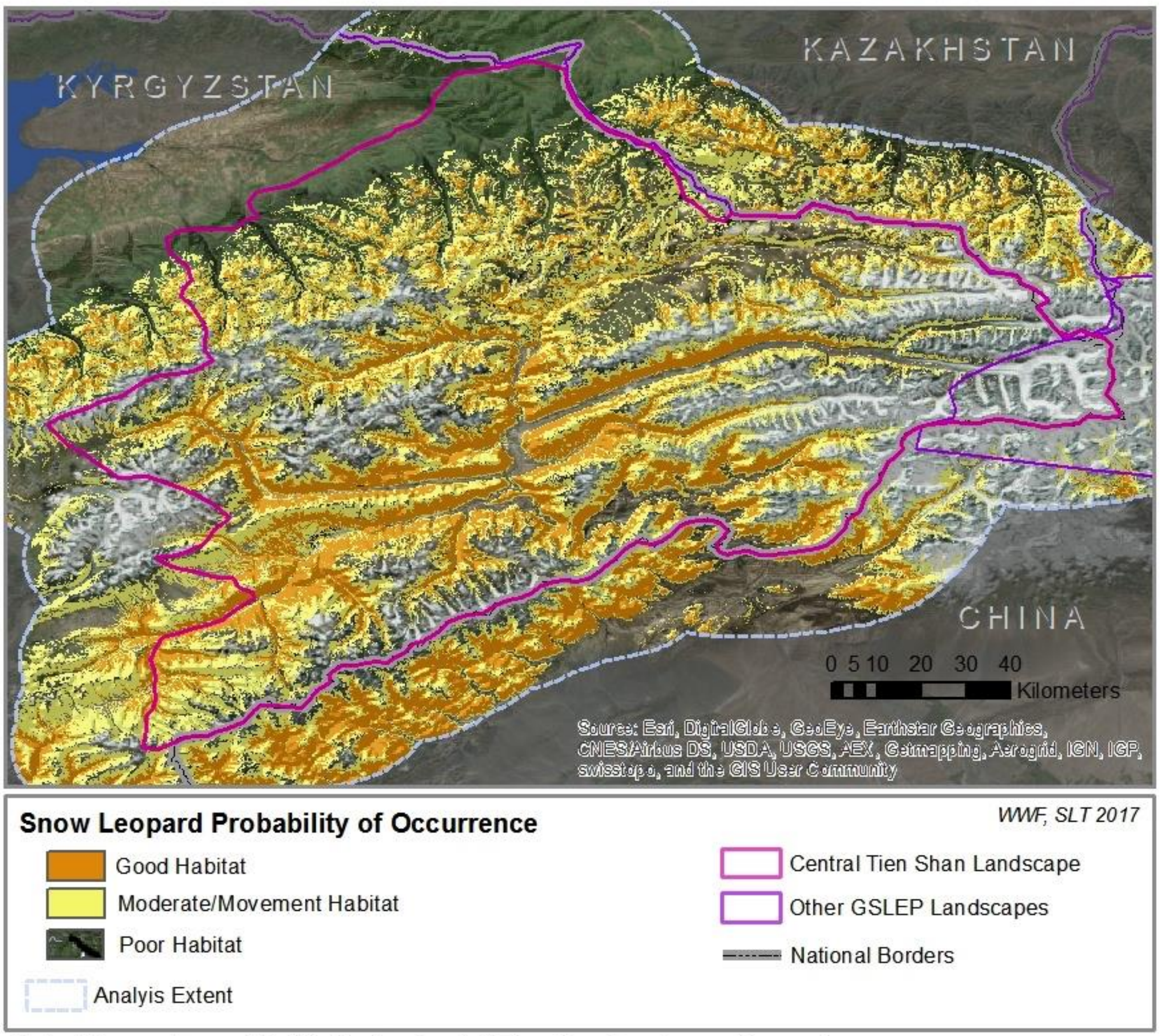
- **Protect key unprotected habitat areas.** Approximately 34% of habitat in the landscape is under some form of protection. Key unprotected habitats are located between Sarychat-Ertash State Nature Reserve and Khan Tengri National Park, and stakeholder discussions are underway to address this gap (United Nations Development Programme and Government of the Kyrgyz Republic). There is also a large area of unprotected habitat south of Sarychat-Ertash, both within the landscape and across the international border in China. Protection of these habitats, both in Kyrgyzstan and China, is crucial for snow leopard metapopulation persistence, since these habitats are vast and form a vital connection to other landscapes. There may be a need to establish management corridors to protect the narrow links between protected areas of the Central Tien Shan (particularly Khan Tengri) with the North Tien Shan landscape in Kazakhstan.

- **Transboundary Management.** The snow leopard habitats of the Central Tien Shan are structurally connected to habitats of the North Tien Shan landscape in Kazakhstan. Habitats of the Central Tien Shan also connect to the habitats of southern Kyrgyzstan via China. Thus, establishing transboundary management strategies with Kazakhstan and China are crucial for metapopulation management. Water resources also have transboundary features. The mountains of eastern Kyrgyzstan have glaciers and snow that melt and flow into the Aksu river basin of China. This provides essential inputs to surface- and groundwater recharge for downstream water use, particularly intensively-irrigated areas around Aksu-city.

- **Conservation strategies that involve people are key**, since much of the core habitat of the landscape is affected by some level of human impact. Perhaps the most critical locations for monitoring include the road and population centers that runs north to south down the center of the landscape; and the road and population corridor to the south of Sarychat-Ertash that runs east- west. While current impacts are purportedly low, these access routes can promote access for hunters, human-wildlife conflict, or habitat loss degradation over time if not zoned and monitored. This can have a fragmenting effect on snow leopard and prey populations. Livestock impacts (including overgrazing, competition with prey, and human-wildlife conflicts) affect large areas of the landscape, including those areas displayed with little to no human impact. For this reason, conservation strategies involving livestock management are also appropriate.

- **Climate change effects in this landscape will likely include improved cropland suitability and shorter winters, accompanied by considerable uncertainty in future spring precipitation. Appropriate natural resource management changes to anticipate such changes include land use zoning, monitoring, and adaptive management.** Improved cropland suitability may cause people to immigrate to the landscape and plant crops, reducing habitat area and connectivity for snow leopards. Shorter and warmer winters can affect phenology (the timing of green-up, breeding, etc.), which can lead to changes in grassland community composition, invasive species prevalence, prey population composition, and presence of competitors. Shorter winters will also upset snow- and glacial-melt water balances, as well as the coverage and depths of permafrost. Such changes may increase the frequency of floods and/or water shortages, landslides, and habitat loss.

Potential Snow Leopard Habitat in the Central Tien Shan Landscape



Potential snow leopard habitat in the Central Tien Shan Landsape, Kyrgyzstan.

This map shows potential snow leopard habitat of the Central Tien Shan Landscape. There is an estimated 6,635 km^2 of potential snow leopard habitat in the Central Tien Shan (CTS) Landscape, representing 50% of the entire area of the landscape. Of this, 2,505 km^2 is classified as good habitat with high probability of snow leopard occurrence and 4,130 km^2 is classified as habitat with moderate probability of occurrence. Snow leopard habitat generally ranges from 2,000-4,700 m in elevation, with the best habitats between 2,600 and 4,200 m. Ninety-six percent of all suitable habitat in the landscape is found in one connected block. The largest expanse of good habitat is located in the central to southwest part of the landscape. Habitats of this landscape appear to be well-connected to expanses of suitable habitat across the southern boundary of the landscape with China. There also appears to be modest structural habitat connectivity between this landscape and the North Tien Shan landscape of Kazakhstan.

Methodology

A Maxent model was developed to produce the probability of snow leopard occurrence map (Phillips et al. 2006). The extent of the analysis was set to within 20 km of the Central Tien Shan Landscape; the area includes eastern Kyrgyzstan and adjacent areas of south-east Kazakhstan and western China (Upper Left: 42.9°N, 77.8°E Lower Right: 41.5°N, 80.6°E)

The final model depicted in these maps was produced through an iterative approach by testing different environmental variables, background extents, and snow leopard occurrence points. The best model used land cover (ESA 2009), elevation, slope, terrain ruggedness index (TRI), (Riley et al. 1999, Lehner et al. 2008), and 500 radio collar observation points from five snow leopards (S. Kachel, Panthera 2017). Landcover had the strongest influence on the model output (47.6% contribution), followed by elevation (35.3%), ruggedness (13.2%), and slope (3.2%). The resulting model output had a training Area under Curve (AUC) value of 0.886, and a test AUC of 0.870. This is considered to be a strong predictive result.

The resulting logistic probability of occurrence (p) map was reclassified into high and moderate probability of occurrence based on p-thresholds. We did this by graphing observation points against p-values where they occurred, and looking for natural breaks in the distribution. We complemented the quantitative approach with expert opinion about snow leopard occurrence. Habitat with high probability of occurrence was defined as $p > 0.4$ (representing 80.6% of observations), coinciding with a surge in snow leopard observations. Habitat with moderate probability of occurrence was defined as 0.0.5> p =< 0.4 (17.4% of observations). The lower threshold of the moderate range was defined using expert opinion about habitat distribution and knowledge about omission error or false negative predictions (2% where $p<0.05$).

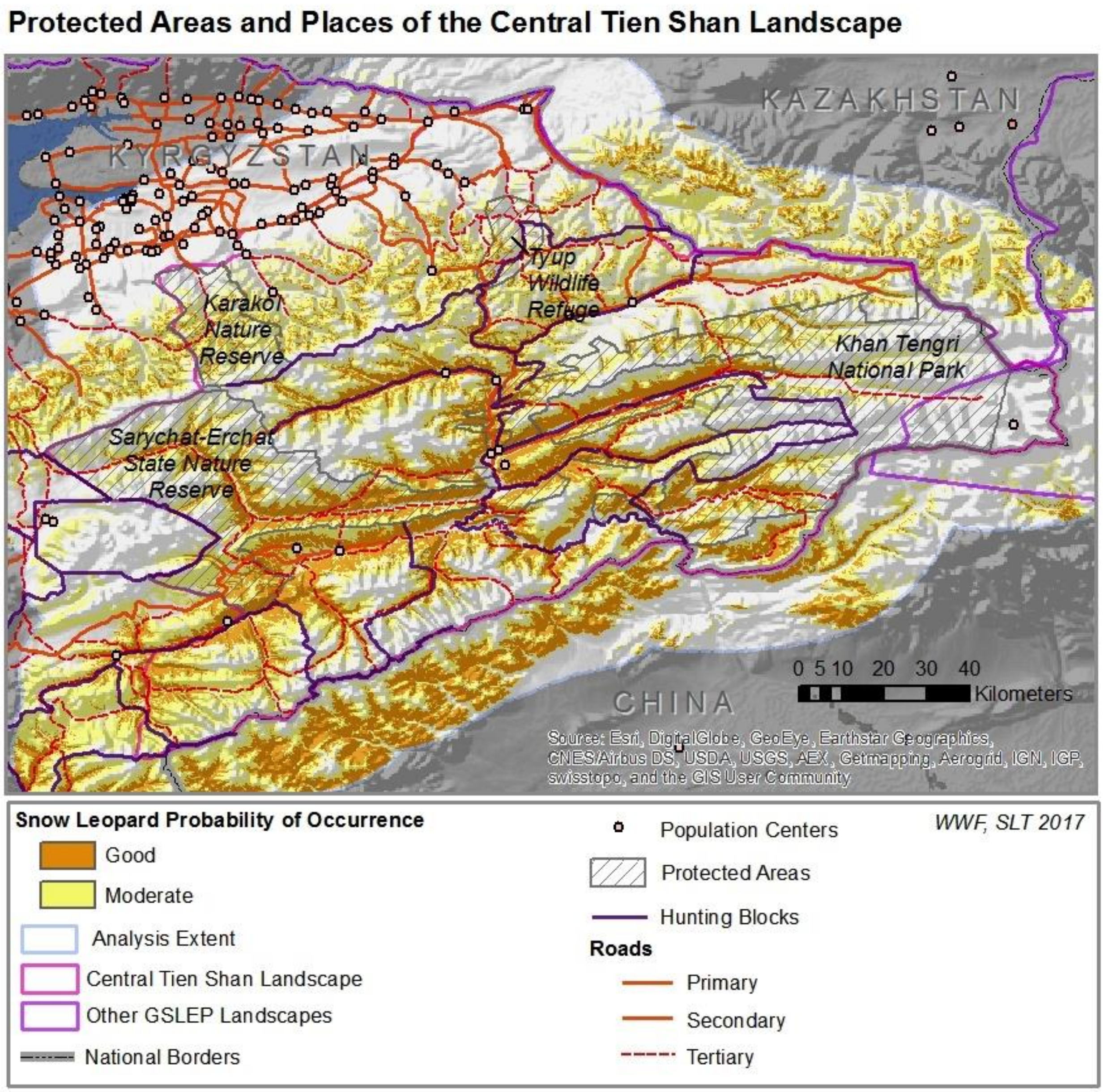
Data Sources

Snow Leopard Habitat Model:

- Land cover (ESA 2009)
- DEM, Slope (Lehner et al. 2008)
- Terrain Ruggedness Index (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations from interview reports (Kachel, 2017)

Other layers for display only:

- GSLEP Landscape Boundaries (GSLEP 2016b)
- ESRI World Imagery (ESRI et al. 2017



Protected areas and places of the Central Tien Shan Landscape. Protected Areas cover 2,238 km^2 or one-third of potential snow leopard habitat in the Central Tien Shan landscape of Kyrgyzstan. These protected areas include Sarychat-Ertash State Nature Reserve (SNR), Karakol Nature Reserve, Khan Tengri National Park, and Tyup Wildlife Refuges. Sarychat-Ertash, which has 881 km^2 of snow leopard habitat, also has the best current knowledge on snow leopard occurrence in the landscape available to this study. Khan Tengri National Park alone represents nearly half of the snow leopard habitat in the landscape. Approximately 4,400 km^2 of snow leopard habitat remains unprotected (Table 4.1).

Important gaps in protection include the corridor between Sarychat-Ertash SNR and Khan Tengri NP, areas south of Sarychat-Ertash, and the northeast of the landscape. The area between Sarychat-Ertash SNR and Khan Tengri NP has already been recognized as a gap in protection, and discussions are underway on how to address this (United Nations Development Programme and the Government of the Kyrgyz Republic). There is also a vast area of unprotected habitat south of Sarychat-Ertash, both within the landscape and across the international border with China. These habitats, in addition to being vast in themselves, appear to form a vital connection to points in southern Kyrgyzstan. Thus, metapopulation persistence may benefit from improved protection of these habitats. Finally, there is a large area of unprotected fair quality habitat in the north of the landscape, which may offer modest connection between the best habitats of this landscape to the North Tien Shan landscape of Kazakhstan. Further survey may be useful to confirm the quality of these habitats and snow leopard presence. Corridors may be appropriate management zones to link the protected habitats of this landscape (particularly Khan Tengri) with the North Tien Shan. Seven hunting reserves cover much of the remaining landscape, but do not necessarily offer protection for snow leopards and their prey.

Table 4.1. **Protected Habitat Area in the Central Tien Shan Landscape**

Protected Area Name	**Snow Leopard Habitat (km^2)**		
	Good Habitat	**Moderate Habitat**	**Total habitat**
Sarychat-Ertash State Nature Reserve	392	489	881
Khan Tengri National Park	399	687	1,086
Karakol Nature Reserve	45	160	205
Tyup Wildlife Refuge	15	51	66
Total protected	**852**	**1,386**	**2,238**

Data Sources

Snow Leopard Habitat Model:

- Land cover (ESA 2009)
- DEM, Slope (Lehner et al. 2008)
- Terrain Ruggedness Index (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations from interview reports and radio collar (GSLEP 2016a, Kachel 2017)

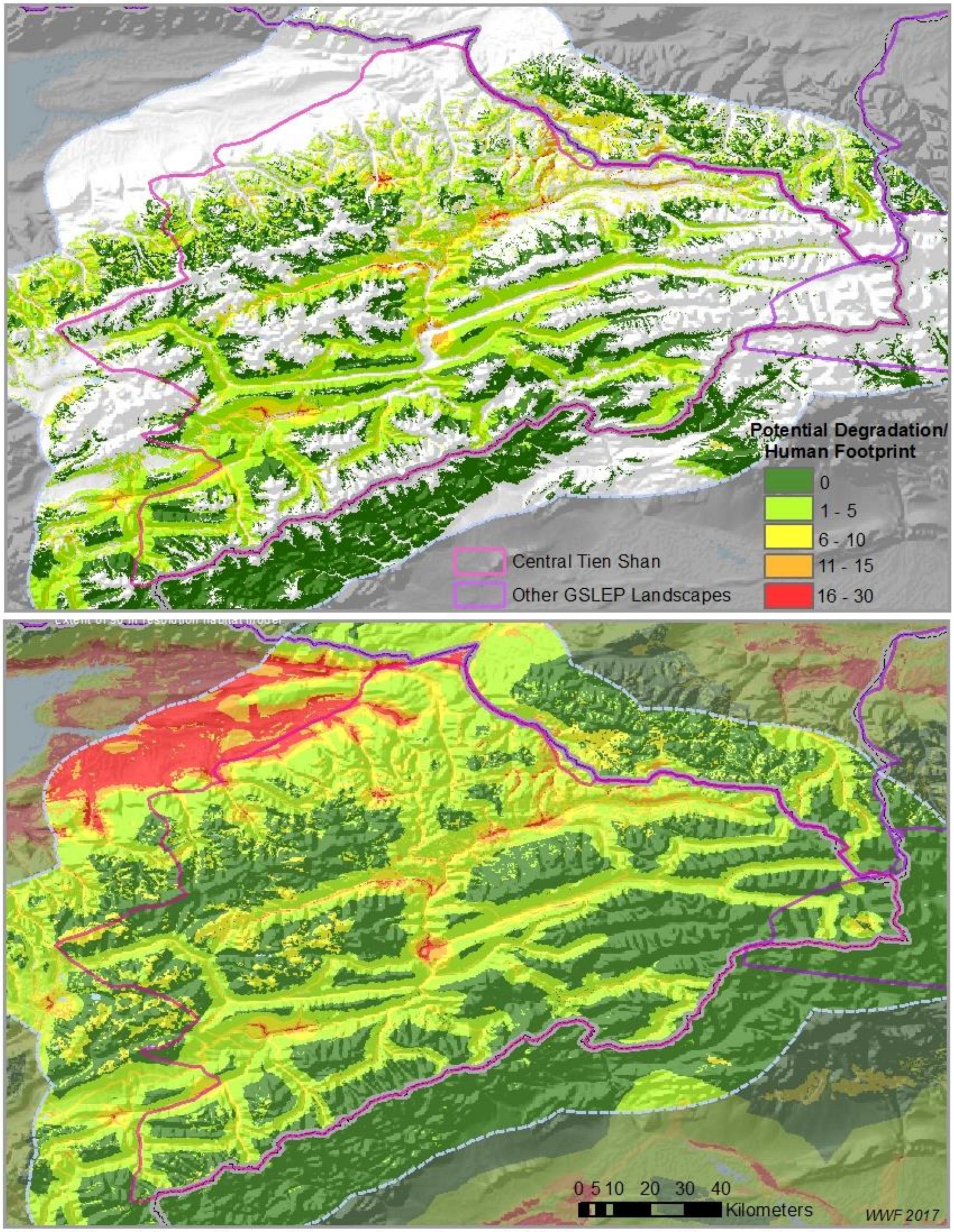
Other layers for display only:

- GSLEP Landscape Boundaries (GSLEP 2016b)
- ESRI World Imagery (ESRI et al. 2016)

Human Landscape:

- Protected Areas (GSLEP 2016c, IUCN & UNEP-WCMC 2017)
- Populated Places (GSLEP 2016c; OpenStreetMap 2016, and CIESIN et al. 2011)
- Roads (GSLEP 2016c, OpenStreetMap 2016

Potential for Degradation and Human Influence in Snow Leopard Habitat



Potential degradation and human influence of snow leopard habitat is represented by current land cover and land use, cost distance to roads, and populated place density weighted by population. Map A shows potential degradation in snow leopard habitat, and Map B shows potential degradation across the entire landscape.

This map shows areas of potential degradation and human influence in Central Tien Shan Landscape. Much of the core habitat of the landscape is affected by some level of human impact, suggesting that conservation strategies that involve people are key. A corridor of infrastructure and modest human population centers bisects the landscape from north to south; and there is a second such corridor running east-west to the south of Sarychat-Ertash. There is also moderate human impact over the fair habitats in the northern portion of the landscape. The direct impact of these may currently be fairly light: However, roads can promote access for poachers, population centers may have higher levels of human-wildlife conflict, and all may serve as a conduit for habitat loss and fragmentation (Sanderson et al. 2002). All of these can have a fragmenting effect on snow leopard and prey populations. For this reason, monitoring and land use zoning along access corridors is useful.

Livestock grazing and its associated effects[1] represent a significant threat to snow leopards, but these are not well represented in this analysis due to the lack of available data (Y. Bhatnagar, personal communication, March 2017). Livestock move from pasture to pasture, and are often far from official roads and population centers. As such, areas depicted as having a low human footprint may not be exempt from livestock-related threats. Programs to manage livestock, human, and snow leopard interactions would be appropriate in many parts of the landscape, regardless of human footprint score on the map.

This analysis assumes that degradation and threats to snow leopards and their habitats are directly correlated with levels of human access (Sanderson et al. 2002). Snow leopards and their habitats are often directly affected by overgrazing and competition between livestock and prey, hunting of snow leopards and prey, human wildlife conflict, tourism, and forest and non-timber forest product collection.

Methodology

Here, we represent human access through GIS layers on populated place density, cost distance to roads, and land cover and land use. Input layers were rescored according to the tables below and summed to produce a potential degradation and human influence layer according to methods developed by Sanderson et al. 2002.

Populated Places:

Since we did not have sufficiently high-resolution data on population density in eastern Kyrgyzstan, we used populated place location and type as a proxy for population, and created a populated place kernel density layer.

The kernel density layer was generated from three data sources: settlements for Kyrgyzstan (GSLEP 2016c), OpenStreetMap for Kyrgyzstan, China and Kazakhstan (OpenStreetMap 2017), and the Global Rural-Urban Mapping Project populated place database (CIESIN et al. 2011). Sources were merged, with obvious duplicates removed. We selected GRUMP locations over the other sources, and GSLEP 2016c over OpenStreetMap 2016 in Kyrgyzstan. Actual population values were used when available, but settlements without population information were assigned a standard estimated population size of 300 people. Permanent water bodies, and areas too high and steep for people (>50° slope and >5500 m high) were masked out of the analysis. The search radius for the kernel density analysis was set to the ArcGIS 10.3 Spatial Analyst default radius (ESRI, Redlands, CA), with results roughly equivalent to a 5 km radius. The result was a kernel density layer with a range of values from 0-57,359.7 people per km^2, though values were interpreted on a relative scale. After close examination of the output population kernel density layer with respect to different settlement types and presumed impact on snow leopard persistence and movement, we applied the following potential degradation scores (Table 4.2).

Table 4.2. Populated Place Kernel Density Scores for Human Footprint

Populated Place Kernel Density (ppl/km^2)		Potential Degradation/Cost of Movement Score
0		0
1-2		2
3-5		4
5-10		6
11-100		8
>100		10

Roads:

We created a cost distance to roads file weighted by road type and the 'permeability' of the matrix for human travel. Cost distance represents the distance to the nearest road in meters, multiplied by the total cost of movement back to that road.

We began with GIS data on roads for eastern Kyrgyzstan (GSLEP 2016c) and adjacent areas of Kazakhstan and China (OpenStreetMap 2016). These were clipped to the Central Tien Shan analysis extent. Roads were assigned to a new common classification system based on the decision rules described in Table 4.3A below, and merged to form one transboundary road file.

Table 4.3A. Reclassification of Road Types for Updated Roads Dataset

	Original Class, Filename, Source		
New_Class	**Kyrgyzstan Roads Source: GSLEP 2016c Field: Name_E**	**Kazakhstan Roads Source: OSM 2016 Field: fclass**	**China Roads Source: OSM 2016 Field: type**
Level 1 (Major roads)	Blacktop Road, Railroad, Motor Road	Primary, primary link, trunk, trunk link, Living street, residential, service	Living_street, motorway, motorway_link, primary_link, primary, residential, service, services, trunk, construction
Level 2 (Secondary Roads)	Unpaved Roads, Ground Road	Secondary, secondary link, unclassified, unknown	Secondary, road, unclassified
Level 3 (Tertiary Roads)	Horsepath	Bridleway, cycleway, footway, path, pedestrian, track, steps, tertiary, tertiary link	Footway, path, pedestrian, tertiary, track

We next created a cost layer to represent cost of movement of people across the landscape away from roads. It is presumed that areas of high slope and altitude are difficult or even impossible for people to traverse. The following scores were applied to describe cost of human movement across pixels, with 0 being the lowest and 10 being the highest, and masked areas being impermeable to movement. Elevation cost of movement: 0-2500m=1, 2500-3500m=4, 3500-4000=6, 4000-5500=8, >5500= Masked (No movement); Slope cost of movement: 0-30°=1, 30-50°= 6, >50° = Masked (No movement). These scores were used to rescore 15s elevation and slope rasters (Lehner et al. 2008). These rasters were next summed to create a single cost of movement grid. The cost grid was rescaled to a scale of 1 to 10.

Next, two cost-distance analyses were run based on the cost grid described above. The first cost distance analysis used primary and secondary roads (level 1 and 2) as a source, and second analysis used tertiary roads and paths (level 3). Each cost distance output was reclassified using the scores in Table 4.3B below. Scores were chosen to be comparable to Euclidean distance categories from roads used in other landscapes, but influenced by cost of movement. The individual cost grids for major and minor roads were finally combined into a single reclassified cost-distance to roads grid by selecting the highest potential degradation/human footprint value present for a given pixel.

Table 4.3B. Distance to Roads Scores for Human Footprint

Cost Distance to Major Roads[1]	Potential Degradation/Cost of Movement Score
0-500	10
500-1500	8
1500-2500	6
2500-15000	3
15000-25000	2
>25000	0
Cost Distance to Unpaved Roads[2]	**Potential Degradation/Cost of Movement Score**
0-500	8
500-1500	6
1500-2500	4
2500-10000	2
10000-15000	1
>15000	0

[1]This represents road levels 1 and 2, primary and secondary roads, [2]These are level 3 roads -tertiary roads as well as tracks and paths

Land Cover and Land Use:

The Globcover 300 m land cover for Central Asia (ESA 2009) was first clipped to the Central Tien Shan analysis extent. It was next rescored to potential degradation/human influence scores by assigning the values in Table 4.4.

