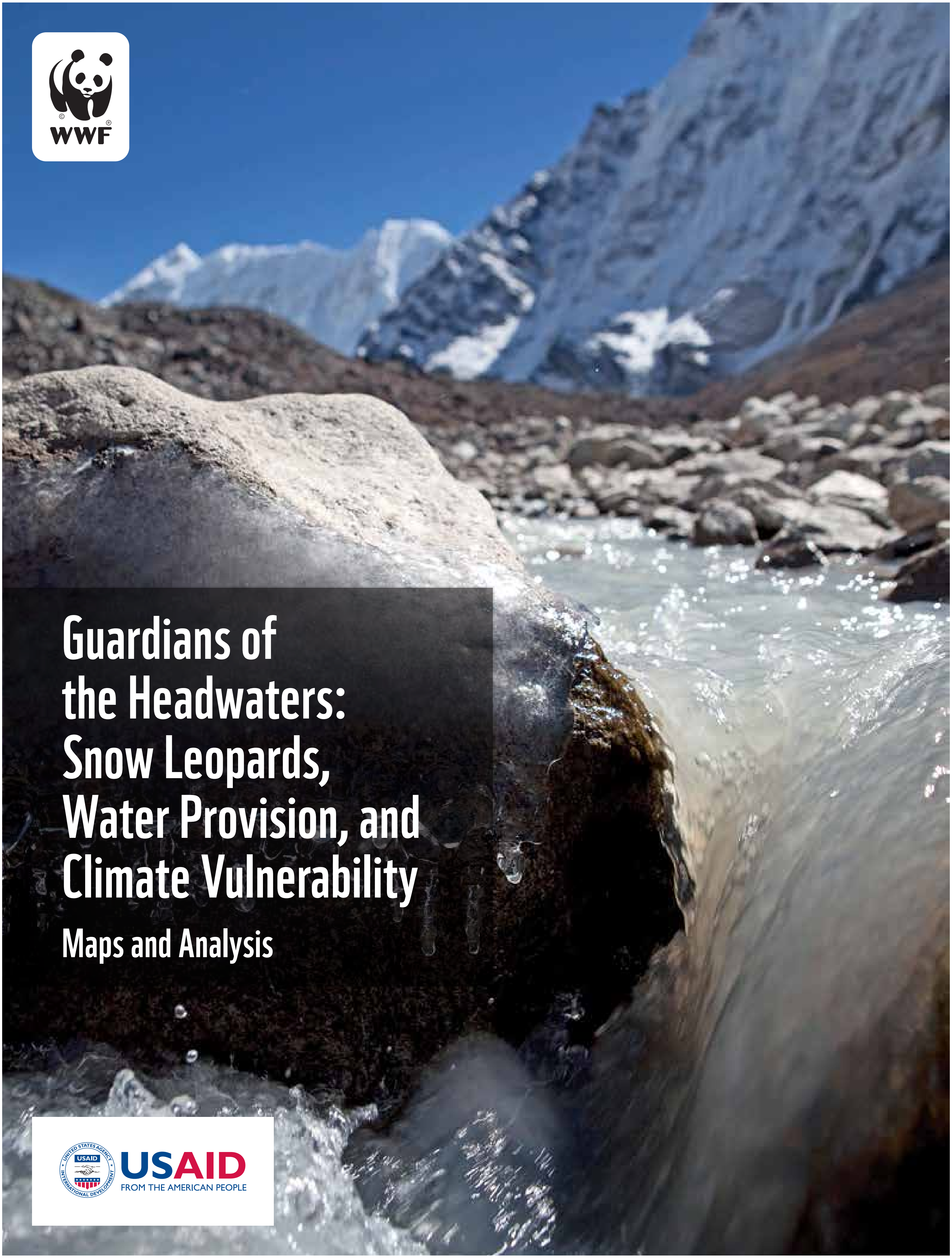


Guardians of the Headwaters: Snow Leopards, Water Provision, and Climate Vulnerability

Maps and Analysis

USAID
FROM THE AMERICAN PEOPLE

COVER PHOTO: THE IMJA RIVER: THE OUTFLOW OF WATER FROM LAKE IMJA IN THE EVEREST REGION OF THE HIMALAYAS IN NEPAL; © WWF-CANON / STEVE MORGAN

Guardians of the Headwaters: Snow Leopards, Water Provision, and Climate Vulnerability

Maps and Analysis

February 19, 2014

NIKOLAI SINDORF

JESSICA FORREST

BERNADETTE ARAKWIYE

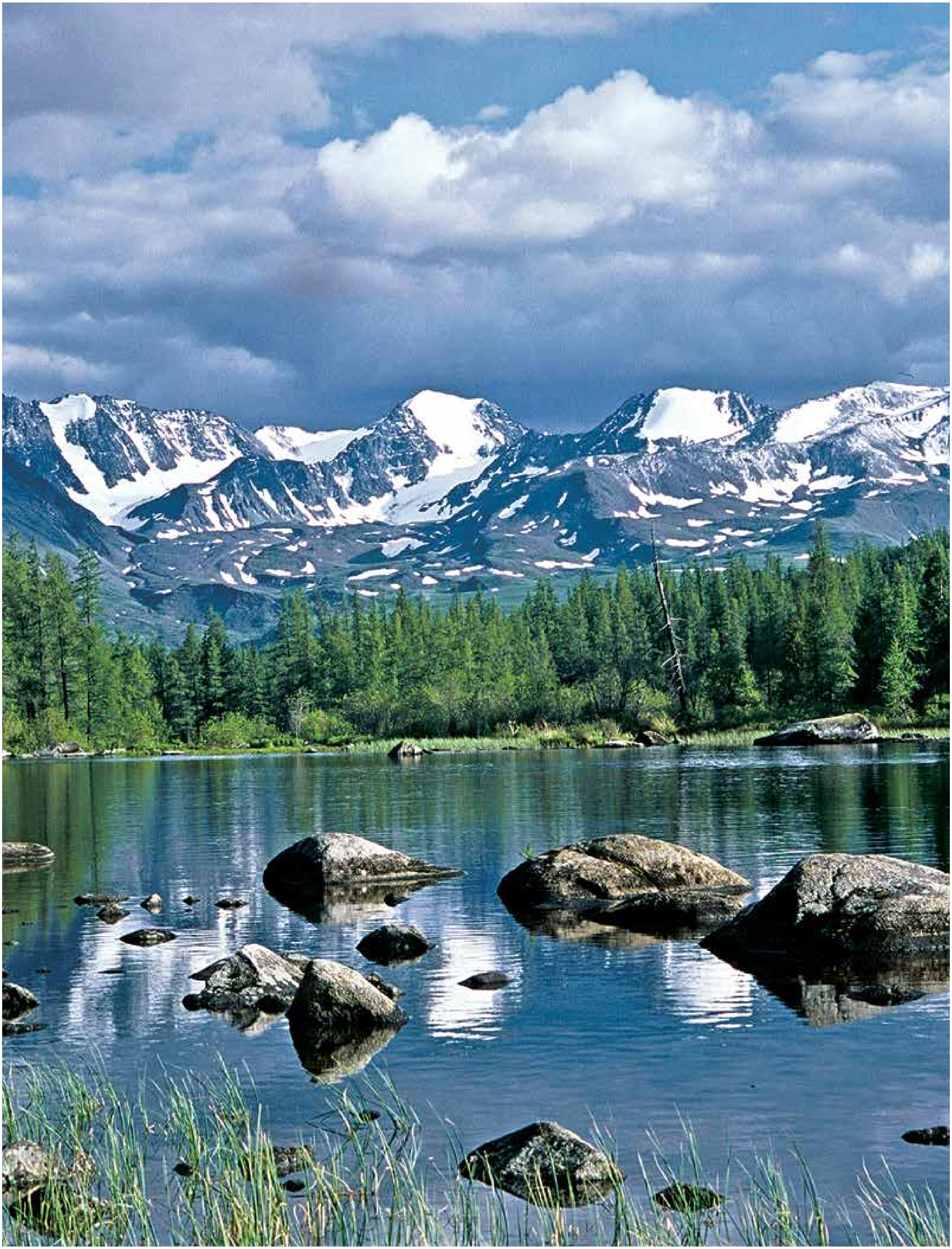
**PREPARED BY
WWF FOR USAID**

IN SUPPORT OF THE GRANT:
Conservation and Adaptation in Asia's |High
Mountain Landscapes and Communities
(No. AID-0AA-LA-12-00003,
under EM-A-OO-09-00006-00)

Acronyms and Abbreviations

AET	Actual evapotranspiration
CGIAR-CCAFS	Consultative Group on International Agricultural Research—Climate Change, Agriculture and Food Security
CIAT	International Center for Tropical Agriculture
CIESIN	Center for International Earth Science Information Network
CO2	Carbon dioxide
CSI-CGIAR	Consortium for Spatial Information—Consultative Group on International Agricultural Research
DEM	Digital elevation model
FAO	Food and Agriculture Organization of the United Nations
FAO-AGA	Food and Agriculture Organization—Animal Production and Health Division
GLIMS	Global Land Ice Measurements from Space
GCM	Global Circulation Model
GIMMS	Global Inventory Modelling and Mapping Studies
GIS	Geographic information system
GLOF	Glacial Lake Outburst Floods
GRUMP	Global Rural-Urban Mapping Project
IFPRI	International Food Policy Research Institute
ISLT	International Snow Leopard Trust
ISRIC	International Soil Reference and Information Centre
IUCN	International Union for Conservation of Nature
NASA-SEDAC	National Aeronautics and Space Administration—Socioeconomic Data and Applications Center
NDVI	Normalized difference vegetation index
NEP	Non-equilibrium paradigm
NPP	Net primary productivity
NSIDC	National Snow and Ice Data Center
P	Precipitation
PET	Potential evapotranspiration
SLCU	Snow leopard conservation unit
SLN	Snow Leopard Network
UNEP	United Nations Environment Programme
WCS	Wildlife Conservation Society

CONTENTS



SNOW LEOPARD (PANTHERA UNCIA); © DAVID LAWSON / WWF-UK

EXECUTIVE SUMMARY

More than two billion people live in river basins that overlap the snow leopard range, but how important are water sources located in snow leopard habitat to local and downstream human communities? This set of maps is meant to illustrate the key water services provided by snow leopard habitat to human populations, highlighting the most important "snow leopard headwaters." We next analyze the vulnerability of these water sources and snow leopard habitat to climate change and other human and natural disturbances. Finally, we consider these results in the context of appropriate management activities to maintain water security and snow leopards through the next millennium.

Snow leopard range is found in 12 countries (Afghanistan, Bhutan, China, India, Kazakhstan, Kyrgyzstan, Mongolia, Nepal, Pakistan, Russia, Tajikistan and Uzbekistan) in northern Asia (spanning the Tibetan Plateau and the Himalayan, Tian Shan and Altai mountain ranges), though the animals are sparsely distributed. Snow leopards prefer rugged and steep terrain, above treeline, but within hunting distance of their favorite prey such as blue sheep, argali, ibex and marmots. Listed as Endangered on the International Union for Conservation of Nature (IUCN) Red List, the greatest current threats to the species are hunting for its pelts, depletion of its natural prey base from hunting (by humans) or competition with livestock, and retaliatory killing by humans for livestock depredation. Anticipated climate change threats include potential changes in grassland communities towards less palatable species for prey and livestock, melting permafrost, increased suitability for cropland and shifting treeline.

The snow leopard range in combination with High Asia (>3000 m) form the headwaters of 20 major basins, with water flowing to a total of 22 countries. The water cycle governing flows from high to low Asia is complex. The water cycle in the southern part of High Asia is largely driven by the monsoon that hits the eastern Himalayas, and moves westward, gradually becoming less severe. In High Asia, precipitation cycles between winter snow and summer rain. Other "stocks" of water in this region include permafrost, glaciers and groundwater. Warming temperatures are expected to affect patterns of evapotranspiration and increase aridity, while changing the timing of water availability.

Through this book, we present a series of analyses surrounding the water provision services of snow leopard habitat and climate change risk. Each analysis is presented as a map, followed by a description to aid in its interpretation and implications, methods and data used. We summarize the key findings of the effort in the first map, called "Snow Leopard Habitat, Water Provision, and Climate Change." But all maps and methods leading to the summary map are provided to support the main conclusions, and to aid other scientists and decision makers in developing further interpretations. Note that all analyses are done at a rangewide scale using the best-available data sources. These may mask local-scale patterns that differ from rangewide norms, and are not meant to preclude local-scale studies. Finally, we do not analyze the services of glaciers explicitly in this report because they deserve extensive study of their own, are too detailed to accomplish in this report, and do not form “snow leopard habitat,” per se.

On the broad scale, we conclude that the headwaters of the western basins (particularly the Indus, Amu Darya and Syr Darya) are most important for downstream water provision and also harbor important core and/or connective habitat for snow leopards. Snow leopard habitat appears most vulnerable to broad-scale changes from climate change in the eastern and northern parts of the range. Potential conflict with humans may increase in the future in the western part of the range if crop suitability improves, as our results suggest. Permafrost acts as a stabilizing force for both water provision and snow leopard habitat, with considerable uncertainty surrounding the impact of melting under climate change.

Good land management (including the restriction of land conversion and degradation through overgrazing) can help improve water security by maintaining natural flood control mechanisms, and slowing the melting of permafrost. Transboundary water management that considers an entire river from headwaters to delta can help maintain water security. For snow leopards, maintaining intact habitat in important areas for habitat and connectivity, representative geographically and by habitat type, can build resiliency into long-term snow leopard conservation strategies.

Snow Leopard Habitat, Water Provision, and Climate Change

Aral Sea Basin

Around 80% of all water in the Amu and Syr Darya rivers is sourced from the upstream Tian Shan mountains. Yet, over-allocation of this water in downstream irrigation systems along the Amu Darya and the Syr Darya, has resulted in the Aral Sea environmental disaster.

Crop Suitability

Cropland suitability may actually improve under climate change in the Tian Shan mountains and Western Himalayas, making good land use planning more important. This implies reservation of land in order to ensure connectivity of snow leopard habitat.

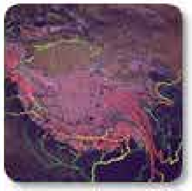
Water Provision

The headwaters of the western basins are extremely important for water provision, but also harbor regionally important snow leopard habitat. These areas will likely become more important under climate change as long as human water use and development are well-managed.

Evapotranspiration

Increased temperatures will lead to increased evapotranspiration. A modeled increase of 2°C shows that specifically wetter (often water source) areas will get drier. This concerns most mountain slopes throughout the range that capture higher amounts of precipitation.

Permafrost

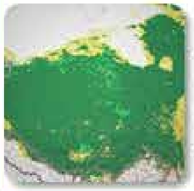


A large part of the snow leopard range overlaps with permafrost. The effects of degrading permafrost on habitat and water supply are not consistent. Conserving land cover and managing for uncertainty in downstream water resources can help build long-term resilience.

Habitat Loss

The eastern range may be more vulnerable to climate change, caused in part by an upward shift in treeline that could significantly decrease available habitat. This area is also moderately impacted by human activities, providing extra challenges for long-term snow leopard conservation.

The Himalayas



The Himalayas may remain a relatively resilient place for snow leopards under climate change, though the lower reaches of the range are more vulnerable. With a northward shift of snow leopard habitat, transboundary conservation becomes a critical priority.

Population

The snow leopard range is sparsely populated but their larger basins contain over 2 billion people. An estimated 330 million people live in direct vicinity of rivers emanating from the range, most notably in the Indus and Ganges basins, and the Sichuan depression.

Expert Knowledge of the Snow Leopard Range (2008 Workshop, Beijing, China)

SL data: Panthera, WCS, ISLT, SLN; McCarthy et al. 2008

EXPERT KNOWLEDGE OF THE SNOW LEOPARD RANGE

This map shows collective expert knowledge of the snow leopard range compiled at a 2008 workshop in Beijing, China. Observations were collected by experts from 1983–2008, and include direct observations, scat, signs and anecdotal reports. Snow leopard conservation units (SLCUs) are defined as large blocks of habitat where snow leopards are known to occur. These areas represent expert opinion on the most important areas for long-term conservation of snow leopards. The Remaining Known Range represents areas where snow leopards are known to occur. The Potential Range depicts areas where snow leopards are currently not known to occur, but where they are believed to have occurred in the past 100 years. The Unknown Range marks areas where snow leopard presence was unknown to this study. Limitations of this map are that the accuracy of observations is not confirmed, it does not reflect more recent surveys after 2008, and the state of what is known about snow leopard habitat use has evolved somewhat since this map was prepared. In China, observation points usually represent the center of the closest townships and not the actual locations of snow leopards. Still, this remains the best existing broad-scale depiction of the snow leopard range. In this study, we define the extent of the current snow leopard range as SLCUs and Remaining Known Range.

Methods

Thirty snow leopard experts from countries across the range submitted georeferenced snow leopard observations to a GIS database. Maps of known and suspected range were refined, and critical conservation units identified at a workshop in Beijing in 2008. Government officials joined scientists to identify critical conservation needs and country-specific actions to be taken in the next five years.

Data Sources:

Snow leopard observations

Snow Leopard Network (SLN)

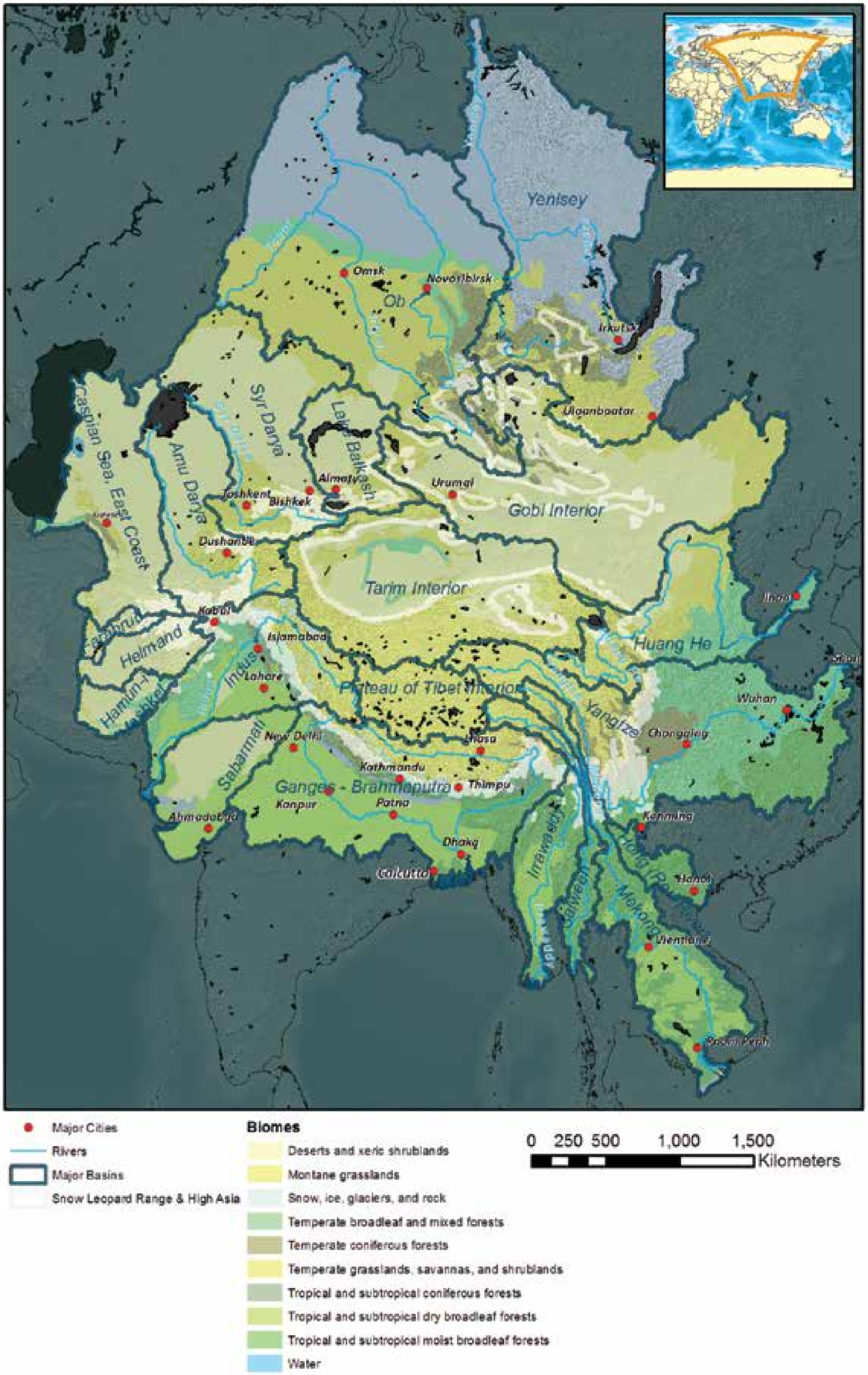
SLCUs, known range, extirpated range, and potential range

International Snow Leopard Trust (ISLT), Panthera, SLN, Wildlife Conservation Society (WCS). Snow Leopard GIS Workshop, Beijing, China, 2008

Reference

McCarthy, T., Sanderson, E., Mallon, D., Fisher, K., Zahler, P. and Hunter, L. 2008. *Range-wide Conservation Planning for Snow Leopards*. SCB Poster. ISLT, Pantera, WCS.

Snow Leopard Range and High Asia: River Basins of Influence



SNOW LEOPARD RANGE AND HIGH ASIA: RIVER BASINS OF INFLUENCE

The snow leopard range in combination with connected areas of High Asia (>3000 m) covers the headwaters of many of Asia's great rivers and 20 of its greater inland basins (the snow leopard range alone overlaps 15 of these). These basins drain into oceans and water bodies with a greater circumference of about one-eighth of the globe, including the Arctic Ocean (Ob, Yenisey), East China Sea (Huang He, Yellow River), South China Sea (Mekong), Andaman Sea (Irrawaddy), Bay of Bengal (Ganges, Brahmaputra), Arabian Sea (Indus), Caspian Sea, Aral Sea (Amu Darya, Syr Darya), Lake Balkash, Tibetan, Gobi and Tarim Interior Basins.

Data sources:

Size of rivers
WaterGAP 2.1, Döll et al., 2003

Hydrography
HydroSHEDS, 30s and 5 min resolution, WWF, Lehner et al., 2008

River basins
HydroBasins, FAO and WWF, 2011

Lakes
GLWD, WWF, 2003

Countries
ESRI

Snow leopard range
ISLT, Panthera, SLN, WCS, Beijing GIS Workshop, 2008

Satellite imagery
NASA, Bluemarble, 2004

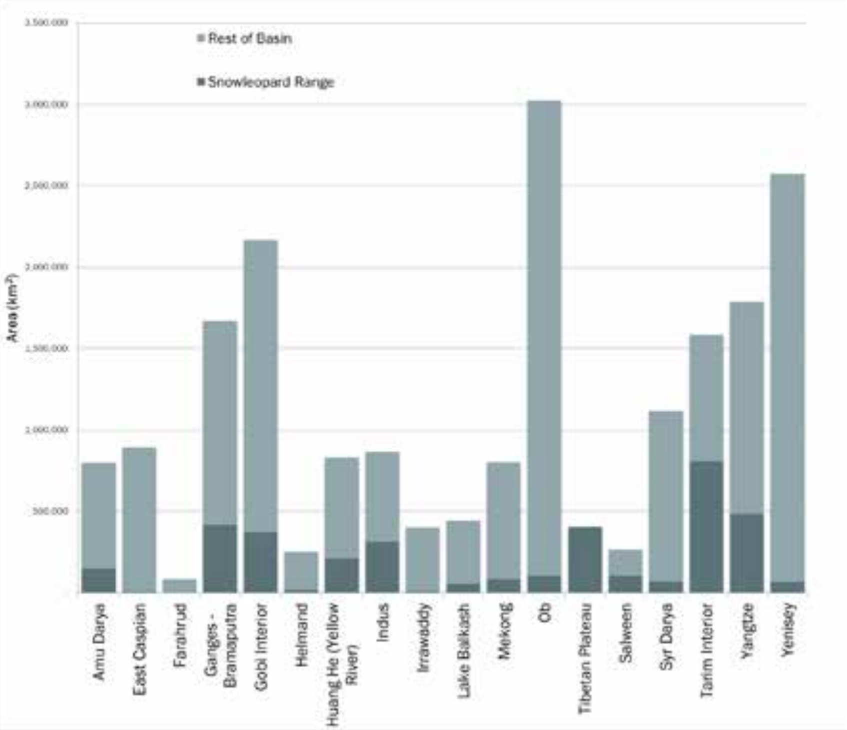
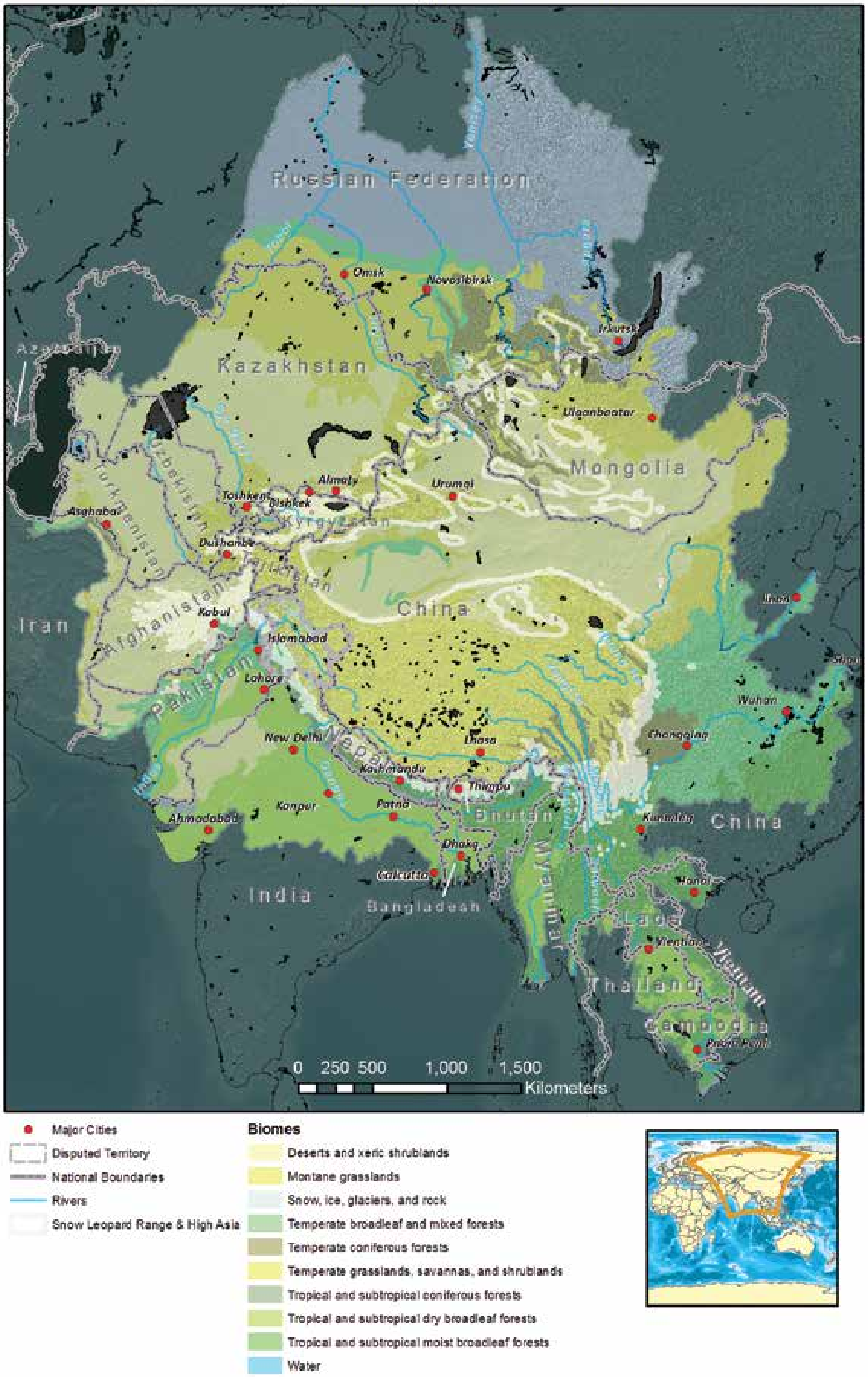


Figure 1. Area of basin that is in snow leopard range

This figure shows that the majority of the snow leopard range is composed of the Tibetan Plateau, Tarim Interior, Yangtze, Ganges-Brahmaputra, and Gobi Interior Basins. Of these, all but the Tibetan Plateau also have large downstream areas.