Table 4.4. Land Cover Class Scores for Human Footprint

Value	Label	New Score
11	Post-flooding or irrigated croplands (or aquatic)	8
12	Post-flooding or irrigated shrub or tree crops	8
14	Rainfed croplands	7
20	Mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%)	5
21	Mosaic cropland (50-70%) / grassland or shrubland (20-50%)	5
30	Mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%)	4
32	Mosaic forest (50-70%) / cropland (20-50%)	4
50	Closed (>40%) broadleaved deciduous forest (>5m)	0
60	Open (15-40%) broadleaved deciduous forest/woodland (>5m)	0
90	Open (15-40%) needleleaved deciduous or evergreen forest (>5m)	0
91	Open (15-40%) needleleaved deciduous forest (>5m)	0
92	Open (15-40%) needleleaved evergreen forest (>5m)	0
100	Closed to open (>15%) mixed broadleaved and needleleaved forest (>5m)	0
110	Mosaic forest or shrubland (50-70%) / grassland (20-50%)	0
130	Closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland (<5m)	0
140	Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	0
141	Closed (>40%) grassland	0
143	Open (15-40%) grassland	0
150	Sparse (<15%) vegetation	0
151	Sparse (<15%) grassland	0
152	Sparse (<15%) shrubland	0
180	Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water	0
190	Artificial surfaces and associated areas (Urban areas >50%)	10
200	Bare areas	0
201	Consolidated bare areas (hardpans, gravels, bare rock, stones, boulders)	0
202	Non-consolidated bare areas (sandy desert)	0
203	Salt hardpans	0
210	Water bodies	0
220	Permanent snow and ice	0

Data Sources

Snow Leopard Habitat Model

- Land cover (ESA 2009)
- DEM, Slope (Lehner et al. 2008)
- Terrain Ruggedness Index (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard radio collar data (Kachel 2017)

Other layers for display only:

- GSLEP Landscape Boundaries (GSLEP 2016b)
- ESRI World Imagery (ESRI et al. 2016)

Human Landscape:

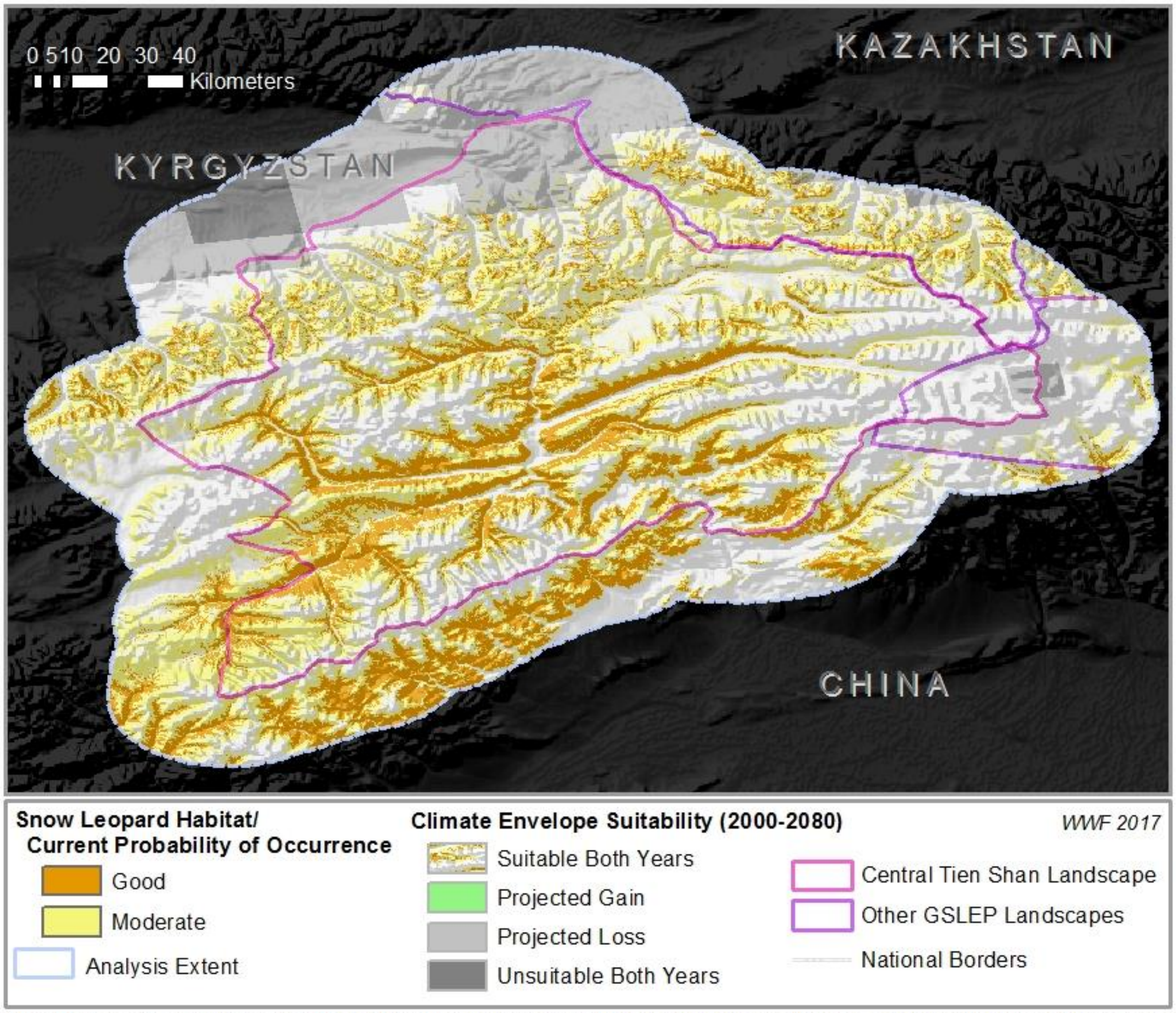
- Land cover (ESA 2009)
- Populated Places (GSLEP 2016c; OpenStreetMap 2016, and CIESIN et al. 2011)
- Roads (GSLEP 2016c, OpenStreetMap 2016)

Climate Change Vulnerability in the Central Tien Shan Landscape

The Central Tien Shan landscape is expected to experience a substantial increase in temperature throughout all months of the year compared with the current time period (+2.2˚C to 3.6˚C by the mid-century time frame of 2041-2070). The increase is expected to be most extreme during the summer. Precipitation is expected to increase particularly during the spring (though with high uncertainty), when run-off from snow melt is already high (Peters et al. 2016). Potential impacts of these climate changes include earlier snow melt and the arrival of spring, grassland community changes that can influence grazing animal populations, permafrost melt, and flooding and landslide risk (Climate Smart Snow Leopard Management Planning Workshop, April of 2016).

Here, we assessed five indicators of climate change impacts in order to better understand the spatial distribution of climate risk for alpine wildlife and human communities. These included potential change in the climate envelope for snow leopards (indicating climate suitability for snow leopards); potential change in the suitable climate envelope for cropland (indicating changing human habitability, but also human pressure on wildlife habitat); water towers (or water provision to the downstream from rainfall); winter duration (indicated by freeze-line, with implications on ecological functions as well as water availability for people); and change in open water availability (which is a good indicator of overall changes to a landscape). The latter three, and other hydrological functions, are covered in more depth by Sindorf 2017.

Potential Climate Envelope Shift in Snow Leopard Habitat



This map overlays a fine scale model of current snow leopard habitat in the Central Tien Shan Landsape of Kyrgyzstan with a regional model of potential shift in climate envelope under a HADCM3 A2A scenario. The climate envelope model shows that climate space appropriate for snow leopards (the "potential climate niche") is larger in extent than current habitat (the "occupied climate niche"). But, it also shows little risk of suitable climate space where snow leopard habitat currently exists. There are no areas of projected gain in suitable climate niche in this map extent.

This map represents the potential change in suitable climate envelope for snow leopards in the Central Tien Shan landscape under a high greenhouse gas emissions scenario (HADCM3 A2A) from the current time (1950-2000) to the 2080's based on 19 bioclimatic variables (Hijmans et al. 2005, Sindorf et al. 2014). A climate envelope represents the necessary climate conditions for a given species to exist. Beyond climate, species usually require additional conditions to live (including access to water, physical features of the landscape to provide cover, presence of food or prey, and low human impact). This analysis overlays the potential change in the climate envelope for snow leopards over its current habitat. The climate envelope is likely to shrink drastically by the 2080's compared with the existing condition. But, the decrease in the extent of climate suitability should not impede on existing habitats that offer all necessary conditions (both climate and non-climate) for the snow leopard to persist. This result suggests that the Central Tien Shan may represent a climate refugia for snow leopards

Data Sources

Snow Leopard Habitat Model:

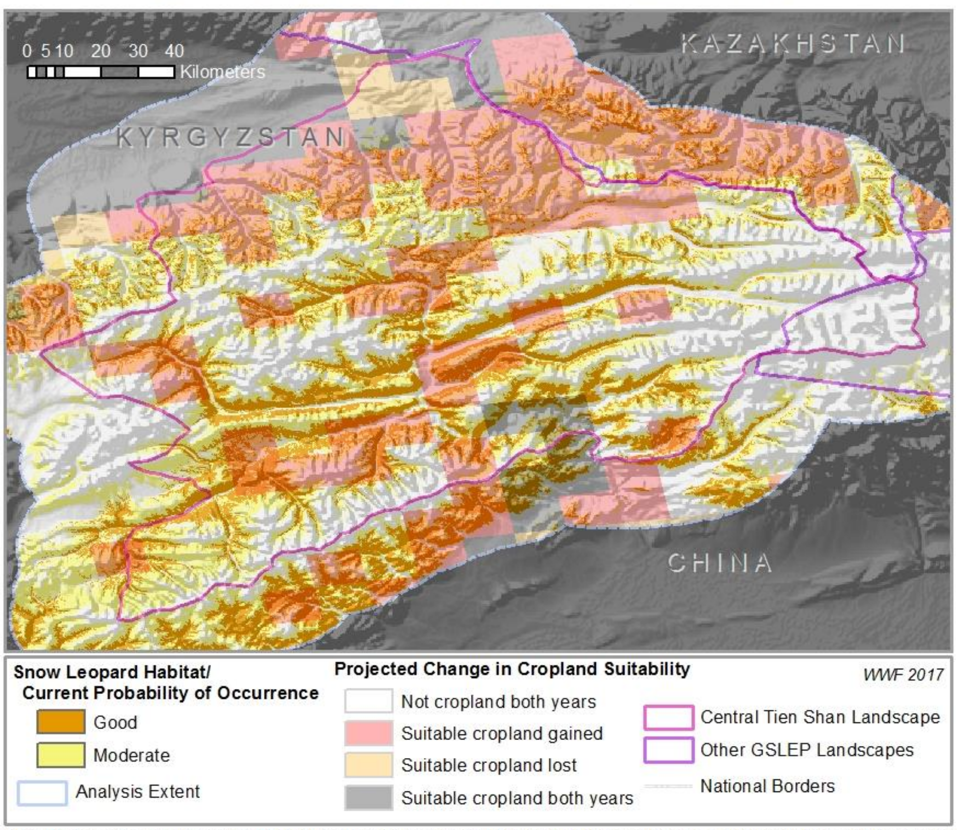
- Land cover (ESA 2009)
- DEM, Slope (Lehner et al. 2008)
- Terrain Ruggedness Index (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (GSLEP 2016a)

Snow leopard climate envelope shift: see Sindorf et al. 2014

Other layers for display only:

- GSLEP Landscape Boundaries (GSLEP 2016b)
- ESRI World Imagery (ESRI et al. 2016)

Potential Change in Cropland Suitability under Climate Change (2000-2100)



This map overlays a fine scale model of current snow leopard habitat in the Central Tien Shan Landsape of Kyrgyzstan with a regional model of potential shift in the climate envelope for cropland suitability under a HADCM3 A2A scenario to the year 2080-2100. The model predicts that the area of suitable cropland may increase and move upslope under a warming climate, potentially threatening snow leopard habitat with land use change and higher probability for human wildlife conflict.

This map shows projections of current climate envelope for arable land (or cropland), and potential change under a high emissions climate change scenario. The model shown is based on the Global Arable Lands database (Ramankutty et al. 2008) and 19 bioclimatic variables (Hijmans et al. 2005). These inputs were used to produce climate envelope projections for the current time period and the 2080's under a high emission scenario (A2A) using the HADCM3 General Circulation Model (see Sindorf et al. 2014). These results suggest that in this landscape, suitable climate envelope for arable land is likely to increase, potentially increasing habitat conversion and human-wildlife conflict with snow leopards and their prey. Likewise, some areas downstream of habitat may become suitable for agriculture, which could increase pressure on water resources. These findings emphasize the need for snow-leopard friendly land use and water management planning and zoning.

Important to note is that many areas projected as currently suitable climate envelope for arable land are not actually "occupied" by crops. Indeed, there are no crops in the landscape known to this study. In these unoccupied but apparently climatically suitable areas for crops, other conditions may exist that have historically inhibited the use of land in such a way (soil type, lack of access to water, steep slopes, the absence of farmers, or government zoning against use of land for crops). Likewise, future increases in arable land climate space does not guarantee that crops will be planted.

Data Sources

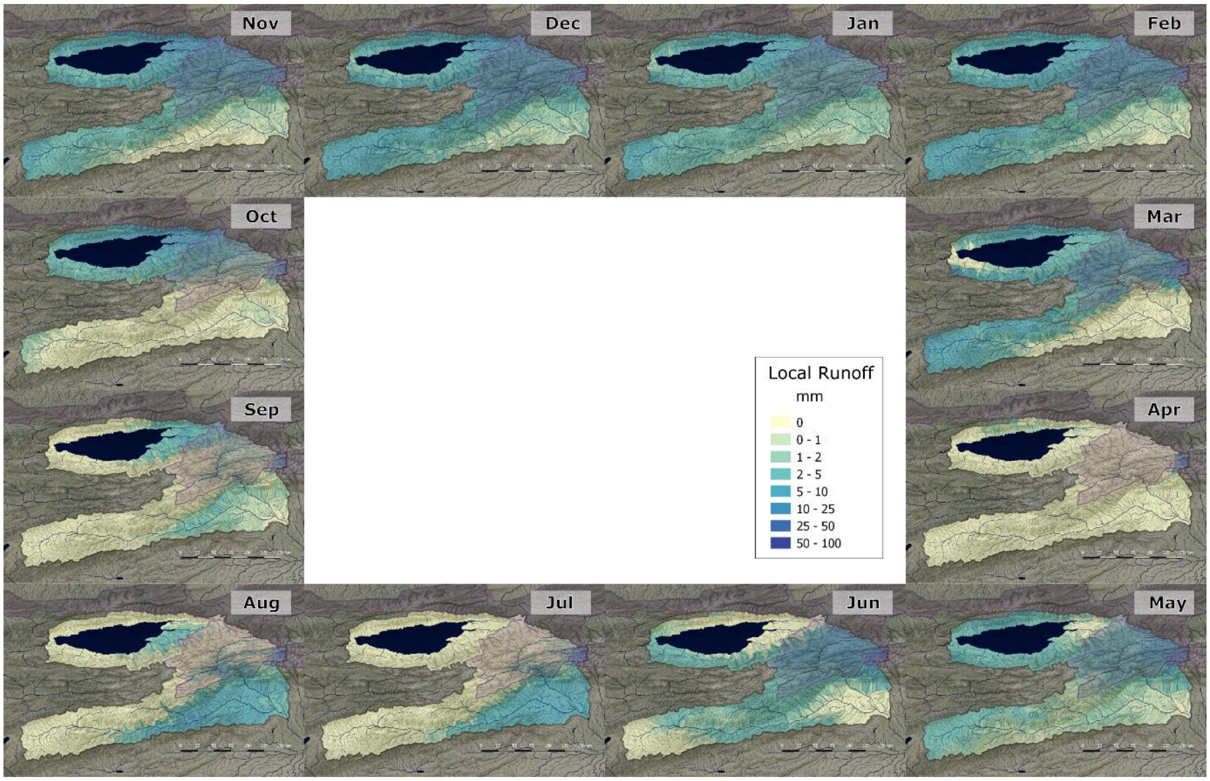
Snow Leopard Habitat Model:

- Land cover (ESA 2009)
- DEM, Slope (Lehner et al. 2008)
- Terrain Ruggedness Index (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard radio collar observations (Kachel 2017)

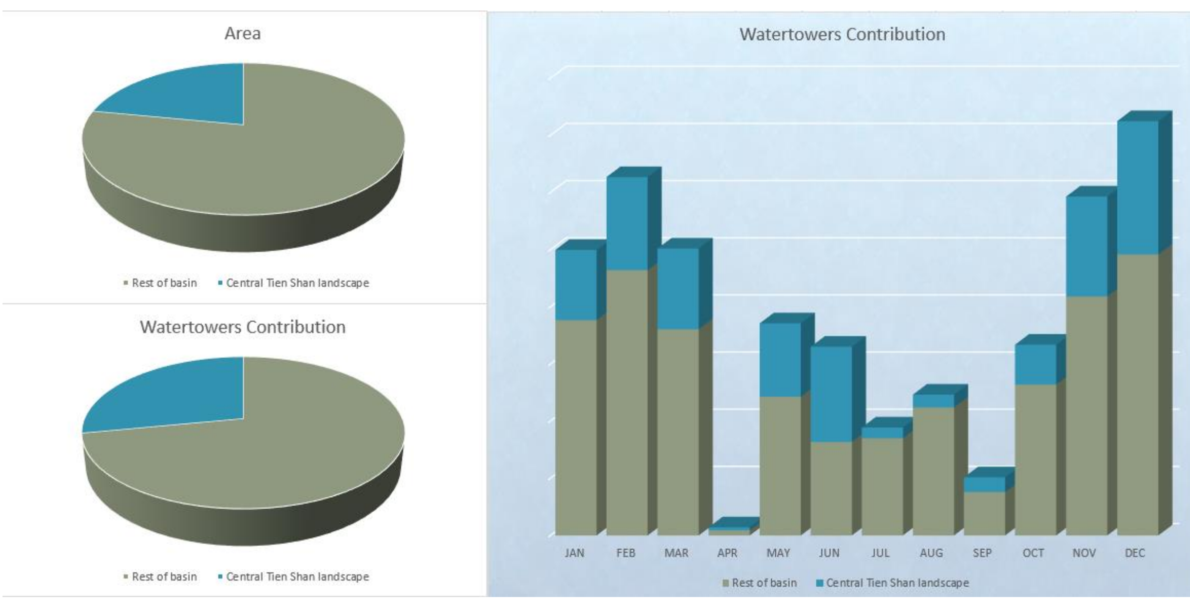
Projected Change in Cropland Suitability: Sindorf et al. 2014

Other layers for display only:

- GSLEP Landscape Boundaries (GSLEP 2016b)
- ESRI World Imagery (ESRI et al. 2016)



Water Towers (Local Runoff) in the Central Tien Shan Landscape and Sub-basin



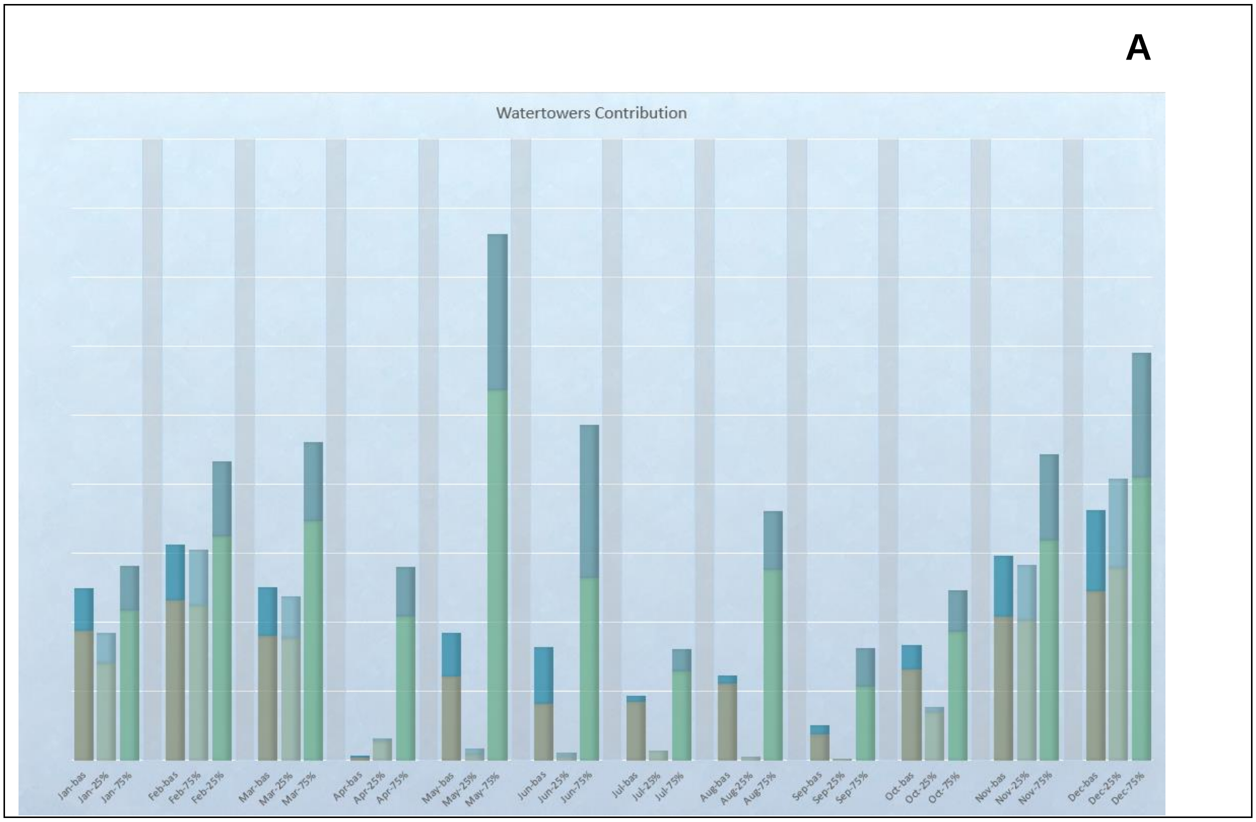
Water Towers/ Local Runoff	
Baseline Conditions	In May and June, the landscape acts as a water tower to the downstream. This is because at this time of year, the downstream has significant water demands. During other months of the year, the landscape either generates less runoff than its downstream, or downstream water demands are limited. Much winter precipitation falls as snow and runs off during the spring, compounding the amount of water available from the landscape in the spring.
Projected Climate Change	There is high uncertainty in projected change in the water tower function of the landscape. During the month of May in particular, the difference between the lowest and highest precipitation projections are extreme, ranging from close to zero runoff generation, to becoming the wettest month of the year and quadrupling the amount of local runoff. When coupled with spring snowmelt, the high precipitation scenario may lead to spring floods.

This analysis compares the amount of run-off from precipitation that originates in the Central Tien Shan landscape with that of the rest of the sub-basin under baseline and future climate scenarios.

Across the subbasin, the landscape acts as a belt between the northern Issyk Kull basin and the southern Aksu and Aksay river basins. In winter, due to very low temperatures, there are no vegetation water demands in the landscape, or crop water demands downstream. A quick rise in temperature in spring likely results in high plant productivity in April, but less relative local runoff originating from the landscape compared with the rest of the sub-basin. Only in the months of May and June, when downstream water demands are significant, does the landscape serve as part of the Tien Shan water towers (see Figure 4.1A). In July to September, when downstream crop water demands are highest over the year driven by high summer temperatures, the landscape water towers are much drier than its downstream. This has led to the presence of intensive irrigation management (reservoirs, canals) downstream of the landscape.

*Within the landscape, l*ocal run-off amounts are relatively low. The eastern part of the Central Tien Shan landscape appears to generate more local runoff than the western parts. Runoff season starts earlier and ends later in the eastern parts, while the amounts of runoff also appear to be higher.

Figure 4.1. Projected change in the relative water tower function of the Central Tien Shan Landscape compared with the rest of the landscape under baseline and future precipitation scenarios.



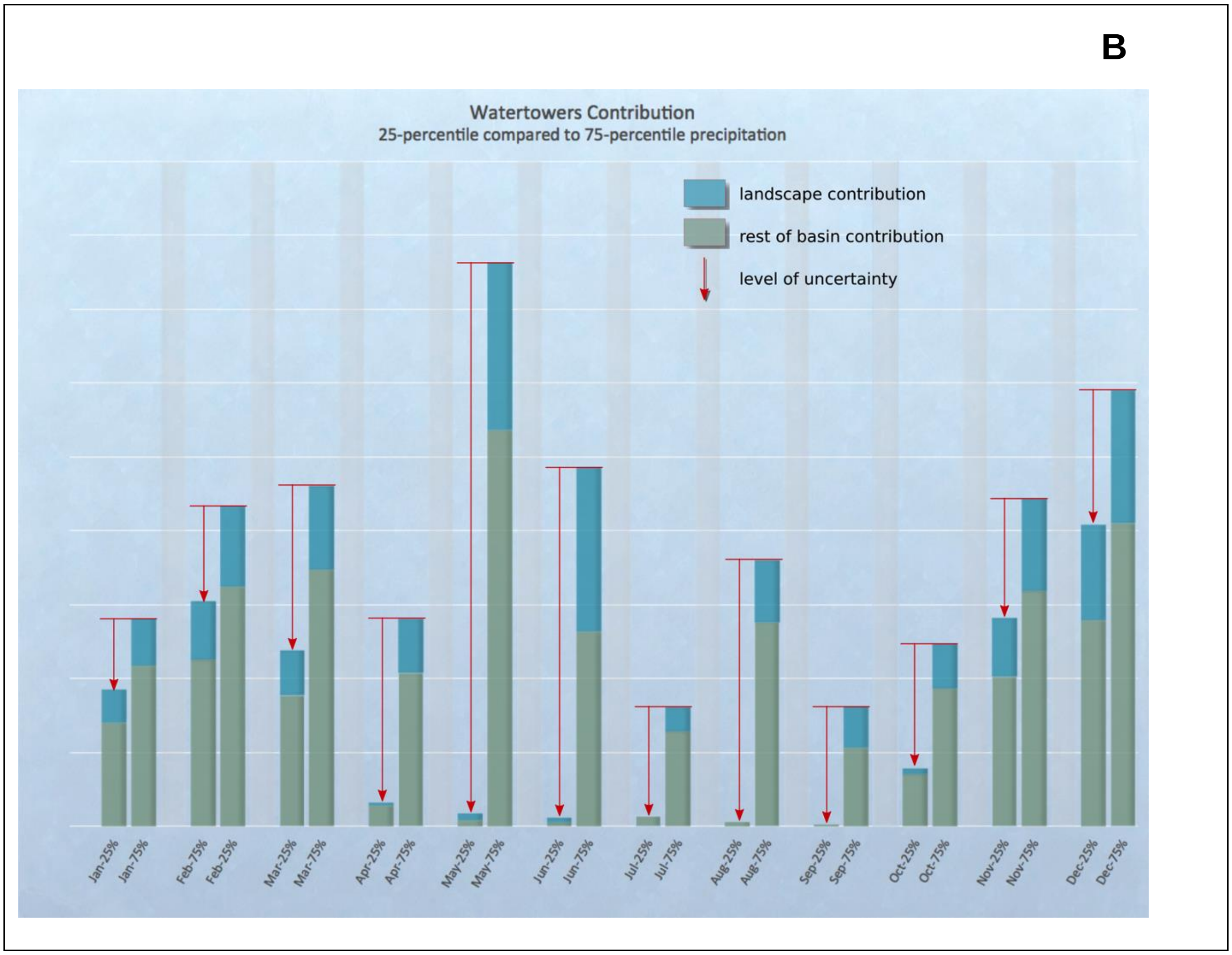


Figure 4.1A shows relative water tower contributions of the Sikkim Landscape compared with the rest of the sub-basin under baseline and 25-percentile and 75-percentile mid-century precipitation projects (Peters et al. 2017, Sindorf 2017). Figure 4.1B compares the relative water tower contribution of the landscape with the rest of the sub-basin under low and high mid-century precipitation projections, and also expresses the range of uncertainty. Relative run-off from the landscape is represented by the blue color at the top of each bar, while run-off from the rest of the sub-basin is represented by the bottom portion of the bars. 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.