Snow Leopard Range and High Asia: Countries of Influence



SNOW LEOPARD RANGE AND HIGH ASIA: COUNTRIES OF INFLUENCE

This map shows High Asia (defined as areas > 3,000 m) merged with the snow leopard range, and countries connected to this region by river basins. The snow leopard range overlaps 12 countries (Afghanistan, Bhutan, China, India, Kazakhstan, Kyrgyzstan, Mongolia, Nepal, Pakistan, Russia, Tajikistan and Uzbekistan), and High Asia alone contributes an additional country (Myanmar). Nine additional countries (Azerbaijan, Bangladesh, Cambodia, Iran, Laos, Thailand, Turkmenistan, Uzbekistan and Vietnam) receive some portion of their water from high mountain sources.

Data sources:

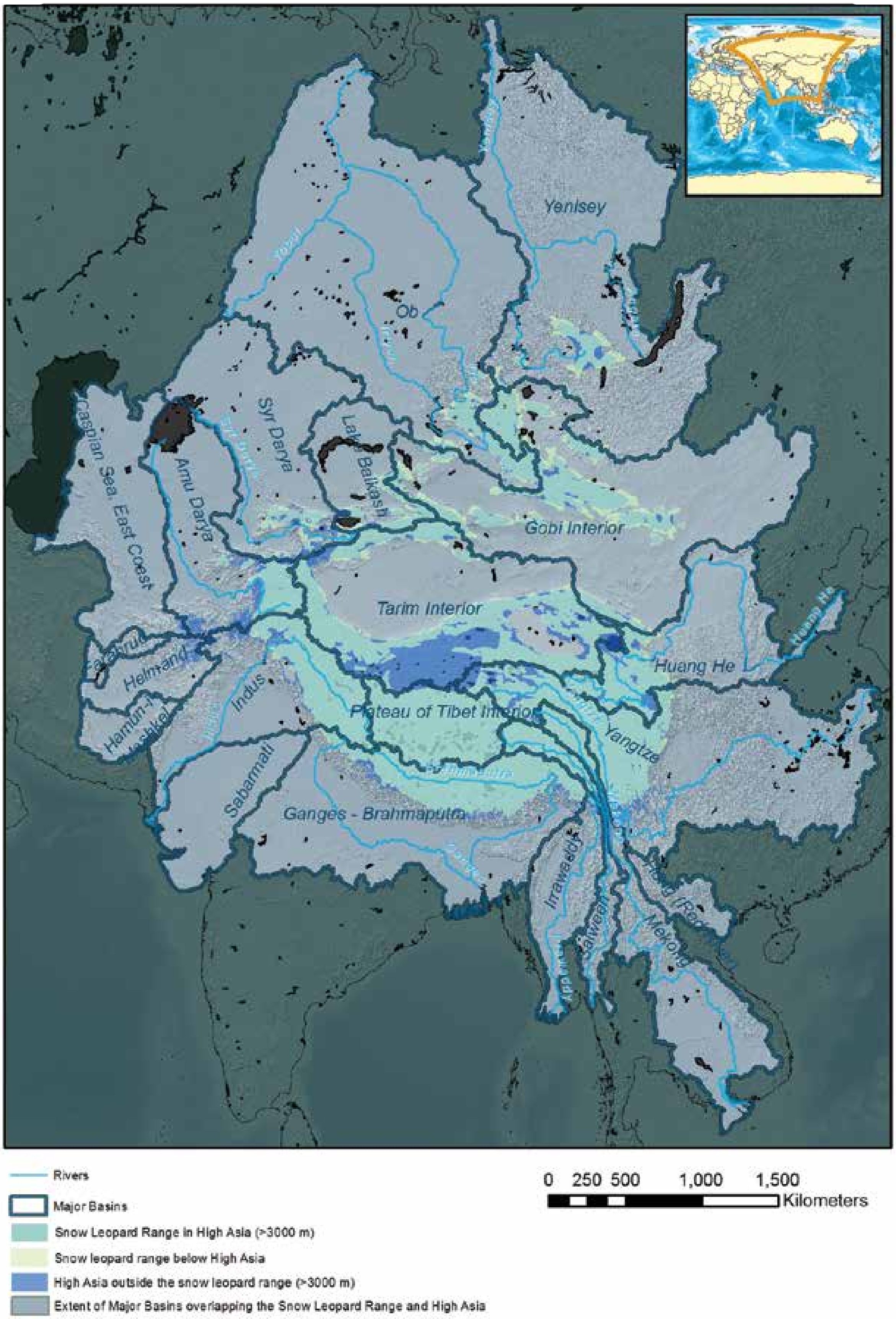
Snow leopard range
ISLT, Panthera, SLN, WCS,
Beijing GIS Workshop, 2008.

High Asia (>3000 m)
HydroSHEDS 15s Void-filled DEM,
WWF and Lehner et al., 2008

Country boundaries
ESRI

Major rivers
ESRI

Snow Leopard Range and High Asia: Analysis Extent



SNOW LEOPARD RANGE AND HIGH ASIA: ANALYSIS EXTENT

We defined a few study extents applied throughout this report. We defined the extent of influence of the snow leopard range and High Asia as the major basins that overlap the snow leopard range merged with High Asia, adding four basins that have minor connectivity to High Asia: the Sabarmati, the Farahrud, the Hamun-i-Mashkel and the Hong (Red River). For maps focused on the snow leopard alone, we restricted our analysis to the vicinity of the snow leopard range.

Data sources:

Snow leopard range
ISLT, Panthera, SLN, WCS, Beijing GIS Workshop, 2008.

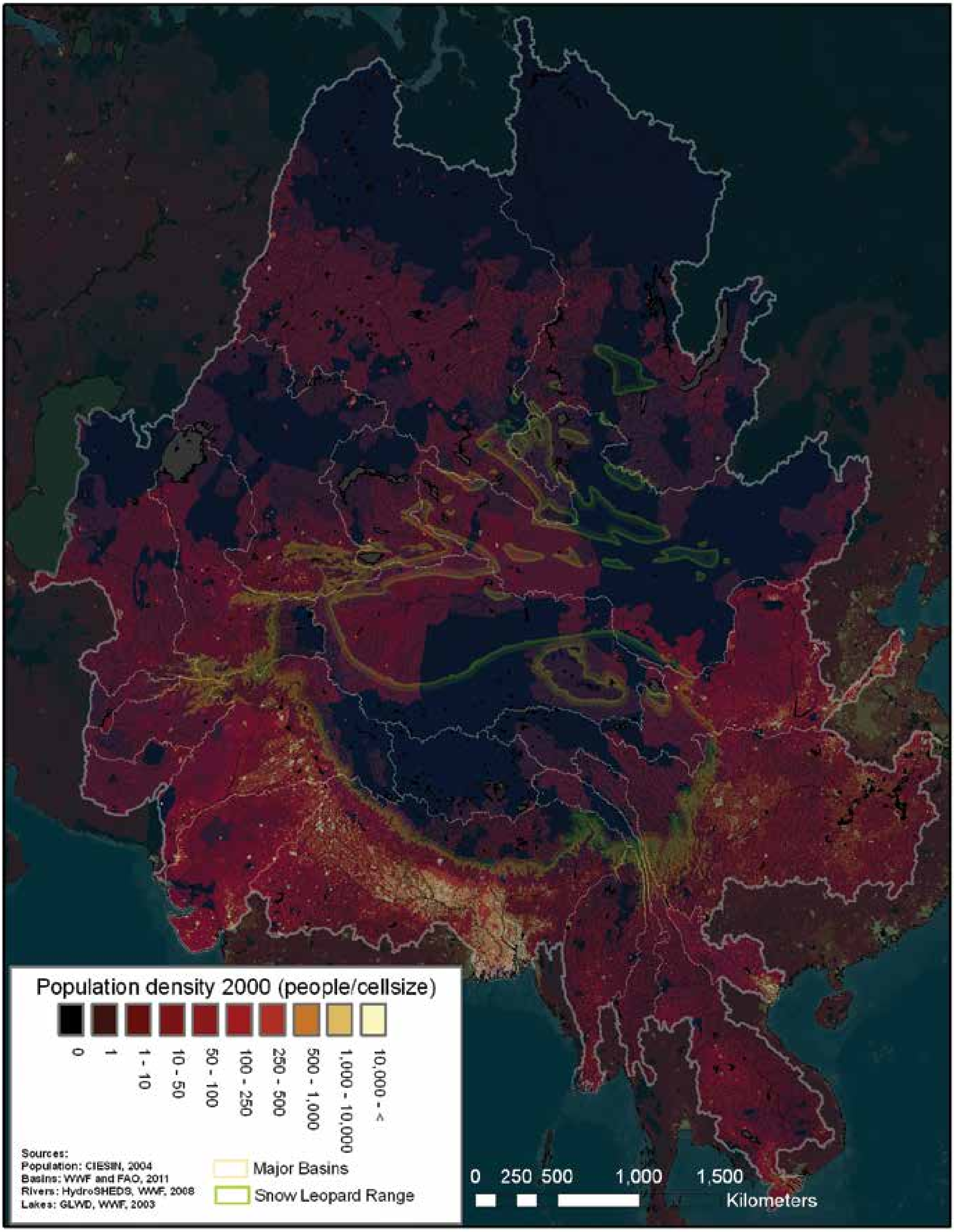
High Asia (>3000 m)
HydroSHEDS 15s Void-filled DEM, WWF and Lehner et al., 2008

River basins
HydroBasins, FAO and WWF, 2011

Country boundaries
ESRI

Major rivers
ESRI

Population Density



Sources:
Population: CIESIN, 2004
Basins: WWF and FAO, 2011
Rivers: HydroSHEDS, WWF, 2008
Lakes: GLWD, WWF, 2003

POPULATION DENSITY

This map shows human population density distribution in the snow leopard range, High Asia and adjoining river basins. An estimated two billion people live in the 20 overlapping major basins, over 330 million of whom live close to rivers flowing directly from the outlined snow leopard range.

The snow leopard range stands out as one of the least densely populated areas in Asia, and, apart from the Sahara, probably in the world. These low-density areas overlap with the Tibetan Plateau, Gobi Desert and the Tarim Basin. Human living conditions there are limited by cold temperatures, aridity and low land productivity. Population density abruptly changes from sparsely populated on the Tibetan plateau and high Himalaya, towards incredibly densely populated areas to the south, particularly in the floodplains of the Ganges River and its tributaries. Inside the snow leopard range, human population pressure is highest in the east, including the headwaters of the Huang He, Yangtze, Mekong, Salween and Brahmaputra Rivers.

The overall population of these basins is estimated to be around two billion (in 2013) based on the 1.7 billion number of the population calculated from data for the year 2000 (CIESIN-data, 2004). This is close to one-third of the world's population. Using a 10 km buffer around the rivers that drain directly from the snow leopard range, over 330 million people are estimated to live under some hydrological influence of the range.

Data sources:

Population

GRUMP, NASA-SEDAC, 2011

Hydrography

HydroSHEDS, 30s and 5 min resolution,
WWF, Lehner et al., 2008

River basins

HydroBasins, FAO and WWF, 2011

Snow leopard range

ISLT, Panthera, SLN, WCS,
Beijing GIS Workshop, 2008.

High Asia (>3000 m)

HydroSHEDS 15s Void-filled DEM,
WWF and Lehner et al., 2008

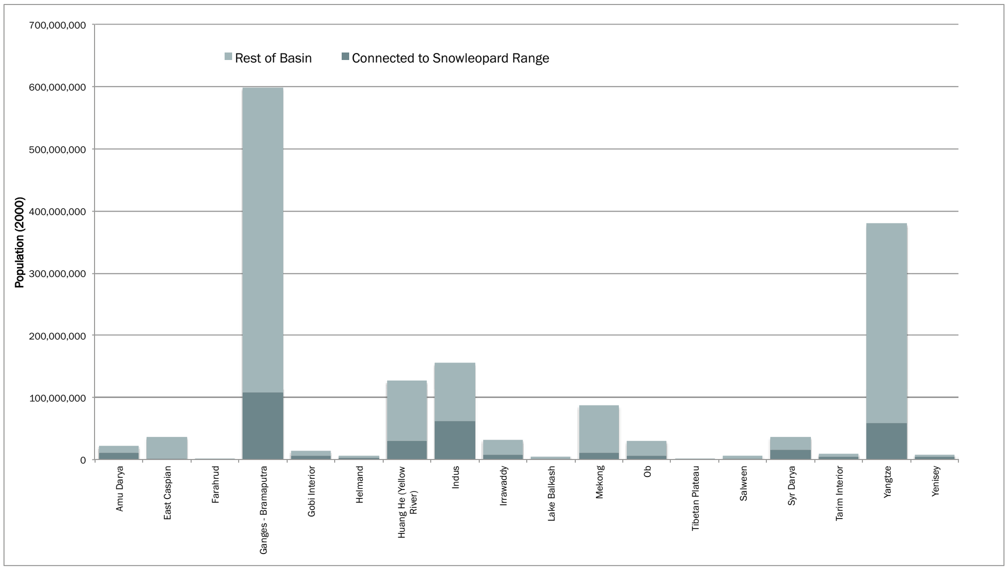
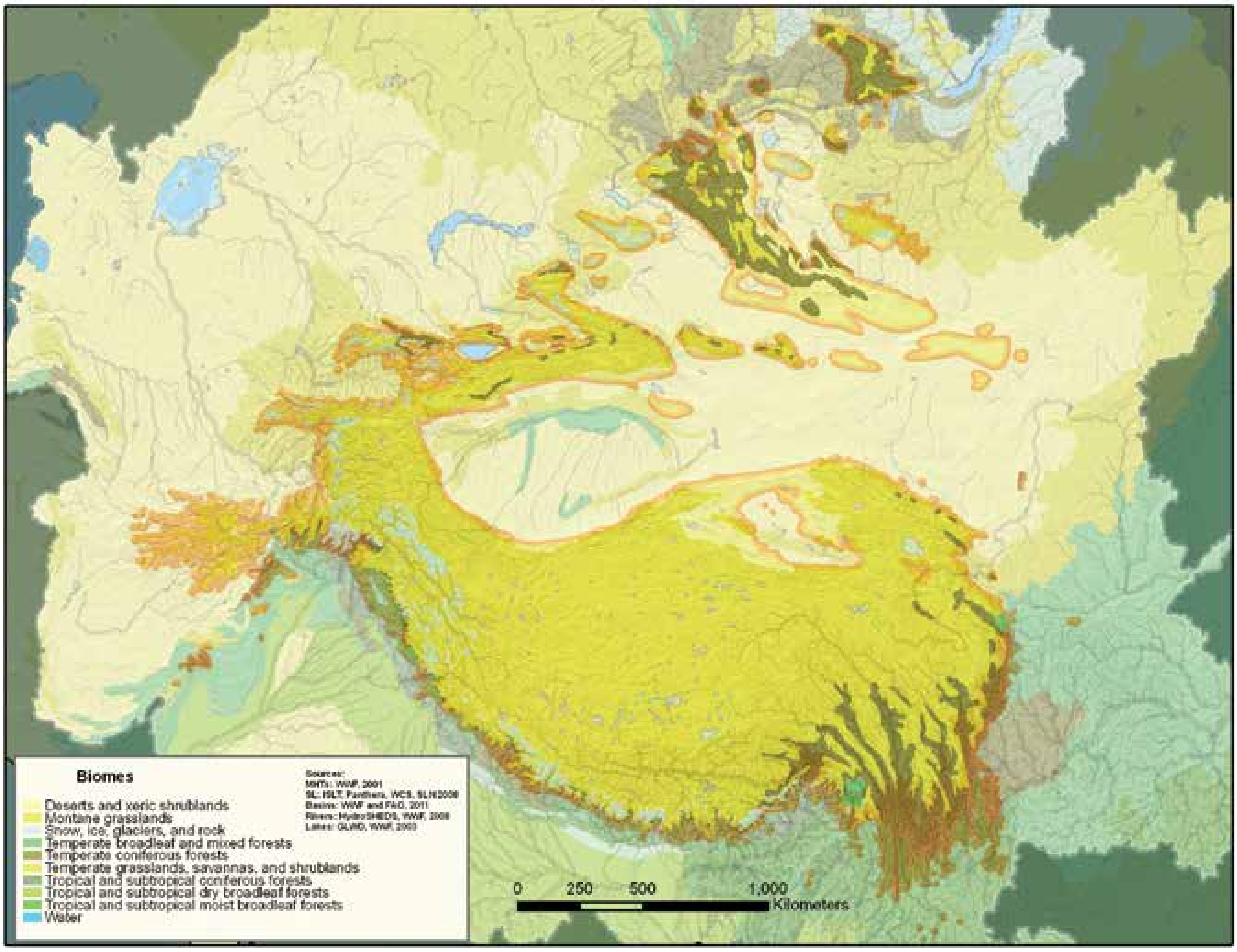


Figure 2. Population living in vicinity of river with source in snow leopard range

This figure shows that the Ganges-Brahmaputra, Indus, Yangtze and Yellow River Basins have the largest populations living within 10 km of a river with a source in the snow leopard range, and also have large populations overall. The Mekong and Sabarmati Basins also have relatively large human populations, but lower numbers along rivers originating in the snow leopard range.

Biomes of the Snow Leopard Range



Sources:
MHTs: WWF, 2001
SL: ISLT, Panthera, WCS, SLN 2008
Basins: WWF and FAO, 2011
Rivers: HydroSHEDS, WWF, 2008
Lakes: GLWD, WWF, 2003

BIOMES OF THE SNOW LEOPARD RANGE

This map illustrates major biome diversity within the greater snow leopard range. The range is predominantly montane grasslands (74%), while this biome contributes only 66% of the local runoff of the range. This implies that other biomes (particularly forest and snow, ice, glaciers and bare ground) are more important for water provision to downstream river systems. These findings are consistent with published literature on the role of high grasslands to downstream water supply (Davies, 2012; Zemmrich, 2010; Yamanaka, 2007).

Ecoregions (Olson et al., 2001), provide a consistent framework to make a region-wide distinction between grasslands and other lands. When overlaid with the snow leopard range, 74% of the range classifies as montane grasslands. Within this biome, 19 separate grassland ecoregions are identified (Olson et al., 2001, Table 1), though it is worth noting that this is one among several grassland classifications for the region (Yang 2010, Jin 2009, Wang 2011, 2012, Bai 2009, Christensen 2004, Schneider 2008, Liobimtseva 2005, 2009).

Data sources:

Major habitat types

Terrestrial Ecoregions of the World, WWF, 2001

Local runoff

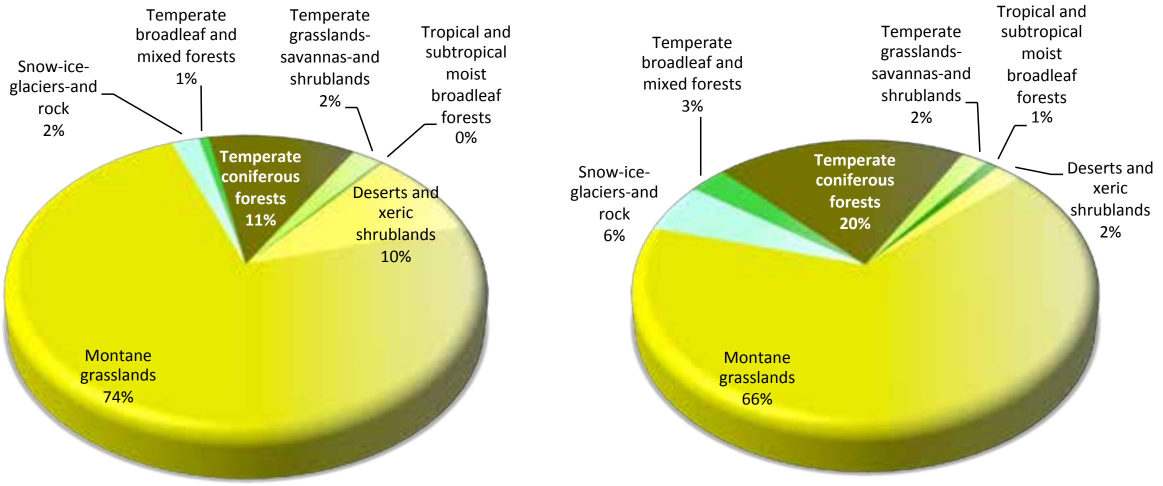
WaterGAP 2.1, Döll et al., 2003

Hydrography

HydroSHEDS, 30s and 5 min resolution, WWF, Lehner et al., 2008

River basins

HydroBasins, FAO and WWF, 2011



Distribution of biomes in the snow leopard range by area

Distribution of biomes in the snow leopard range by flow contribution

Figure 3. Distribution of biomes in the snow leopard range by area and flow contribution

This graph shows that while the montane grassland biome covers the largest area of the snow leopard range, it contributes less runoff per area to downstream flows than areas classified as forest biome and snow, ice, glacier and bare ground. It is important to note that the forest biome includes areas that are currently forest habitat and areas deforested for other land uses, such as crops and development.

Despite being located at the headwaters of many of Asia's great rivers, the montane grasslands are largely classified as drylands (Davies, 2012). As these marginal lands are too dry and/or too cold for cultivated agriculture, the only suitable agricultural use of the grasslands in High Asia is for livestock grazing (Davies, 2012). For millennia, pastoralism formed one of the region's main means of subsistence, and it still does (Shrestra, 2007; Davies, 2012). In this context, especially regarding snow leopard prey, there is an important relationship between humans, livestock and wild grazers' densities. Livestock and wild grazers have been observed in some locales to be increasingly in competition over grassland resources, both in grazing intensities and expanse (Meshra, 2002). Where grazing is less intensively practiced, this is usually due to limitation in water rather than to overgrazing.

% OF TOTAL SNOW LEOPARD RANGE	MONTANE GRASSLAND ECOREGIONS:
1.32	Altai alpine meadow and tundra
9.85	Bayau Har Mountains alpine steppe
30.52	Central Tibetan Plateau alpine steppe
1.75	Eastern Himalayan alpine shrub/meadow
3.67	Gandise Mountains alpine tundra
1.24	Ghorat/Hazarajat alpine meadow
1.45	Hindu Kush/Karakoram alpine meadows
0.52	Khangai Mountains alpine meadow
1.20	Northwestern Himalayan alpine shrub/meadow
3.23	Pamir alpine desert and tundra
0.54	Qaidam Basin saline meadow
3.74	Qilian Mountains subalpine meadow
0.64	Sayan alpine meadow and tundra
21.59	Southeastern Tibet Plateau alpine scrub meadow
7.54	Tian Shan alpine meadow and tundra
2.45	Trans-Himalaya alpine meadows
4.07	West Tibetan Plateau alpine steppe
1.64	Western Himalayan alpine shrub/meadow
3.01	Yarlung Zambo Valley alpine steppe

Table 1. Composition of the montane grassland biome in the snow leopard range by ecoregion

This table shows that the alpine scrub meadow of the Southeastern Tibet Plateau and steppe of the Central Tibetan Plateau are the predominant grassland ecoregions of the snow leopard range, followed by Bayau Har Mountains alpine steppe.

Across the region, there are different socio-economic and environmental factors that result in different grazing intensity trends. In Mongolia, grazing intensity has been increasing (Sankey, 2009), while in Kazakhstan, observed grazing intensity has been decreasing (Karnieli, 2008). Many locations in Mongolia are on the brink of being overgrazed due to a shift from highly-controlled collectives since the early 1990s, to an unregulated context at present (Sankey, 2009); here, cattle densities have doubled and sometimes tripled. In Mongolia, much of the growth in herd size has been in goats, which can be particularly damaging to grazing lands. This increase is largely driven by the rising price for raw cashmere in China (personal communication, John Farrington, 2013). In Tibet and Bhutan, by contrast, herd sizes are decreasing and grazing pressure declining, although grasslands continue to deteriorate anyway. This is largely due to increasing numbers of people digging for caterpillar fungus, which also inflicts damage to grasslands. High market prices for caterpillar fungus allow people to reduce their herd sizes and buy meat in the market, but with environmental effects, nonetheless (personal communication, John Farrington, 2013).