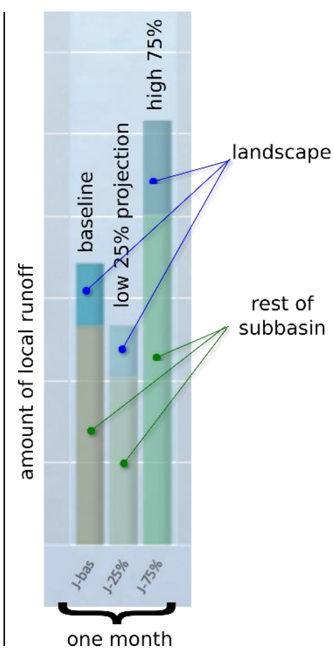


Figure 4.1A shows that under baseline conditions, the landscape serves a modest water tower function in the spring compared to it downstream, and in the summer months, the landscape is much drier. Under a high precipitation future scenario, the water tower function of the landscape could increase greatly during the months of May and June, perhaps contributing to flooding during that season as this coincides with the snowmelt season. The water tower function of the landscape may increase modestly under this same scenario during the summer months of July to September, when water demand downstream is high. There is, however, significant uncertainty in future precipitation scenarios. There is a possibility that the entire sub-basin could become much drier (Figure B). It is worth noting that under the high precipitation scenario, local runoff from the landscape may increase by 112% compared with baseline amounts, despite the fact that precipitation is expected to increase by about half that (55%). This is because projected evapotranspiration is not expected to increase at the same rate.

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 areas in order to convert from millimetres to cubic meters. Then, monthly actual evapotranspiration means were subtracted from monthly precipitation means (P – AET). Local runoff values that are less than zero were displayed and flagged as being zero. Inside the subbasin, those watersheds that drain the snow leopard landscape were also flagged. While the methodology expresses local runoff during the winter months; in reality, precipitation often falls as snow and accumulates in the landscape to melt off during spring. In addition, after snow falls, it is often transported over the land surface by wind before it melts off. This local runoff model is therefore not the best prediction of snowfall and snowmelt. For more information on this and other hydrological analyses for this landscape, please see Sindorf 2017.

Data sources

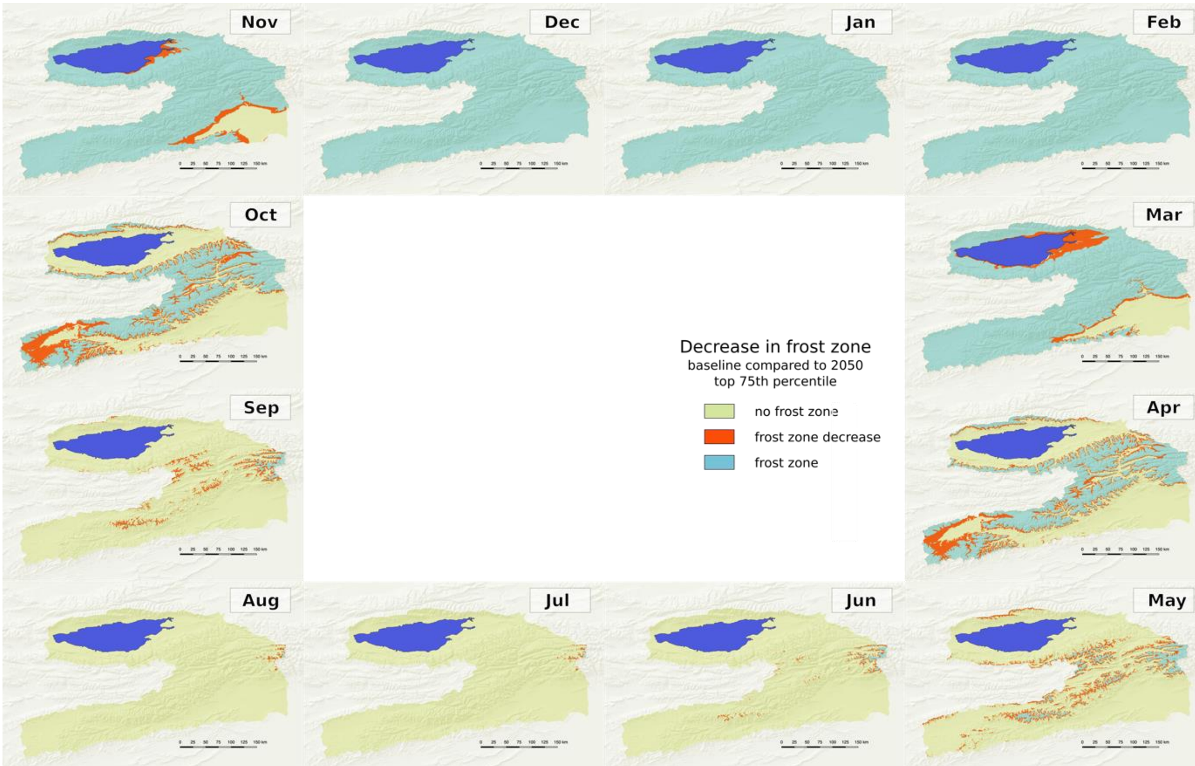
Current Mean Monthly Precipitation, based on historic WorldClim, 30s resolution (Hijmans et al. 2005)

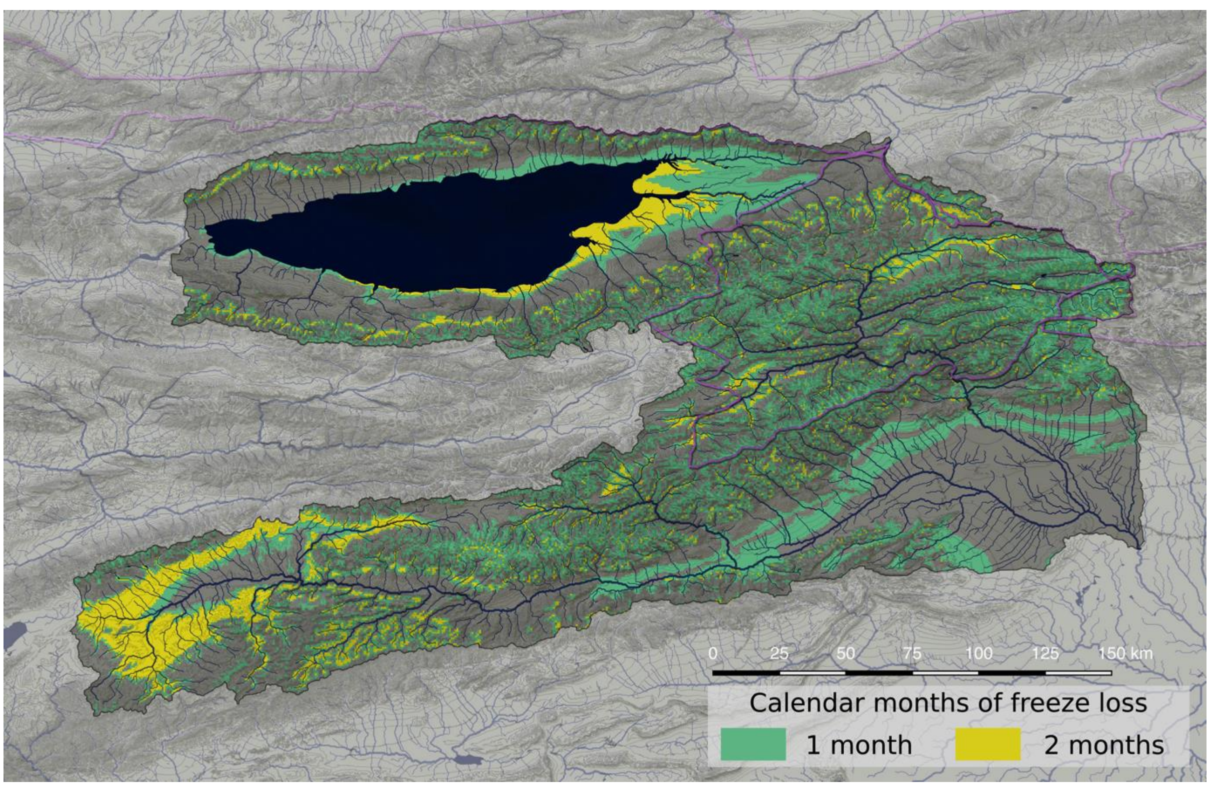
Current Mean Monthly Actual Evapotranspiration, based on historic Global Soil-Water-Balance, CGIAR, 30s resolution (Trabucco and Zomer 2010)

HydroBASINS, level 12, ~100 km^2 watershed outlines (Lehner and Grill 2013)

Climate Projections on future temperatures and precipitation (Peters et al. 2017)

Decrease in Monthly Freeze Extent under Temperature Rise in the Central Tien Shan Sub-basin





Snow cover, Frozen Ground and Freeze Line	
Baseline Conditions	Snowcover occurs throughout the year in the landscape. It accumulates and covers most of the landscape during winter, and remains in summer on many mountain tops. The freeze line retreats to the eastern-most mountain ranges during the summer months, but occurs throughout the landscape around mountaintops for the largest part of the year.
Projected Climate Change	Much of the landscape will lose 1-2 months of winter by mid-century. This loss will occur mainly during the transitional months of April and October. In the summer, the shift in freeze line could range from hundreds of meters to kilometers upslope from the current freeze line. This shift will still encircle snow covered mountain tops. A severe impact on snow and glacial melt-off is likely, with consequences for downstream hydrology. The composition of vegetation and wildlife communities may shift in response to shorter winters, though these may remain within the adaptive realm for snow leopards.

The above maps illustrate for each month how the spatial footprint of the freeze frontier is expected to change under projected temperature rise to mid-century. The freeze line is an indicator of the average timing of snowfall and snowmelt, glacial melt, permafrost coverage and depths, and subsequent water availability. It is also an indicator of phenological processes such as the timing of green-up and leaf-fall, breeding and birthing, and animal movements. Seasonal changes can selectively impact some species, ultimately affecting the composition of vegetation and animal communities in the landscape.

In general, the decrease in freeze extent under future projections closely follows the baseline freeze frontier, and changes are within the range of a few hundred meters to a few kilometers. For mountaintop snow cover and glaciers, this impact might be dramatic from May to September.

The headwaters of the Aksay in the southwest of the Central Tien Shan landscape will likely experience a large change during the transitional months of April and October. This might cause precipitation to fall as rain rather than snow during these months. This could result in more direct runoff from rain during these transitional months, and less water from snowmelt during other months – such as summer when demand is higher.

Figure 4.2. Overall duration (months) of historic versus projected winter, as a proportion of total area (Top 75th-percentile precipitation projection at mid-century, Peters et al. 2017)

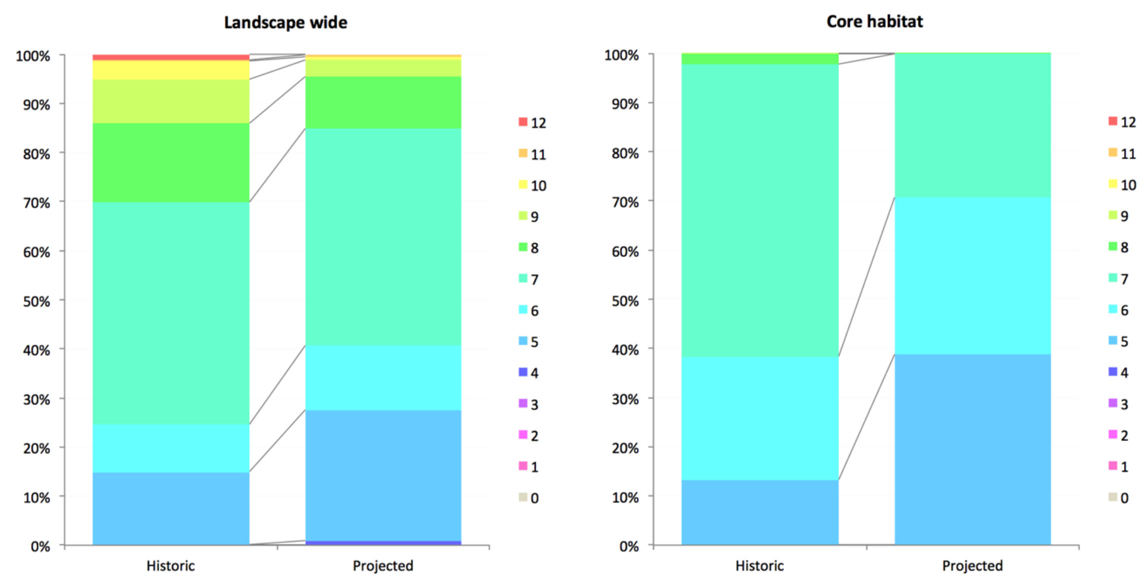


Figure 4.2 shows that under baseline conditions, core snow leopard habitat rarely contains areas with more than 8 months of winter (though areas of > 8 months winter represent ~30% of the landscape historically). No part of the landscape experiences less than 5 months of freeze, and under the temperature projection, this should not change by mid-century.

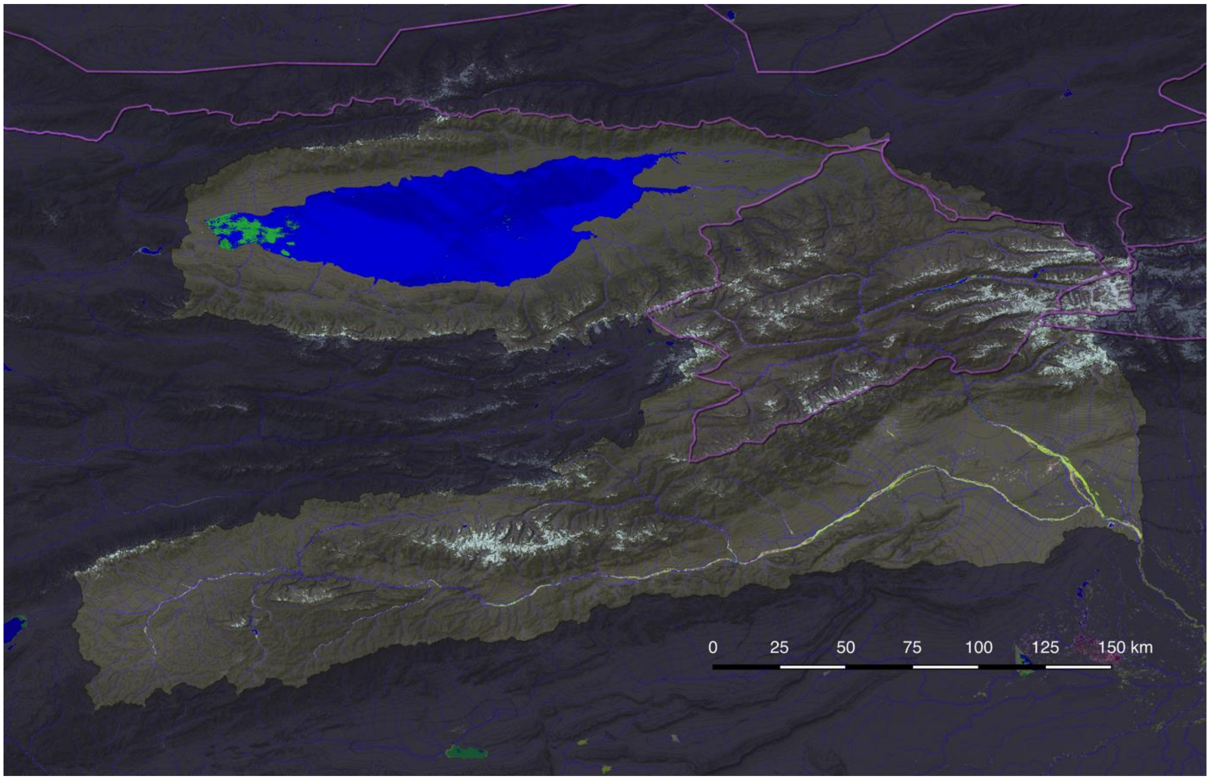
Under projected change in temperature, snow leopard habitat will experience a decrease in winter duration, but will stay within the historic upper and lower limits. Where historically the majority of the snow leopard landscape experiences 7 months of winter (~60 %), climate projections suggest that this area would halve (~30 %). At the same time, the area that experiences 5 months of freeze (12 %) would increase to about 40 % in the core habitat. This result indicates that while most habitat of the landscape will experience warmer conditions, that mid-century climate conditions across the habitat may be within the adaptive range of snow leopards.

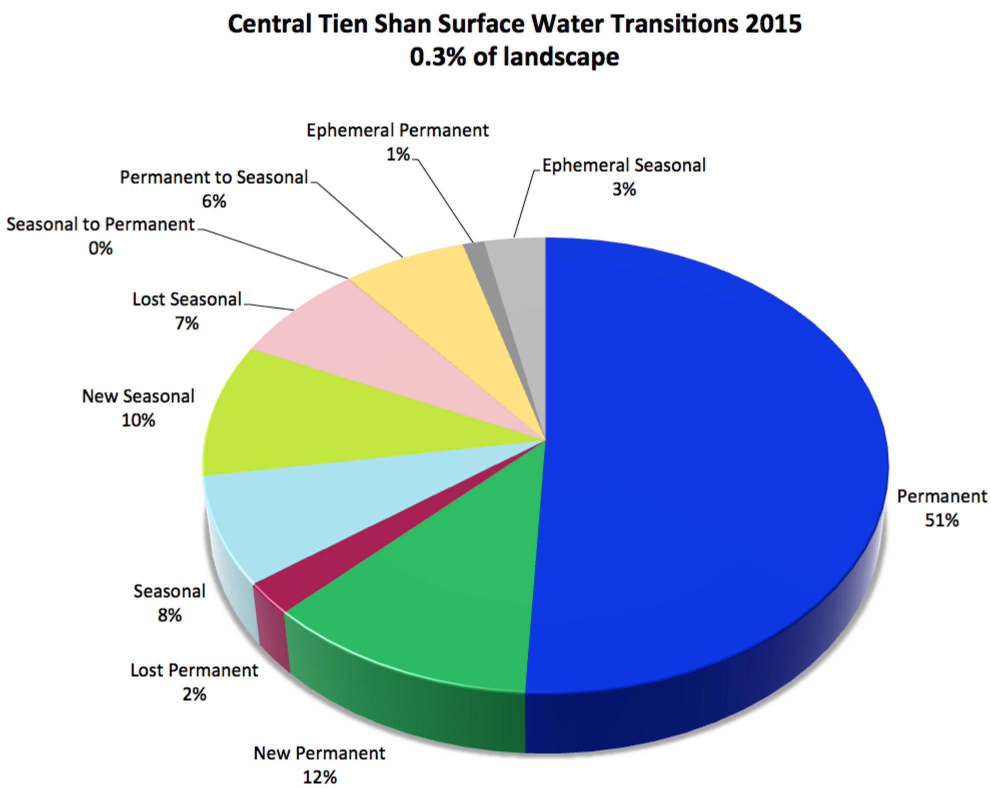
Data sources

Current Mean Monthly Precipitation, based on historic WorldClim, 30s resolution (Hijmans et al. 2005)

Climate Projections on future temperatures and precipitation (Peters et al. 2017)

Observed Surface water transitions (1984-2015) in the Central Tien Shan Sub-basin





Lakes, wetlands and floodplains	
Baseline Conditions	The northern parts of the landscape drains into Issyk Kul, which is a Ramsar site (a globally important wetland). Floodplains of the Aksu river reach into the landscape. In total 0.3 % of the landscape area is covered by surface water, mainly concentrated along the floodplains. There are many smaller glacial lakes in the landscape as well.
Observed Historic Change (1984-2015) and Anticipated Climate Impacts	Open surface water in the 2,500-3,500 elevation belt has experienced a dramatic increase in the 21 year observation period, indicating a likely increase in glacial fed lakes and floodplains. This trend may continue with warming temperatures, accompanied by an increased risk of glacial lake outburst floods (GLOFs).

Within the Sub-basin, there are two relevant water covers *in the wider subbasin*, the Issyk Kul lake (downstream of the landscape), and floodplains in the Aksu/Aksay basin.

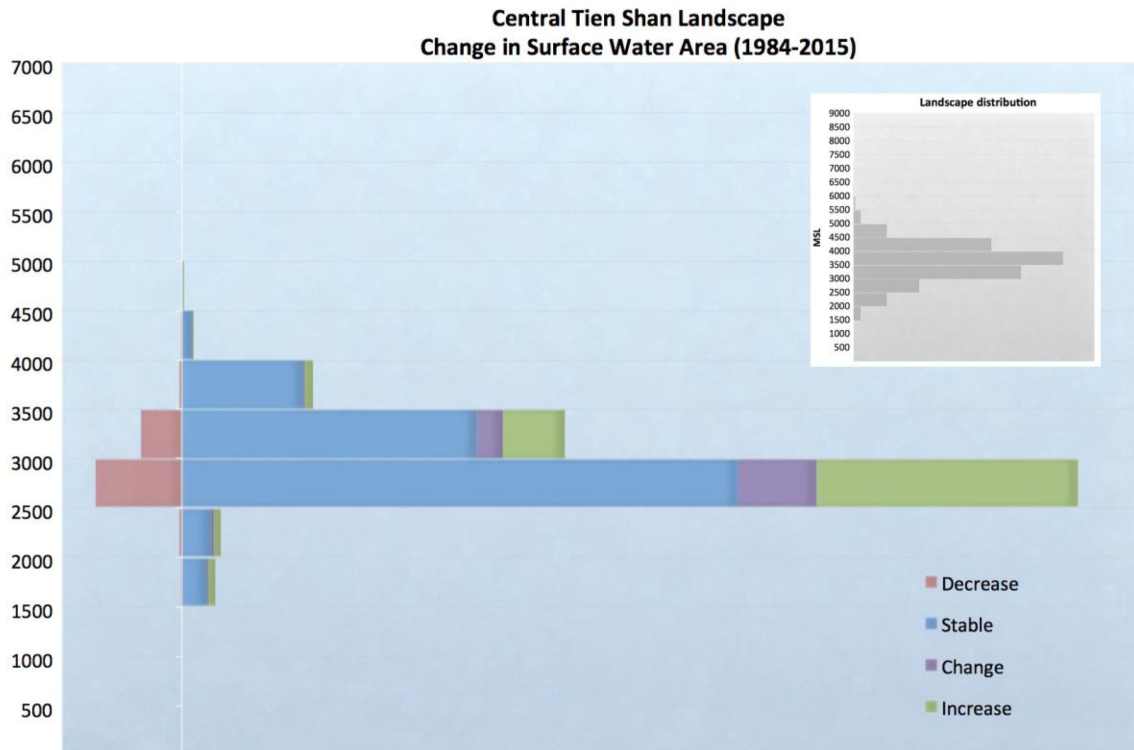
Issyk-Kul lake is an endorheic lake and Ramsar site of globally significant biodiversity (Ramsar Site RDB Code 2KG001) and forms part of the Issyk-Kul Biosphere Reserve. Issyk-Kul means "warm lake" in the Kyrgyz language; as it never freezes over in winter, which is exceptional given the cold temperatures.

Within the landscape, only 0.3% of the area is classified as open surface water (Pekel et al. 2016). The following transitions occurred between 1984 and 2015:

- 63% of the open water surface was *stable* (permanent 51 %, seasonal 8 %, ephemeral 4%)
- 9% of the open water surface *disappeared* (permanent 2%, seasonal 7 %)
- 22% classified as *new* surface water (permanent 12%, seasonal 12 %)
- 6% of all open water surface *changed from permanent to seasonal*.

These shifts in open surface waters were located mainly in the active floodplains that are fed mainly by snow and glacial melt.

Figure 4.3. Change in Surface Water Area by Elevation in the Central Tien Shan Landscape (1984-2015)



According to Figure 4.3, most of the open surface water is located in the 2,500-3,500 elevation belt, peaking between 2,500 and 3,000 msl. The landscape itself is mainly located between 3,500-4,000 msl (see inset), where most of the glacial fields are located. This implies that the open water entities are mainly glacial-fed lakes and floodplains. The increase over the 1984-2015 period might indicate that the glaciers are melting off, leading to expanded glacial lakes. This may also increase the risk of glacial lake outburst floods (GLOFs). The graph only displays surface water *areas*, and *not volumes* of water.

Methodology

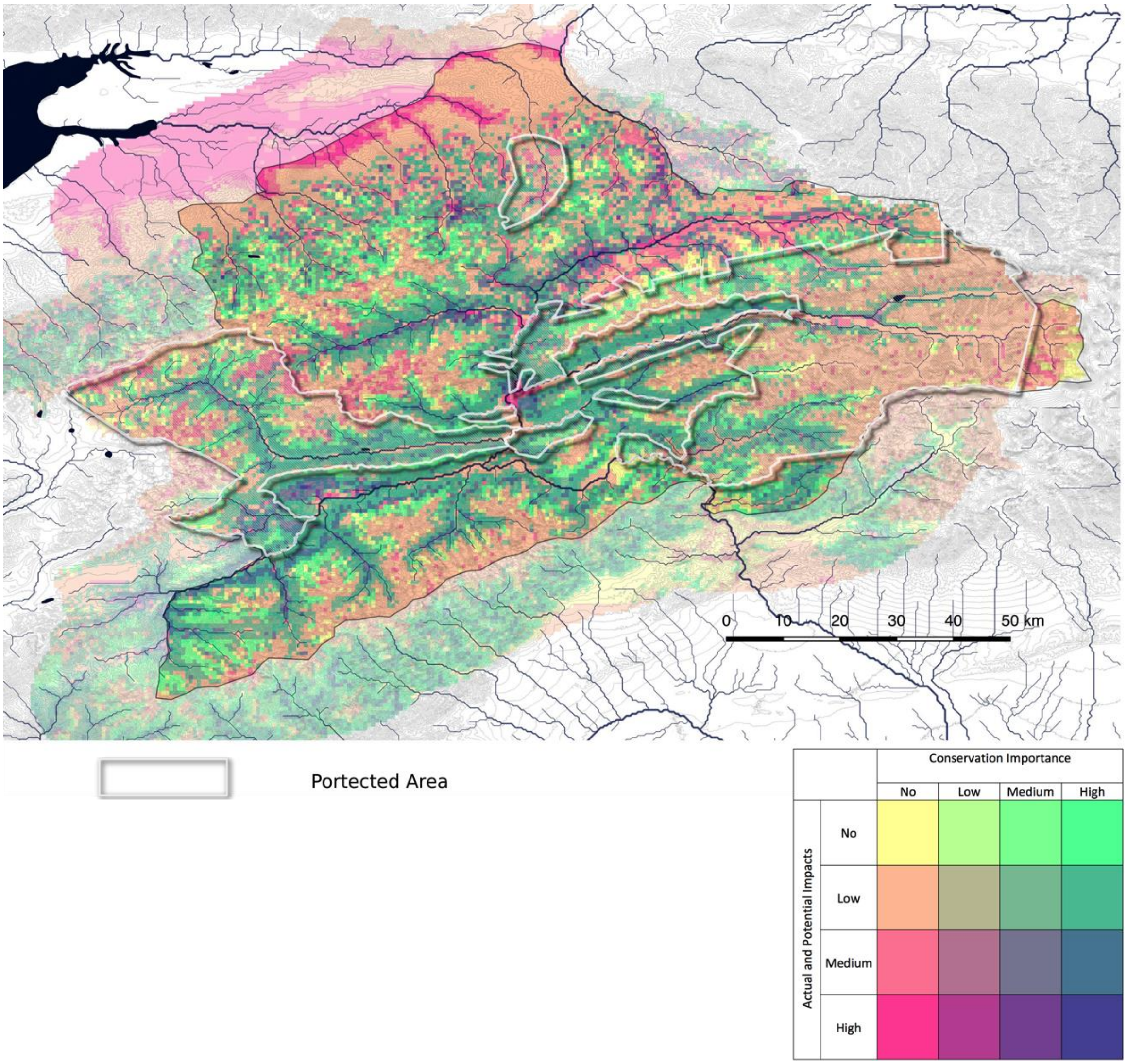
The map of global surface water and its long-term changes, is a recent high-resolution product (Pekel, 2016). It contains at least 6 different datasets, and allows time-lapse analysis from 1984-2015, which coincides with Landsat coverage. See Sindorf 2017 for more information.