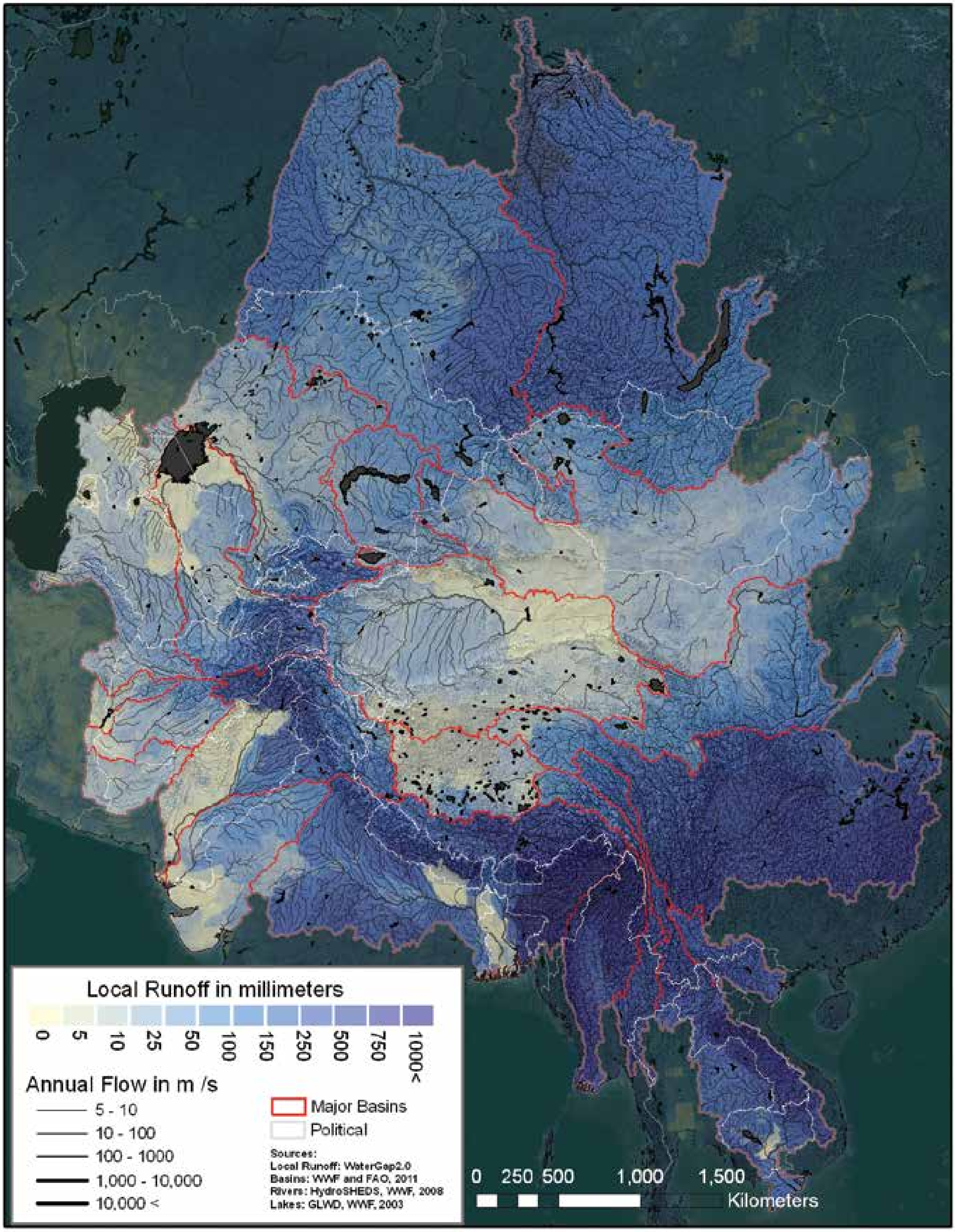
When considering water provision in terms of a land cover's ability to generate quantities (or quality) of water towards the downstream (local runoff), local water balances provide essential insights on the interaction between soil, vegetation and rainfall. In the most basic terms, the water balance can be understood as a function of precipitation and evapotranspiration:

Local Runoff* = *Precipitation – Actual Evapotranspiration

Where evapotranspiration concerns the total amount of water that is evaporating from a soil and that is transpiring from its vegetation, among other factors, temperatures form a major driver of evapotranspiration; higher temperatures mean higher evapotranspiration.

The water balance assumes a certain status quo between runoff, precipitation and evapotranspiration. Yet precipitation is a limiting factor to the productivity of montane grasslands (Yamanaka, 2007). Montane grasslands have become a dominant vegetation type because they are the only land cover that grows under such limited rainfall regimes. Zemmrich (2010) references this as "*the non-equilibrium paradigm (NEP) of rangeland dynamics.*" The highly variable grassland biomass productivity can be understood mainly by the highly variable rainfall patterns (Zemmrich, 2010). The reason that montane grasslands do not form good water provision habitats is that they are themselves limited by water availability. In wet years, rainfall gets allocated into extra biomass productivity; in dry years, "grasses can survive under limited rainfall" (Zhao, 2005; Zemmrich, 2010). Thus, they serve the essential function of *buffering* or *absorbing* most rainfall (for Mongolia: Yamanaka, 2007; for US dry regions: Lauenroth, 2012, also Yamanaka, 2007). This absorbing function of grasslands limits connectivity with downstream river systems; extra rainfall is first allocated by plants and soils to balance their deficiencies, and then to increase biomass productivity.

Water Towers



Sources:
Local Runoff: WaterGap2.0
Basins: WWF and FAO, 2011
Rivers: HydroSHEDS, WWF, 2008
Lakes: GLWD, WWF, 2003

WATER TOWERS

This water tower map shows each terrestrial area, river and stream's contribution to overall annual river basin flows (or runoff) within each of the major basins.

Different geographic patterns stand out in the water tower analysis:

- **In all basins under consideration, the snow leopard range covers at least part of the headwaters of the basin.**

- **The upper reaches of the Indus, Amu Darya and Syr Darya in the west form critical water towers**, with a very large proportion of water flowing from the upstream mountain ranges.

- **The Himalayas represent an important water tower that reflects the large amount of precipitation that occurs as part of the South-Western Monsoon**. But the lower parts of the Brahmaputra Basin (below snow leopard habitat) capture the largest amount of monsoon rainfall, and these areas classify as the world's wettest area. From East to West along the Himalayas, the amount of monsoon precipitation gradually decreases; but concurrently, the overall importance of the high Himalayas' monsoon flow contribution increases compared to flow contributions from the lower western basins.

- **Asia's internal, or endorheic, basins are hydrologically fragmented and disconnected from wide-ranging downstream impacts, and thus do not emerge as important water towers.** Endorheic basins—the Gobi Interior, Tarim Interior and Tibetan Plateau—make up a considerable part of the snow leopard range (36.6%). From a water resources perspective, these areas provide marginal amounts of water to sparsely populated areas. The human populations in these areas probably depend on more seasonal and rainfall-based distributions of water resources. These endorheic basins are too arid to support large perennial river systems, making them very sensitive to relative small changes in weather and climatic conditions.

- **The headwaters of the Northern rivers (Ob, Yenisey) contribute less runoff than the downstream parts of the basin,** with the dryness of interior Asia around the Gobi desert. But the effects of seasonal snowmelt, and the frozen and iced conditions of these rivers, are not represented in this annual runoff balance. The effects of frozen conditions and snowmelt are analyzed further in the cryosphere maps, presented later.

Data sources:

Local runoff

WaterGAP 2.0, Döll et al., 2003

Hydrography

HydroSHEDS, 30s and 5 min resolution,
WWF, Lehner et al., 2008

River basins

HydroBasins, FAO and WWF, 2011

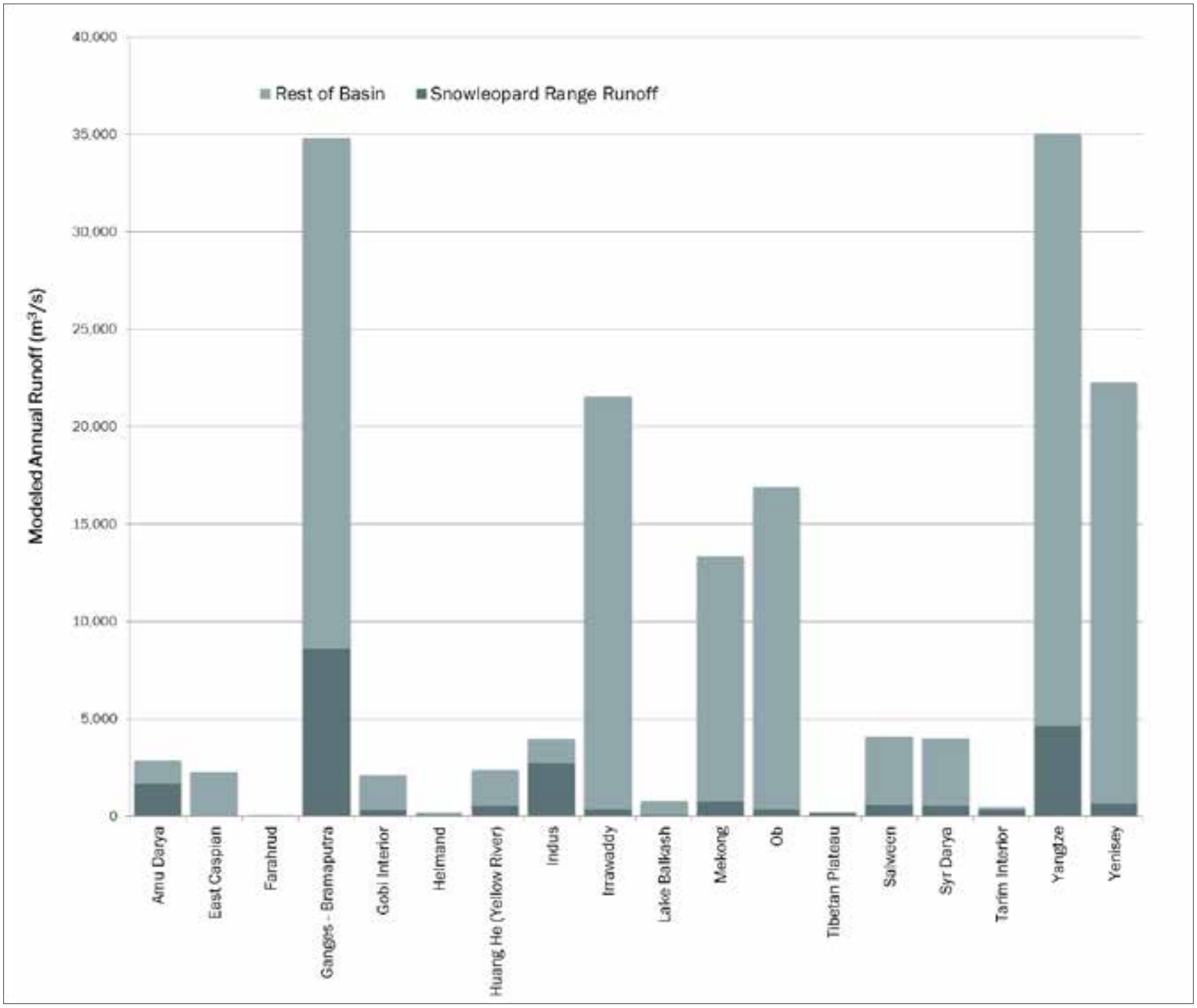


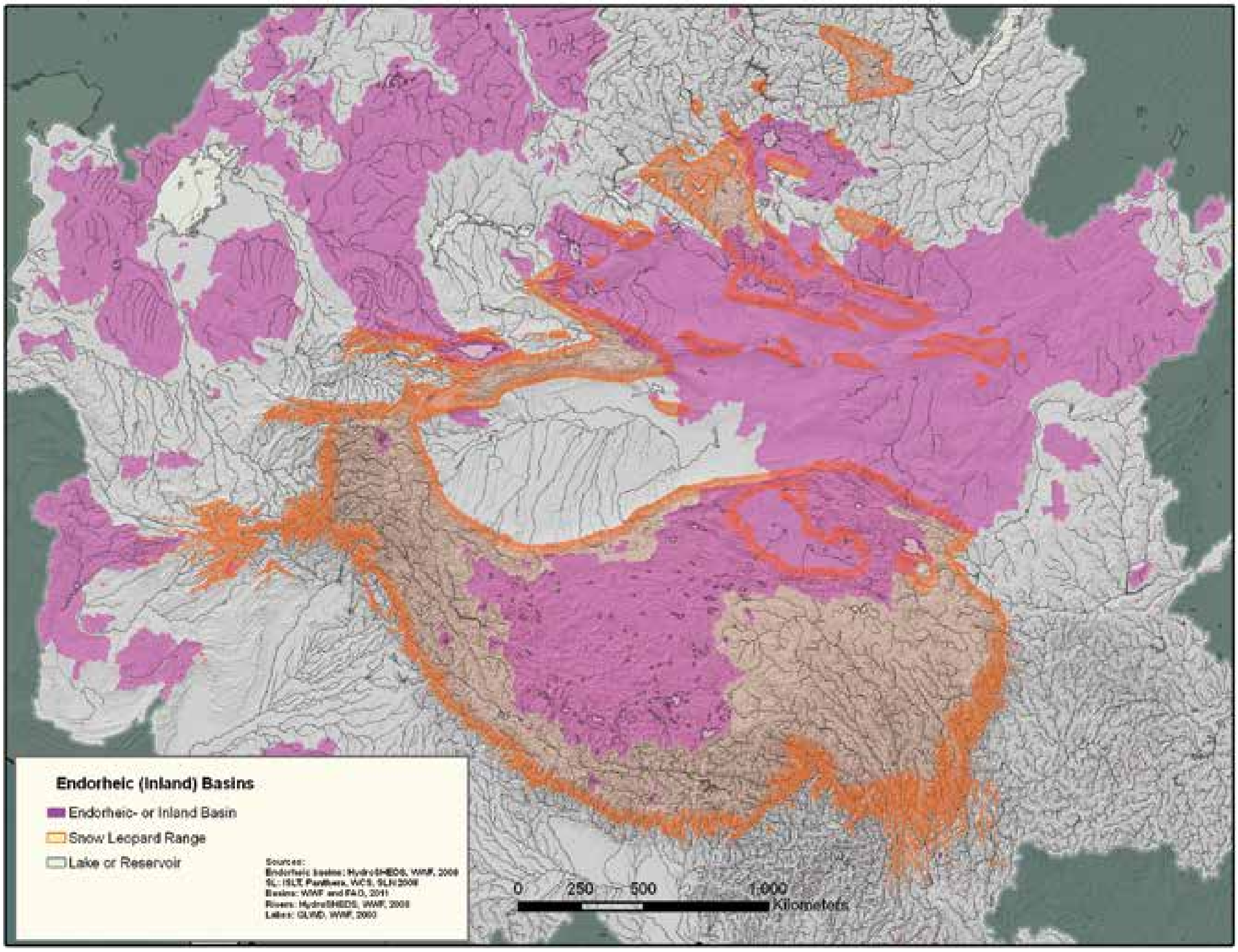
Figure 4. Total annual runoff by major basin, contributions of snow leopard range compared to rest of the basin

This figure shows that while the upper reaches of the Ganges-Brahmaputra and Yangtze River Basins contribute the largest amounts of runoff to their basins compared with other basins in the snow leopard range, the amount of basin runoff is proportionally small compared with the proportion of runoff from snow leopard habitat in the Indus and Amu Darya Basins.

Methods:

The WaterGAP model provides global runoff estimates based on the period 1961–1990 at a 0.5° grid. These were then summarized at the resolution of HydroBasins. Runoff values in millimeters were converted to flow contributions in m^3/s, and accumulated over HydroSHEDS drainage directions, resulting in the annual river discharge classes (river sizes on the map).

Endorheic Basins in the Snow Leopard Range



Sources:
Endorheic basins: HydroSHEDS, WWF, 2008
SL: ISLT, Panthera, WCS, SLN 2008
Basins: WWF and FAO, 2011
Rivers: HydroSHEDS, WWF, 2008
Lakes: GLWD, WWF, 2000

ENDORHEIC BASINS IN THE SNOW LEOPARD RANGE

Endorheic basins represent 36.6% of the snow leopard range. We defined these basins as those that have no significant connection to larger river systems. In this region, they are particularly arid basins, generating only 3.8% of the range's local runoff, which remains inside these basins.

Endorheic (or inland) basins are typically defined as river systems that do not drain into the sea and therefore offer limited connectivity. By that definition, the Aral, Balkash and Tarim Basins would be endorheic basins. Yet at the regional scale, these three basins do offer relevant connectivity functions, linking the snow leopard range to downstream water uses and human populations. For this analysis, we therefore identified endorheic basins of the snow leopard range as those inland basins smaller than 100,000 km^2.

Data sources:

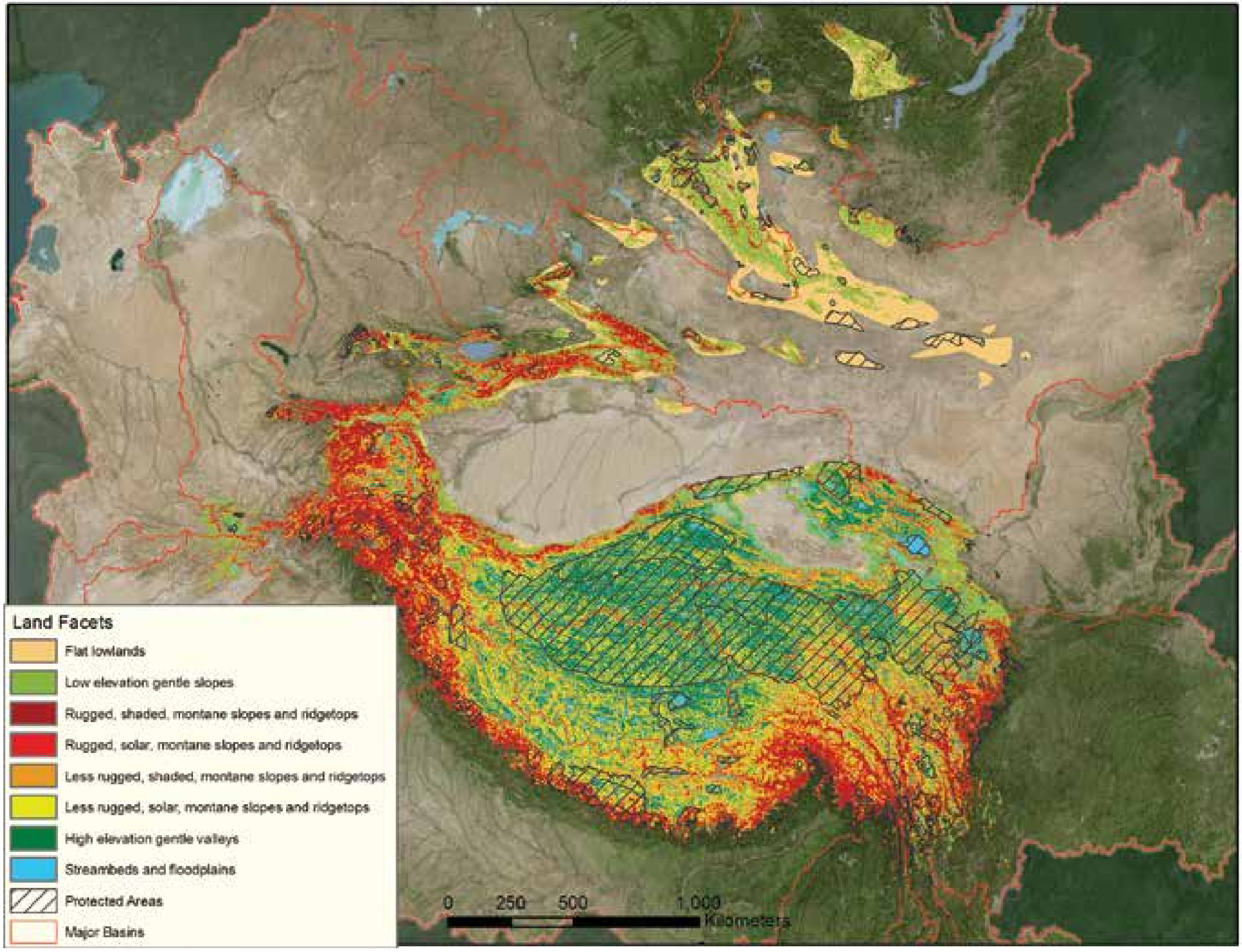
Hydrography, endorheic basins

HydroSHEDS, 30s and 5 min resolution,
WWF, Lehner et al., 2008

River basins

HydroBasins, FAO and WWF, 2011

Distribution of Land Facets as Proxies for Geophysical Diversity and Biodiversity



DISTRIBUTION OF LAND FACETS AS PROXIES FOR GEOPHYSICAL DIVERSITY AND BIODIVERSITY

This map shows the distribution of land facets in High Asia and the snow leopard range. Preserving geophysical diversity has been proposed as a way of building resilience into conservation plans aimed at conserving biodiversity under climate change (Anderson & Ferree 2010). Geophysical diversity, which includes slope, elevation, soil type, solar insolation and topographic position, is expressed here as units called land facets. Ensuring that the protected area network represents each land facet, and connectivity between facets, may help ensure that the evolutionary components for biodiversity are preserved (Beier & Brost 2010). Currently, the protected area network in this region shows under-representation of specific land facets, particularly flat lowlands, low elevation gentle slopes, and rugged montane slopes and ridgetops (Governali et al., 2010).

Methods:

Following Heiner et al. (2013), an isocluster algorithm was employed to bin every pixel into one of eight statistically distinct classes, based on four input layers: elevation, ruggedness, solar insolation and topographic wetness (as a proxy for geographic position).

Data sources:

Land facets (input layers below)

Land Facets, Governali, Rowe, and Wheelock, 2013

Elevation

15s Void-filled DEM, WWF Hydrosheds, Lehner et al., 2008

Ruggedness

Vector Ruggedness Measure, using a 81 cell (20.25 km^2) moving window, Sappington et al., 2007

15s Void-filled DEM, WWF Hydrosheds, Lehner et al., 2008

Compound topographic index

Moore et al. 1991; 15s Flow Accumulation, WWF Hydrosheds, Lehner et al., 2008

'upslope area = (flow accumulation + 1) x 250,000' and 'TWI = ln(upslope area / tan(slope(radians)))'

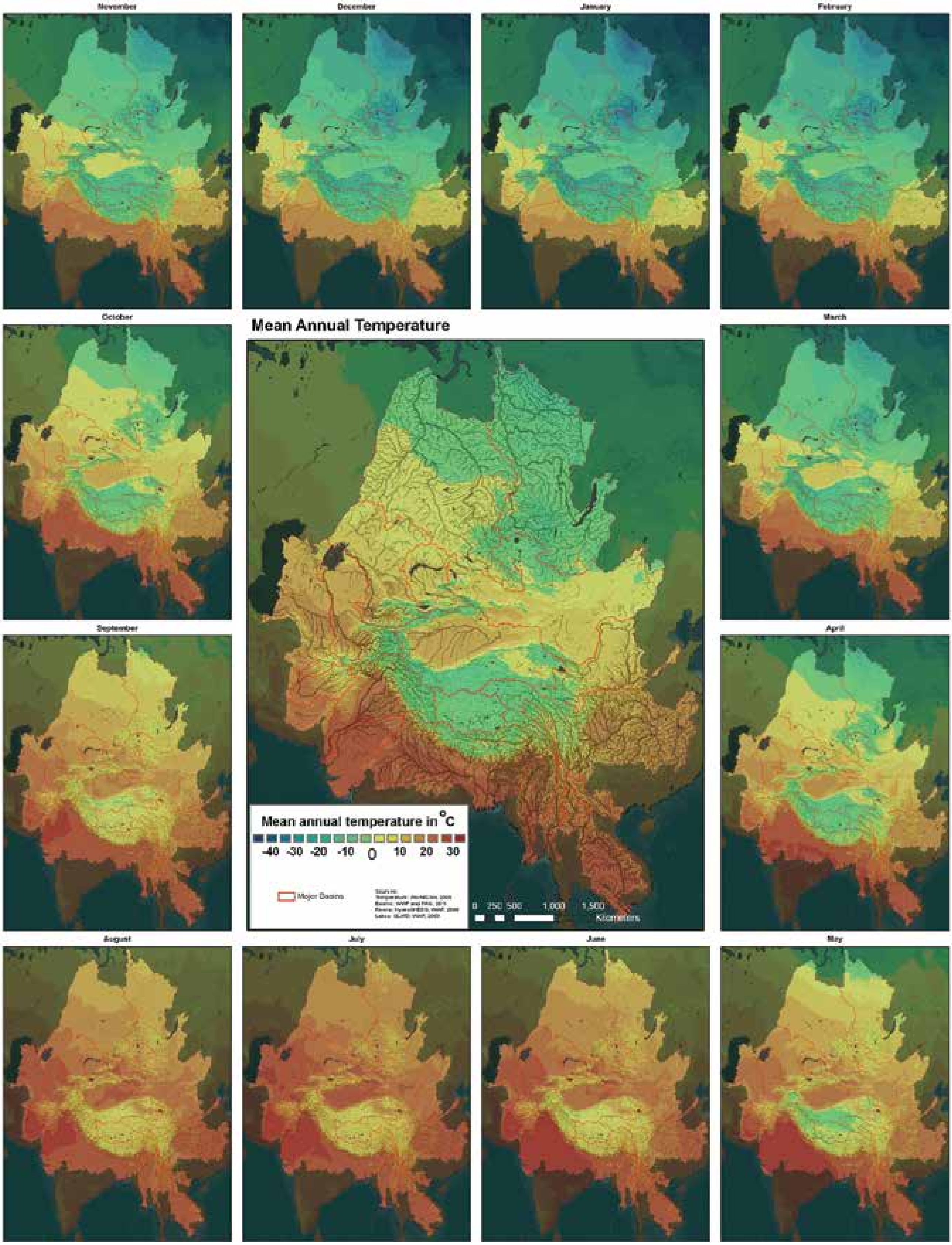
Solar insolation

15s Void-filled DEM, WWF Hydrosheds, Lehner et al., 2008

Calculated with ArcGIS Area Solar Radiation tool (ESRI, Redlands, CA) 200 m x 200 m sky size