Data sources

Open surface water (Pekel et al. 2016)

Volume and age of water stored in global lakes (Messager et al. 2016)

Summary of Conservation Importance and Potential Impacts in the Central Tien Shan Landscape



This map displays the landscape according to conservation importance and actual and potential impacts. Conservation importance is represented by habitat suitability for snow leopards. Actual and potential impacts are represented by the expected severity of climate change impacts and human impacts. Much of the important habitat in the landscape has low to moderate risk of loss (darker green and light blue). Areas of high conservation importance and high risk tend to be found bisecting important habitats, along roads and between the two major protected areas (dark blue). These high risk habitats have the potential to fragment important habitats that may at first glance be at lower direct risk of loss. Managing important habitats for connectivity is key to maintaining snow leopard metapopulation.

Methodology

This summary map combine different analyses of the overall quality and condition of the landscape, using a consistent approach across different snow leopard landscapes. Conservation importance was represented by habitat suitability for snow leopards. Actual and potential impact from future climate change was represented by the predicted loss in number of winter months (ie, freezeline loss). Actual and potential impact from direct human impact was represented by the human footprint.

For each of these layers, scores representing value (in the case of conservation importance) or severity (in the case of impacts) were developed in collaboration with field experts, and assigned as presented in Table 4.5. A score of 0 indicates the lowest score possible, and a score of 8 indicates the highest. Protected areas were not included, since most habitat in the landscape is under protected status. The values in the tables correspond with the 'raw' values of each input GIS data layer. The qualitative scores of conservation importance and impacts were summed with others in their class, then combined into a single map with 16 different combinations.

Table 4.5A. Conservation Importance Weights

Score	Habitat Suitability
0	0
1	
2	
3	
4	
5	
6	2
7	
8	1

Table 4.5B. Actual and Potential Impacts Weights

Score	Months of freeze loss	Human Footprint
0	0	0
1		1-5
2	1	
3		6-10
4	2	
5		10-14
6		
7		
8		>15

Combined scores:
No: 0
Low: 1-3
Medium: 4-7
High: >8

V. Analysis and Mapping of Snow Leopard Habitat in the Karakoram-Pamir Landscape, Pakistan

September 11, 2017

Jessica Forrest[1], Shoaib Hameed[2], Nikolai Sindorf[1], Muhammad Ali Nawaz[2], Doost Ali Nawaz[2]

World Wildlife Fund[1] and Snow Leopard Foundation[2],
with funding from USAID

Chapter 5 of 6 of the report:
Guardians of the Headwaters, Volume 2:
Biodiversity, Water, and Climate
in Six Snow Leopard Landscapes

Key Findings and Management Recommendations

- **The Karakoram-Pamir (KKP) Snow Leopard Landscape has an estimated 7,400 km^2 of habitat in eight 'big patches' - of substantial quality and size to support snow leopards.** The largest and most central block of habitat is located along the Khunjerab river corridor and its headwaters. A further 1,280 km2 of habitat is available in smaller patches that may serve a vital connectivity function.

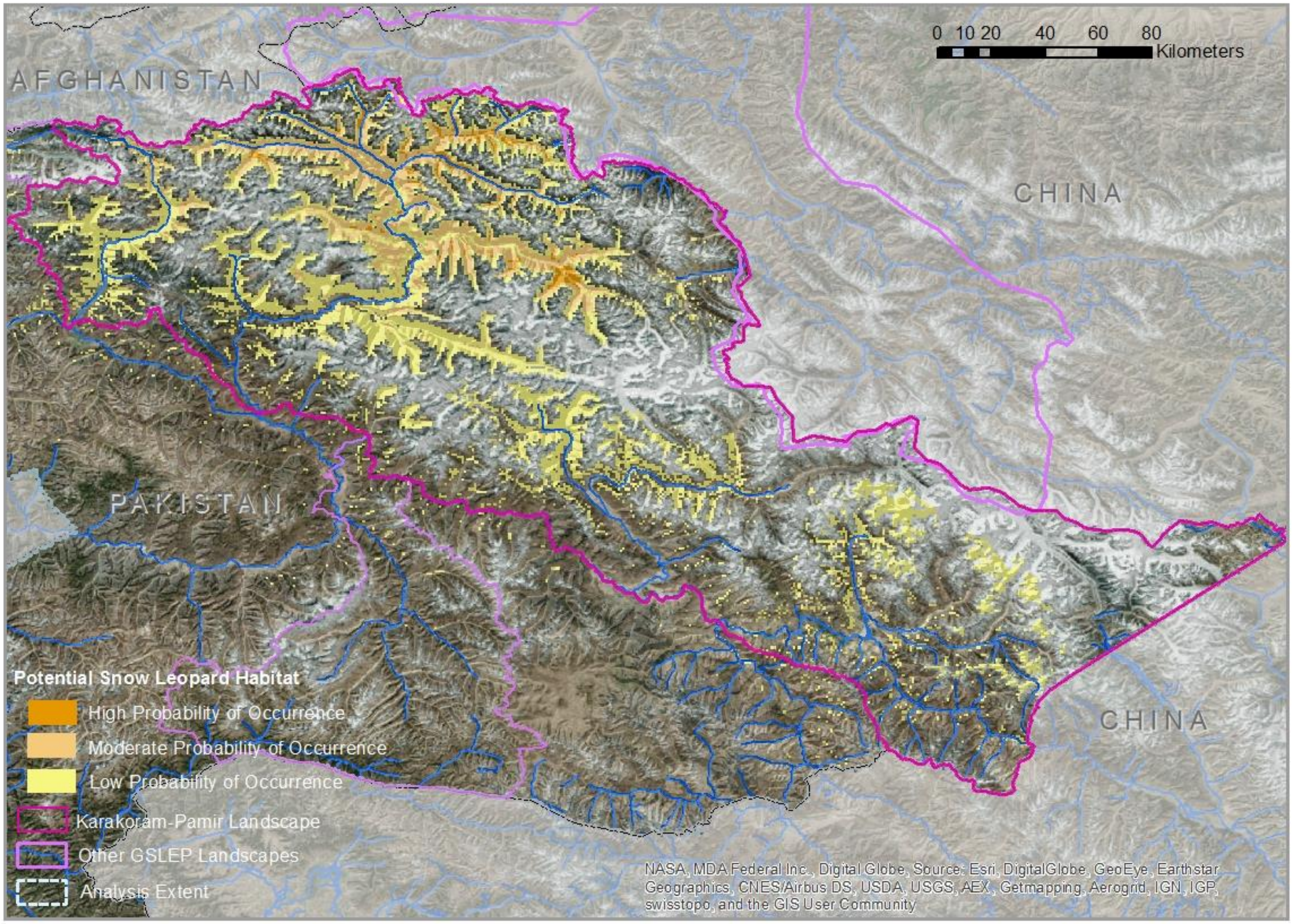
- **Protected areas cover nearly 54% of all potential snow leopard habitat in the KKP Landscape.** Roughly 18% of all habitat is in national parks that offer the highest level of protection, while the remaining habitat area is protected only by Conservation Reserves and/or Community Conservation Areas. Notably, 46% of snow leopard habitat remains unprotected, particularly some of the large, intact areas to the southwest of Khunjerab National Park. This unprotected habitat may form a vital connection to the habitat in Qurambar National Park at the western edge of the landscape. There are also areas of unprotected habitat in the far eastern part of the landscape.

- **The snow leopard habitat of the Khunjerab river corridor its tributaries is a conservation priority.** This area offers some of the best and centrally located snow leopard habitat, but this region also has relatively high human impact and climate risk, particularly along the main stem of the river. Some of these habitats are also not protected. Adequate zoning and management of human activities can help to to minimize habitat loss and fragmentation in this central habitat location.

- **Climate projections suggestion that the landscape will become hotter year-round, with a mild to moderate increase in winter precipitation, mostly as snow. In addition, the length of winter will decrease. Monitoring and adaptive management will be key to maintaining wildlife populations and ecosystem services.** Almost the entire landscape will experience a decrease of 1 month of frost, and some areas (particularly the lowest elevations of habitat and the highest peaks) may experience 2-3 months loss. This will be accompanied by shorter winters, earlier arrival of spring, and a later arrival of fall. This could result in permafrost loss, earlier flowering and leaf out, changes in grassland community composition, a disrupted timing of life-cycle events for wildlife, as well as glacial melting and a higher risk of glacial lake outburst floods.

- **The amount of arable land downstream of snow leopard habitat may increase under climate change.** This may result in increased pressure on water originating in snow leopard habitat, particularly on the Khunjerab/Hunza/Gilgit River, emphasizing the need for snow-leopard friendly water management practices and planning.

Potential Snow Leopard Habitat in the Karakoram-Pamir Landscape



Potential snow leopard habitat of the Karakoram-Pamir Landscape.

SLF & WWF 2017

The Karakoram-Pamir Snow Leopard Landscape has an estimated 7,400 km^2 of habitat that appears to be of adequate quality and area to support snow leopards. This habitat consists of eight discrete habitat blocks > 100 km^2. The largest and most central block of habitat is located along the Khunjerab river and its headwaters.

Our model identified a further 1,280 km^2 of "suitable snow leopard habitat". However, this is located in patches smaller than 100 km^2 – with the vast majority in clusters smaller than 10 km^2 (n=26 clusters between 10 and 100 km^2, and n=406 clusters <=10 km^2). Most of these patches may be too small and isolated to serve as suitable habitat, though some may function as stepping stones. Among all pixels that that classifier identified as "habitat," regardless of cluster size and isolation, 300 km^2 is classified as good habitat with high probability of snow leopard occurrence, 1,945 km^2 is classified as habitat with moderate probability of occurrence, and 6,430 km^2 is classified as connectivity habitat with low probability of occurrence.

The vast majority (98.8%) of potential habitat ranges in elevation between 2,300 and 5,800 m. Potential habitat has an average elevation of just below 4,000 m (3,974 m), and standard deviation of 961 m. The area adjacent to the Khunjerab/Hunza river has the highest probability of occurrence, consistent with observation data (SLF 2016a).

Methodology

A Maxent model was developed to produce probability of snow leopard occurrence maps at the extent of Northern Pakistan (Hameed et al. 2016, Phillips et al. 2006). The analysis extent included all land in Northern Pakistan within a distance of 30 km of the current snow leopard range, and encapsulates the high mountains of the Himalaya, Karakoram, Pamir, and Hindu Kush ranges (ISLT and WCS 2008, Hameed 2016). Environmental variables incorporated into the final model included temperature seasonality, mean temperature of the wettest quarter, annual precipitation, precipitation seasonality, altitude, slope, Normalized Difference Vegetation Index (NDVI), ruggedness, distance to roads, distance to rivers, land cover, and soil (see data sources below for references). The final set of environmental variables were selected from a larger set of 28 variables. The candidate variables also included all 19 bioclimatic variables (Hijmans et al. 2005) and distance to settlements. These were pruned down to 13 by identifying variables that were autocorrelated and selecting the ones believed to have the most logical influence on snow leopard habitat.

The Maxent model also incorporated a total of 350 snow leopard observations. These were collected by the Snow Leopard Foundation (SLF) through camera trapping, sign-based site occupancy surveys, and DNA analysis of scats samples (SLF 2016a) across the Pakistani Himalaya, Karakoram, Pamir and Hindu Kush mountain ranges (Hameed 2016, SLF 2016a). Camera traps were placed at 774 locations throughout Northern Pakistan, though only 94 capture events occurred at 56 stations. Sign data were verified with DNA tests for scat, and by using scrape and pugmark observations only when less than 10 days old. Among surveyed sites, snow leopards were not detected at more than 2000 locations, and 252 of these were selected for model evaluation (Hameed 2016, SLF 2016).

The resulting model output had an Area under Curve (AUC) value of 0.961, and standard deviation of 0.016. This is considered to be a very strong predictive result. Hameed (2016) also performed model evaluation through receiver operative curve (ROC) AUC, by measuring the error of false positive (FP) and false negative (FN) rates against a range of defined thresholds (Figure 3.8). Lowest error was found at a threshold of 0.05 which was selected to create a binomial map i.e., suitable and unsuitable habitat, of the snow leopard distribution. The binomial map was re-evaluated by plotting presence and absence points on it and it showed that at this threshold, almost all presence points were classified as suitable habitat and absence points were classified as unsuitable habitat. The values of 350 presence points and 252 absence points were extracted from the model and plotted against different thresholds. The value of AUC by ROC curve was calculated at 0.05 was 0.974, which means the model performed excellently (Hameed 2016).

It was calculated that 341 points were true positive (TP) and 252 were true negative (TN) while false positive (FP) was 0 and false negative (FN) was 9. The true positive rate (TPR) was calculated at 0.974 while false positive rate (FPR) was 0. Accuracy and specificity were 0.985 and 1.000, respectively, while positive predictive value (PPV) was 1.000 and negative predictive value (NPV) was 0.966. False discovery rate (FDR) was 0 (Hameed 2016).

After confirming a satisfactory model, the resulting logistic probability of occurrence (p) map was reclassified into high, moderate, and low probability of occurrence and non-habitats based on p-thresholds. Habitat with low probability of occurrence is defined as $0.05 > p > 0.4$, moderate probability of occurrence was defined as areas where $0.4 > p =< 0.7$, and high probability of occurrence was defined as $p > 0.7$. (Hameed 2016). The threshold for habitat was set to $p>0.05$ to be consistent with the results of the ROC AUC analysis described above.

The habitat model resulted in 400 discrete patches of habitat, the vast majority (n=406) of which are less than 10 km^2. We thus produced two area calculations. One area calculation includes all pixels classified as habitat located within the landscape boundary. The second estimate includes only the largest habitat blocks (>= 100 km^2). This second estimate might more accurately reflect resident habitat area since it consists of large blocks suitable for living and breeding. Smaller and patchier habitats (included in the first estimate) should not be disregarded since they may provide a complementary connectivity function.

Data Sources:

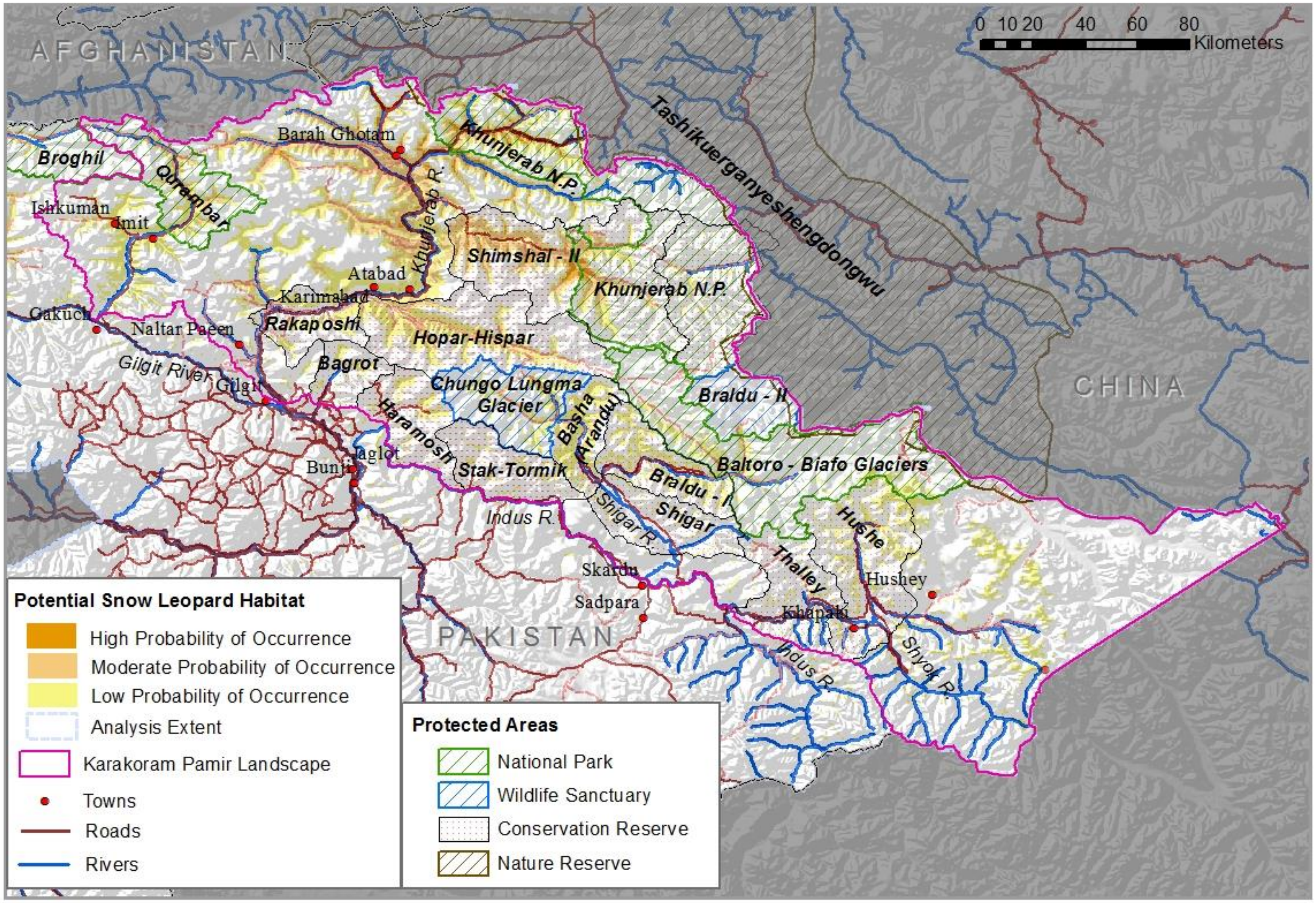
Snow Leopard Habitat Model (*Hameed 2016):*

- Climate: Temperature Seasonality, Mean Temperature of Wettest Quarter, Annual Precipitation, Precipitation Seasonality (Hijmans et al. 2005)
- Land Cover (Loveland et al. 2000)
- DEM, Ruggedness (Lehner et al. 2008, Center for Nature and Society, Peking University, Sappington et al. 2007)
- NDVI (NASA 2014)
- Roads (SLF 2016b)
- Rivers (SLF 2016b)
- Soil (FAO, 2003)
- Snow leopard observations (SLF 2016a)

Other layers for display only:

- GSLEP Landscape Boundaries (Government of Pakistan & GSLEP 2017)
- Blue Marble Imagery (NASA, MDA Federal Inc., Digital Globe 2016)

Protected Areas and Places of the Karakoram-Pamir Landscape



Protected areas, roads, major rivers, and towns in and near the Karakoram-Pamir Landscape, displayed over snow leopard habitat.

SLF & WWF 2017

Protected areas cover nearly 54% of potential snow leopard habitat in the KKP Landscape. National parks, the most strictly managed, cover about 18% of snow leopard habitat. Other habitats are located in Conservation Reserves and/or Community Conservation Areas, and some habitats are found in a few managed area types. Notably, 4,011 km^2 (46%) of snow leopard habitat remains unprotected, particularly south and west of Khunjerab National Park and in the easternmost part of the landscape. The unprotected portion of the Khunjerab river corridor may form a vital connection to the habitat in Qurambar National Park at the western edge of the landscape. Habitat in the easternmost part of the landscape may provide connectivity to habitats in China. Human presence is also most heavily concentrated in the unprotected zone along the Khunjerab/Hunza River.

As shown in Table 4.1, Khunjerab National Park has the most habitat among the protected areas. A large amount of habitat is also found in the Conservation Reserves.

Table 4.1. Protected Habitat Area in the Karakoram-Pamir Landscape

	Probability of Occurrence/ Habitat Quality (Area km2)			All Habitat Types
Protected Area Name	**Good**	**Moderate**	**Low**	**Total**
Baltoro - Biafo Glaciers National Park	0	1	278	**280**
Khunjerab National Park	103	257	593	**953**
Qurambar National Park	4	116	205	**326**
Bagrot Conservation Reserve	0	0	47	**47**
Basha (Arandu) Conservation Reserve	0	1	284	**285**
Braldu - I Conservation Reserve	0	1	304	**306**
Braldu - II Conservation Reserve	0	0	14	**14**
Haramosh Conservation Reserve	0	0	108	**108**
Hopar-Hispar Conservation Reserve	0	32	613	**644**
Hushe Conservation Reserve	0	4	371	**375**
Shimshal - II Conservation Reserve	7	27	33	**66**
Central Karakoram Conservation Complex	48	323	889	**1260**

*Note that some habitat is found in more than one type of protected area

Data Sources:

Snow Leopard Habitat Model (*Hameed, SLF 2016):*

- Climate: Temperature Seasonality, Mean Temperature of Wettest Quarter, Annual Precipitation, Precipitation Seasonality (Hijmans et al. 2005)
- Land cover (Loveland et al. 2000)
- DEM, Ruggedness (Lehner et al. 2008, Center for Nature and Society, Peking University, Sappington et al. 2007)
- NDVI (NASA 2014)
- Roads (SLF 2016b)
- Rivers (SLF 2016b)

- Soil (FAO 2003)
- Snow leopard observations (SLF 2016a)

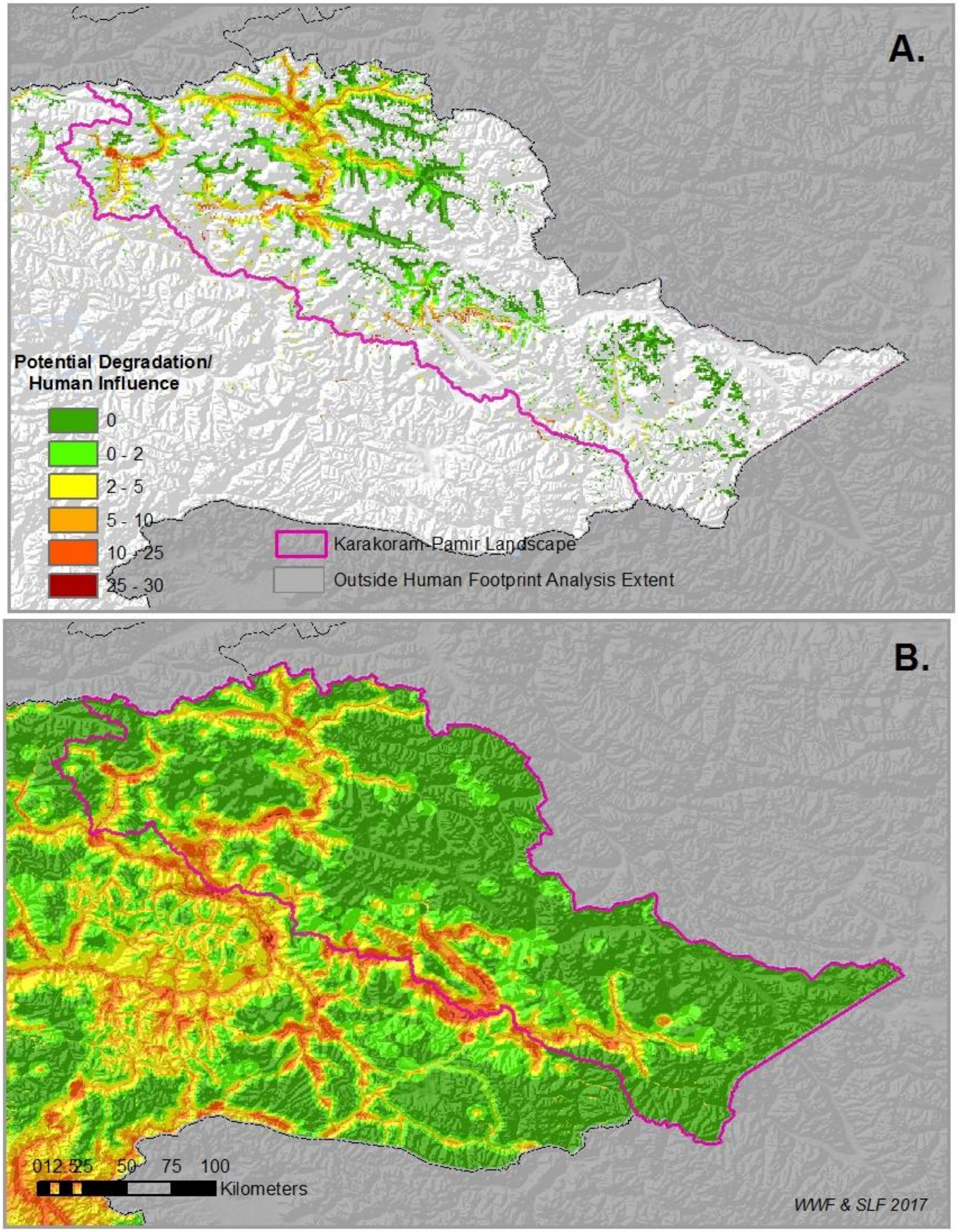
Human Landscape:

- Protected Areas (SLF 2016b, IUCN & UNEP-WCMC 2016)
- Roads, Rivers and Settlements (SLF 2016b, OpenStreetMap 2016)

Other Data:

- KKP Landscape Boundary (Government of Pakistan & GSLEP 2017)

Potential for Degradation and Human Influence in Snow Leopard Habitat



Potential degradation and human influence of snow leopard habitat, derived from current land cover and land use, cost distance to roads, and populated place density. Map A shows potential human influence in snow leopard habitat, and Map B shows human influence across the broader landscape.

This map shows areas of potential degradation and human influence in the Karakoram-Pamir Landscape. The result shows that the highest levels of human access and potential degradation also coincide with the largest and most centrally located habitats along the Khunjerab River.

Snow leopards and their habitats are often directly affected by overgrazing and competition between livestock and prey, hunting of snow leopards and prey, human wildlife conflict, tourism, forest and non-timber forest product collection. We assume that degradation and threat drivers to snow leopards and their habitats are directly correlated with levels of human access (Sanderson et al. 2002). Here, we represent human access through GIS layers on populated place density, cost distance to roads, and land cover and land use. Input layers were prepared according to the methods below and summed to produce a potential degradation and human influence layer (Sanderson et al. 2002).

Methodology

Here, we represent human access through GIS layers on populated place density, cost distance to roads, and land cover and land use. Input layers were rescored according to the tables below and summed to produce a potential degradation and human influence layer according to methods developed by Sanderson et al. 2002.