Protected areas

IUCN and UNEP 2009, 2013



Mean Annual Temperature

MEAN ANNUAL TEMPERATURE

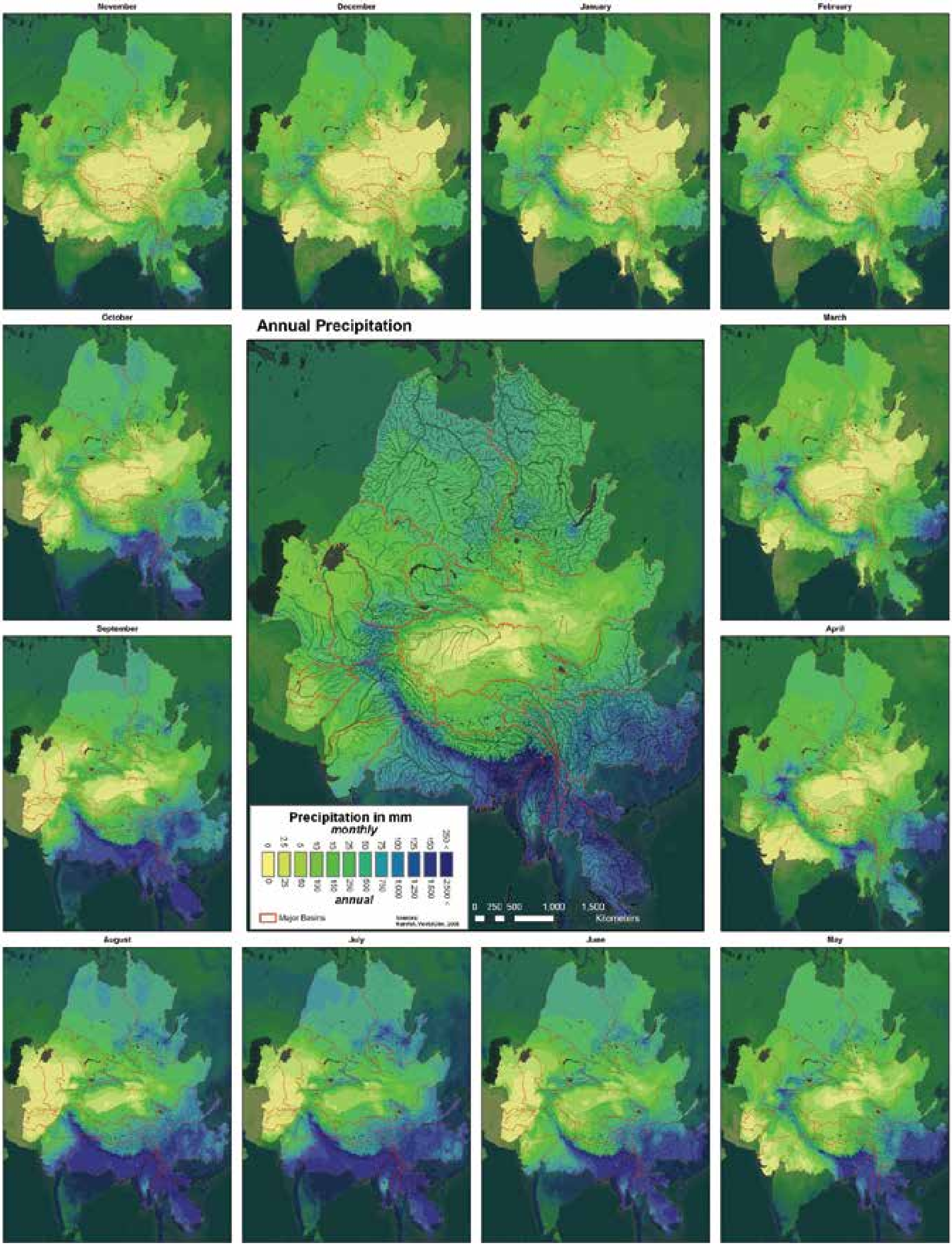
This map shows monthly temperature means over the 50-year period from 1950–2000. Since temperatures are highly correlated with elevation, the Tibetan Plateau stands out as an island in the temperature map. The entire region seems to be mostly frost-free for three months (June-July-August). There are no clear seasonal disparities at this scale; the distribution of April and October temperatures is very similar to the map of annual means. The frost range of the annual mean map shows a similar distribution as the snow leopard range.

In general, larger areas with flatter slopes (and flatter temperature gradients) are ecologically more sensitive to temperature rise (more likely to reach their tipping point). Large, flat areas (like the Tibetan Plateau) will offer less connectivity to temperature refuges, since the travel distance to suitable temperature ranges is a limiting factor. Second, because of the spatial extent, minimal shifts in temperature affect a large spatial footprint. Diffenbaugh et al. (2013) call this gradient "the velocity of climate change;" on their global map, the Tibetan plateau stands out as an area of higher climate change velocity.

Data sources:

Temperature

WorldClim at 30s resolution,
Hijmans et al., 2005,
http://www.worldclim.org


November
December
January
February
October
Annual Precipitation
March
September
April
Precipitation in mm
monthly
0
2.5
5
10
15
25
50
75
100
125
150
250 <
0
25
60
100
150
250
500
750
1,000
1,250
1,500
2,500 <
annual
Major Basins
0 250 500 1,000 1,500
Kilometers
August
July
June
May

ANNUAL PRECIPITATION

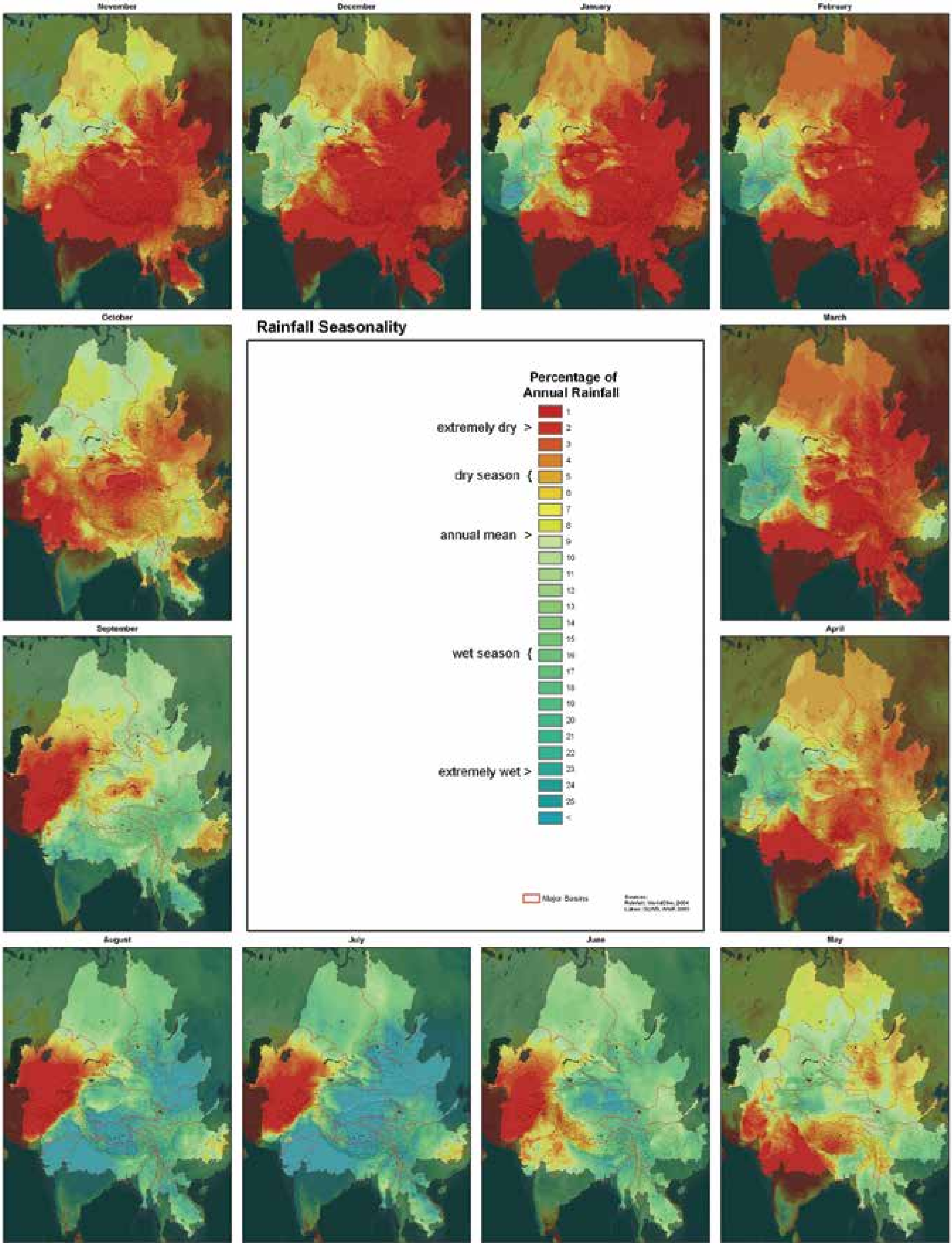
This map shows monthly precipitation means from 1950–2000. In the precipitation map, the mountain slopes stand out throughout the year. These mountain slopes also coincide with the boundaries of the snow leopard range, while the largest part of the snow leopard range covers a much drier area, in terms of precipitation.

The Eastern Himalayas and area south of the Himalayas receive the largest portion of the region's rainfall, delivered by the summer monsoon between May and September. The rest of the year, the western slopes of the Tibetan Plateau and the downstream of the Yangtze get the highest amounts of rainfall. Throughout the year, the Tarim Basin is the driest part of the region.

Data sources:

Precipitation

WorldClim at 30s resolution,
Hijmans et al., 2005,
http://www.worldclim.org


November
December
January
February
October
March
September
April
August
July
June
May
Rainfall Seasonality
Percentage of Annual Rainfall
extremely dry >
dry season {
annual mean >
wet season {
extremely wet >
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
<
Major Basins
Sources:

RAINFALL SEASONALITY

This map shows the relative seasonality of rainfall, with monthly precipitation as a percentage of annual rainfall. In this map, it does not matter whether a location receives 500 or 1,500 millimeters of precipitation on average a year; every location has its (relative) wet and dry seasons. It represents how people and environments are experiencing their local seasonality in precipitation.

The map illustrates that the floodplains of the Ganges and its tributaries suffer an extremely low precipitation condition for about eight months of the year (October to May), followed by a peak (monsoon) rainfall for four months (June to September). For the eight months, people and environment survive on minimal flows coming from the upstream Himalayan slopes.

Another insight based on this map is that the influence of the monsoon may stretch far beyond the northeastern of the Himalayas. From June to September, there is a wide band of seasonally high precipitation that generates a wet season running from the southwest to the northeast of this map. This pattern does not emerge as clearly on the precipitation map, because the precipitation quantities in the northeast are not notable at a regional scale, yet they are notable in terms of local seasonality.

The map also shows that the western basins (Amu Darya, Syr Darya) and the downstream of the Yangtze have a rainfall seasonality that is opposite to the monsoon influence; wetter seasons occur from October to May (in winter). Yet the headwaters of these basins do capture some of the monsoon during the summer months. Thus, downstream areas are quite dependent on hydrological connectivity to the upstream headwaters during the summer dry season.

For agricultural and pastoral systems, seasonality is at least as important as total precipitation. At the local scale, it is the combination of precipitation, seasonality and connectivity that drives migratory movements.

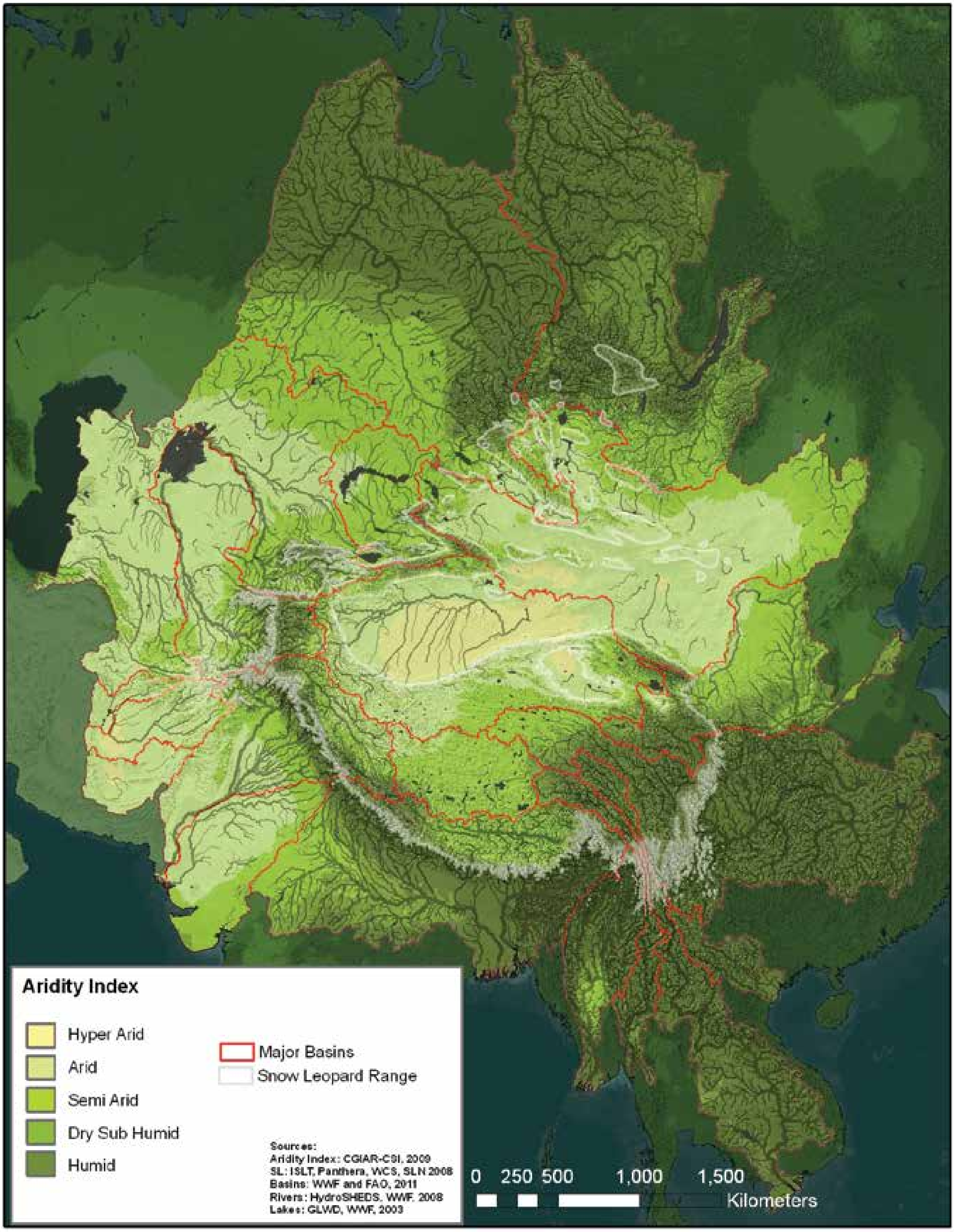
For climate change, these maps illustrate where extreme dry or wet spells are taking place on a yearly basis. If, for example, under climate change, dry areas become drier and wet areas become wetter, this map shows where these areas would be located, and for how long more extreme seasons would last.

Data sources:

Precipitation

WorldClim at 30s resolution,
Hijmans et al., 2005,
http://www.worldclim.org

Aridity Index



Sources:
Aridity Index: CGIAR-CSI, 2009
SL: ISLT, Panthera, WCS, SLN 2008
Basins: WWF and FAO, 2011
Rivers: HydroSHEDS, WWF, 2008
Lakes: GLWD, WWF, 2003

ARIDITY INDEX

Aridity is a measure of dryness and is defined as the status of being without moisture. The Aridity Index describes the extent that rainfall is the limiting factor in soil-vegetation productivity. The map shows that the snow leopard range is a largely semi-arid to arid area, but the North-Western regions (Indus, Amu Darya, Syr Darya) also overlap with mountain ranges that stand out as wetter islands in relative arid zones.

Arid areas exhibit the following tendencies with respect to changes in precipitation, such as those expected under climate change:

- Arid areas are very sensitive to decreases in rainfall, or increased temperatures, which result in decreased productivity; and
- Increased rainfall in arid areas usually results in increased vegetation productivity, but not necessarily increased runoff. Increasing precipitation in arid areas is less likely to increase runoff patterns, since a significant amount of that rainfall is allocated towards evapotranspiration.

Data sources:

Aridity

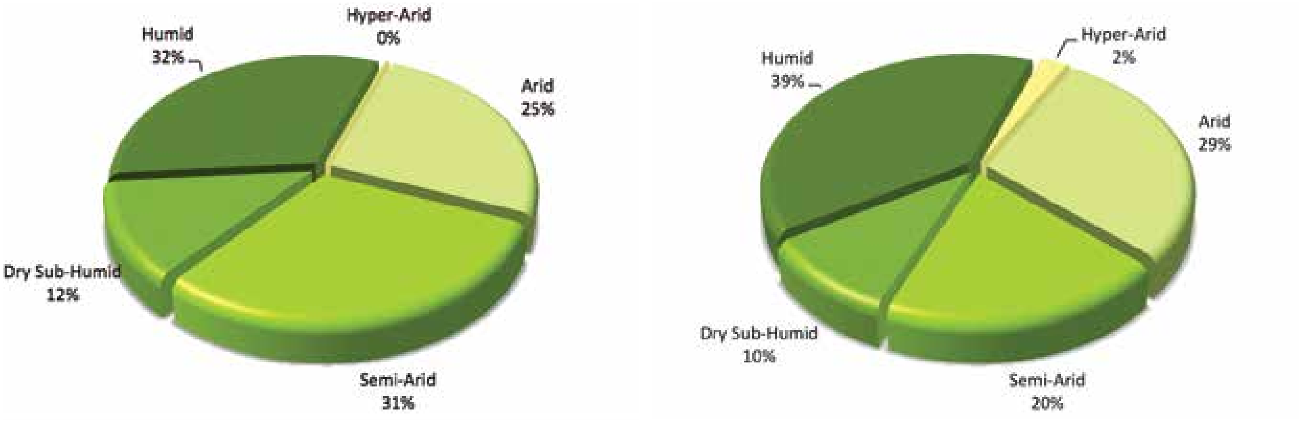
Global Aridity Index, CSI-CGIAR, Trabucco et al., 2009

Hydrography

HydroSHEDS, 30s and 5 min resolution
WWF, Lehner et al., 2008

River basins

HydroBasins, FAO and WWF, 2011



Aridity distribution of the entire region

Aridity distribution in the snow leopard range

Figure 5. Aridity distribution in the snow leopard range

This figure shows that snow leopards tend to thrive in a variety of aridity zones (except hyper-arid), but they are particularly adapted to semi-arid zones. This analysis suggests that snow leopards may fare relatively well across a variety of future precipitation scenarios. In terms of water provision, the humid and sub-humid zones in the snow leopard range (representing 44% of the area) are the predominant contributor to downstream water supply, and the arid zones contribute relatively minute amounts of runoff.

Methods:

The Aridity Index is a function of precipitation and potential evapotranspiration (PET) (Trabucco et al., 2009):

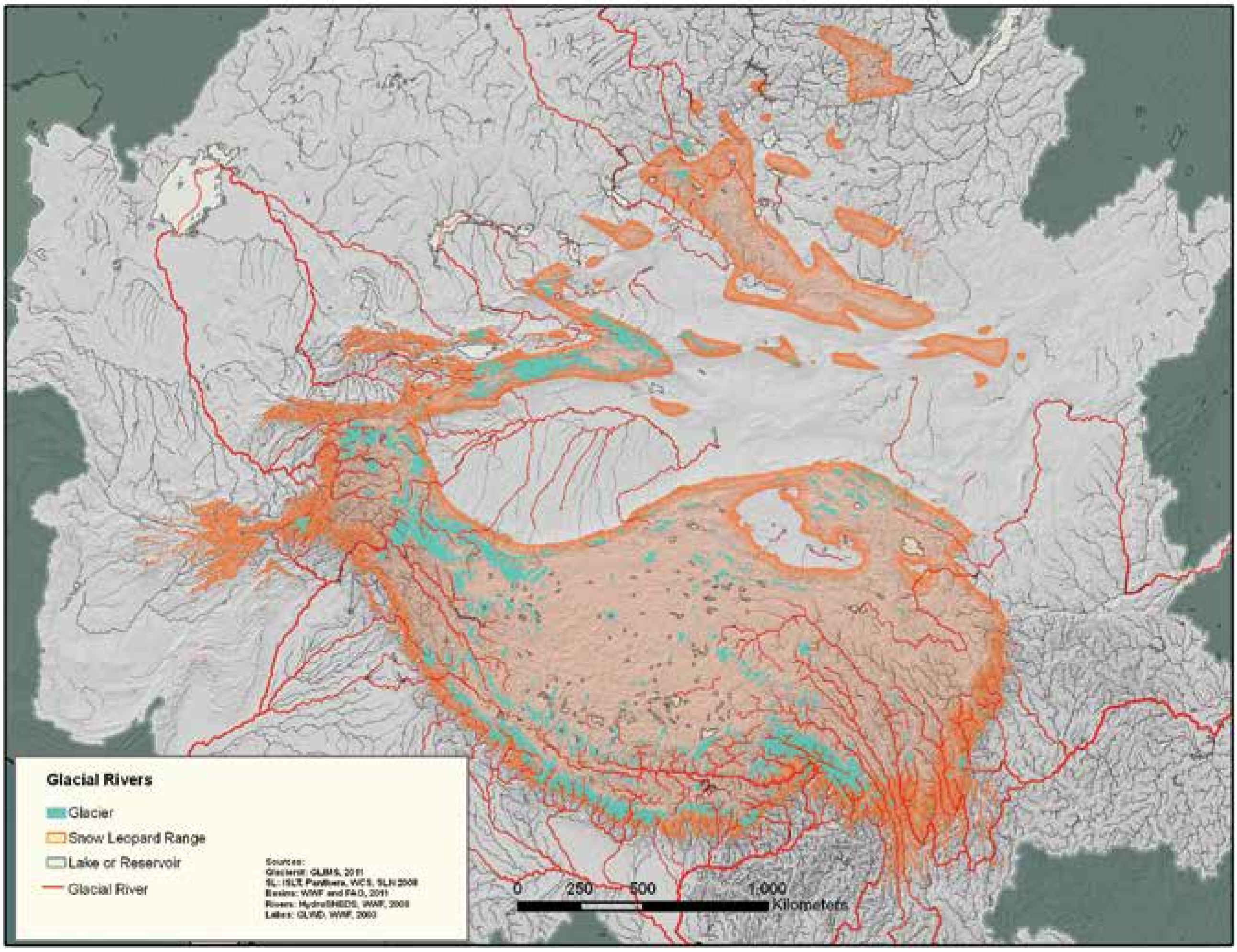
Aridity Index** = **Mean Annual Precipitation / Mean Annual PET

where evapotranspiration *is a measure of the ability of the atmosphere to remove water through evaporation* (soil) *and transpiration* (vegetation) *processes* (Trabucco et al. 2009). PET *provides that measure under optimal conditions,* assuming there is enough water available. Aridity classes, as identified on the map, are (UNEP 1997):

CLASS	ARIDITY INDEX
Hyper-Arid	<0.03
Arid	0.03–0.2
Semi-Arid	0.2–0.5
Dry Sub-Humid	0.5–0.65
Humid	>0.65

This map is a version of the Global Aridity Index of the CSI-CGIAR (Trabucco et al., 2009) which comes at 30s (~1km) resolution. The classifications are based on figures provided with the data, and refer to the UNEP (1997) classification of aridity.

Glaciers and Glacial Rivers



Sources:
Glaciers: GLIMS, 2011
SL: ISLT, Panthera, WCS, SLN 2008
Basins: WWF and FAO, 2011
Rivers: HydroSHEDS, WWF, 2008
Lakes: GLWD, WWF, 2000

GLACIERS AND GLACIAL RIVERS

This map shows the distribution of glaciers and rivers sourced at glaciers in the snow leopard range. Depending on their geography, glaciers can form an important water source to the downstream during drier months of the year, often just before the start of the monsoon. Those water balance functions are sustainable as long as there is an overall balance of seasonal snow accumulation and glacial melt-off. Areas downstream of melting glaciers are at risk from Glacial Lake Outburst Floods (GLOF), and this risk may increase under shifting climate.

Data sources:

Glaciers

GLIMS, and NSIDC. 2005, updated 2012. GLIMS Glacier Database. Boulder, Colorado US: National Snow and Ice Data Center. http://dx.doi.org/10.7265/N5V98602.