Populated Places:

We created a populated place kernel density layer as a proxy for population density. The kernel density layer was generated from a settlements file from SLF (2016b). The impact of cities and capitals (levels 1, 2 and 11) was given a relative weight of 50, towns (level 3) were given a weight of 10, and villages (level 4) were given a weight of 1. Hamlets (level 5) and landmarks (level 6) were excluded from the analysis because impact from these places on snow leopards and their habitat is believed to be minimal. The search radius for the kernel density was set to the ArcGIS 10.3 Spatial Analyst default radius (ESRI, Redlands, CA), with results roughly equivalent to a 5 km radius. The result was a kernel density layer with a range of values from 0-11,045.8 per km^2, though values were interpreted on a relative scale. After close examination of the output with respect to different settlement types, we applied the following human footprint/potential degradation scores (Table 4.2).

Table 4.2. Populated Place Kernel Density Score for Human Footprint

Populated Place Kernel Density (ppl/km^2)	Potential Degradation/ Cost of Movement Score
>1500	10
1000-1500	9
750-1000	8
500-750	5
250-500	3
100-250	2
0-100	1
0	0

Roads:

We created a cost distance to roads file weighted by road type and the 'permeability' of the matrix for human travel. Cost distance represents the distance to the nearest road in meters, multiplied by the total cost of movement back to that road.

We began with GIS data on roads for Northern Pakistan (SLF 2016b) and divided this into two shapefiles based on presumed traffic and associated impact to wildlife. The first shapefile, major roads, consists of level 1 and 2 roads, including highways and paved roads. The second shapefile, unpaved roads, consists of level 3 roads, including unpaved, jeepable, and unmettled roads. We omitted level 0 and 4 roads, which represent walking tracks since the impact of these on snow leopards and their habitat are believed to be minimal.

We next created a cost layer to represent cost of movement of people across the landscape away from a road. It is presumed that areas of high slope and altitude are difficult or even impossible to traverse. The following scores were applied to describe cost of human movement across pixels, with 0 being the lowest and 10 being the highest, and masked areas being impermeable to movement. Elevation cost of movement: 0-2500m=1, 2500-3500m=4, 3500-4000=6, 4000-5500=8, >5500= Masked (No movement); Slope cost of movement: 0-30°=1, 30-50°= 6, >50° = Masked (No movement). These scores were used to rescore 15s elevation and slope rasters (Lehner et al. 2008). These rasters were next summed to create a single cost of movement grid. The cost grid was rescaled to a scale of 1 to 10.

Next, a cost-distance analysis was run on both the major and minor road shapefiles and the cost grid described above. Each cost distance output was reclassified using the scores in Table 4.3. Scores were assigned to be comparable to Euclidean distance categories from roads used in other landscapes, but influenced by cost of movement. The individual cost grids for major and minor roads were combined into a single cost grid by selecting the highest potential degradation/human footprint value present for a given pixel.

Table 4.3. Cost Distance to Roads Score for Human Footprint

Cost Distance to Major Roads[1]	Potential Degradation/Cost of Movement Score
0-500	10
500-1500	8
1500-2500	6
2500-15000	3
15000-25000	2
>25000	0
Cost Distance to Unpaved Roads[2]	**Potential Degradation Score**
0-500	8
500-1500	6
1500-2500	4
2500-10000	2
10000-15000	1
>15000	0

[1]This represents road levels 1 and 2, highways and paved roads. [2]. These are level 3 roads. Includes jeepable, unmettled, and unpaved roads

Land Cover and Land Use:

The Greater Himalaya land cover and land use map (FAO 2010) was rescored by assigning the values in Table 4.4. When a given class was composed of two land cover types, a weighted average of the two scores was applied, with the first land cover type receiving a weight of 0.6, and the second land cover class receiving a weight of 0.4. This is consistent with the fact that in the FAO map, a land cover class consisting of two types is approximately 60% of the first land cover type listed and 40% of the second (FAO 2010).

Table 4.4. Land Cover Score for Human Footprint

Land Cover/Land Use Category	Potential Degradation Score
Herbaceous Crops	7
Irrigated Herbaceous Crops	8
Tree Crop	8
Tea Crop	9
Small Herbaceous Crops in sloping land	5
Large to Medium Herbaceous Crops in valley floor	7
Small Herbaceous Crops in valley floor	6
Closed to Open Medium Tall Herbaceous Vegetation	0
Sparse Short Herbaceous Vegetation	0
Sparse Short Herbaceous Vegetation OR Bare Rock	0
Closed to Open Herbaceous Vegetation OR Rainfed Herbaceous Crops	5
Closed to Open Medium to High Shrubland (Thicket)	0
Sparse Shrubs with Sparse Herbaceous	0
Sparse Dwarf Shrubs with Sparse Herbaceous	0
Open Dwarf Shrubs with Sparse Herbaceous	0
Closed to Open Needleleaved Trees OR Closed to Open Broadleaved Trees	0
Closed to Open Needleleaved Evergreen Trees	0
Closed to Open Broadleaved Trees	0
Sparse Needleleaved Evergreen Trees OR Sparse Broadleaved Evergreen Trees	0
Sparse Needleleaved Evergreen Trees	0
Sparse Broadleaved Evergreen Trees	0
Closed to Open Medium Tall Herbaceous Vegetation on Permanently Flooded Land	0
Closed to Open Medium High Shrubs With Herbaceous Vegetation On Temporarily Flooded Land.	0
Urban and Industrial Areas	10
Bare Rock	0
Bare Soil	0
Rock Debris	0
Glacier	0
Rocky Glacier	0
Perennial Snow	0
Seasonal Snow	0
Non-Perennial Lakes	0
Bare Soil in seasonally flooded area	0
Lakes	0
Rivers	0

Data Sources:

Snow Leopard Habitat Model (Hameed 2016):

- Climate: Temperature Seasonality, Mean Temperature of Wettest Quarter, Annual Precipitation, Precipitation Seasonality (Hijmans et al. 2005)
- Land cover (Loveland et al. 2000)
- DEM, Ruggedness (Lehner et al. 2008, Center for Nature and Society, Peking University, Sappington et al. 2007)
- NDVI (NASA 2014)
- Roads (SLF 2016b)
- Rivers (SLF 2016b)
- Soil (FAO 2003)
- Snow leopard observations (SLF 2016a)

Potential Degradation and Human Influence

- Roads and Settlements (SLF 2016b)
- Land cover Map of the Greater Himalayan Region (FAO 2010)

Other layers for display only:

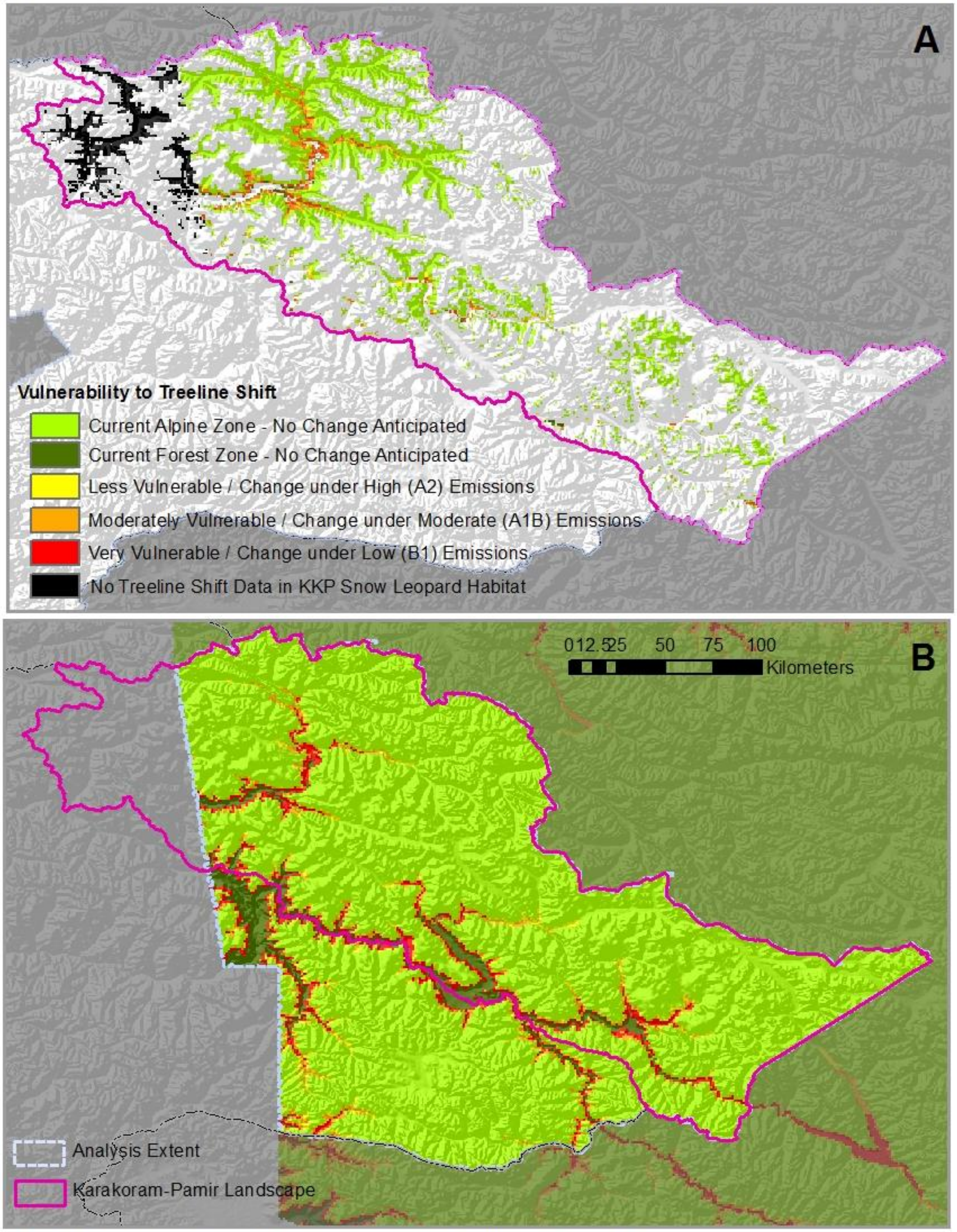
- GSLEP Landscape Boundaries (Government of Pakistan & GSLEP 2017)
- Blue Marble Imagery (NASA, MDA Federal Inc., Digital Globe 2016)

Potential Climate Change Impacts in the Karakoram-Pamir Landscape

The Karakoram Pamir landscape is expected to experience a substantial increase in average annual temperature (+2.2˚C to 3.6˚C by the mid-century time frame of 2041-2070). The highest degree of warming will likely occur during the months of September and October. In addition, warmer temperatures in November and March could shorten the length of winter, snow cover, and the timing of snow melt. Precipitation is also expected to increase slightly, with the greatest percentage increase during the months of October to January (Peters et al. 2017). Potential impacts of these climate changes include changes in grassland communities as a result of shorter winters and hotter and drier summers; loss of permafrost and alpine habitats, changes in water availability, changes in livestock grazing patterns; and increased risk of extreme events such as flooding, landslides, and drought (Climate Smart Snow Leopard Management Planning Workshop, April of 2016).

We selected a few indicators of climate change impacts for mapping in order to better understand the spatial distribution of climate risk for alpine wildlife and human communities. These included the distribution of treeline shift risk in the landscape (or the transition from a climate zone favouring alpine grassland to one favouring forest); potential change in the suitable climate envelope for cropland (indicating changing human habitability, but also human pressure on wildlife habitat); water towers (or water provision to the downstream from rainfall); winter duration (indicated by freeze-line, with implications on ecological functions as well as water availability for people); and change in open water availability (which is a good indicator of overall changes to a landscape). The latter three, and other hydrological functions, are covered in more depth by Sindorf 2017. Note that the latter three analyses are based on an early version of the landscape boundary that is slightly smaller than the current landscape. It excludes some areas along the Khunjerab river and the far eastern edge of the current landscape.

Potential Vulnerability of Snow Leopard Habitat to Climate Change Induced Treeline Shift



Vulnerability of snow leopard habitat to climate-change induced treeline shift.
Map A shows projected change of snow leopard habitat to forest under climate change.
Map B shows projected change in the forest and alpine zones across the analysis extent.

WWF & SLF 2017

This map represents the vulnerability of current snow leopard habitat to climate change-induced treeline shift in the Karakoram-Pamir Landscape. Several future climate scenarios predict a warmer and wetter climate, which may cause treeline to increase in elevation (Forrest et al. 2012). Areas at highest risk of treeline shift are at the lowest elevations and at the southern periphery of the landscape. While only about 12% of current snow leopard habitat is at risk of loss from treeline shift under a high emissions scenario, the habitat likely to be lost would affect a centrally located and relatively intact block of habitat around the Khunjerab river. This loss may have a fragmenting effect in the landscape and contribute to bottlenecks if narrowing swaths of habitat are not adequately managed. It is worth noting that treeline shift data is available for 88% of the landscape – we lacked data for the westernmost habitats.

While models suggest that treeline shift may affect a relatively small percentage of habitat in the landscape (though with a potentially fragmenting effect to the broader area), the remaining habitat in the landscape is not without risk under climate change. Climate projections anticipate warmer and drier growing seasons (Peters et al. 2017), which are not conducive to tree growth, but are also not conducive to overall productivity. This may negatively affect wildlife populations outside of high risk areas for treeline shift.

Data Sources:

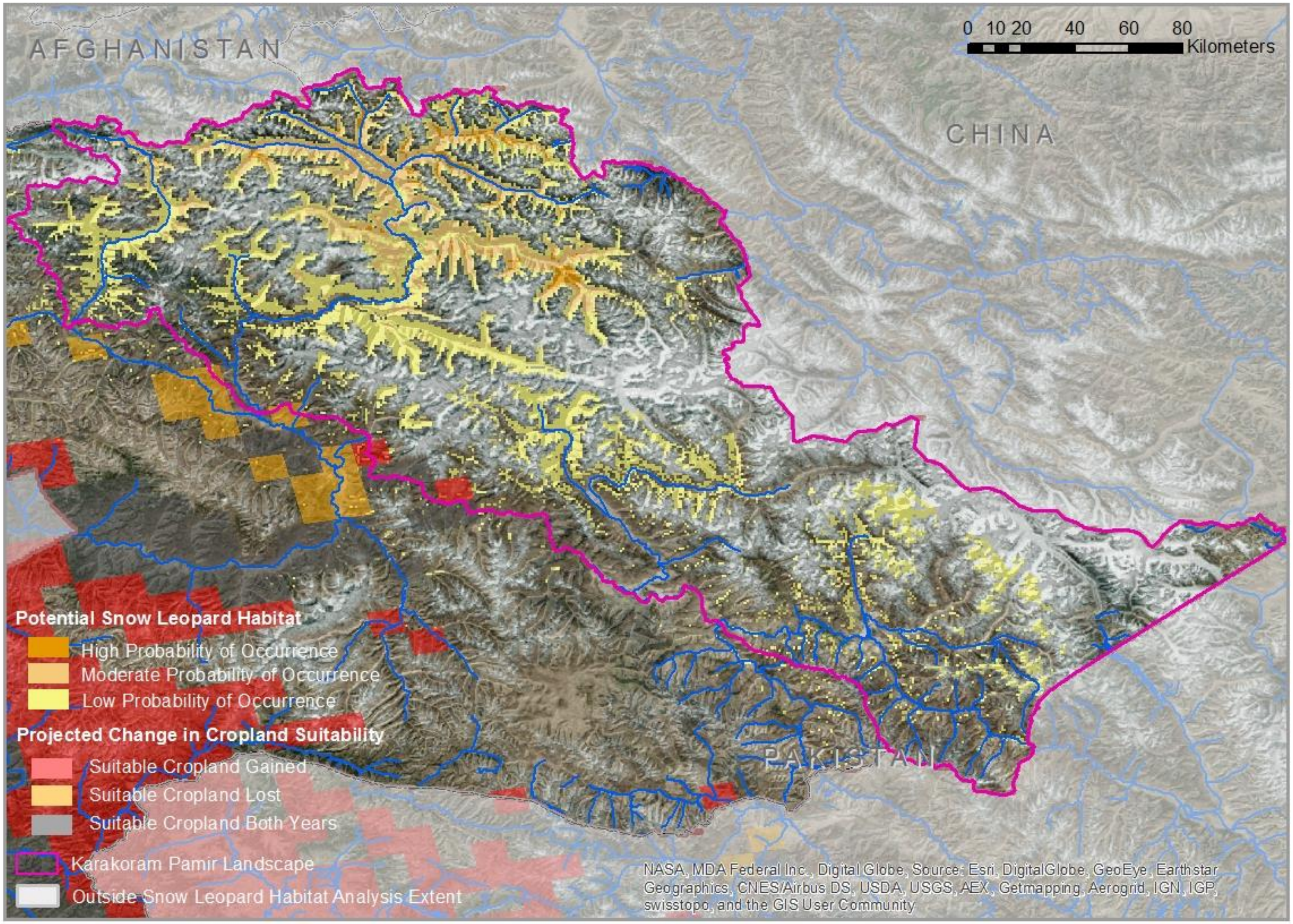
Snow Leopard Habitat Model (*Hameed 2016):*

- Climate: Temperature Seasonality, Mean Temperature of Wettest Quarter, Annual Precipitation, Precipitation Seasonality (Hijmans et al. 2005)
- Land cover (Loveland et al. 2000)
- DEM, Ruggedness (Lehner et al. 2008, Center for Nature and Society, Peking University, Sappington et al. 2007)
- NDVI (NASA 2014)
- Roads (SLF 2016b)
- Rivers (SLF 2016b)
- Soil (FAO 2003)
- Snow leopard observations (SLF 2016b)

Snow leopard landscape boundary (Government of Pakistan & GSLEP 2017)

Projected Change in Treeline under Climate Change: Forrest et al. 2012 and Sindorf et al. 2014

Projected Change in Cropland Suitability under Climate Change near the Karakoram-Pamir Landscape



Projected change in climate suitability for agricultural crops under a high emissions (A2) scenario to the year 2100. *WWF & SLF 2017*

This map shows current climate envelope for arable land (or croplands) and potential change in this niche under a high emissions climate change scenario. These results suggest that in this landscape, "encroachment" of suitable climate niche for arable land into the snow leopard range may not be a major concern. Arable land is likely to generally increase in the basin south of the Karakoram-Pamir landscape. This means that pressure on water originating in snow leopard habitat may increase, particularly along the Khunjerab/Hunza/Gilgit River. This emphasizes the need for snow-leopard friendly water management practices and planning.

The map of current climate suitability for arable land was projected using the Global Arable Lands database (Ramankutty et al. 2008) as observations, and 19 bioclimatic variables (Hijmans et al. 2005) as environmental layers. It was then projected under a high emission scenario (A2A) using the HADCM3 General Circulation Model to the year 2100. This model extent includes the entire snow leopard range, though only the portion encompassing the Karakoram-Pamir landscape is displayed here (Sindorf et al. 2014).

Data Sources

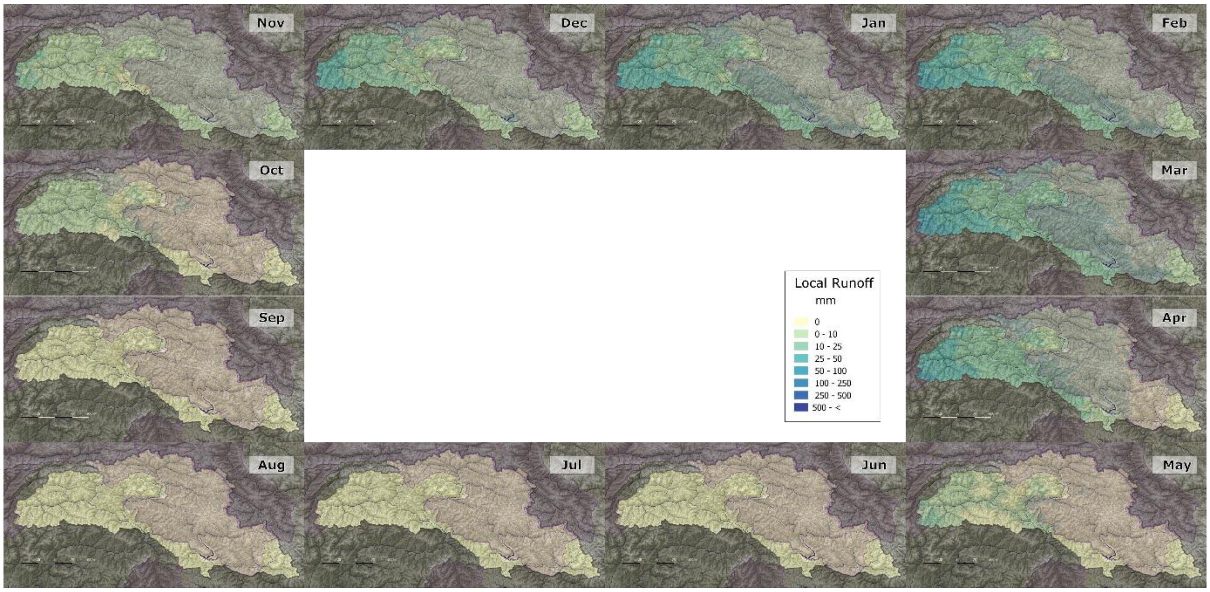
Snow Leopard Habitat Model (*Hameed 2016):*

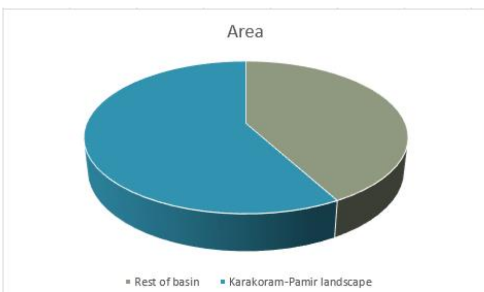
- Climate: Temperature Seasonality, Mean Temperature of Wettest Quarter, Annual Precipitation, Precipitation Seasonality (Hijmans et al. 2005)
- Land cover (Loveland et al. 2000)
- DEM, Ruggedness (Lehner et al. 2008, Center for Nature and Society, Peking University, Sappington et al. 2007)
- NDVI (NASA 2014)
- Roads (SLF 2016b)
- Rivers (SLF 2016b)
- Soil (FAO 2003)
- Snow leopard observations (SLF 2016a)

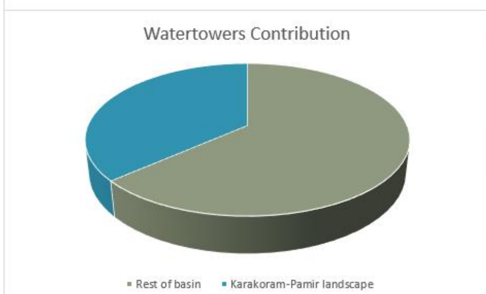
Snow Leopard Landscape Boundary (Government of Pakistan & GSLEP 2017)

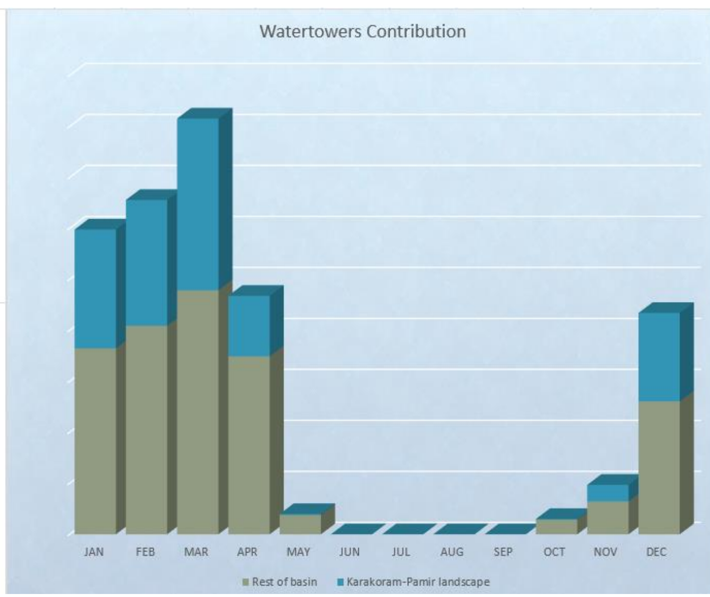
Projected Change in Cropland Suitability: Sindorf et al. 2014

Water Towers (Local Runoff) in the Karakoram-Pamir Landscape and Sub-basin









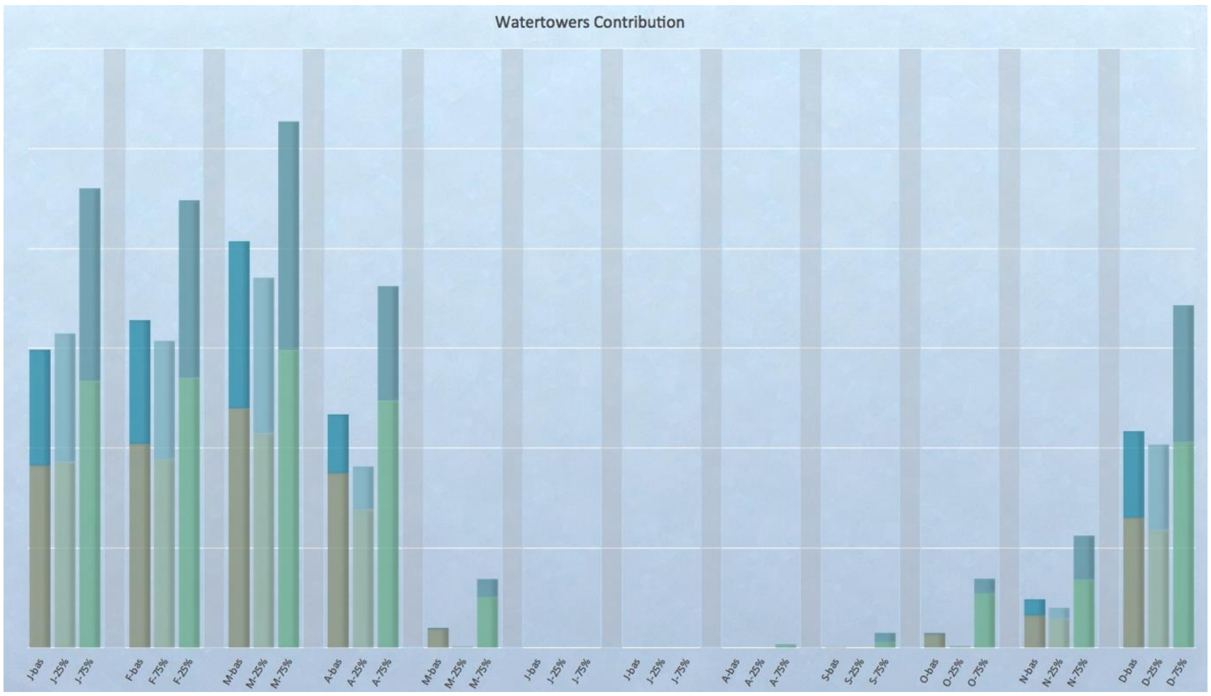
Water Towers / Local Runoff	
Baseline Conditions	By area, the landscape covers 58% of the subbasin, yet it only provides 36% of the subbasin's local runoff. Since the landscape produces less run-off than its surroundings, it does not serve as a water tower to the rest of the sub-basin.
Projected Climate Change	Under low-precipitation projections, not much is going to change in terms of water balance. Under the high-precipitation scenario, an extra 35% precipitation is expected, particularly during the winter months. Much of this would accumulate as snow. There would thus be a delay in the timing of run-off and perhaps larger amounts of snowmelt during the early spring.

This analysis compares the amount of run-off from precipitation that originates in the Karakoram-Pamir landscape with that of the rest of the sub-basin under baseline and future climate scenarios (Sindorf 2017).

The majority of precipitation in this landscape occurs during the winter to early spring months of November to April. Much of this water accumulates as snow and runs off during the late spring and summer. There is little precipitation in the summer months, and no local runoff generation from rain when water demands for people and crops are at their highest (also see Figure 4.1). This model does not represent the timing of run-off (such as from snowmelt), only the total amount of run-off that would occur with varying delay based on the temperature. Winter precipitation and subsequent run-off may increase in this landscape under a changing climate (Peters et al. 2017, Figure 4.1), which may contribute to more water availability or flooding during the spring and summer months.

Figure 4.1. Projected change in the relative water tower function of the Karakoram-Pamir Landscape compared with the rest of the landscape under baseline and future precipitation scenarios

A



B

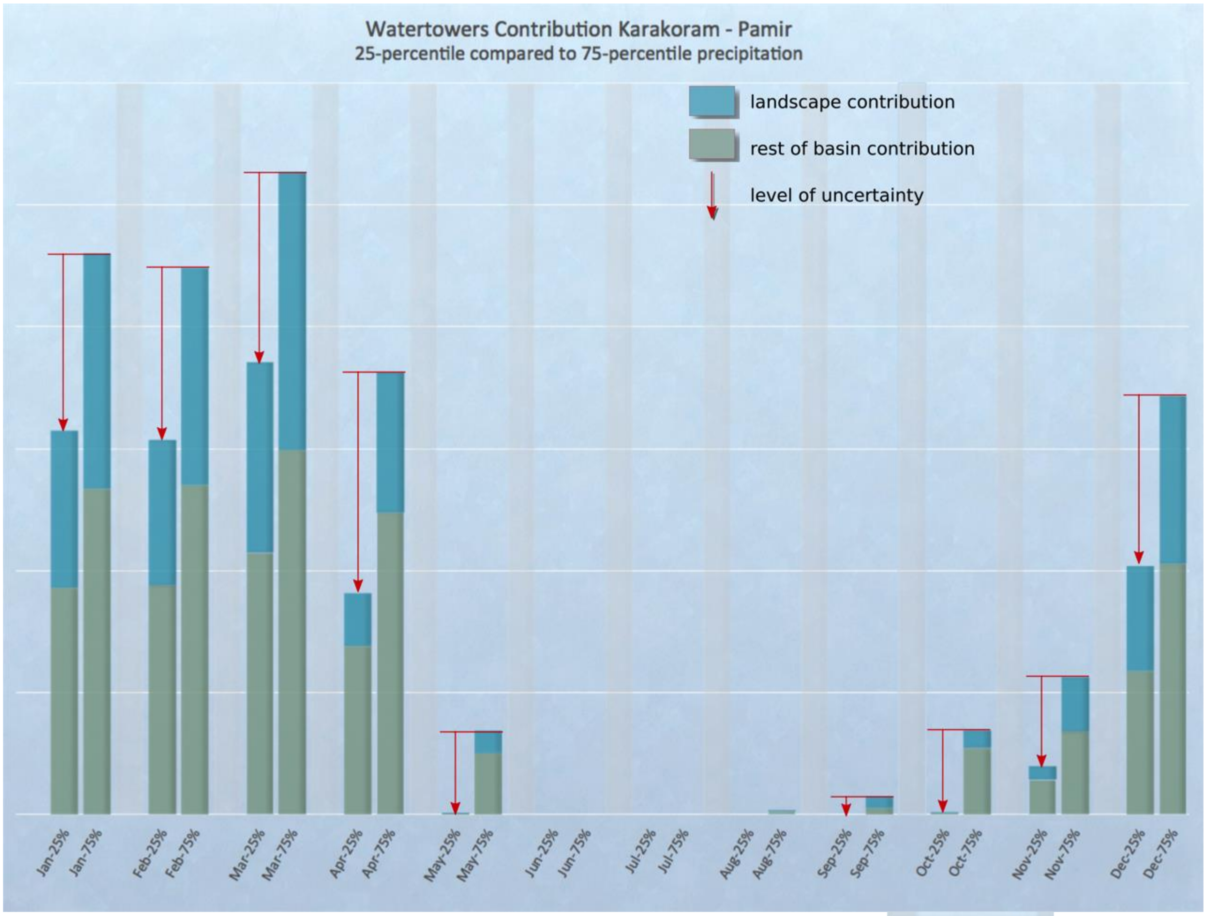


Figure 4.1A shows relative water tower contributions of the Karakoram-Pamir Landscape compared with the rest of the sub-basin under baseline year and 25-percentile and 75-percentile mid-century precipitation projections (Peters et al. 2017, Sindorf 2017). Figure 4.1B compares the relative water tower contribution of the landscape with the rest of the sub-basin under low and high mid-century precipitation projections, and also expresses the range of uncertainty. Relative run-off from the landscape is represented by the blue color at the top of each bar, while run-off from the rest of the sub-basin is represented by the bottom portion of the bars. Red arrows show the range of changes in runoff based on the two projections, and therefore illustrates uncertainty in future climate impacts on runoff.

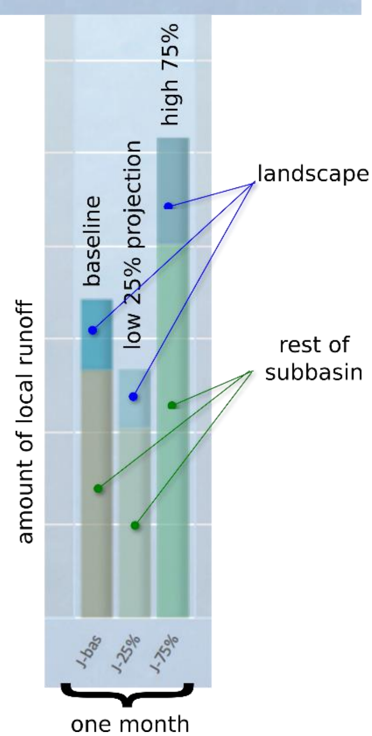


Figure 4.1 indicates that water towers under a low-precipitation climate change projection should not vary drastically from the baseline. Under a high-precipitation model, water for local run-off is likely to increase throughout the sub-basin, though usually not affecting the relative role of the landscape with that of the sub-basin. Projected change for the month of May might increase the duration of the runoff-generation season a little bit. There is a high degree of variation between low- and high-precipitation projections in all but the driest months (June to September). It is worth noting that under the high precipitation scenario, local runoff from the landscape may increase by 64% compared with baseline amounts, despite the fact that precipitation is expected to increase by about half that (35%). This is because projected evapotranspiration is not expected to increase at the same rate as precipitation.

For more information on methods used for this analysis, please see Sindorf 2017.

Data sources:

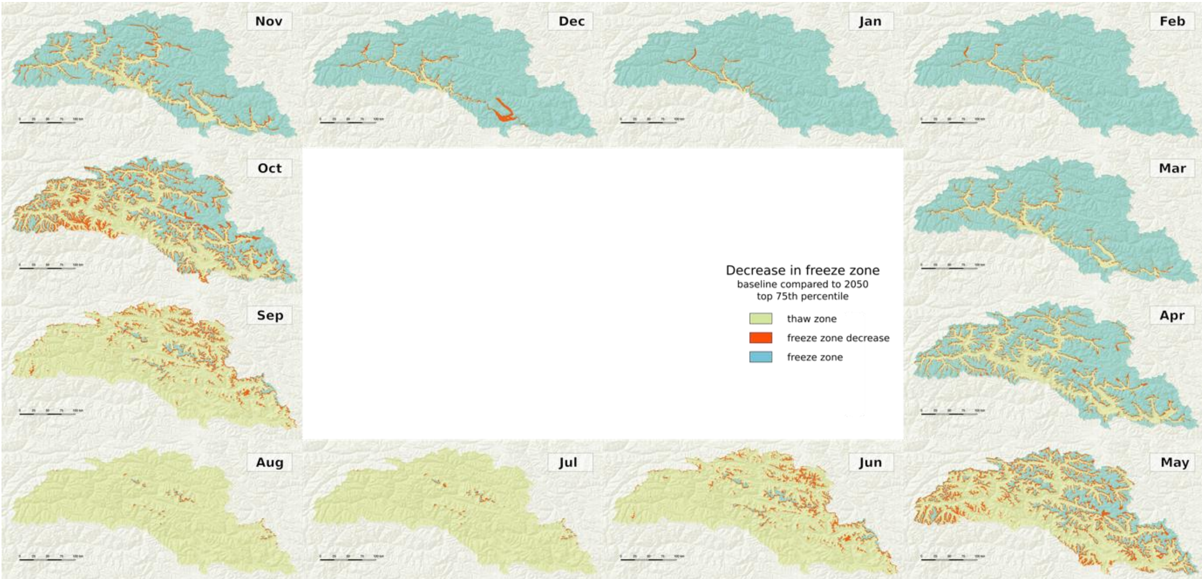
Current Mean Monthly Precipitation, based on historic WorldClim, 30s resolution (Hijmans et al. 2005)

Current Mean Monthly Actual Evapotranspiration, based on historic Global Soil-Water-Balance, CGIAR, 30s resolution (Trabucco and Zomer 2010)

HydroBASINS, level 12, ~100 km^2 watershed outlines (Lehner and Grill 2013).

Climate Projections on future temperatures and precipitation (Peters et al. 2017).

Decrease in Monthly Freeze Extent under Temperature Rise in the Karakoram-Pamir Sub-basin



Calendar months of freeze-loss

Snow cover, Frozen Ground and Freeze Line	
Baseline Conditions	Freeze line is fragmented and shows a very long circumference throughout the year, suggesting that changes under temperature rise will have very significant impacts throughout the sub-basin and downstream.
Projected Climate Change	The freeze-line runs through the landscape during all months 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 from current freezeline. But, since it surrounds historically snow-covered mountaintops in summer, such shifts can mean dramatic change.

The above maps illustrate for each month how the spatial footprint of the freeze frontier is expected to change under projected temperature rise to mid-century. The freeze line is an indicator of the average timing of snowfall and snowmelt, glacial melt, permafrost coverage and depths, and subsequent water availability. It is also an indicator of phenological processes such as the timing of green-up and leaf-fall, breeding and birthing, and animal movements. Seasonal changes can selectively impact some species, ultimately affecting the composition of vegetation and animal communities in the landscape.

In general, the projected change in freezeline moves upslope of the current freeze frontier. Projected changes are within the range of a few hundred meters to a few kilometers. For mountaintop snow cover and glaciers, the impact of May and October changes may be particularly dramatic. In addition, it is during these months that the southwest corner of the subbasin (though outside the landscape) would experience a disproportiate amount of loss in freezing conditions. These areas have little 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, leading to earlier spring melting and later arrival of winter, which would indirectly result in a changed hydrological regime towards the downstream (Sindorf 2017).

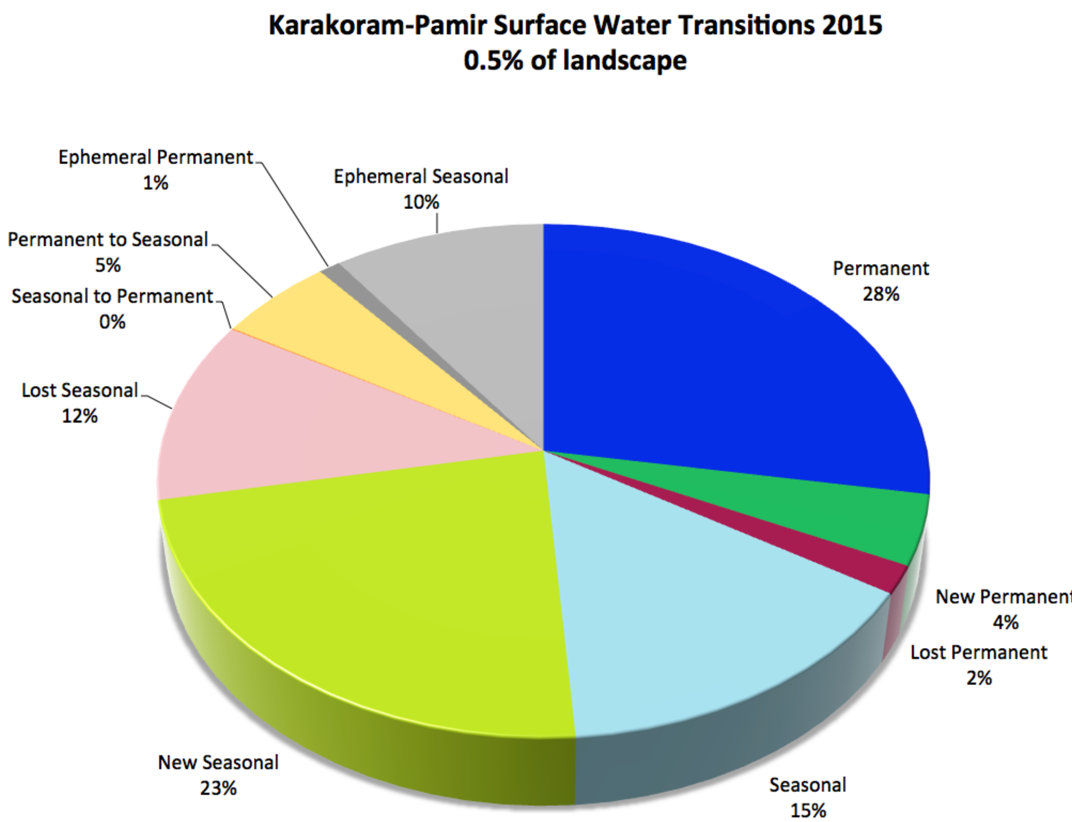
For more information on methods, please see Sindorf 2017.

Data sources:

Current Mean Monthly Temperatures, based on historic WorldClim, 30s resolution (Hijmans et al. 2005)

Climate Projections on future temperatures and precipitation (Peters et al. 2017).

Observed Surface Water Transitions (1984-2015) in the Karakoram-Pamir Sub-basin



Lakes, Wetlands, and Floodplains	
Baseline Conditions	The majority of open water in the landscape is associated with the active Indus and Shigar floodplains. There are also numerous small lakes, directly downstream from glaciers and snowfields.
Observed Historic Change (1984-2015) and Anticipated Climate Impacts	The surface water database registers an increase in the area of many small lakes in the landscape from 1984-2015. Yet, the largest shifts that do occur might mainly be shifting floodplains, where increase- is largely balanced out by a decrease of surface water. As snowfall increases in parallel with snowmelt, it is likely that the size and number of glacial lakes and floodplains directly downstream of the seasonal snowfields and glaciers will increase.

Inside the landscape, only 0.5% of the area is classified as open surface water (Pekel, 2016). 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 are largely due to changes in the open surface waters located around the very active Indus and Shigar floodplains that are fed mainly by snow and glacial melt.

Figure 4.2 Change in Surface Water Area by Elevation in the Karakoram-Pamir Landscape (1984-2015)

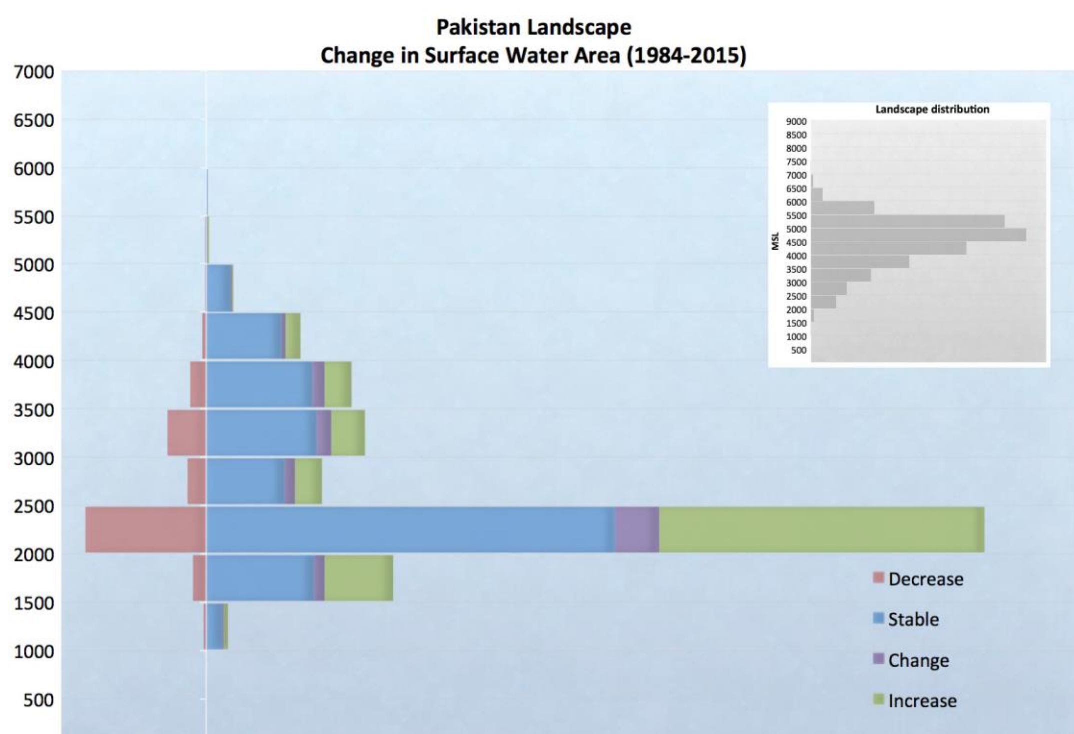


Figure 4.3 indicates that the 2,000-2,500 msl elevation band contains the largest amount of surface water area. This is disproportionate to the overall landscape distribution of elevations, as per the inset. It is also below the mean elevation of snow leopard habitat. It is very likely that this elevation band includes the floodplains of the tributaries that feed into the Indus, with large glaciated areas directly upstream. The transitions at this elevation are dramatic, which might be related to dynamic shifts 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, but expanding coverage of the landscape
- An increase in water is coming in from upstream, which might be from glacial melt or increased precipitation
- Dams or reservoirs have been constructed and the reservoir filled in the period 1984-2015, which is unlikely to have occurred at this elevation

Above 2,500 m, the increase in surface water in some places is balanced with decreases in others. This indicates a shift of location of open surface water in the landscape, but not necessarily in the overall amounts of water. The water at the high elevations coincides with small lakes fed largely by snow- or glacial melt (Pekel et al. 2016, Messager et al. 2016, Google Earth). Many of these pose a risk of GLOFS. The graph depicts surface water *areas* and *not volumes* of water, so increases or decreases in water storage may be masked by the depth of water bodies.

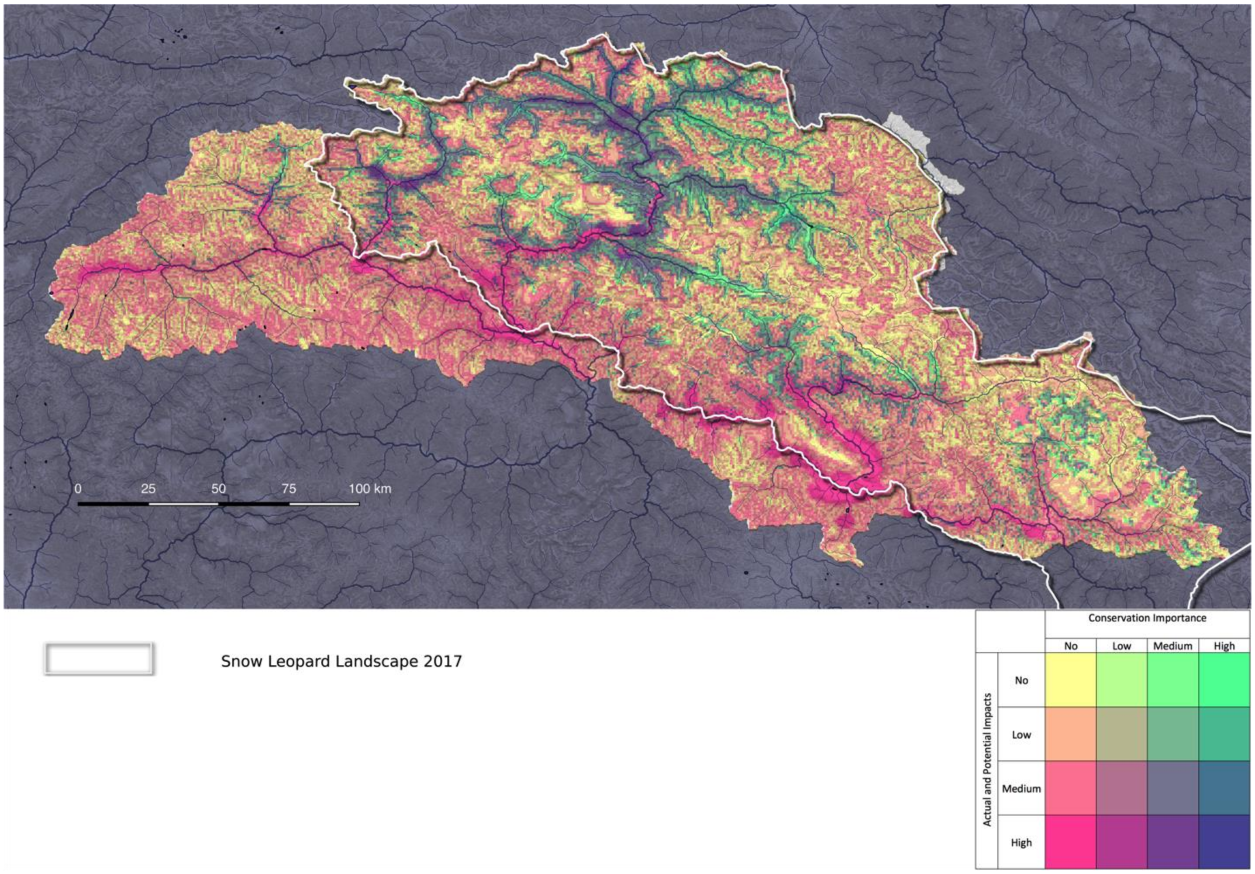
Please see Sindorf 2017 for more information on methods used for this analysis.

Data sources:

High-resolution mapping of global surface water and its long-term changes (Pekel et al. 2016)

HydroLAKES (Messager et al. 2016)

Summary of Conservation Importance and Potential Impacts in the Karakoram-Pamir Landscape



This map displays the landscape according to conservation importance and actual and potential impacts. Conservation importance is represented by habitat suitability for snow leopards. Actual and potential impacts are represented by the expected severity of climate change impacts and human impacts. As shown, the area of highest conservation importance and impact (dark blue) is along the Khunjerab river corridor. Areas of high conservation importance but lower impact (in lighter blue and bright green) are located upstream along its tributaries. But, these areas will become fragmented if the more impacted area along the river is not conserved.

Methodology

This summary maps combine different analyses of the overall quality and condition of the landscape, using a consistent approach across different snow leopard landscapes. Conservation importance was represented by habitat suitability for snow leopards. Actual and potential impact from future climate change was represented by the predicted loss in number of winter months (ie, freezeline loss). Actual and potential impact from human impacts was represented by the human footprint.

For each of the input layers, scores were discussed with field experts and assigned as presented in Table 4.5. The values in the tables correspond with the ‘raw’ values that are used for each of the analysis in the GIS. The qualitative scores of conservation importance and actual and potential impacts were then combined into a single map with 16 different combinations.

Table 4.5A. Conservation Importance Weights

Score	Habitat Suitability
0	0
1	
2	
3	
4	
5	
6	3
7	2
8	1

Table 4.5B. Actual and Potential Impacts Weights

Score	# Months Freeze Loss	Human Footprint
0	0	0
1		
2	1	1-5
3		
4	2	6-10
5		
6	3	
7		
8		>11

Combined scores: No: 0; Low: 1-3; Medium: 4-7; High: >8

VI. Analysis and Mapping of Snow Leopard Habitat in the South Gobi Landscape, Mongolia

September 20, 2017

Jessica Forrest[1], Nikolai Sindorf[1], Koustubh Sharma[2]

World Wildlife Fund[1] and the Snow Leopard Secretariat[2],
with funding from the United States Agency for International Development

Chapter 6 of 6 of the report:

Guardians of the Headwaters, Volume 2:
Biodiversity, Water, and Climate
in Six Snow Leopard Landscapes

Key Findings and Management Recommendations

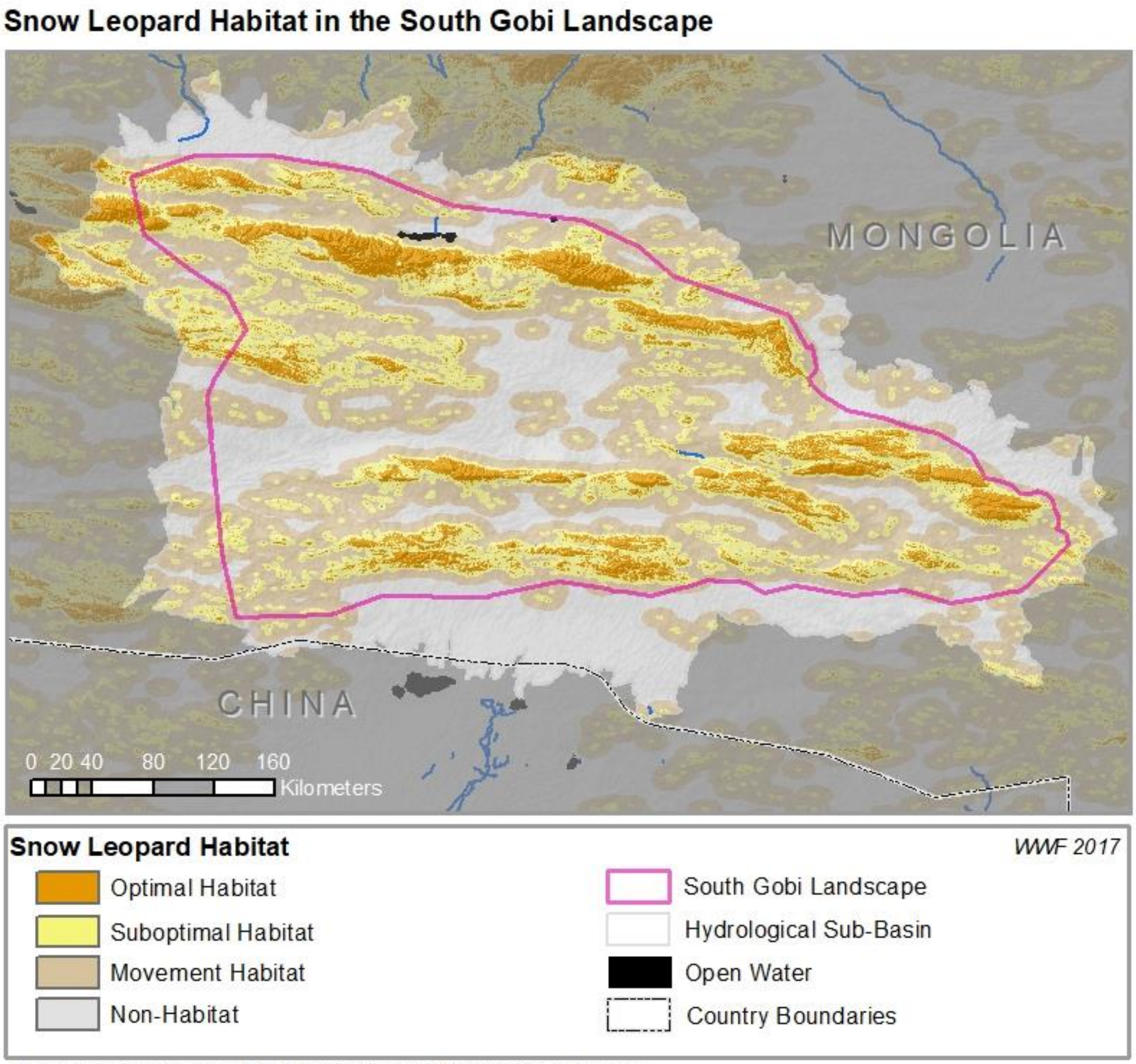
- **The South Gobi landscape is one of the largest landscapes in the snow leopard range, with over 63,000 km^2 of habitat.** While vast in area, the South Gobi landscape has very limited water availability and this impacts grassland productivity and wildlife population densities. Thus, vast areas are necessary to support adequate populations of prey and snow leopards. The habitat of this landscape consists of a mosaic of rugged, elevated "core" habitat areas interspersed by more homogenous, flat areas that snow leopards move across. Habitat in this landscape connects to other habitats in Mongolia, and to habitat in China to the south.