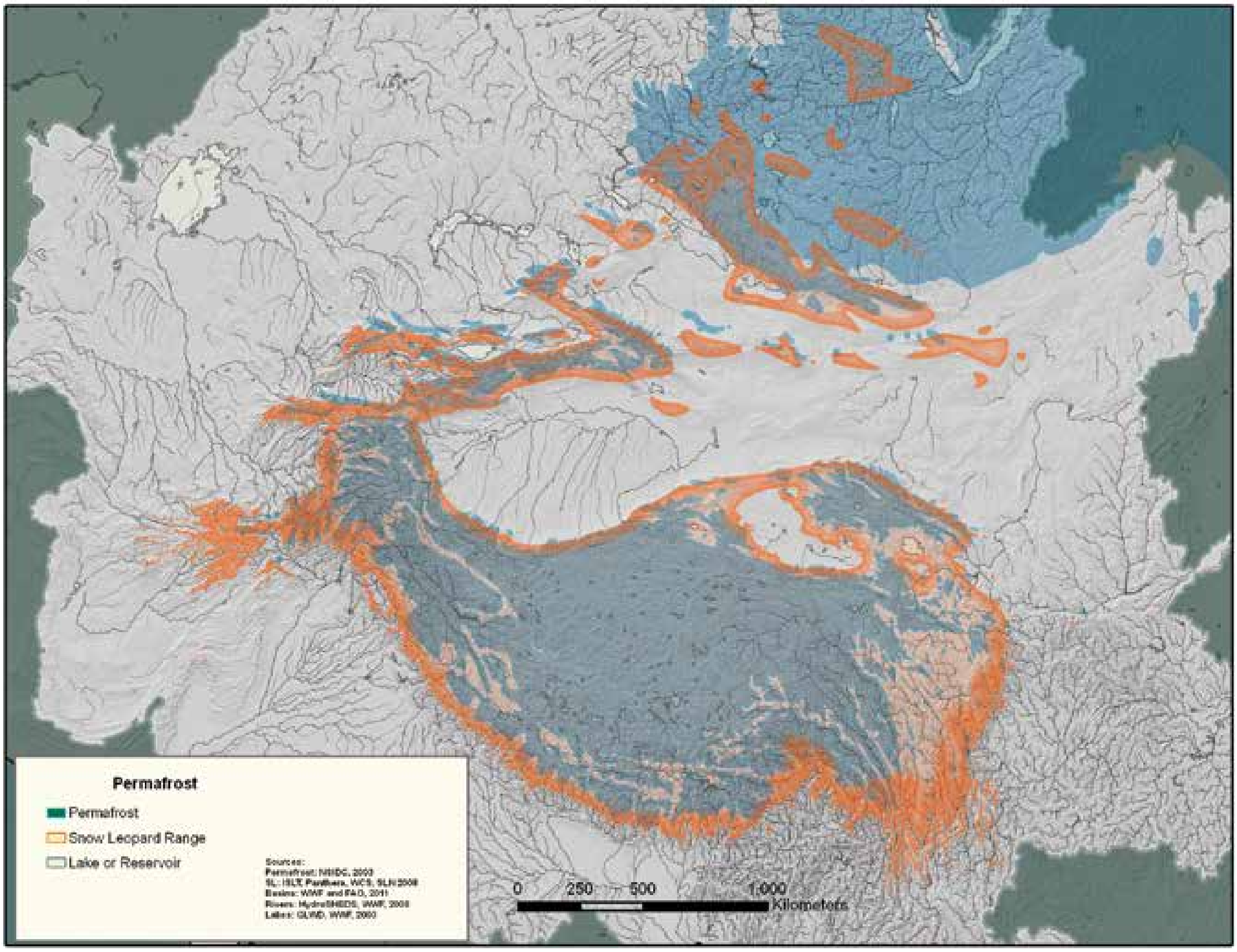
Greater snow leopard range

Combination of High Asia (>3,000 m) and Snow Leopard Range maps, ISLT, Panthera, SLN, WCS, 2008 and HydroSHEDS 15s Void-filled DEM, WWF, Lehner et al., 2008

River basins

HydroBasins, FAO and WWF, 2011

Permafrost


Permafrost
Permafrost
Snow Leopard Range
Lake or Reservoir
Sources:
Permafrost: NSIDC, 2003
SL: ISLT, Panthera, WCS, SLN 2008
Basins: WWF and FAO, 2011
Rivers: HydroSHEDS, WWF, 2008
Lakes: GLWD, WWF, 2000
0
250
500
1,000
Kilometers

PERMAFROST

There is overlap between the spatial extents of permafrost and the snow leopard range. Range-wide, and globally, dramatic impacts of climate change on permafrost have been reported. In many locations, the depth of permafrost is an important input to downstream hydrology; if permafrost decreases in depth or extent, this has important impacts for downstream hydrology and vegetation type. Most observations, however, have been very site-specific (e.g., on certain slopes in the headwaters of the Yangtze, or along the Tibetan highway), and thus cannot be consistently upscaled to the entire region.

In the headwaters of the Yangtze River, Wang (2011) found that wetter alpine meadows and swamps are much more sensitive to permafrost degradation than alpine steppe systems. Zhao-ping et al. (2010) describe two main succession processes in a global review of permafrost:

- Alpine meadows or swamps will get drier and be succeeded by steppe ecosystems or even desertify; and
- Lowland tundra forest types will get wetter and disappear into bog/marsh ecosystems (observed in Alaska/Canada).

They also note that, with melting permafrost, an immense amount of carbon will get mobilized. Though there are no generalizations possible on whether the changed lands will sequester or contribute to atmospheric carbon gases, like methane (CH4) and carbon dioxide (CO2), some areas were observed to emit increasing greenhouse gases, and have lost some sequestering capabilities. They mention that there is a lack of consistent and scientific observation on these processes, and more research is required. In the Qinghai-Tibetan Plateau, Zhao-ping (2010) noted that there is a general need for more research on the process and implications of permafrost degradation.

In their study of alpine permafrost under warming in the Tien Shan mountains, Marchenko et al. (2007) observe that the lower boundary of permafrost has moved 150 to 200m up in the 20th century. Here, permafrost seems to completely coincide with the snow leopard range and upper treeline. Permafrost on the southern slopes is notably 400 to 800m higher than on the northern slopes. Marchenko et al. (2007) mention the observed hazards associated with permafrost thawing, slope instability, landslides, thermokarsts and mudflows.

Data sources:

Permafrost

Circum-Arctic Map of Permafrost and Ground-Ice Conditions v.2, Brown et al., 2002

Greater snow leopard range

Combination of High Asia (>3,000 m) and Snow Leopard Range maps, ISLT, Panthera, SLN, WCS, 2008 and HydroSHEDS 15s Void-filled DEM, WWF, Lehner et al., 2008

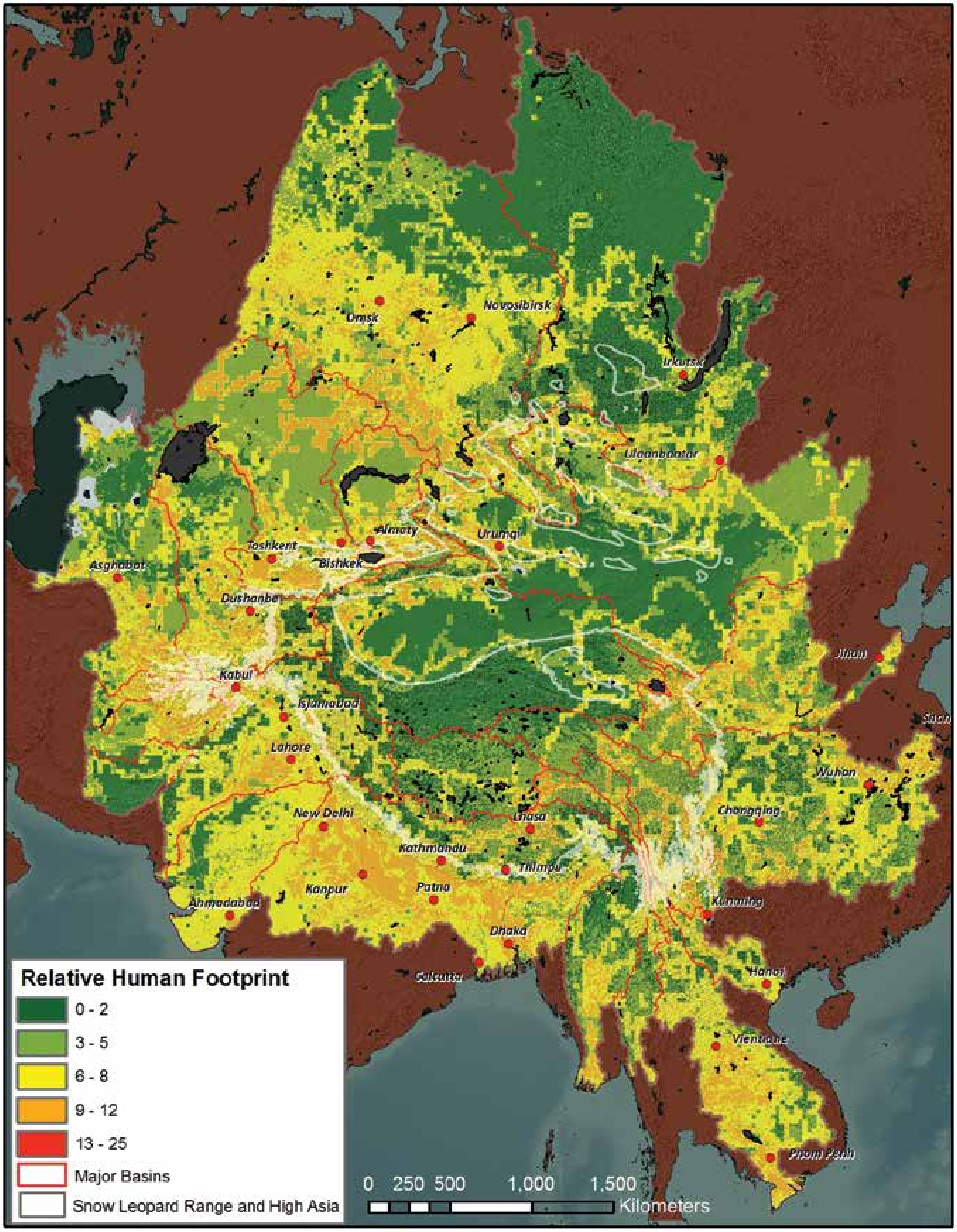
Hydrography

HydroSHEDS, 30s and 5 min resolution, WWF, Lehner et al., 2008

River basins

HydroBasins, FAO and WWF, 2011

The Human Footprint



THE HUMAN FOOTPRINT

The human footprint represents relative human impact caused by land use and accessibility. It also shows areas that have experienced relatively little impact from humans and that represent the most intact habitat areas. Areas of relatively low human impact are expected to maintain more natural resilience under climate change for biodiversity and water security.

Human disturbance can lead to habitat loss and fragmentation, human wildlife conflict and pollution. Where human disturbance exists, the exploitation of natural resources such as water may also be high. High human footprint areas may be more vulnerable to climate change, by compromising species' ability to move or adapt to habitat changes. For people, high rates of water diversion in high human footprint areas may reduce water availability to the system during droughts. Disturbed land next to rivers can compromise their ability to buffer floods.

It is particularly important to manage human activities with relation to snow leopards and water supply in areas that are important for water provision (such as the Indus, Amu Darya and Syr Darya watersheds), and important and resilient for snow leopards (especially the central and western Himalaya, Tibetan plateau and mountains of Central Asia). Conservation practices should encourage activities targeting habitat restoration, reconnecting fragments, and managing water from source to sea.

Data sources:

Population
GRUMP v1, 2011.

Roads
OpenStreetMap, 2013.

Land cover
GlobCover, 2009.

Pasture
Global Agricultural Lands, Ramankutty et al., 2010.

Land degradation
Decrease in net primary productivity (1981–2006), Bai et al., 2008

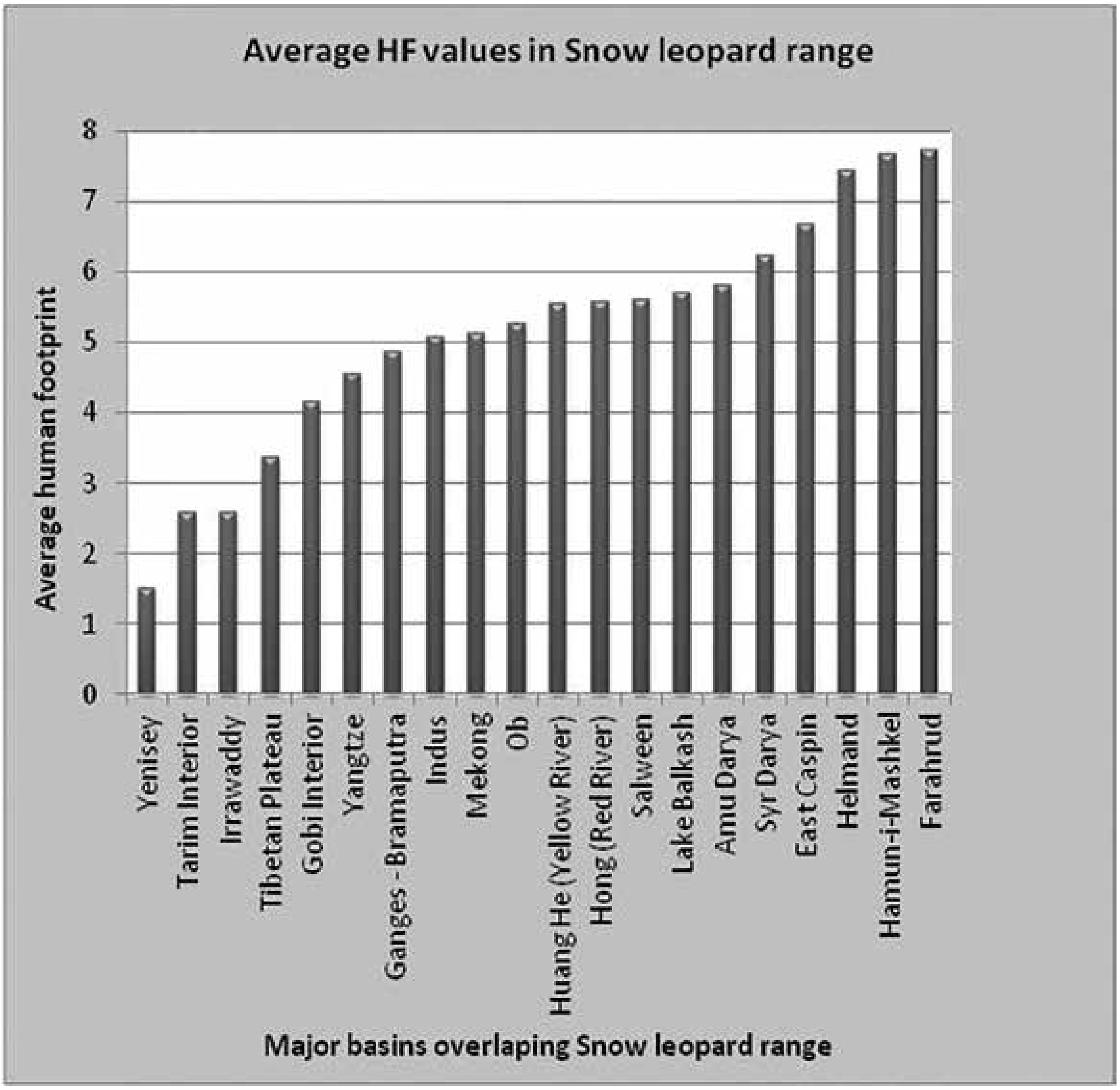


Figure 6. Average human footprint values within the snow leopard range

Average human footprint values within the snow leopard range vary from about 1.5 to almost 8. Among basins of particular importance to snow leopards, the Amu Darya and Syr Darya Basins have high human footprint values; the Ob, Mekong, Ganges-Brahmaputra and Indus have moderate footprints; and the Tarim Interior and Tibetan Plateau have the lowest human footprints.

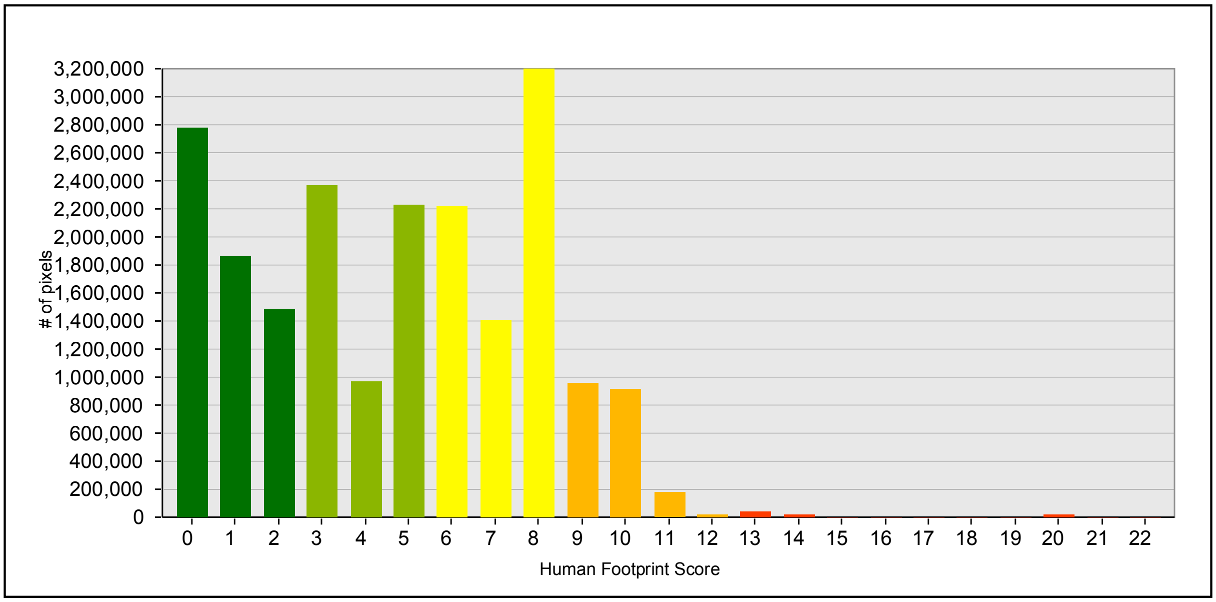


Figure 7. Distribution of Human Footprint Values across Major Basins

This graph shows the general distribution of human footprint scores across major basins that overlap the snow leopard range and High Asia. Scores range from 0 to 25 (with 25 as the highest human footprint score), with the majority of pixels in the range of 0 to 10. This is in contrast to the human footprint published by Sanderson et al. (2002), which normalizes scores to a scale of 0 to 100.

Methods:

We used five input layers to create the human footprint: population density, distance to roads, change in net primary productivity (1981–2006), percent pasture area, and land use/land cover. Each of the five layers were reclassified into standardized scores reflecting their estimated contribution to human impact on terrestrial habitat, using a scale of 0 to 10 (0 for low human footprint and 10 for high human footprint) as shown in Tables 2, 3, 4, 5 and 6. A weighted average was computed on the five layers (with the following weights: land cover = 3; population density = 2; distance to roads = 2; net primary productivity (NPP) change = 1; Pasture = 1), averaging over the number of layers with data at a particular pixel.

Table 2. Human footprint scores for population layer (# of people per km²)

OLD VALUES	HF SCORES
0–10	0
10–20	1
20–40	2
40–70	4
70–100	5
100–200	6
200–300	7
300–400	8
400–500	9
500–75848.01563	10

Table 3. Human footprint scores for road layer (meters from road)

OLD VALUES	HF SCORES
0–1000	10
1000–3000	6
3000–5000	2
5000–576469.4375	0

Table 4. Human footprint scores for pasture layer (proportion pixel occupied by pasture)

OLD VALUES	HF SCORES
0	1
0.00–0.25	2
0.25–0.50	3
0.50–1.00	5

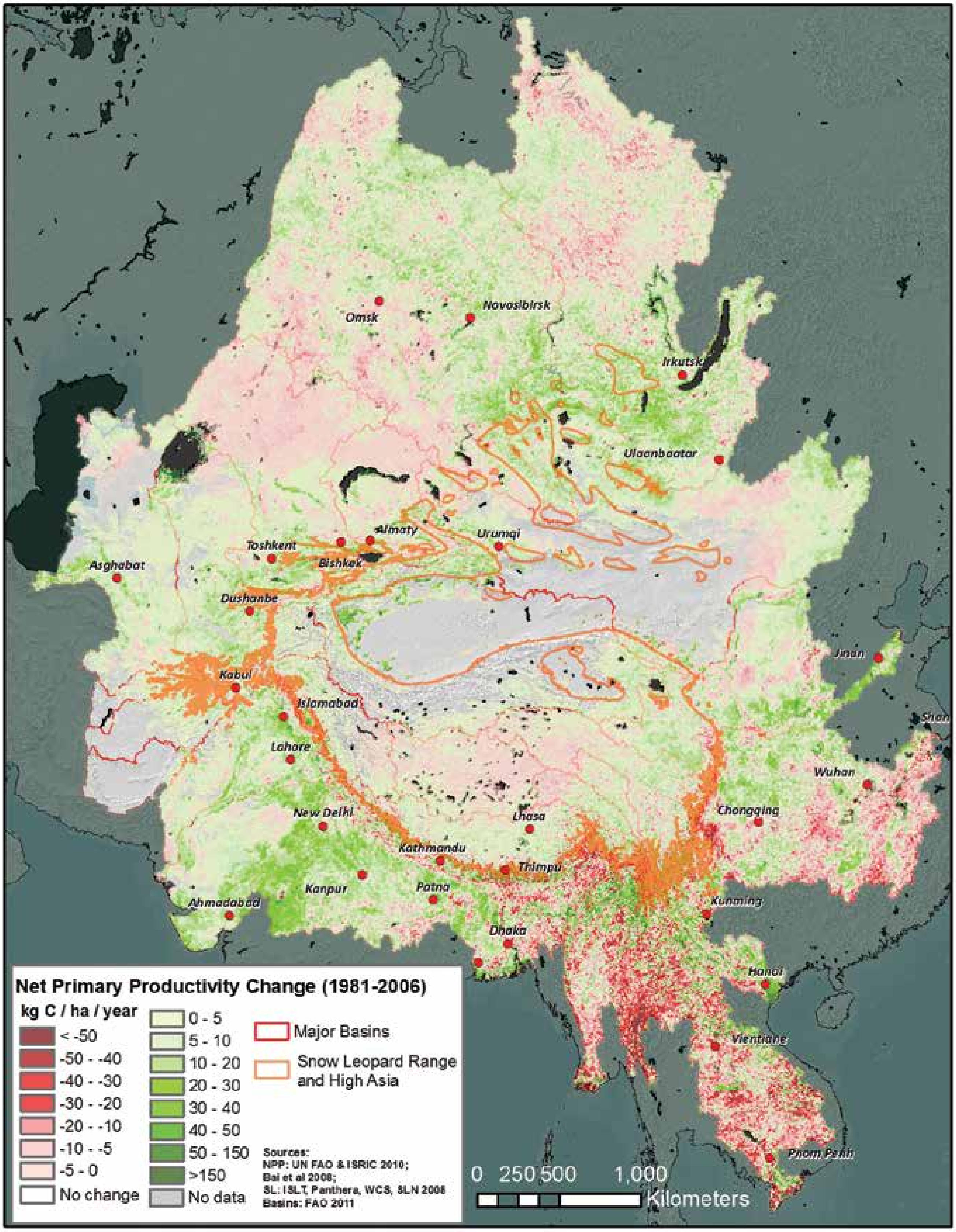
Table 5. Human footprint scores for land degradation (NPP change) layer (change in Kg C/ha/year from 1981–2006)

OLD VALUES	HF SCORES
-1129.270775195– -50	10
-50– -30	9
-30– -25	8
-25– -10	7
-10– -0	6
0–2812.40161133	0

Table 6. Human footprint scores for land cover layer

VALUE	LABEL	HF SCORES
11	Post-flooding or irrigated croplands (or aquatic)	7
14	Rainfed croplands	6
20	Mosaic cropland (50–70%) / vegetation (grassland/shrubland/forest) (20–50%)	5
30	Mosaic vegetation (grassland/shrubland/forest) (50–70%) / cropland (20–50%)	4
40	Closed to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)	0
50	Closed (>40%) broadleaved deciduous forest (>5m)	0
60	Open (15–40%) broadleaved deciduous forest/woodland (>5m)	0
70	Closed (>40%) needleleaved evergreen forest (>5m)	0
90	Open (15–40%) needleleaved deciduous or 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
120	Mosaic grassland (50–70%) / forest or shrubland (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
150	Sparse (<15%) vegetation	2
160	Closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily)—Fresh or brackish water	0
170	Closed (>40%) broadleaved forest or shrubland permanently flooded—Saline or brackish water	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
210	Water bodies	0
220	Permanent snow and ice	0
230	No data (burnt areas, clouds,…)	1000

Net Primary Productivity Change (1981-2006)



Sources:
NPP: UN FAO & ISRIC 2010;
Bai et al 2008;
SL: ISLT, Panthera, WCS, SLN 2008
Basins: FAO 2011

NET PRIMARY PRODUCTION CHANGE (1981–2006)

This map depicts general trends in net primary productivity (NPP) change from 1981–2006, as measured by satellite image analysis. Changing productivity may occur due to land cover changes (such as transition from forest to non-forest or from grassland to bare ground), or transitions within plant communities from one set of dominant species to another. Indirect causes of NPP change are not evident from this map, but can include changes in human land use and disturbance, wildlife species use or climate driven changes. The relationship of NPP to climate change is two-fold: 1. Trends in NPP can occur as a result of climate change; and 2. Decreasing productivity may result in decreasing resilience to climate change.

We compared patterns of livestock density to degrading lands using global scale data (UN FAO-AGA 2005). We found an insignificant relationship between net primary productive change and livestock density (r=0.0052) (see Figure 8. below). It is important to note that this regional analysis was based on coarse-scale accumulations of all livestock types, which may mask more detailed conclusions that consider grazing species, number of concurrent grazers, timing of grazing, and natural carrying capacity. Local-scale studies, however, have noted the correlation between overgrazing by livestock and significant grassland degradation or even local extinction of wild grazers (Sankey, 2009, Mishra 2002). Degradation may be exacerbated due to certain types of grazers (goats) or the number of concurrently grazing species (Sankey 2009). It is also widely known that overgrazing can induce transitions toward more grazing-resistant species that might look “greener” from space (R. Shrestha, personal communication, 2013). While studies from space may not necessarily reveal decreases in productivity in response to grazing pressure, functional or nutritional productivity for grazers may decrease.

Data sources:

Global Change in Net Primary Productivity (1981–2006)
ISRIC and UN FAO, 2010,
Bai et al., 2010.

Livestock density, predicted distribution 2000, adjusted to match FAOSTAT 2000 totals
FAO-AGA, 2005

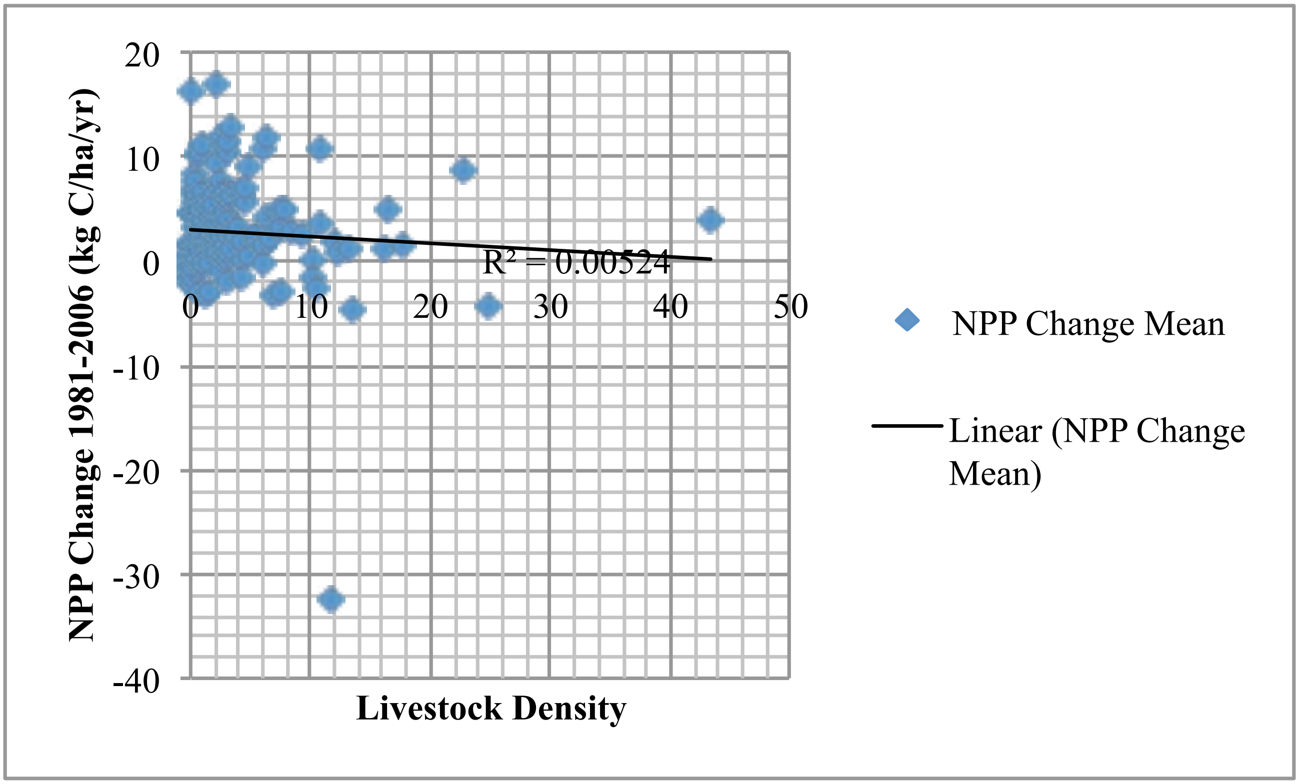


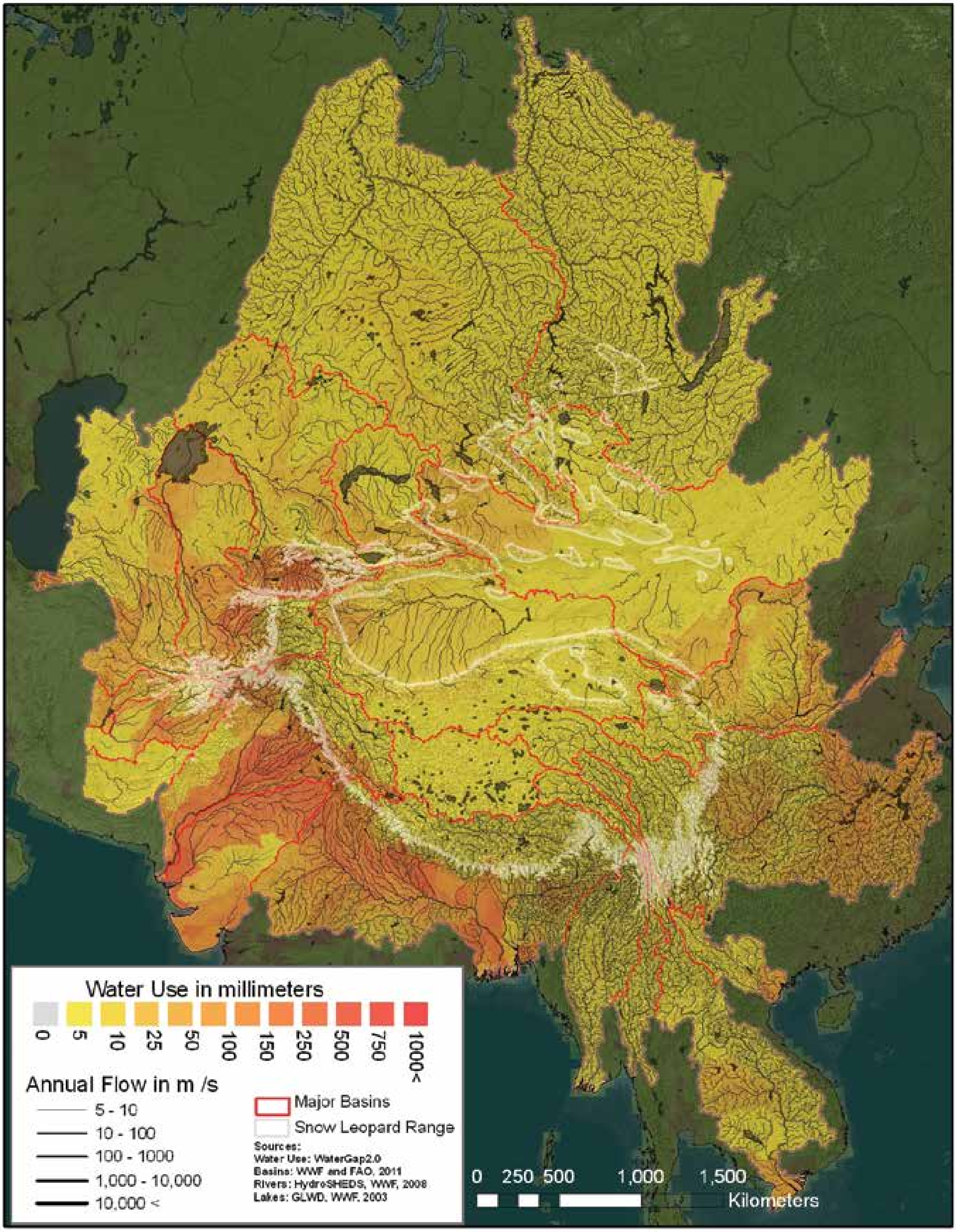
Figure 8. Correlation between NPP change and livestock density

The correlation between observed NPP change (1981–2006) and livestock density (2000) is insignificant by this analysis. In some cases, high livestock density was correlated with increasing NPP; in other cases, with decreasing NPP. However, the study is inconclusive and more research should be done to better understand patterns. Additional studies might consider livestock type and number of concurrently grazing species, finer scale livestock density datasets, livestock density at the start and end of the NPP study period, and grass species and transitions.

Methods:

Land degradation is defined here as a long-term decline in ecosystem function and measured in terms of NPP. Long-term NPP measurement is not available; the remotely-sensed normalized difference vegetation index (NDVI) is used as a proxy; its deviation from the norm may serve as an indicator of land degradation and improvement if other factors that may be responsible (climate, soil, terrain and land use) are accounted for. NDVI is a ratio measuring of photosynthetically active green biomass. The higher the NDVI, the more living green biomass can be found. There is a high correlation between NDVI and NPP; the Global Inventory Modeling and Mapping Studies (GIMMS) NDVI time series has been translated to NPP using MODIS NPP data (Justice and others 2002, Running and others 2004) for the overlapping period 2000–2006; i.e., NPP was estimated by correlation with MODIS eight-day NPP values for the overlapping years of the GIMMS and MODIS datasets (2000–2006), re-sampling the annual mean MODIS NPP at 1km resolution to 8km resolution using nearest-neighbor assignment.

Water Use



Sources:
Water Use: WaterGap2.0
Basins: WWF and FAO, 2011
Rivers: HydroSHEDS, WWF, 2008
Lakes: GLWD, WWF, 2003

WATER USE

This map illustrates that major water use takes place directly downstream of the snow leopard range, most notably in the southwestern basins (Amu Darya, Syr Darya, Indus and Ganges Rivers), as well as in the Sichuan Valley along the Yangtze River in Central China. These are important irrigated areas, and irrigation water use is overwhelming other water uses (such as domestic, industrial and livestock uses) (see Sectoral Water Use map next).

While this map shows water use, the key source areas (whether within or outside the snow leopard range) vary by basin. The main water source areas for the Ganges are the Himalayan slopes that capture most of the monsoon rains (see Water Tower map). These slopes are just below the elevation of the snow leopard range. In the Indus, Amu Darya and Syr Darya Basins, the overlap between snow leopard range and water source areas is much more explicit: most of the water there originates from source areas in snow leopard habitat, and the water use map shows that water is being used very intensively downstream.

The data on this map are from the WaterGAP 2.1 model (Döll et al., 2003) and translated to sub-basin resolution.

Data sources:

Water use

WaterGAP 2.1, Döll et al., 2003

Greater snow leopard range

High Asia (>3,000 m) and Snow Leopard Range,
ISLT, Panthera, SLN, WCS, 2008 and
HydroSHEDS 15s Void-filled DEM,
WWF, Lehner et al., 2008

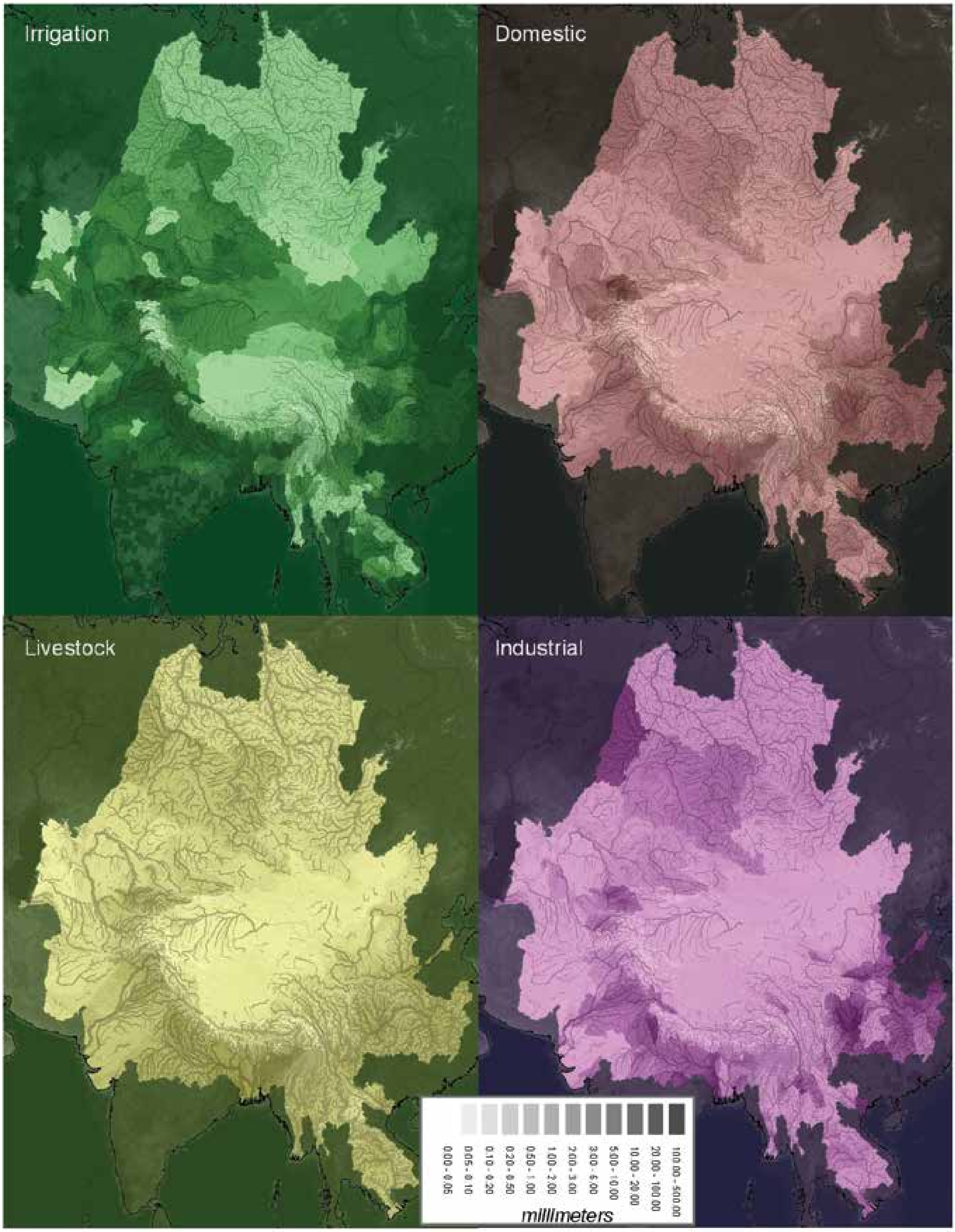
Hydrography

HydroSHEDS, 30s and 5 min resolution,
WWF, Lehner et al., 2008

River basins

HydroBasins, FAO and WWF, 2011

Sectoral Water Use



SECTORAL WATER USE

WaterGAP 2.1 describes global historic water use for four sectors: irrigation, domestic, livestock and industrial use. In every basin, the majority of water (~90%) is being allocated to irrigation.

Most of the water uses show a similar distribution to water towers and human population density (see these maps). In general, the Indus, Ganges and Sichuan (Yangtze) Basins are population centers, resulting in more intensive water uses for all sectors. In the northwest, the industrial water use of the Ob Basin stands out, though this is along a tributary with no upstream connection to the snow leopard range. These are very likely the Russian Ural industries surrounding Yekaterinburg.

Data sources:

Water use

WaterGAP 2.1, Döll et al., 2003

Hydrography

HydroSHEDS, 30s and 5 min resolution ,
WWF, Lehner et al., 2008

River basins

HydroBasins, FAO and WWF, 2011

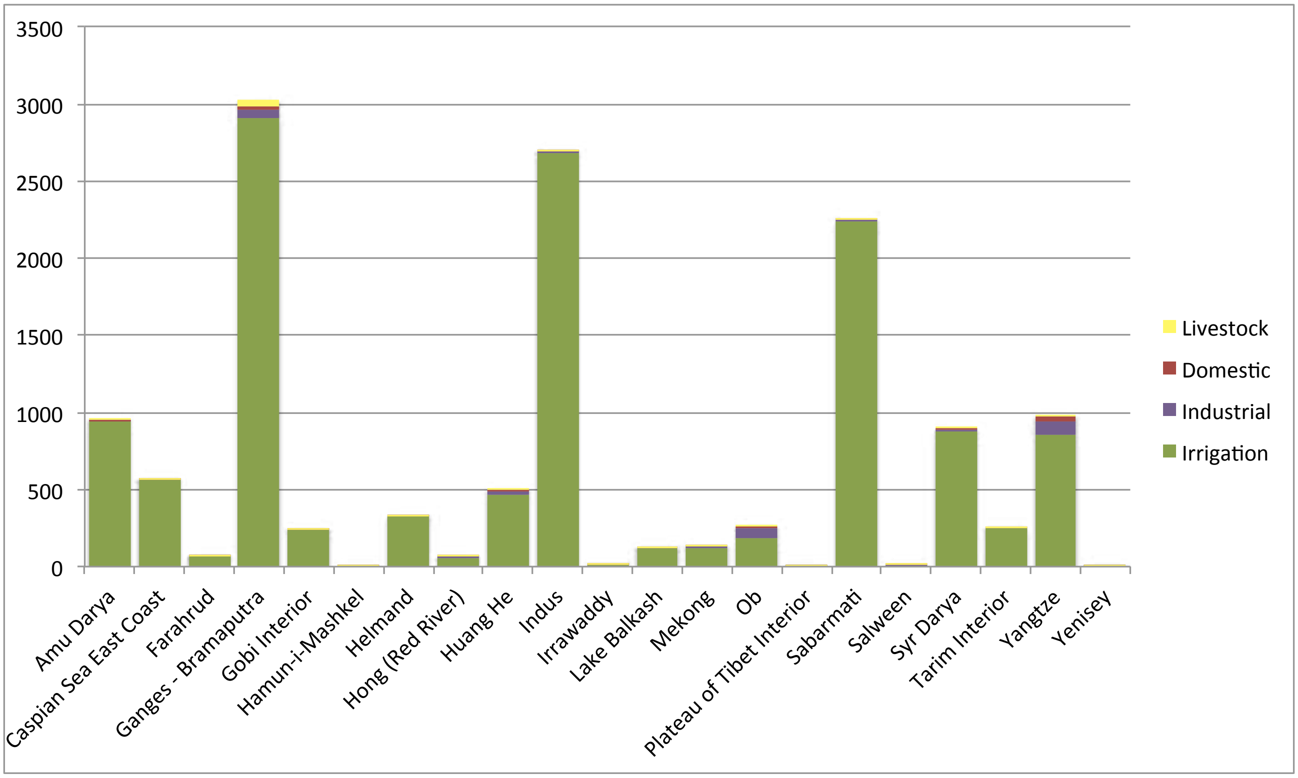


Figure 9. Annual sectoral water use by major basin in m^3/s *(source WaterGap 2.1)*

This figure shows irrigation as the predominant water use in all basins. The Ganges-Brahmaputra, Indus and Sabarmati are the largest consumers of water overall.

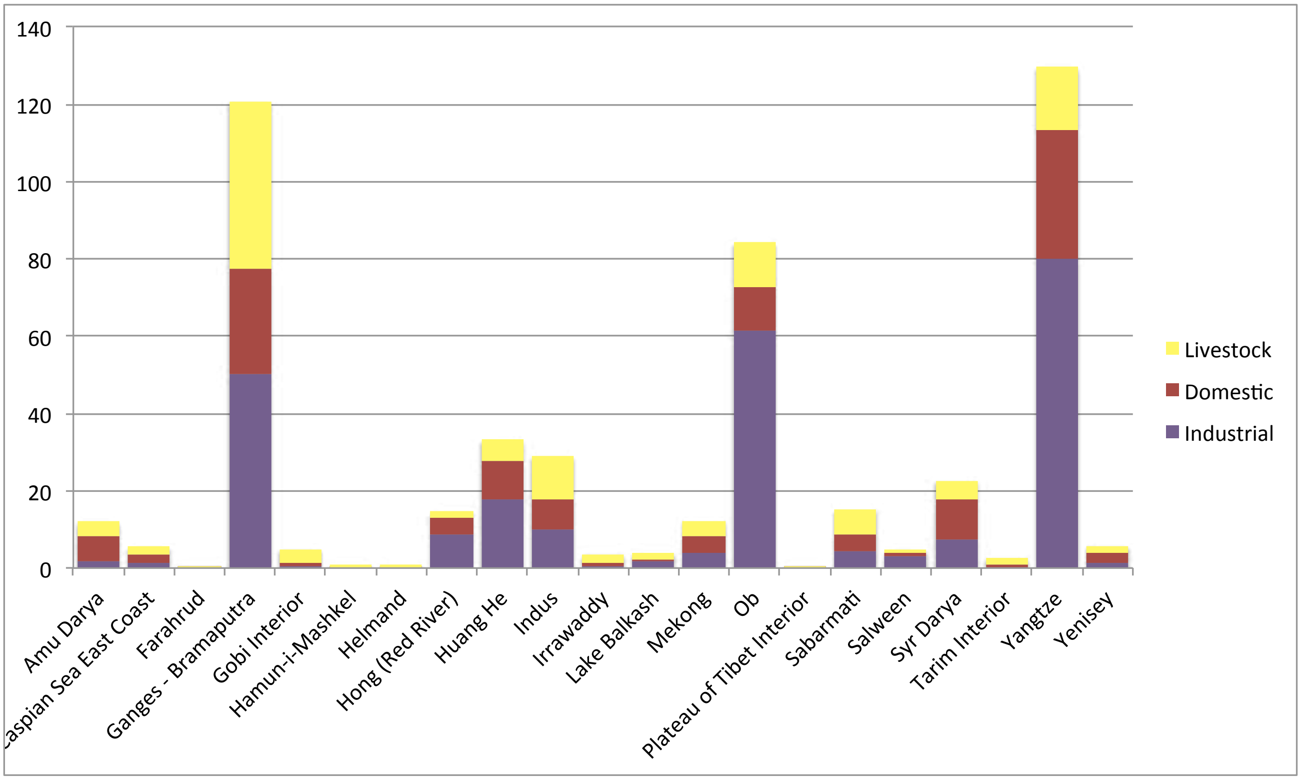
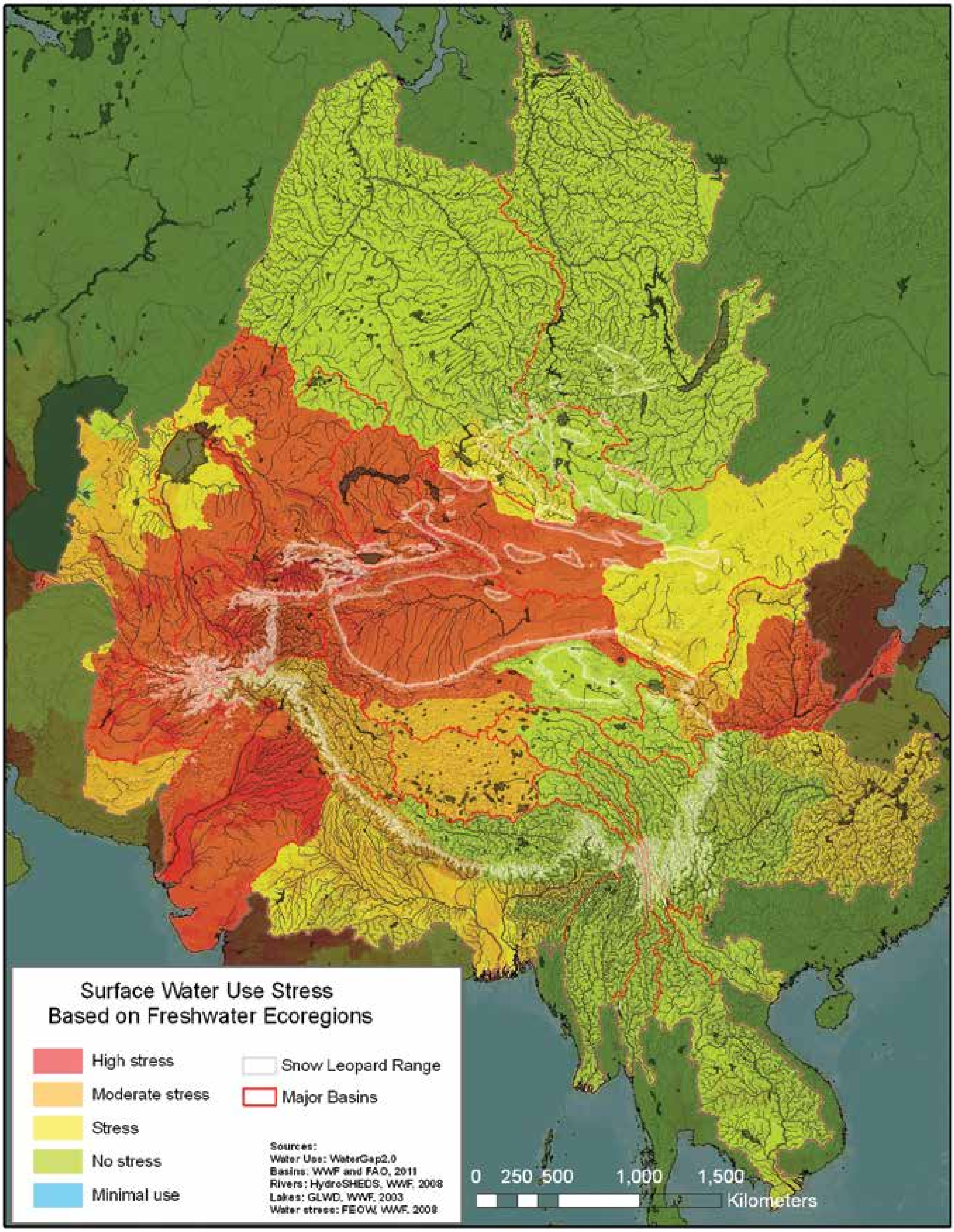


Figure 10. Annual sectoral water use by major basin in m³/s, excluding irrigation *(source: WaterGap 2.1)*

After irrigation, industrial is the second largest use of water. People in the Ganges-Brahmaputra, Ob, and Yangtze Basins consume the most water for industrial, followed by other non-irrigation purposes.