- **Protect key unprotected habitat areas.** There are two protected areas in the landscape: Gobi Gurban Saxan and Ix Bogd Uul National Conservation Parks. While these two parks protect large core habitat areas, some key habitats remain unprotected, particularly on the eastern side of the landscape connecting the two protected areas. These habitats may not be at high risk currently due to transient human populations, but impacts may increase in the future if people begin to adopt more intensive or longer-term land uses, particularly in response to a slightly wetter climate. The designation of snow leopard focused management areas or corridors linking existing protected areas should help to preserve metapopulation connectivity in the landscape.

- **Nomadic lifestyles are supportive of metapopulation connectivity, as long as key sources of conflict with snow leopards are kept in check.** Human presence in this landscape is relatively transient, as people live a nomadic lifestyle and the few existing roads are infrequently travelled. Key threats include livestock overgrazing and grassland degradation, livestock kills by snow leopards, and retaliatory killings of snow leopards by local people. Compensation programs for taken livestock can be helpful to prevent killings, and alternate livelihood strategies can keep livestock numbers in check. Both of these strategies have been pioneered in this landscape (Bayarjargal 2012). The formation of permanent settlements and roads, if poorly managed, may lead to habitat degradation and disrupt connectivity.

- **Climate forecasts suggest that the South Gobi Landscape will become warmer and wetter, but impacts on snow leopards and their prey are difficult to predict.** For example, historical data indicates an increase in open water and net primary productivity in the rugged areas of the northern and eastern parts of the landscape. This may work to the benefit of the snow leopard if the trend continues; as long as it doesn't favor natural competitors, or human competition for the same land for livestock grazing or crop production. Climate envelope predictions are more severe, indicating that a vast area of snow leopard habitat in this landscape will be lost, except for habitats in the northwest of the landscape around Ix Bodg Uul. Permafrost plays an important role in key habitat areas, and melt under climate change could imply habitat loss. **To anticipate changes, it is advisable to protect habitat connectivity throughout the landscape, with particular attention on the potential microrefugia in the vicinity of Ix Bogd Uul. Since areas to the northwest of the South Gobi may also remain relatively resilient under climate change, maintaining trans-landscape connectivity to the northwest could be important.**

Because future climate change impacts are uncertain, monitoring and adaptive management throughout the landscape will be important.



Potential snow leopard habitat in the South Gobi Landscape.

This map shows potential snow leopard habitat of the South Gobi Landscape. There is an estimated 68,310 km^2 of potential snow leopard habitat in the South Gobi Landscape of Mongolia. Of this, 11,550 km^2 is classified as optimal habitat, 22,380 km^2 is classified as suboptimal habitat, and 34,380 km^2 is classified as movement habitat. 13,380 km2 is classified as non-habitat. Potential habitat ranges in elevation from 750 to 3,950 m.

This model represents expert opinion about snow leopard habitat use in the South Gobi. In this landscape, snow leopards tend to gravitate toward rugged, elevated mounts which provide shelter and viewpoints from which to observe prey. Snow leopards move frequently between mounts that are close together (2-3 km). But, they can also move long distances with less frequency but as needed (15-40 km in a day). Based on this knowledge, we produced the following definitions.

- **Optimal habitat:** Rugged areas that are best for snow leopards because they include adequate shelter for breeding and raising young, and rugged mounts from which to target prey. We defined rugged areas as those areas where Terrain Ruggedness Index (TRI) > 270. TRI was generated from a 90-m void-filled DEM, based on a 3x3 pixel neighborhood (Riley et al. 19999, Lehner et al. 2008). This threshold was selected because it overlay well with snow leopard observations (ISLT et al. 2008). It also coincided with a snow leopard habitat prediction generated through this study with a maxent model (Phillips et al. 2006) based on slope, ruggedness and DEM (Lehner et al. 2008) and snow leopard observations (ISLT et al. 2008).

- **Suboptimal habitat**: Connects optimal habitat patches located up to 3 km apart

- **Movement habitat:** Connects optimal habitat patches located up to 15 km apart

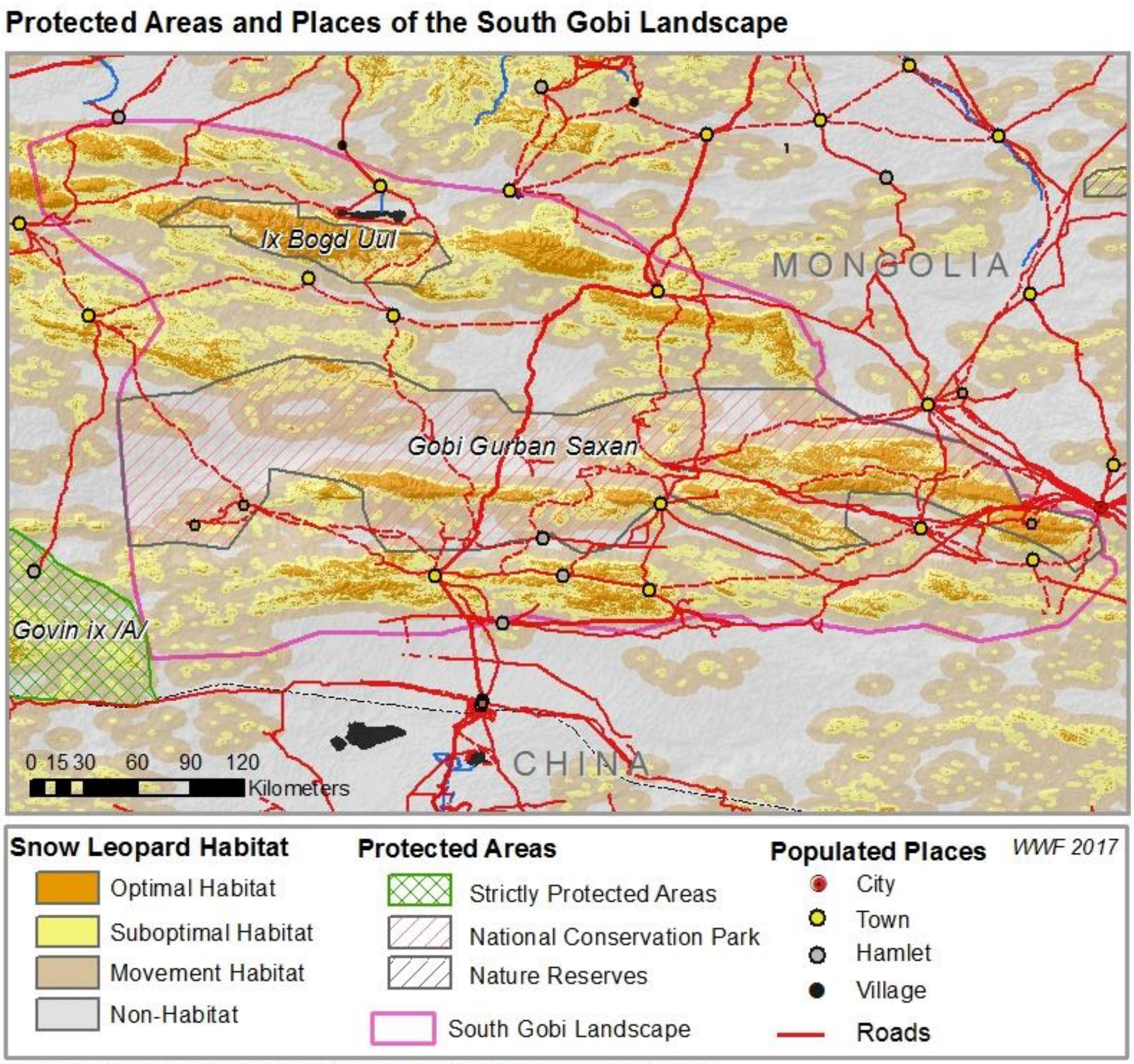
Data Sources:

Snow Leopard Habitat Model:

- DEM, Slope (Lehner et al. 2008)
- Terrain Ruggedness Index (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (ISLT et al. 2008)

Other Data:

- GSLEP Landscape Boundaries (GSLEP 2016)
- Hydrological sub-basin boundaries (derived from Lehner et al. 2008)



Protected areas and places of the South Gobi Landscape, Mongolia.

Protected areas cover over 22,600 km^2 or 33% of potential snow leopard habitat in the South Gobi Landscape in two national conservation areas: Gobi Gurban Saxan and Ix Bogd Uul. Core habitat areas are best represented in the protected area network, with 45% of optimal habitat protected. Approximately 30% of suboptimal habitat and movement habitats are also protected. Gobi Gurban Saxan is much larger than Ix Bodg Uul. It protects nearly 10 times more habitat than the smaller protected area to the north. However, the habitat in Ix Bogd Uul is primarily optimal habitat, so it is nonetheless a valuable protected area for snow leopards (Table 6.1). This habitat is also projected to remain more resilient to climate change than the protected area to the south.

A vast area of snow leopard habitat remains unprotected in this landscape (over 45,000 km^2). This extent is many times more than the total area of habitat in most other snow leopard landscapes. Currently, humans that reside in the landscape live transient lifestyles with low impacts, so these unprotected habitats may not be at high risk. However, if the level of human impact should intensify in the future (perhaps in response to a more favorable climate) with the development of more permanent roads, settlements, and associated land uses, the unprotected zones may be at higher risk of fragmentation. For this reason, it is important to manage the unprotected zones on the eastern edge of the landscape for habitat connectivity between the two conservation areas.

Table 6.1. Protected Habitat Area in the South Gobi Landscape, Mongolia

Protected Area Name	Snow Leopard Habitat Area (km^2)			
	Optimal	Suboptimal	Movement	Total
Gobi Gurvan Saixan	3,701	5,739	10,559	19,999
Ix Bogd uul	1,534	900	188	2,622
Total	**5,235**	**6,639**	**10,747**	**22,622**

Data Sources for Snow Leopard Habitat Model:

- DEM, Slope (Lehner et al. 2008)
- Terrain Ruggedness Index (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (ISLT et al. 2008)

Other layers for display only:

- GSLEP Landscape Boundaries (GSLEP 2016)
- Hydrological sub-basin boundaries (derived from Lehner et al. 2008)

Human Landscape:

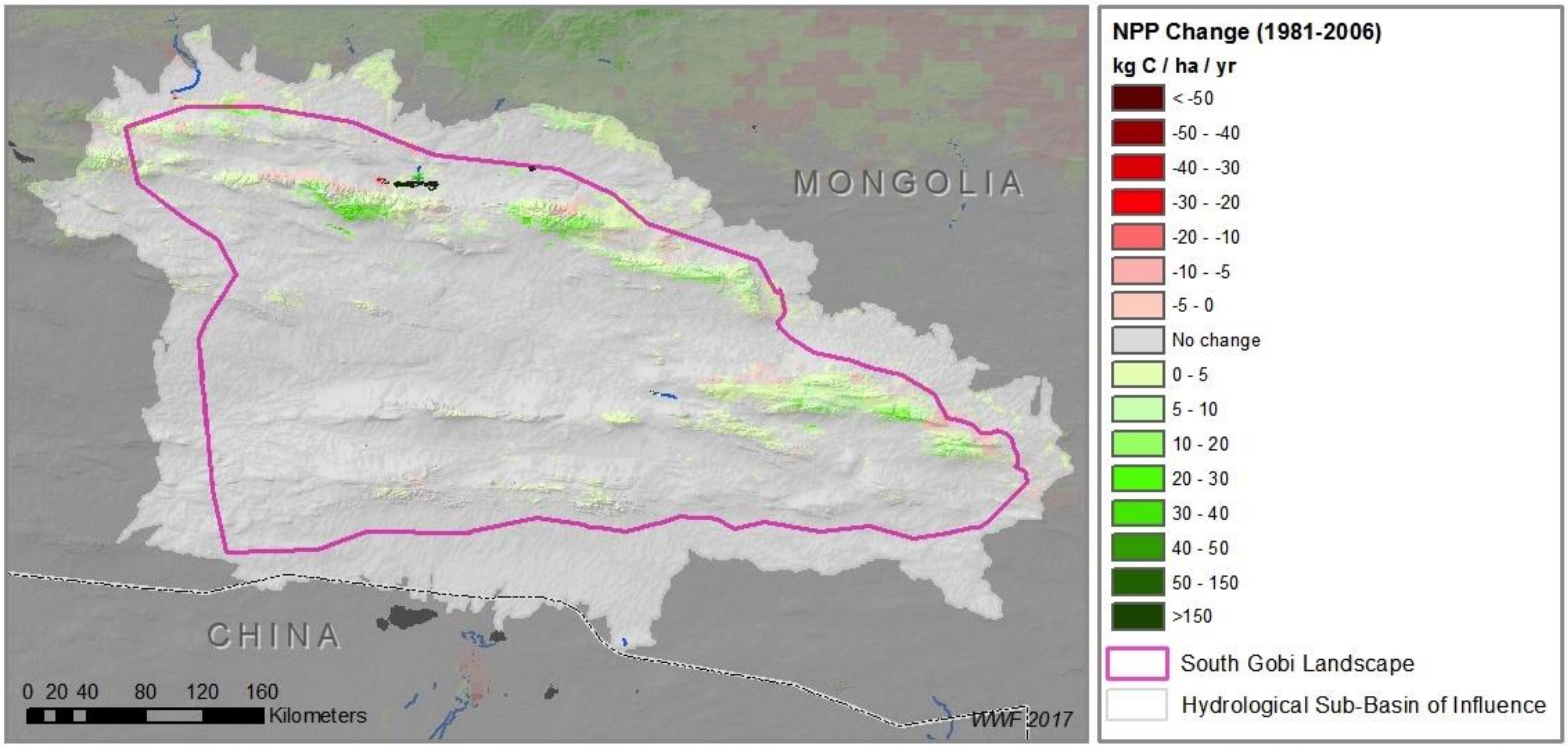
- Protected Areas (Mongolia MoEGD 2016)
- Populated Places (OpenStreetMap 2017)
- Roads (OpenStreetMap 2017)

Potential Climate Change Vulnerability in the South Gobi Landscape, Mongolia

The South Gobi landscape is expected to experience a substantial increase in average annual temperature compared with the current time period (+2.0˚C to 3.3˚C by the mid-century time frame of 2041-2070). The warmest months of the year are expected to experience greater warming than the cold months, extending the length of the growing season. Precipitation in this desert landscape is already extremely minimal, and falls mainly during the summer. Precipitation is expected to increase slightly (by 12-18% by mid-century), and this increase will also occur primarily during the summer months (Peters et al. 2016). Potential impacts of these climate changes include melting permafrost and increased slope instability, potentially greater plant productivity, changing grassland communities with potential changes in palatability for livestock and wild ungulates; habitat encroachment by people; and an increasing frequency and/or intensity of winter dzud storms, floods and droughts (Climate Smart Snow Leopard Management Planning Workshop, April of 2016, Peters et al. 2016).

Here, we assessed several indicators of climate change impacts in order to better understand the spatial distribution of climate risk for alpine wildlife and human communities. These included historical net primary productivity change to detect evidence of recent climate trends; potential change in the climate envelope for snow leopards (indicating climate suitability for snow leopards); and potential change in the suitable climate envelope for cropland (indicating changing human habitability, but also human pressure on wildlife habitat). We also looked at patterns of mean annual precipitation, snowfall, snowmelt, permafrost, and observed trends in surface water availability to frame baseline conditions in water availability in the landscape and to indicate potential future vulnerabilities. These hydrological functions are covered in more depth by Sindorf 2017.

Trend in Net Primary Productivity in the South Gobi Landscape (1981-2006)



This map demonstrates average trend in net primary productivity (NPP) in the South Gobi landscape. While most of the landscape experienced a stable NPP over time, the large rugged areas of the north generally experienced a slight increase in NPP. The northern sides of these rugged areas, however, tended to experience a decrease in NPP over time. Decreasing NPP may be an indicator of potential degradation (Data source: Bai et al. 2008).

Historical Net Primary Productivity (NPP) change (1981–2006) was used as a proxy to look at a) broad-scale evidence of potential degradation, and b) evidence of climate change impacts[5]. Here, we note a historical trend towards increasing NPP in the elevated rugged areas of the South Gobi landscape, which are also optimal snow leopard habitats. This may indicate a trend toward a warmer and wetter climate that favors plant productivity. There are small areas of decreasing NPP on the northeastern slopes of the rugged areas, probably also climatically driven.

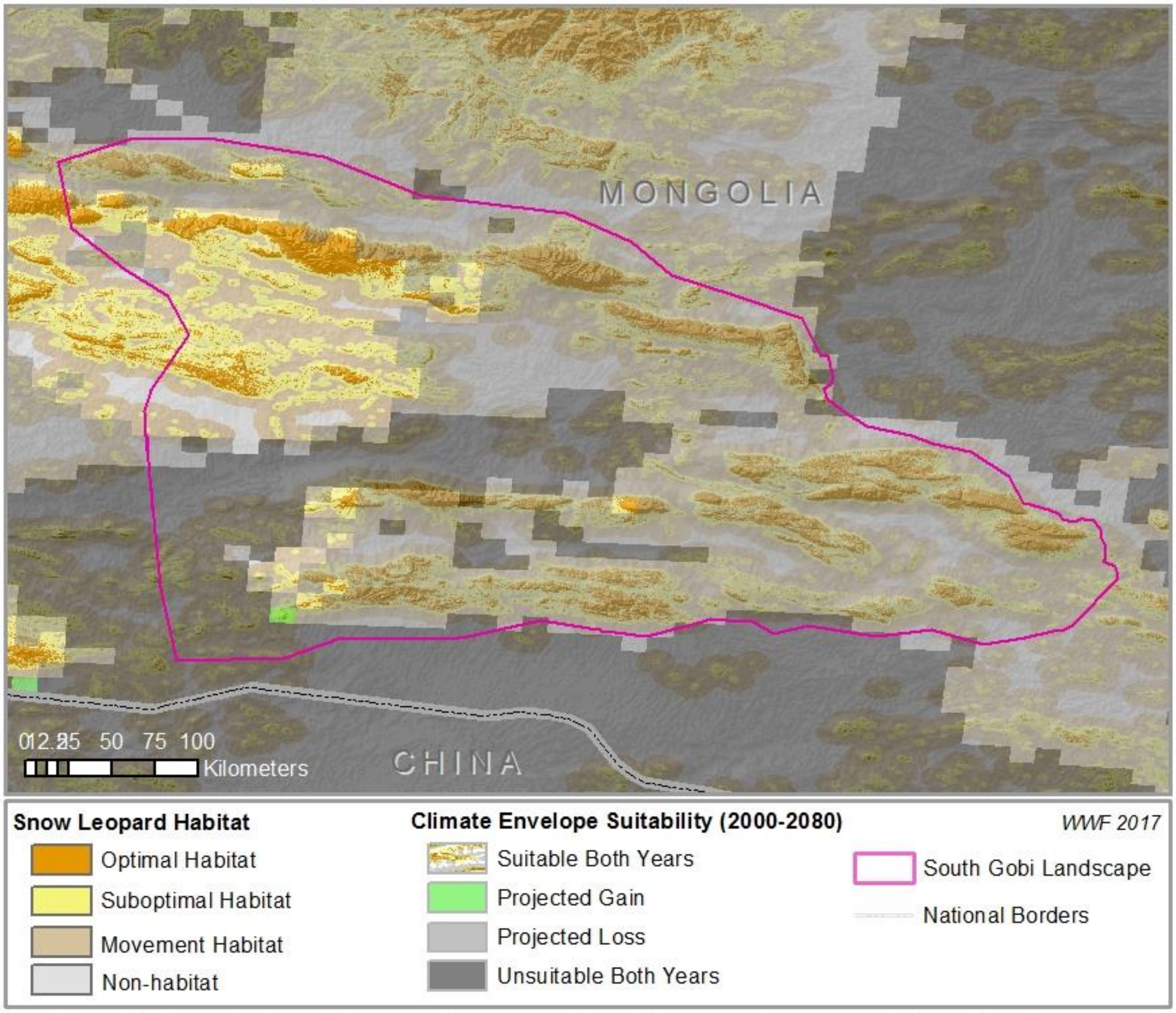
We used NPP to detect potential degradation in the South Gobi rather than developing a human footprint model. This is because humans in the South Gobi follow a traditional, nomadic lifestyle in this landscape; settlements tend to be transient and roads infrequently travelled. The spatial locations of human impact are quite variable on an annual basis, and this is believed to generate a relatively homogeneous impact over several years. Thus, the human footprint model may not be appropriate for detecting or predicting human impact in this landscape.

Data sources:

Net Primary Productivity Change (1981-2006) (Bai et al. 2008)

[5] Decreases in NPP may indicate increasing aridity in the landscape, overgrazing by livestock or wild ungulates, or shifts in plant communities. Increases in NPP, alternately, may be linked to changing climate conditions favoring plant growth (precipitation, longer length of growing season), and /or changes in plant communities as a result of grazing or invasive species.

Potential Climate Envelope Shift for the Snow Leopard in the South Gobi Landscape



This map overlays a fine scale model of current snow leopard habitat in the South Gobi Landscape of Mongolia with a regional model of potential shift in snow leopard climate envelope under a HADCM3 A2A scenario. The model predicts that nearly all of the existing suitable climate envelope for snow leopards in the landscape will disappear by the end of the century due to global climate change; with the exception of an area in the northwest portion of the landscape that may remain as a macrorefugia.

This map represents the potential change in suitable climate space for snow leopards in the South Gobi landscape. The analysis shows that much of the existing climate envelope for snow leopards will disappear by the end of the century, with the exception of a potential macrorefugia in the northwestern area of the landscape. This model does not show microrefugia that may exist as a result of local climate conditions. The advent of a slightly longer and wetter growing season may explain this trend, if it favors competitors to the snow leopard. Since the precise nature of changes are uncertain and in case this model overpredicts the potential for climate envelope loss in this landscape, monitoring and adaptive management are recommended.

Methodology

We display a regional model of snow leopard climate envelope shift under a high greenhouse gas emissions scenario (HADCM3 A2A) from the current time (1950-2000) to the 2080's based on 19 bioclimatic variables (Hijmans et al. 2005, Sindorf et al. 2014). A climate envelope represents the necessary climate conditions for a given species to exist. Suitable climate space (or climate envelope) for snow leopards can also be suitable habitat, provided that other environmental factors-such as ruggedness, presence of prey, low human impact-are also favorable.

Data Sources for Snow Leopard Habitat Model:

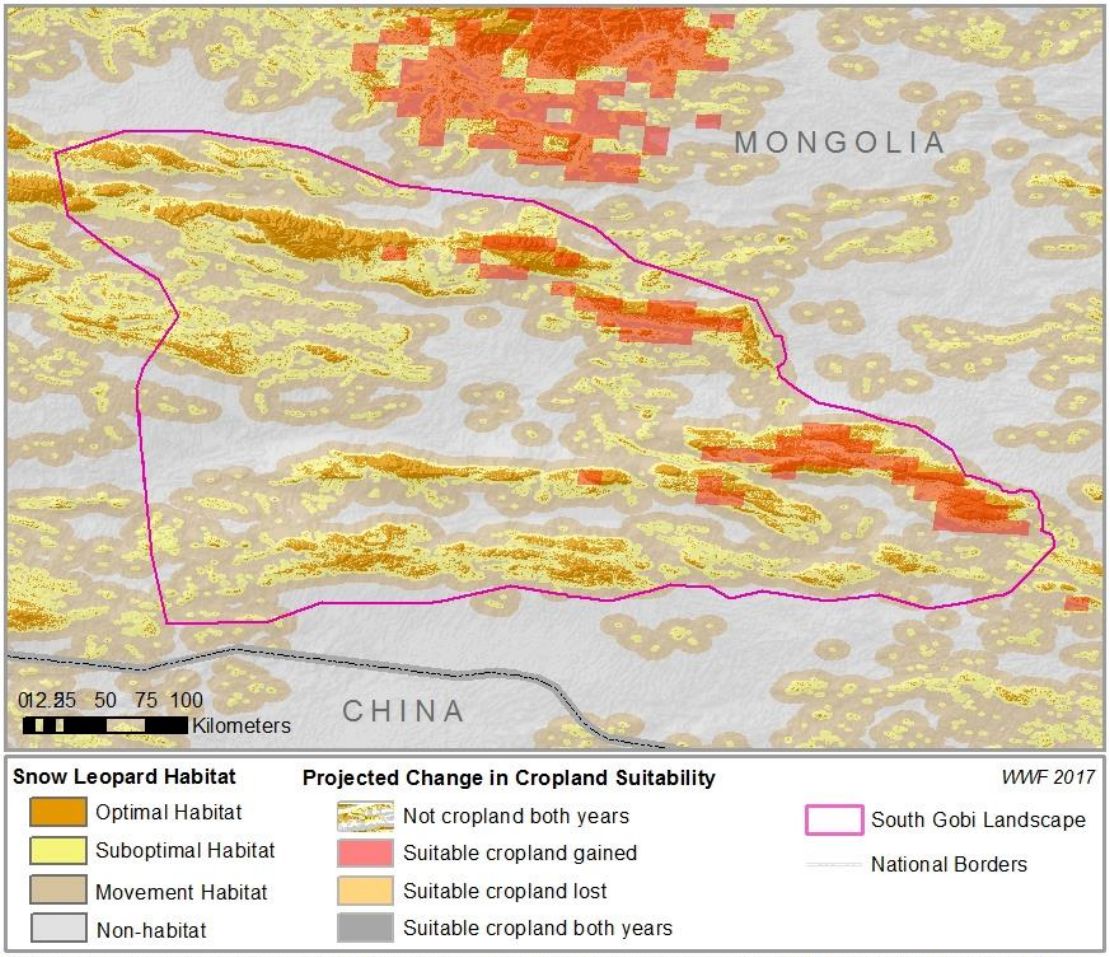
- DEM, Slope (Lehner et al. 2008)
- Terrain Ruggedness Index (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (ISLT et al. 2008)

Other layers for display only:

- GSLEP Landscape Boundaries (GSLEP 2016)

Projected Change in Snow Leopard Climate Envelope: see Sindorf et al. 2014

Projected Change in Cropland Suitability in the South Gobi Landscape



Projected change in climate suitability for agricultural crops under a high emissions (A2) scenario to the year 2100. According to this projection, climate may become more suitable for cropland in some of the existing habitat blocks in the north-central to eastern side of the landscape.