Surface Water Use Stress at the Freshwater Ecoregion Level



Sources:
Water Use: WaterGap2.0
Basins: WWF and FAO, 2011
Rivers: HydroSHEDS, WWF, 2008
Lakes: GLWD, WWF, 2003
Water stress: FEOW, WWF, 2008

SURFACE WATER USE STRESS AT THE FRESHWATER ECOREGION LEVEL

***Water stress is the relative use of water compared to what is running off in the rivers.* Water stress is an indicator of vulnerability of freshwater ecosystems, terrestrial species and human communities during dry seasons or years. Water stress can also indicate vulnerability to climate change, if accompanied by increasing droughts or trends toward aridity. Reducing water stress on rivers necessitates good water conservation activities, particularly with respect to irrigation and industrial uses.**

Methods:

Water stress is defined as the ratio of water use (i.e., surface water withdrawn for domestic, agriculture and livestock use) to water availability, measured as discharge by subbasins, which were delineated at 25,000 km^2, globally. "The data used to calculate the water stress indicator is from WaterGAP, a global hydrologic model developed by the University of Kassel in Germany. WaterGap 2.1 provides both water use and discharges on a global scale. For this analysis, all non-marine areas were divided into consistently-sized subbasins using HydroSHEDS tools. The water stress ration was then calculated for each subbasin [based on intensity and spatial impact of each stress,] and the results upscaled to the [freshwater] ecoregion level. Corrections were made for both very small ecoregions with a high proportion of their area under water stress, and for very large ecoregions with large absolute areas under water stress. Due to data limitations, the analysis incorporates only annual values. An analysis of seasonal water stress would likely result in increased stress levels; agricultural water demands, for example, are generally highest in the dry seasons." (http://www.feow.org)

Data sources:

Greater snow leopard range

Combination of High Asia (>3,000 m) and Snow Leopard Range maps, ISLT, Panthera, SLN, WCS, 2008 and HydroSHEDS 15s Void-filled DEM, WWF, Lehner et al., 2008

Freshwater ecoregions

http://www.feow.org, WWF, 2008

Local runoff, water use

WaterGAP 2.0, Döll et al., 2003

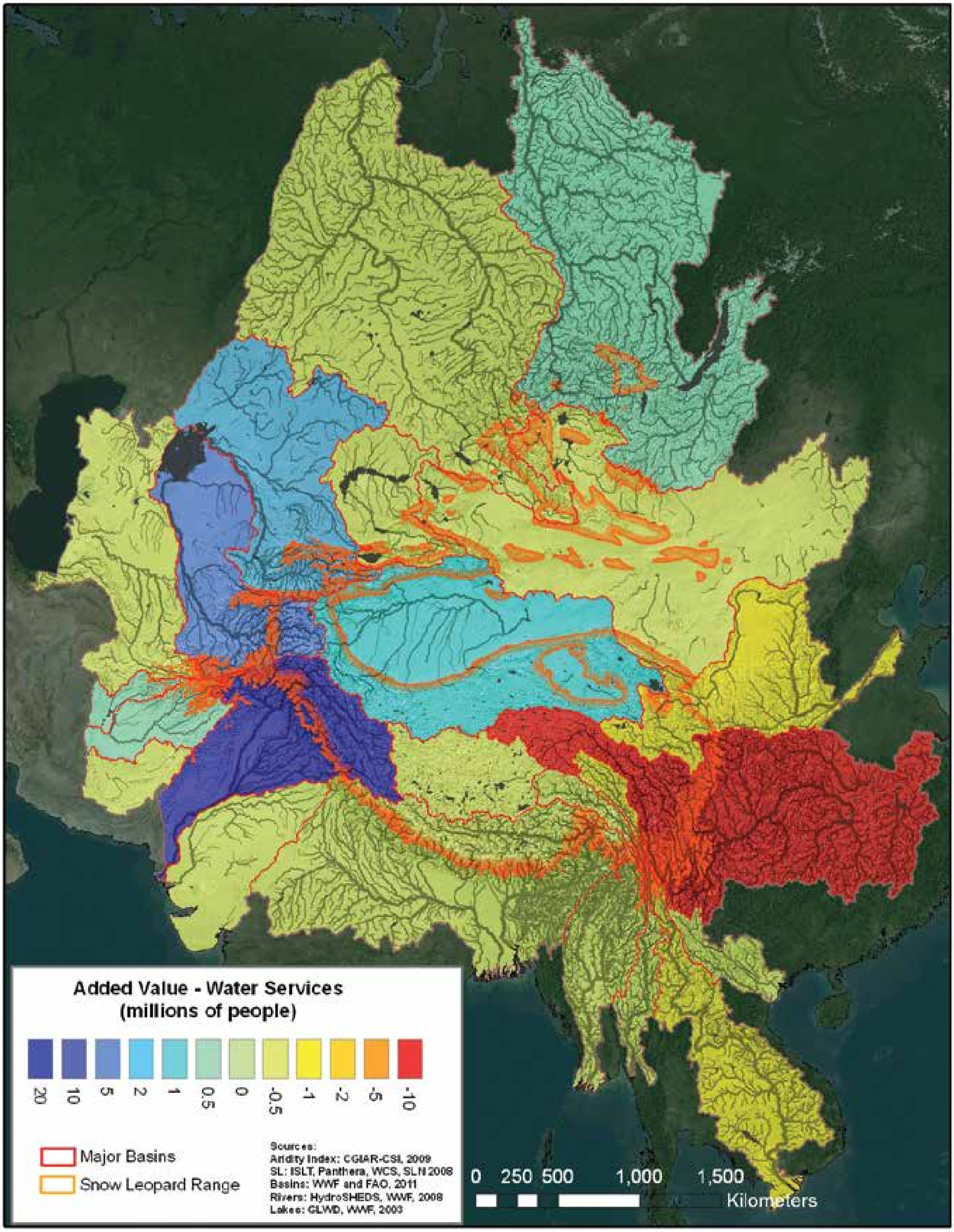
Hydrography

HydroSHEDS, WWF, Lehner et al., 2008

River basins

HydroBasins, FAO, 2011

Water Provision by Snow Leopard Range - Added Value



Sources:
Aridity Index: CGIAR-CSI, 2009
SL: ISLT, Panthera, WCS, SLN 2008
Basins: WWF and FAO, 2011
Rivers: HydroSHEDS, WWF, 2008
Lakes: GLWD, WWF, 2003

WATER PROVISION BY SNOW LEOPARD RANGE—ADDED VALUE

This map shows the importance of water originating from the snow leopard range to downstream human populations. People in positive "Added Value" basins (shown in shades of blue) rely disproportionately on water originating from the snow leopard range. Those people found in negatively ranked "Value Added" basins are more reliant on water originating from parts of the basin located outside the snow leopard range. The western river basins (Indus, Amu and Syr Darya) offer the most important water sources to downstream populations, followed by the Tarim and Yenisey Basins. We see an opposing pattern in the Yangtze Basin. Here, a large human population exists downstream of the snow leopard range, yet the most important flow contributions to that population originate from areas outside the snow leopard range. In some of the endorheic basins (Tibetan Plateau, Gobi Interior), both the flows and population are too low to illustrate a significant balance.

This map provides two essential insights:

- Regionally, it identifies those basins where water resource conservation, in combination with snow leopard conservation, would have the highest impact on people living inside and downstream of the snow leopard range.

- Inside each river basin, it compares to which extent working on water conservation in the snow leopard range is the most effective way of having the broadest impact in terms of population served.

Methods:

The map compares the snow leopard range as a percentage of total upstream area, to water provision by the snow leopard range as a percentage of total discharge. Both values are expressed as a balance (or value added in millions of people) between the total number of people who are served by the upstream flow contribution minus the number of people expected to be served based on upstream acreage. In this way, the balance is expressed by basin as a figure *in* capita; i.e., the total number of people being "served" respectively by upstream acreage and flow contribution. This is different from *per* capita figures. In basins where more people are served by upstream water resources than would be expected by upstream snow leopard acreage alone, the combination of water resource conservation with snow leopard conservation is considered to be an added value.

There are a few key data inputs: rivers linked to discharge rates, and human population density data. River discharges are based on water tower calculations. The snow leopard range was overlaid with the inputs to the water tower maps in order to calculate their flow contribution and upstream area accumulations. Rivers with sources in the snow leopard

Data sources:

Greater snow leopard range

Combination of High Asia (>3,000 m) and Snow Leopard Range maps, ISLT, Panthera, SLN, WCS, 2008 and HydroSHEDS 15s Void-filled DEM, WWF, Lehner et al., 2008

Population

GRUMP, CIESIN, IFPRI, and CIAT, 2011,

Local runoff

WaterGAP 2.0, Döll et al., 2003

Hydrography

HydroSHEDS, WWF, Lehner et al., 2008

River basins

HydroBasins, FAO, 2011

BASIN NAME	BASIN POPULATION (2000)	FLOW CONTRIBUTION TO BASIN (%)	SNOW LEOPARD RANGE INSIDE BASIN (%)	POPULATION LIVING IN VICINITY OF STREAMS SOURCED IN SNOW LEOPARD RANGE	WATER PROVISION BY SNOW LEOPARD RANGE (IN CAPITA)	SERVED BY UPSTREAM ACREAGE (IN CAPITA)	BALANCE (VALUE ADDED IN MILLIONS OF PEOPLE)
Amu Darya	22,569,425	58.4	18.6	11,329,950	6,612,159	2,108,504	4,503,655
East Caspian	36,747,228	0.6	0.7	1,307,539	7,714	9,153	-1,438
Farahrud	905,292	2.7	1.3	234,224	6,207	3,045	3,162
Ganges - Brahmaputra	598,904,224	24.7	25.0	108,500,395	26,788,748	27,135,949	-347,201
Gobi Interior	14,848,992	15.8	17.1	5,524,453	871,206	945,786	-74,580
Helmand	6,416,259	15.2	7.1	3,018,592	459,732	215,527	244,204
Hong (Red River)	57,683,537			25,422	-	-	0
Huang He (Yellow River)	127,263,915	22.6	25.3	30,681,291	6,937,040	7,756,230	-819,190
Indus	155,350,333	68.2	36.4	61,666,054	42,056,249	22,421,777	19,634,472
Irrawaddy	32,176,986	1.7	2.1	7,466,903	126,191	155,312	-29,121
Lake Balkash	5,461,335	11.0	12.6	2,195,412	241,495	275,524	-34,029
Mekong	87,211,409	5.6	10.5	10,391,628	576,735	1,091,121	-514,386
Ob	30,696,724	2.1	3.5	5,818,437	121,023	203,645	-82,622
Tibetan Plateau	109,951	100.0	100.0	49,372	49,372	49,372	0
Sabarmati	95,428,262			348,912	-	-	0
Salween	7,004,644	13.9	39.9	1,768,244	246,493	705,883	-459,390
Syr Darya	36,449,591	13.5	6.3	15,645,595	2,105,897	977,850	1,128,047
Tarim Interior	9,866,505	67.2	51.0	4,258,591	2,860,921	2,170,178	690,743
Yangtze	380,367,061	13.2	27.1	58,713,822	7,756,096	15,887,960	-8,131,864
Yenisey	8,020,720	2.8	2.6	4,211,169	117,913	107,385	10,528
Region Total	**1,713,482,393**			**333,156,005**	**97,941,191**	**82,220,404**	**15,720,788**

Table 7. Water provision balance as a function of water flow, human population and upstream basin area in snow leopard habitat

This table shows the difference between the number of people supported by actual runoff from the snow leopard range and the number of people who might be served if runoff was evenly distributed basin-wide.

range and discharges over 1 m^3/s were buffered with a 10 km buffer. The buffers were assigned to each of the major basins, and attributed with year 2000 population numbers. The regional population in all basins amounted to around 1.7 billion people. But the total population in the direct (10 km) vicinity of a stream with its source in the snow leopard range amounted to around 330 million people, with one-third of them living along the Ganges-Brahmaputra Rivers.

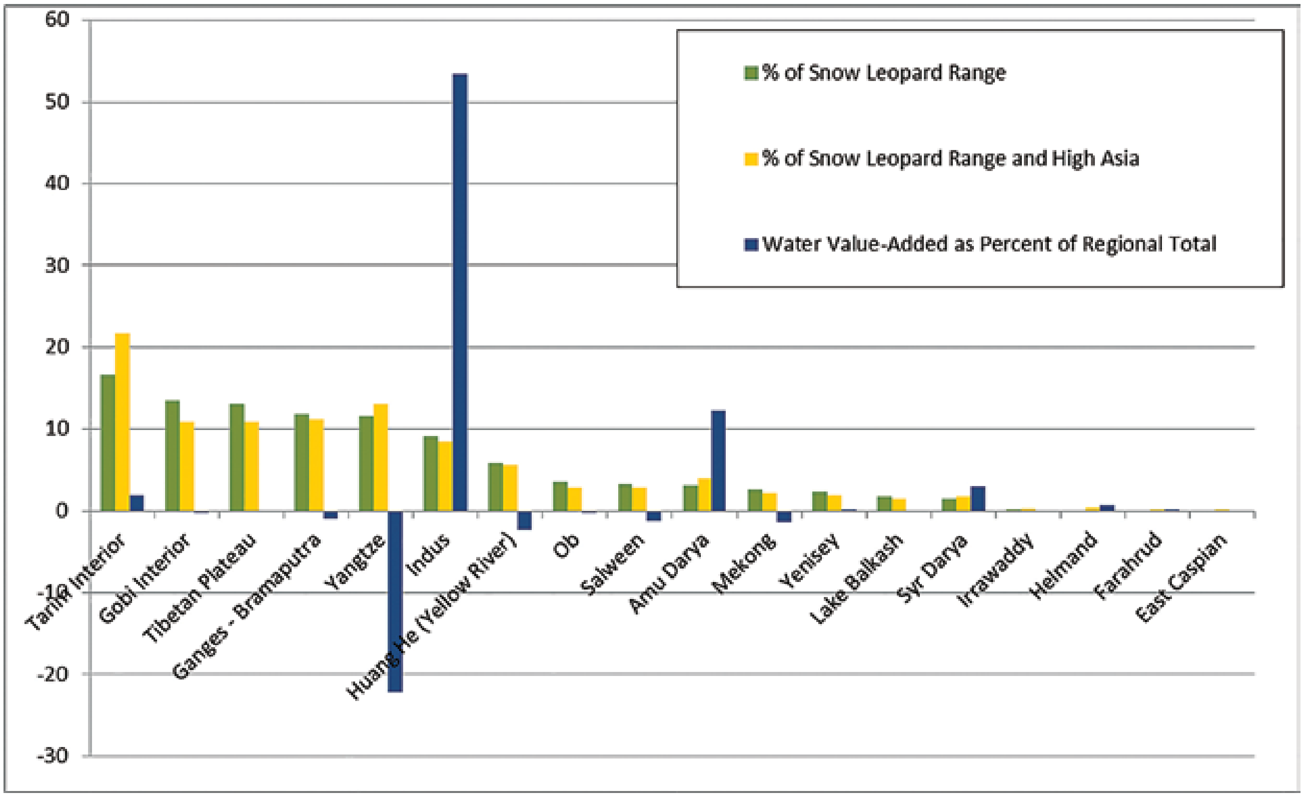
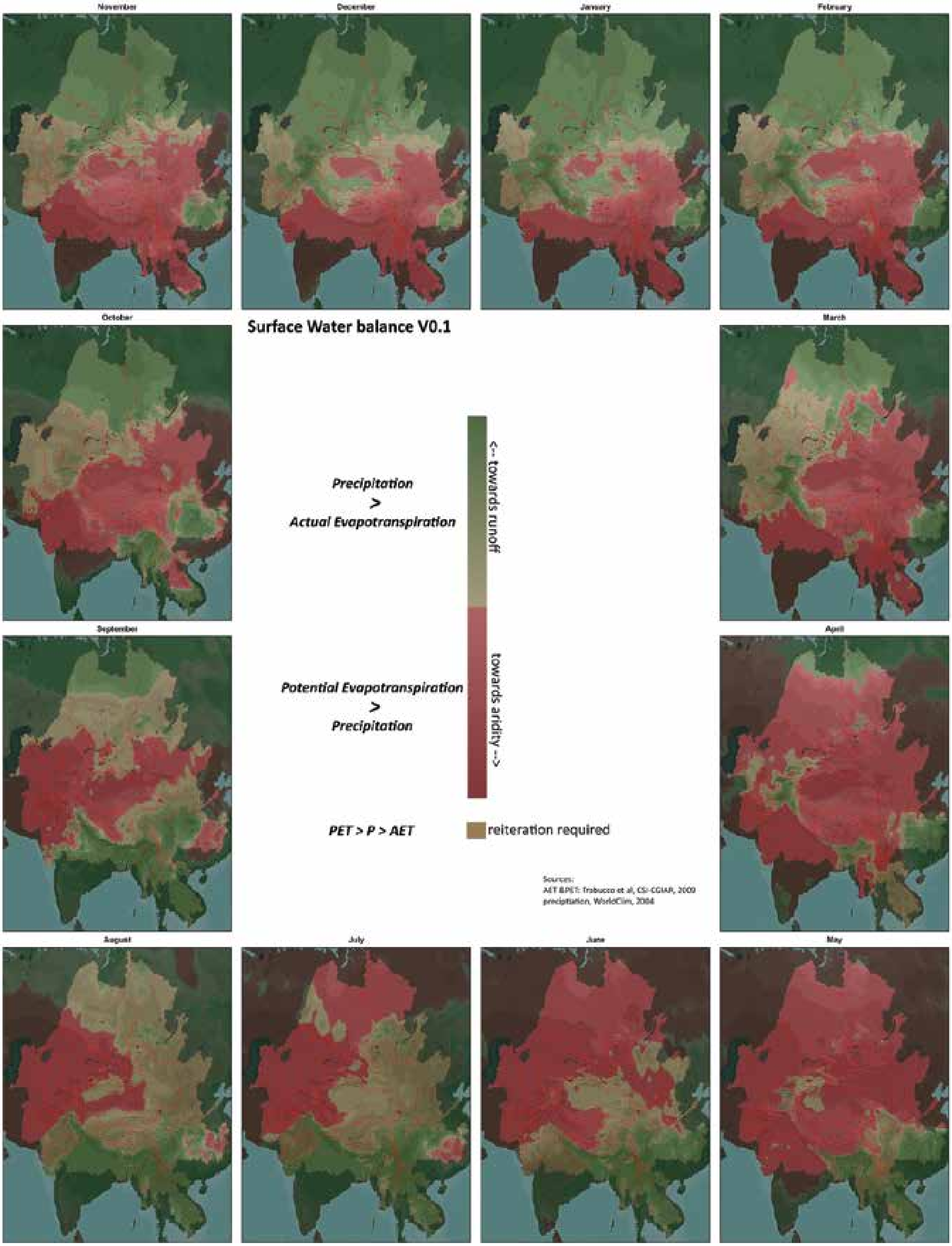


Figure 11. Basin contribution to snow leopard habitat and water provision

This graph shows the importance of each basin for snow leopard habitat and water provision. The Tarim Interior, Gobi Interior, Tibetan Plateau and Ganges-Brahmaputra make up the largest proportion of the snow leopard range by area. Of these, only the Tarim Interior Basin shows positive value added for water provision. The Indus, Amu Darya and Syr Darya Basins are particularly important for water provision. While the Amu Darya and Syr Darya do not form a significant proportion of the snow leopard range by area, they host entire national populations of snow leopards and are important for rangewide metapopulation connectivity.



Sources:
AET &PET: Trabucco et al, CSI-CGIAR, 2009
precipitation, WorldClim, 2004

MONTHLY SURFACE WATER BALANCES

This map indicates the historic seasonal shift of surface water balance functions (combining WorldClim precipitation and CSI-CGIAR evaporations). In green areas, precipitation is contributing to local runoff, while in red areas, local evapotranspiration is limiting local runoff. The map provides the essential insight that every location in the region does have a runoff season and a dry season when it is not actively generating runoff, and no location is providing runoff year-around.

In this map, the headwaters of the Syr Darya, Amu Darya and Indus are collecting runoff (snow, in winter) from December to April/May, which runs off during the spring melt. This pattern differs from the monsoon-driven runoff of the more southeastern Himalayas.

Once water balances are properly considered at the monthly interval, it becomes clear how much of the seasonal interaction is lost when climate change is discussed in annual water balances. Inherently, due to quantitative methods, extreme dry seasons get averaged away since their quantity does not contribute significantly to the annual average; hence the occurrence and importance of dry seasons gets neglected. For example, the floodplains of the Ganges and its tributaries have a water balance towards aridity for eight months of the year. Precipitation quantities in the monsoon overwhelm the aridity of the area in an annual water balance (compare, e.g., to the water towers map).

Data sources:

AET and PET

CSI-CGIAR, Trabucco et al, 2010, 30s resolution

Precipitation

WorldClim 30s, Hijmans et al., 2005. http://www.worldclim.org

LOCAL SEASONAL TREND	TEMPERATURE RISE	PRECIPITATION CHANGE
Towards runoff	• limits local runoff generation since this will increase evapotranspiration • when actual evapotranspiration (AET) increases too much, locations will turn towards aridity and downstream locations will lost part of their upstream runoff component	*Increase:* • when it coincides with peak runoff, there is a risk that (downstream) flood risks increase Decrease: • limits local runoff generation, might shift towards aridity if precipitation (P) falls behind AET; also impacts on downstream locations
Towards aridity	• the most-arid locations will move towards desertification, especially when considering dry seasons that last multiple months, or arid locations that survive on minimal wet seasons • overall, more locations will move towards aridity through increased evaporation	*Increase*: • initial increase will largely be allocated to compensate for moisture deficit of vegetation and soils; thus minimal rise in runoff generation • only after P exceeds potential evapotranspiration (PET), locations will move towards runoff generation *Decrease:* • the most arid locations will move towards desertification, especially when considering dry seasons that last multiple months, or rely on minimal wet seasons • overall, more locations will move towards aridity

Table 8. Runoff responses resulting from temperature and precipitation change

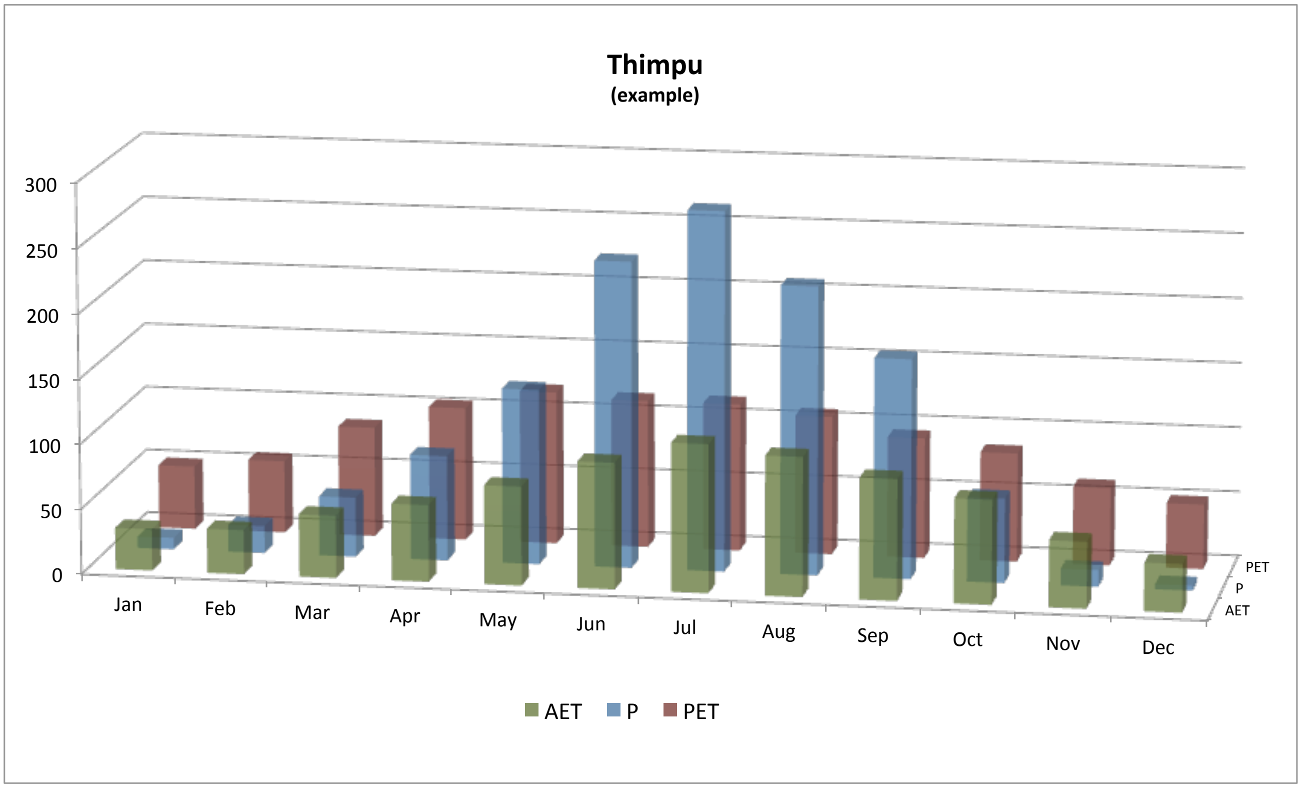


Figure 12. Monthly distribution of AET, PET, and precipitation (P) in Thimpu, Bhutan (example)

Methods:

This map visualizes the combination of two water balances, based on precipitation, actual evapotranspiration and potential evapotranspiration:

Actual evapotranspiration (AET) is defined as the amount of water delivered to the atmosphere by soil evaporation and vegetation transpiration. In the dataset used here (CSI-CGIAR, Trabucco et al, 2010), AET is a function of vegetation coefficients, soil water contents, rooting depths and potential evapotranspiration.

Potential evapotranspiration (PET) is defined as the amount of water delivered to the atmosphere by soil evaporation and vegetation transpiration, assuming no limit on water supply. In the dataset being used here, PET is a function of temperature, monthly temperature range and extra-terrestrial radiation.