This map shows current climate niche and potential change in the extent of the arable land (or cropland) climate envelope under a high emissions climate change scenario. In this landscape, suitable climate for arable land is likely to increase, particularly in the elevated, rugged areas in the north central to eastern portion of the landscape. Interestingly, these areas of projected improving cropland suitability coincide with areas that have already demonstrated a historical trend toward increasing net primary productivity (Bai et al. 2008). Since improving cropland suitability may increase and/or change the distribution of human presence in the landscape, these findings emphasize the need for snow-leopard friendly land use and water management planning and zoning.

The model shown is based on the Global Arable Lands database (Ramankutty et al. 2008) and 19 bioclimatic variables (Hijmans et al. 2005). These inputs were used to produce climate envelope projections for the current time period and the 2080’s under a high emission scenario (A2A) using the HADCM3 General Circulation Model (see Sindorf et al. 2014).

Data Sources:

Snow Leopard Habitat Model:

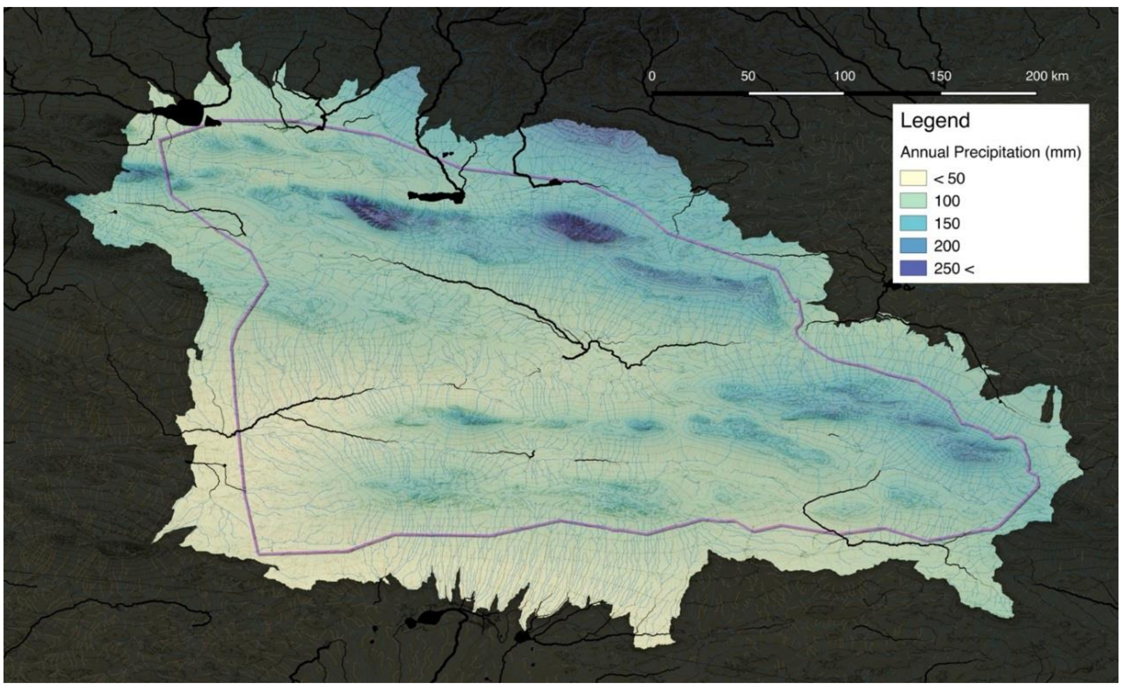
- Land cover (ESA 2009)
- DEM, Slope (Lehner et al. 2008)
- Terrain Ruggedness Index (Lehner et al. 2008, Riley et al. 1999)
- Snow leopard observations (GSLEP 2016a)

Projected Change in Cropland Suitability: Sindorf et al. 2014

Other layers for display only:

- GSLEP Landscape Boundaries (GSLEP 2016b)

Mean Annual Precipitation in the South Gobi Landscape

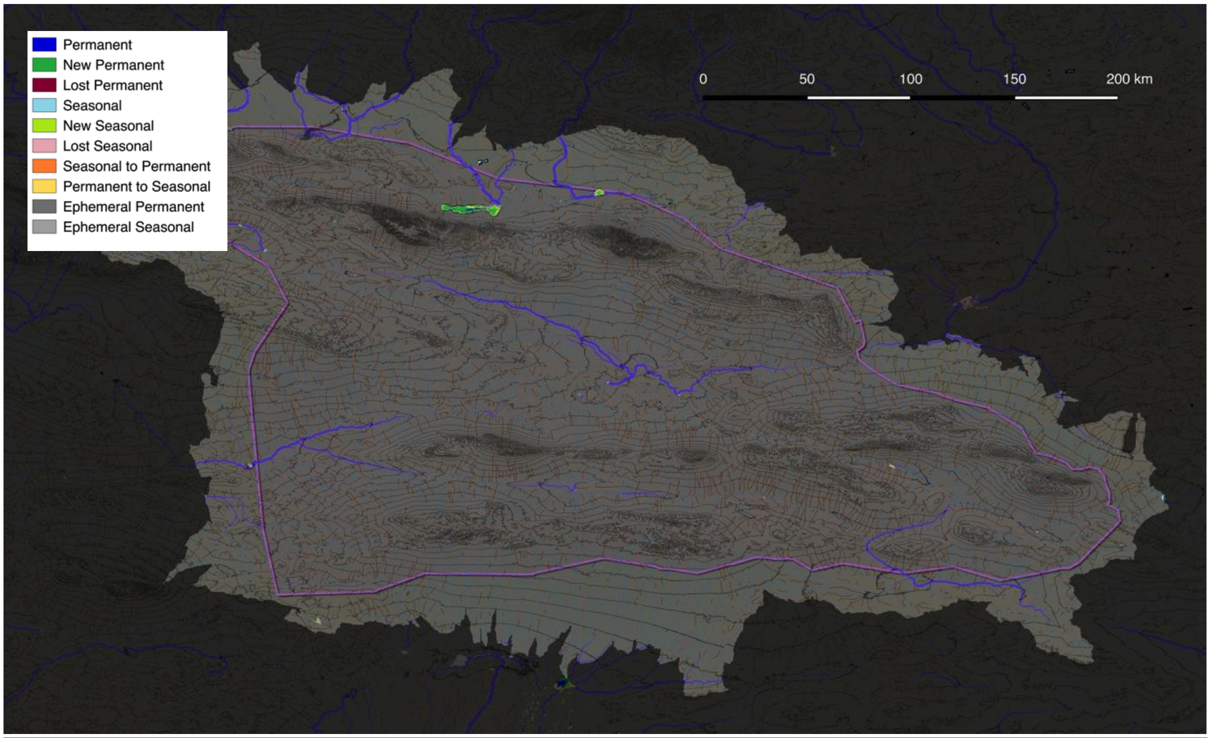


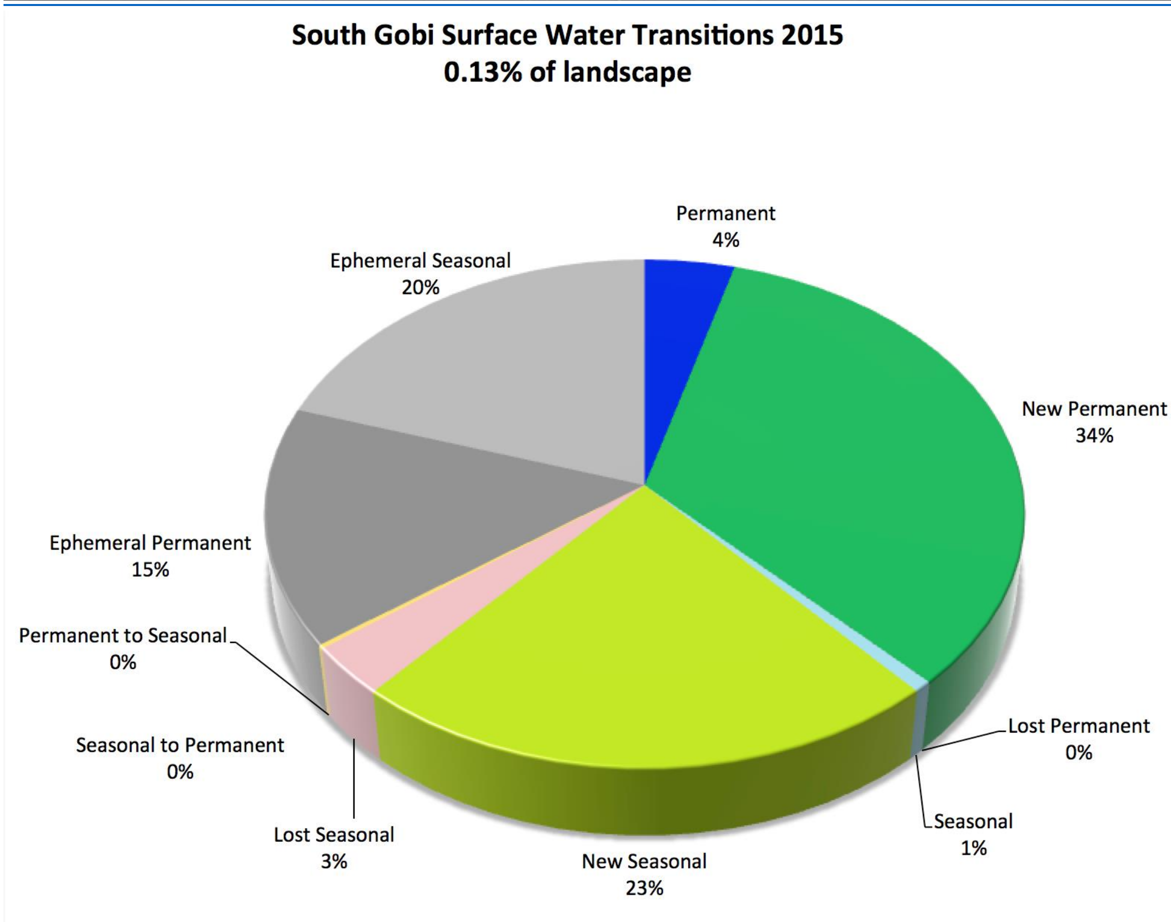
The mountain ranges in the South Gobi receive the highest amount of precipitation. These rugged areas also coincide with the best snow leopard habitats, are more productive than the surrounding landscape, and feed the intermittent streams and groundwater in landscape. Precipitation in this landscape has high intra- and inter-annual variability, though not expressed by this map. For example, the small amount of precipitation here typically falls during the summer months. Under a changing climate, precipitation is expected to increase in general (Peters 2017, Sindorf 2017).

Data Source:

- Current Mean Monthly Precipitation, based on historic WorldClim, 30s resolution (Hijmans et al. 2005)

Historical Surface Water Transitions (1984-2015) in the South Gobi Landscape





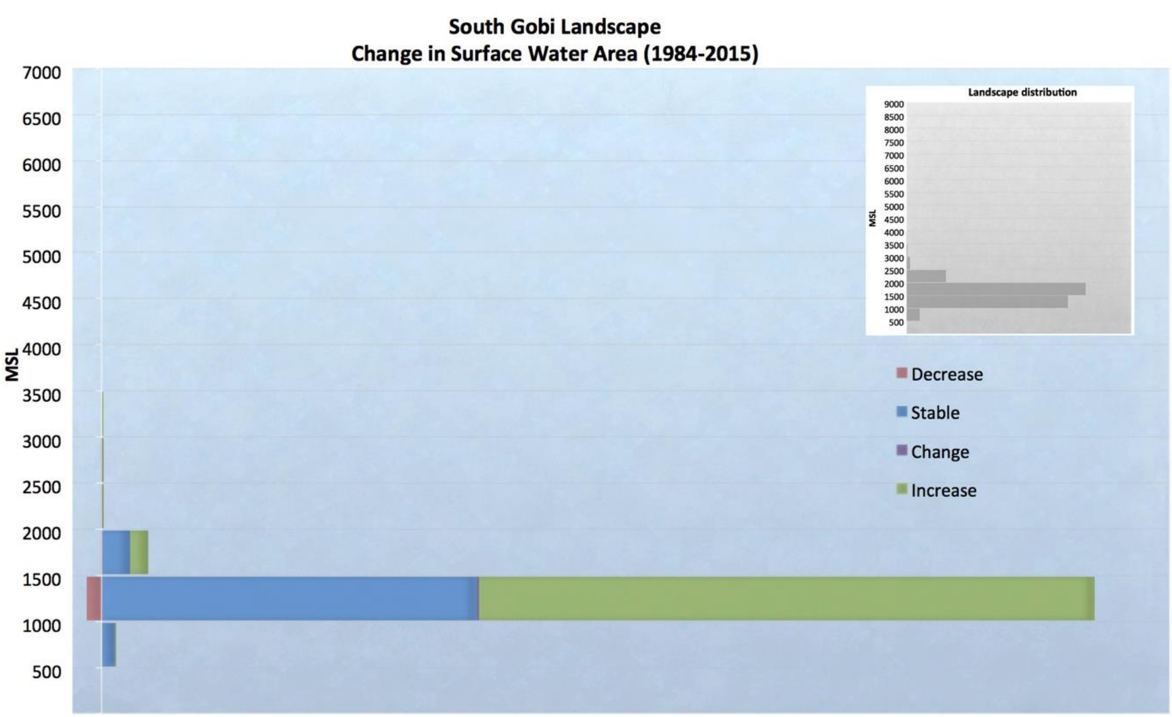
Only 0.13% of the South Gobi Landscape is classified as open surface water (Pekel, 2016). There are four lakes inside the landscape, including a large part of the Valley of the Lakes Wetland, which is a Ramsar Wetland of International Importance (Messager et al. 2016).

The following transitions occurred across all surface water bodies between 1984 and 2015 (Pekel et al. 2016):

- 40% of the open water surface was *stable* (permanent 4 %, seasonal 1 %, ephemeral 35%)
- 3% of the open water surface *disappeared* (permanent 0 %, seasonal 3 %)
- 57% classified as *new* surface water (permanent 34 %, seasonal 23 %)

Figure 6.1 breaks down these surface water changes by elevation. The largest surface water areas are found between 1000-1500 msl, which has experienced an increase of about 250% over the study period (1984-2015). This is mainly a single water body, Lake Orog. Lake Orog is an endorheic lake, which means that it is the endpoint, or the most downstream, of several rivers and streams. The increase in size is likely the result of increased precipitation and runoff upstream of the lake, and *not* of decreased evaporation (temperature) of the lake surface. Under a changing climate, surface water in the landscape will continue to increase as a result of increased precipitation here and also in the headweaters of the intermittent streams that connect to the lakes.

Figure 6.1. Change in Surface Water Area by Elevation in the South Gobi Landscape



Methodology

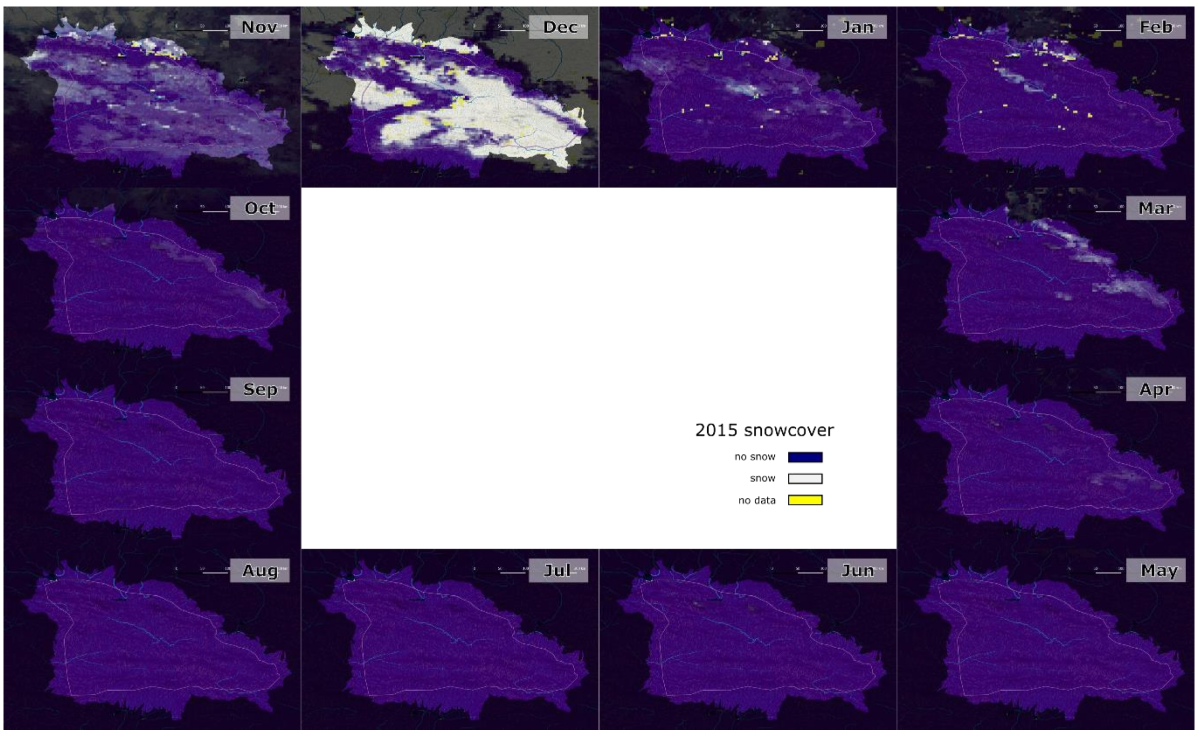
The map of global surface water and its long-term changes, is a recent high-resolution product (Pekel, 2016). It contains at least 6 different datasets, and allows time-lapse analysis from 1984-2015, which coincides with Landsat coverage. See Sindorf 2017 for more information.

Data sources:

Open surface water (Pekel et al. 2016)

Volume and age of water stored in global lakes (Messager et al. 2016)

Monthly Snow Cover in the South Gobi Landscape (2015)



The map shows the percent of each cell covered by snow during all months of 2015. The December 2015 snowfall occurrence is the so-called *white dzud*; a recurring climate extreme of extreme cold or snow which precedes the mass-starvation of grazing animals (ReliefWeb 2016). Under climate change, the occurrence of white dzuds are expected to increase. This will bring increased risks to nomadic peoples and their livelihoods, but also to wild ungulate populations and the snow leopards that feed on them.

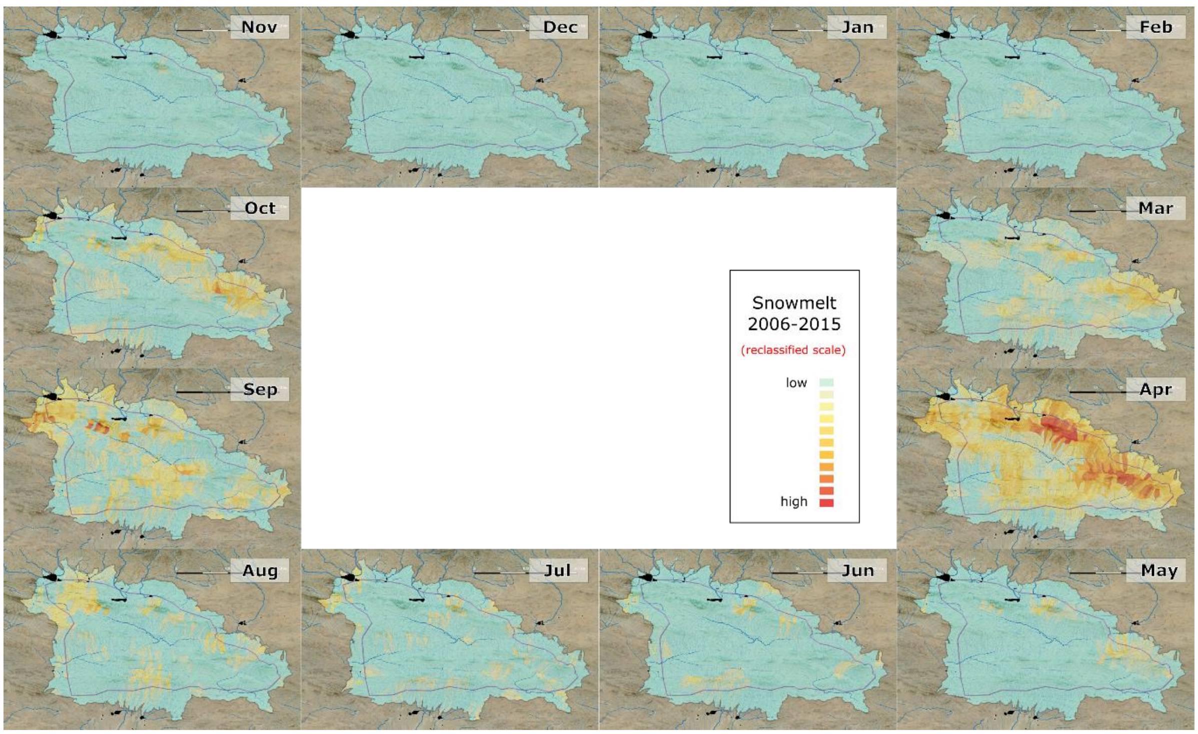
Methodology

This is a map of MODIS/TERRA snow cover at 0.05 degree resolution with no additional processing. For each cell, the percentage of monthly snow cover is reported. Due to some data artifacts (e.g., no data as a result of cloud cover), it is difficult to calculate inter-annual means, hence only the snow cover for the year 2015 was mapped out (Sindorf 2017).

Data Source:

MODIS/TERRA Montly Snowcover L3 at 5km (0.05 degree) resolution (Hall et al. 2015)

Average Monthly Snowmelt in the South Gobi Landscape (2006-2015)



This map shows average snowmelt quantities over the 2006-2015 period. Periods of snowmelt typically occur in the landscape from March to October, with peak snowmelt occurring during April. The The mountain ranges play an important role as sources of snowmelt. This is because they not only capture more snowfall, but because they capture snow that is blown from the plains during the winter months.

Some snowmelt also occurs during September and October. This may be because some early snowfall melts off before the winter season. It is important to note that patterns of snowfall, wind drift, and snowmelt are actually highly variable both seasonally and interannually.

Under a changing climate, spring snowmelt may occur earlier in the landscape, which would result in an earlier arrival of spring and transition toward ecological communities that prefer shorter winters. Earlier snowmelt may influence permafrost melting, with implications for habitat stability, water availability, and greenhouse gas emissions.

Methodology

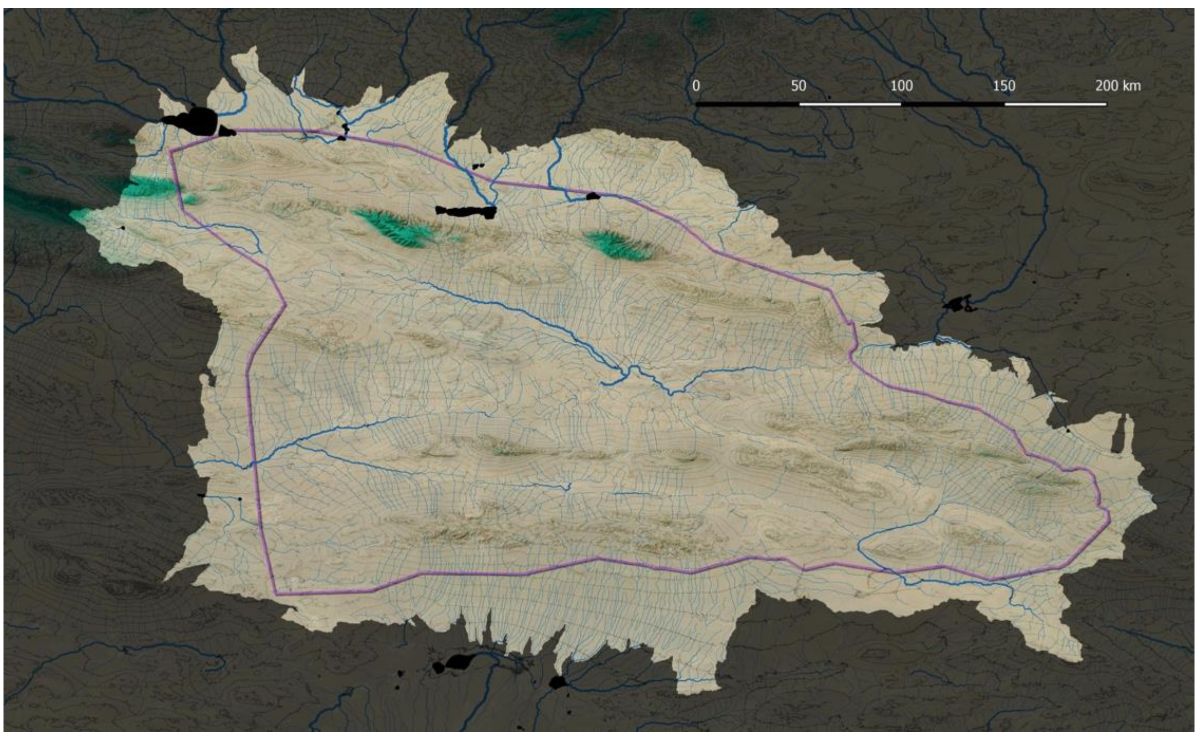
NOAH-GLDAS monthly data for the years 2006-2015 was downloaded. Band 11 (snow melt) was selected, and means calculated for each month of the 10-year period. Mean snowmelt was then summarized in a GIS for each month by the selected HydroBASIN level 12 watersheds, and multiplied by each watershed area (in order to calculate quantities), both for the entire basin and the snow leopard landscape (Sindorf 2017).

Data Sources:

Monthly data on snowmelt from 2006-2015 at 0.25 degrees resolution (NOAH-GLDAS V. 2.0)

HydroBASINS, level 12, ~100 km^2 watershed outlines (Lehner and Grill G 2013)

Permafrost in the South Gobi Landscape



Permafrost of the South Gobi landscape are located at the highest elevations in the mountain ranges; which are also the most important precipitation areas. A warming climate may result in melting permafrost. Permafrost loss can result in habitat loss and fragmentation, including loss of meadows and wetlands; landslides; changes in seasonal water availability, including groundwater; and significant greenhouse gas emissions. Since key permafrost areas overlap with optimal snow leopard habitats, there may be a significant risk of habitat loss with warming climate and permafrost melt.

Methodology

We used the permafrost database from Gruber (2012), which models permafrost as a function of air temperature, ruggedness, and permafrost extents from earlier global assessments. The study acknowledges that the permafrost extents are modelled for a consistent reference, but it does not provide a reliable groundtruth (Gruber, 2012).

Though this map provides essential insight on the extent of permafrost, there are a wide range of permafrosts, all with their specific seasonal importance for 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. This map depicts where permafrost loss and associated landscape change are likely to happen under changing climate, but it does not indicate how the landscape will change.

Data Source:

Global permafrost database, Permafrost Zonation Index (PZI) (Gruber, S. 2012)

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