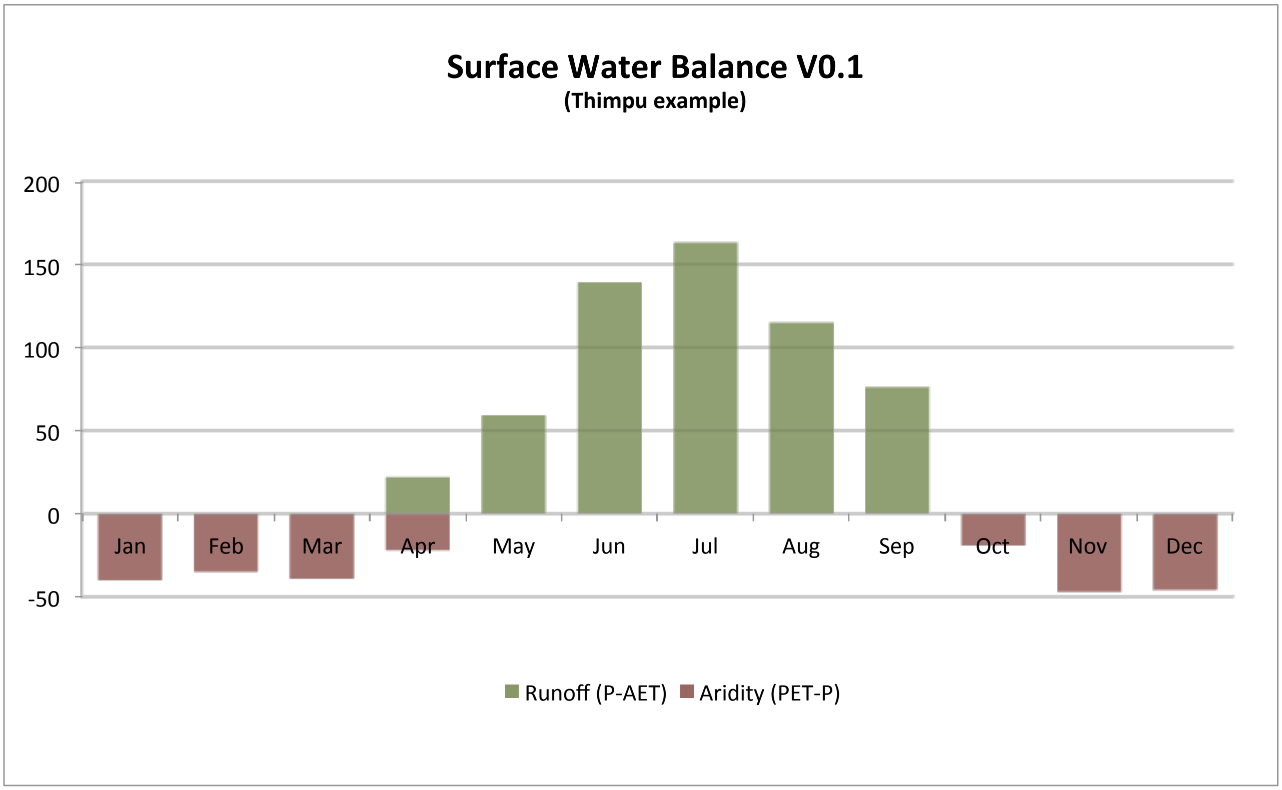


Figure 13. Surface water balance in Thimpu, Bhutan (example)

From these values (in millimeters), a combination of two simple water balances can be mapped out:

Local Runoff** = **Precipitation – Actual Evapotranspiration

where precipitation > actual evapotranspiration

and

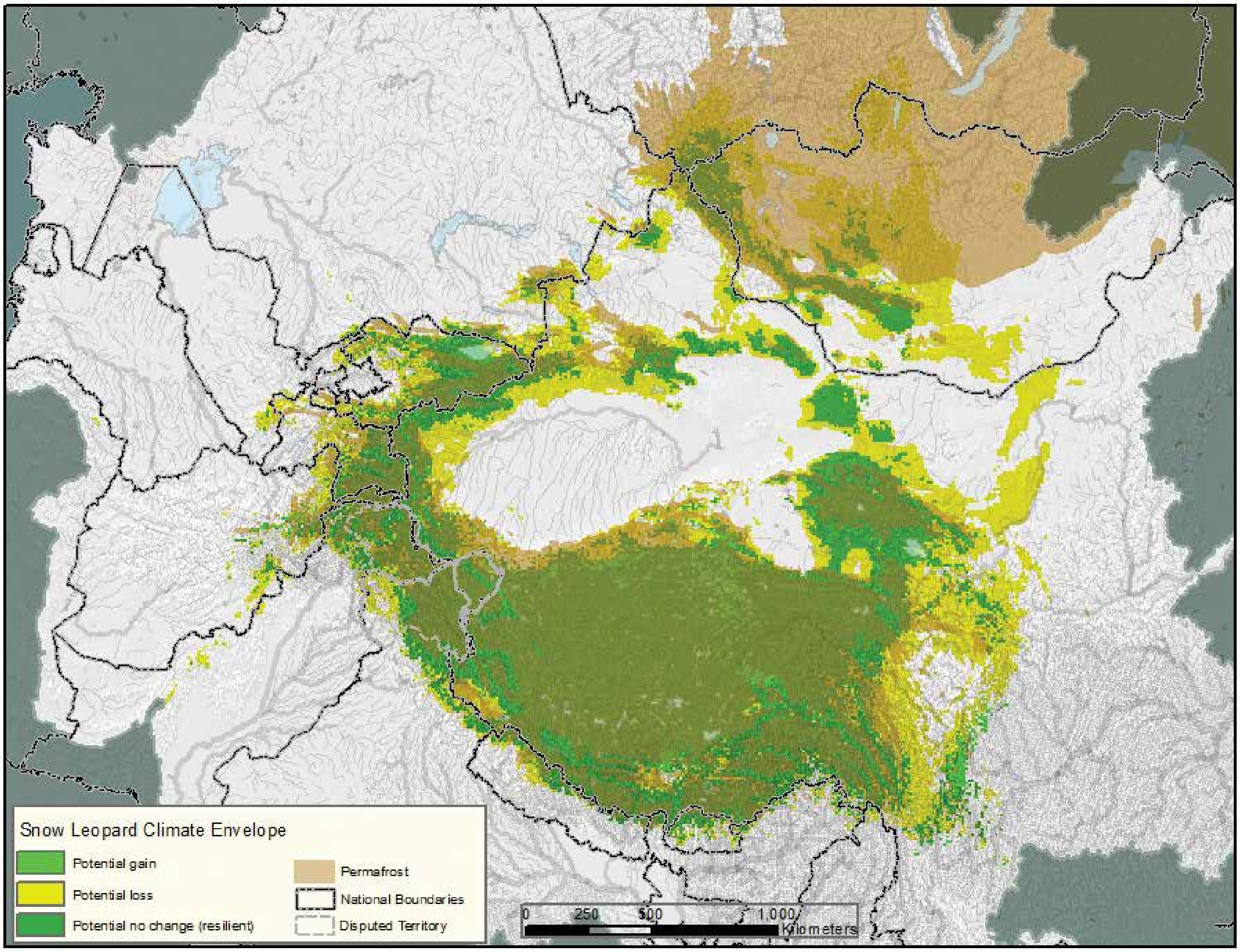
Local Aridity = Potential Evapotranspiration – Precipitation

where precipitation < potential evapotranspiration

The advantage of the current approach is that it is quite straightforward, without using too many assumptions. But the overlap of the two models that occurs, in this example in April, illustrates the requirement for new iterations in fine-tuning the approach in relation with both the internal evaporation functions.

This is a first iteration of surface water balances, i.e., without doing any refitting or calibration of the CSI-CGIAR's evaporation models (Trabucco et al., 2010). It is a surface water balance because it considers only surface water inputs, and does not include groundwater, baseflow or snowmelt interactions.

Snow Leopard Climate Envelope Projected Change (2000-2100)



SNOW LEOPARD CLIMATE ENVELOPE PROJECTED CHANGE (2000–2100)

This map shows vulnerability in the suitable climate envelope for snow leopards to the year 2100. The analysis suggests that 39% of the current snow leopard climate envelope might be lost under a high emissions climate scenario. On the other hand, a minimal amount of climate envelope may be gained following climate change (amounting to a 2% gain of the current climate envelope). The results show more vulnerability in the southeastern portion of the range in China and Myanmar and in the north, and a general shrinking from the edge of the range. In mountainous areas, this represents a "creeping" of the climate envelope up the mountainsides. The permafrost layer indicates an area of uncertainty in vulnerability: if melting occurs, this could result in rapid desertification and subsequent habitat loss. It is important to note that this map represents the snow leopard range, and that areas of actual habitat are a much smaller portion of the range.

Climate envelopes represent suitable climate, but overestimate the actual amount of habitat available to the species. Actual snow leopard habitat is also dependent on ruggedness, prey availability, land cover and grassland quality, human depredation and oxygen availability. The future climate envelope reflects the climate of 2080–2100, but there may be delays beyond this for snow leopard populations to respond and reach equilibrium with the new climate envelope.

The figure below indicates vulnerability of snow leopard habitat to climate change by major basin as a function of the climate envelope projection. Snow leopard climate envelopes in many of the northern basins are very vulnerable to loss, while western basins (the Amu Darya and Syr Darya, followed by the Indus) are intermediately vulnerable to climate-driven habitat loss. The southern basins that flow into India and southeast Asia are least vulnerable to climate envelope loss, but still may experience some significant change in certain places. The Tibet Interior Basin does not appear vulnerable to change, and we expect that it may remain a stronghold for snow leopards under this analysis. The Tibet Interior, however, is dominated by permafrost. Permafrost melting can result in rapid habitat loss and is not well captured by the climate envelope analysis. Permafrost represents areas of considerable uncertainty for the future of snow leopards. Other climate issues that may not be well captured by the climate envelope analysis are changes in grassland communities toward less nutritious grasses for prey, or climate-driven diseases that may affect snow leopards or their prey.

Data sources:

Current climate (19 bioclimatic variables, 1950–2000, 5-min resolution)
Worldclim, Hijmans et al., 2005 (http://www.worldclim.org)

Future climate (SRES A2A Scenario, HADCM3, 19 bioclimatic variables, 2080s, 5-min resolution, delta downscaling method)
CGIAR-CCAFS (http://www.ccafs-climate.org/)

Snow leopard observations
Snow Leopard Network, compiled by ISLT/Panthera/SLN/WCS, Beijing, China, 2008

***Extent*—Major basins overlapping with the snow leopard range**
15-s Hydrosheds, FAO/WWF, Lehner et al., 2008, and **ISLT, Panthera, SLN, WCS,** Beijing, China, 2008

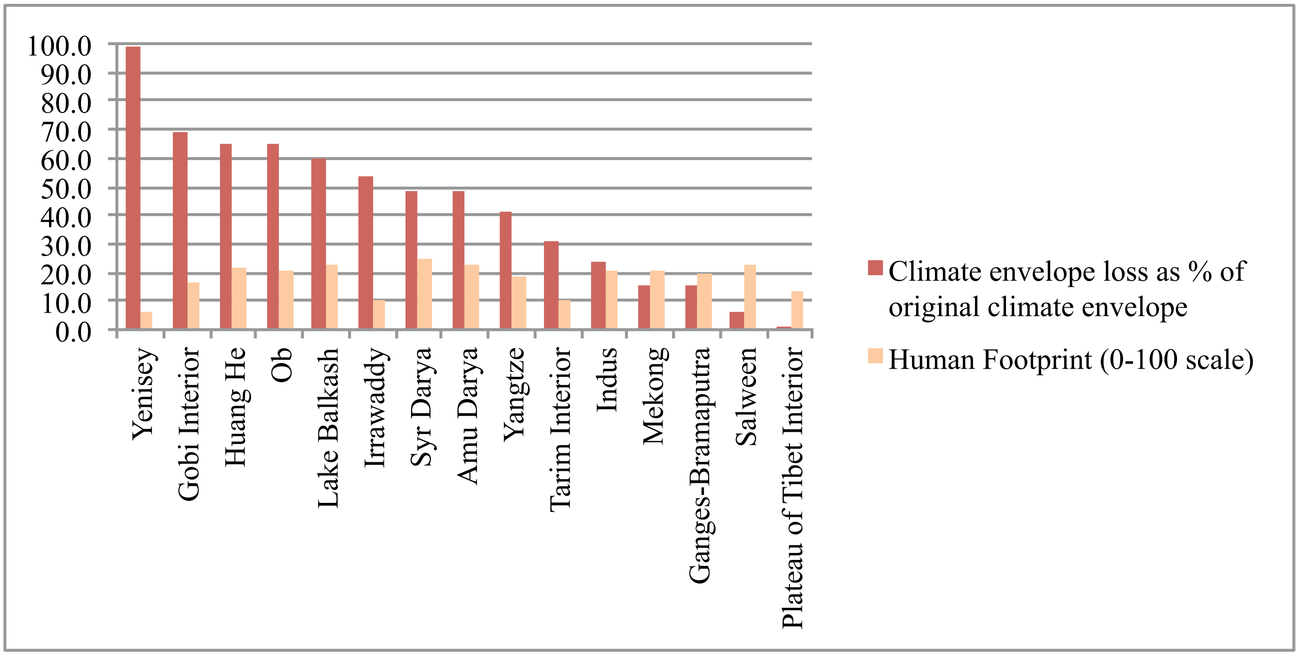


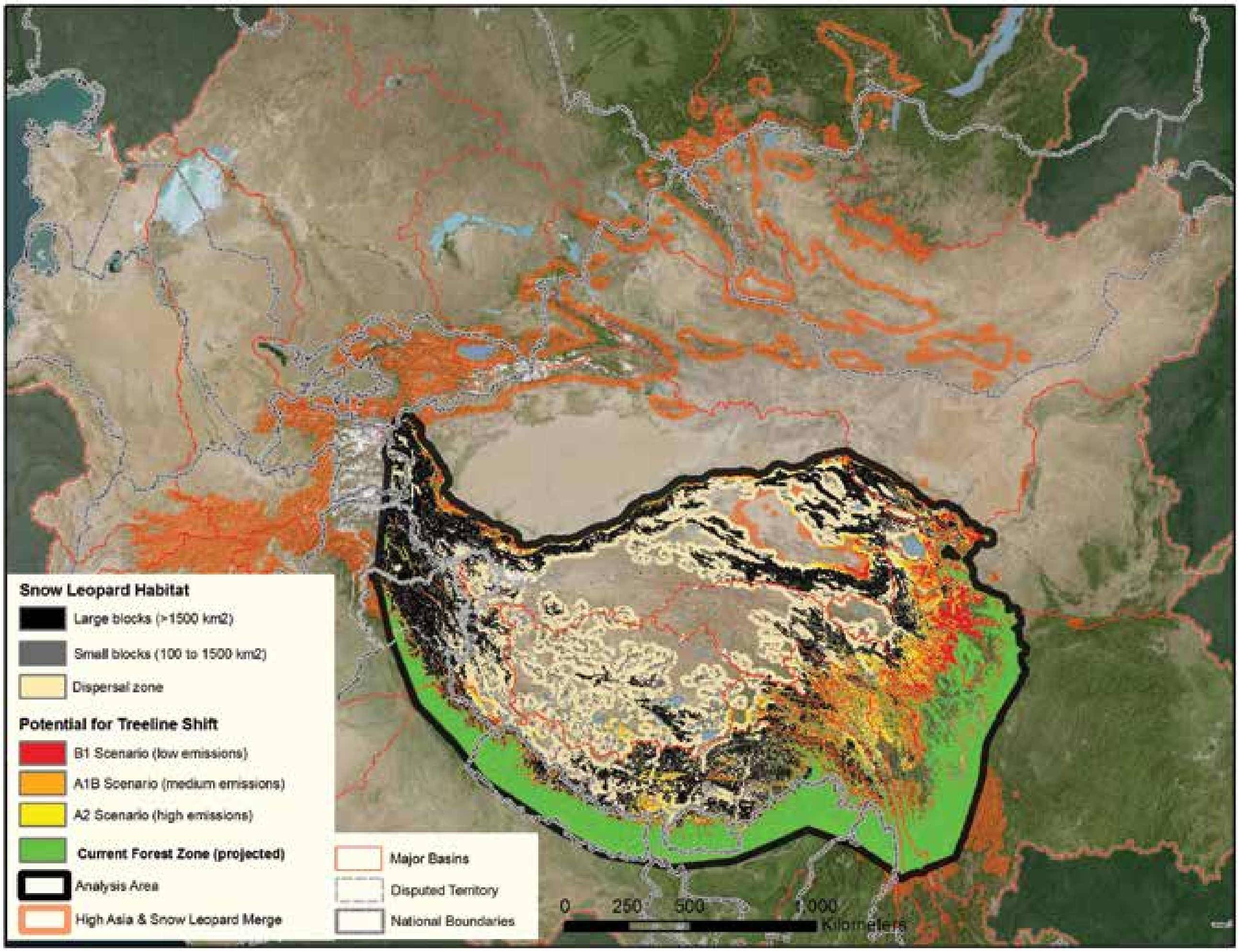
Figure 14. Relative vulnerability of snow leopard habitat to climate envelope change and human disturbance

This graph shows that among the major basins for snow leopards, the Yenisey and Gobi Interior (of Mongolia and northern China) emerge as the most vulnerable. The eastern basins, particularly the Huang He and the Irrawaddy, are also very vulnerable to change, and the Syr and Amu Darya are moderately vulnerable. Snow leopard habitat in the Ganges-Brahmaputra, Indus, and Tibet Interior basins is perhaps the least vulnerable to climate change. The human footprint indicates a level of "adaptability" to climate change, and high human footprint indicates a potentially lower capacity for snow leopards to naturally adapt to climate change, due to concurrent human stresses. Addressing these concurrent direct threats to the species is one way to assure survival of the species through climate change. Note that this graph omits basins that have < 2% of regional snow leopard habitat.

Methods:

We projected current and potential future snow leopard climate envelopes based on 19 bioclimatic variables. Current climate reflects 1950–2000 averages, while future climate reflects the climate of the 2080s under a high emissions scenario (SRES A2A). Bioclimatic variables representing current and future climate were clipped to the extent of major basins that overlap the snow leopard range. These were entered into Maxent (modeling software that determines likely habitat extent based on environmental variables), along with snow leopard observations, to produce probability surfaces of current and future climate envelopes for snow leopards (Training AUC=0.887, Test AUC = 0.877). We selected the threshold that would maximize training sensitivity plus specificity to define the current snow leopard climate envelope (p>0.289), which produced training and test omission rates of 8 to 8.5%, which we deemed acceptable. We then produced a map of potential climate envelope gain and loss from current to 2080s conditions, based on this threshold. Finally, we produced statistics on percent vulnerable climate envelope rangewide and by major basin.

Vulnerability of Snow Leopard Habitat to Treeline Shift



VULNERABILITY OF SNOW LEOPARD HABITAT TO TREELINE SHIFT

A warmer and wetter climate is expected to cause treeline to ascend to higher elevations, thereby reducing habitat available to snow leopards by about 20% in the Himalayas and Tibet. The southeast area of the current snow leopard range in China is likely to be most vulnerable to treeline shift. Habitat in northern Myanmar, Bhutan, Nepal and India will become smaller and more fragmented, requiring transboundary cooperation to conserve adequate connected habitat areas for snow leopards.

As snow leopard habitat becomes smaller, anthropogenic activities such as livestock grazing may become confined and intensified, thus putting more pressure on habitat. This may result in increasing incidents of human wildlife conflict, as snow leopards kill livestock rather than prey, and retaliatory killings of snow leopards ensue. The western Himalaya and Tibet should be less affected by treeline shift, though other factors (invasive grasses, competition with livestock, illegal hunting of livestock and prey) may continue. It is necessary to anticipate and minimize concurrent threats to climate change, and to monitor the status of snow leopard and prey populations, habitat and people, in order to keep conservation strategies current.

The projected forest zone represents the full area that might be climatically suitable for trees, but it does not mean that the entire area will be occupied as such. There are various reasons that trees may not grow in areas that otherwise may be climatically suitable. Reasons include: areas are also suitable for crops or for livestock grazing, do not have suitable soil, or are too steep or subject to high winds. Areas that are instead occupied by crops or overgrazed would still remain unsuitable to snow leopards. Microclimates and local water balances that differ from regional norms are not well captured in the models as well, which may suggest more variation within projected forest zones. We expect a delay beyond the future climate representation (2100) to when forests would be at equilibrium with that particular climate point.

Generally, growing trees can also affect the amount of runoff available downstream. This amount varies throughout the life cycle of trees, with younger, growing trees requiring more water.

Methods:

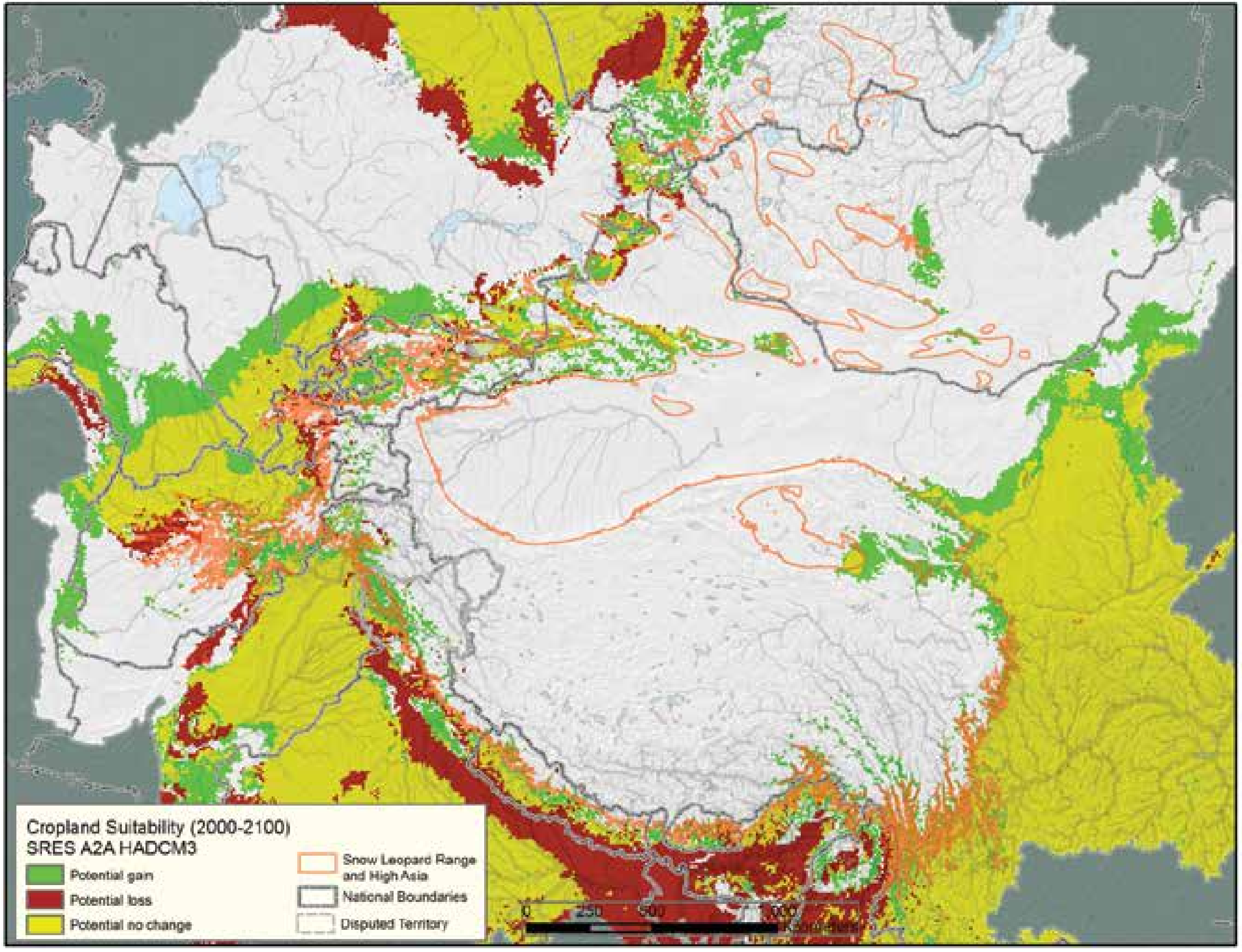
Snow leopard habitat was mapped as a function of land cover, ruggedness, and elevation. The current alpine zone (which is the inverse of the forest zone) was projected by taking observation points of alpine zone and finding the correlation between mean growing season temperature, total growing season precipitation, total precipitation as snow, and December to February precipitation using a generalized linear model. The result was then projected spatially using ArcGIS Spatial Analyst and a logistic equation (ESRI, Redlands, US). The future alpine zone was projected using the ensemble average of 17 General Circulation Models in the year 2100 and recalculating future versions of the four variables.

Data sources:

Snow leopard range
ISLT, Panthera, SLN, WCS, Beijing, China, 2008

Snow leopard habitat in the Himalaya and Tibet, and vulnerability to treeline shift
Forrest et al., 2010, 2012

Potential Change in Cropland Suitability due to Climate Change (2000-2100)



POTENTIAL CHANGE IN CROPLAND SUITABILITY DUE TO CLIMATE CHANGE (2000–2100)

This map shows current and potential change in arable land (or cropland) after climate change. Cropland is defined as the accumulation of all crops in the year 2000. These results suggest that at a rangewide scale, "encroachment" of arable land into the snow leopard range may not be a major concern; however, the northwestern portion of the range (particularly the Tien Shan and Altai Sayan mountain ranges) could see significant improvement of crop suitability. This is significant, since these areas are also very important for water provision to relatively dry basins. In this area, proper management of land is necessary to ensure that habitat remains available for snow leopards, and also that adequate water is available as runoff for people downstream.

Results here are somewhat consistent with other studies that suggest that climate change in South Asia will lead to a decrease in productivity of current crops, due to higher temperatures and more variable rainfall. Within adequate climatic bounds, however, carbon dioxide (CO2) fertilization (not considered in this study) may lead to increases in crop productivity (Wassmann et al., 2009, Nelson et al., 2009, 2010, World Bank 2013). This model does not look at the introduction of new crops which may have broader adaptability to evolving climate conditions, and does not consider other global circulation models (GCMs). The results should be interpreted with caution, and planning should incorporate adaptive management.

Methods

To prepare arable land observations, we randomly dropped 2000 points in the major basins overlapping the snow leopard range, and selected for pixels where >0.006 of the pixel is cropland in the year 2000. This threshold was selected by overlaying with snow leopard habitat and finding the average and standard deviation of crop area per pixel in definite, probable, possible, and not snow leopard habitat in the year 2000. Cropland area > 0.006 seemed to correlate with fewer snow leopards, and cropland < 0.006 tends to correlate with more snow leopards. Reasons for this pattern may be that cropland over a certain area inhibits snow leopard habitat, or that cropland occupies a separate "niche" from snow leopards. It is probably a little of both. Cropland observations were entered into Maxent, along with 19 bioclimatic variables from the current and future, to produce probability surfaces of current and future climate envelopes for cropland (Training AUC=0.824, Test AUC = 0789). We selected the threshold that would maximize training sensitivity plus specificity to define snow leopard climate envelope (p>0.433). We then produced a map of potential climate envelope gain and loss from current to 2080s conditions, based on this threshold.

Data sources:

Current climate (19 bioclimatic variables, 1950–2000, 5-min resolution)

Worldclim, Hijmans et al., 2005 (http://www.worldclim.org)

Future climate (SRES A2A Scenario, HADCM3, 19 bioclimatic variables, 2080s, 5-min resolution, delta downscaling method)

CGIAR-CCAFS (http://www.ccafs-climate.org/)

Cropland observations

Geographic distribution of global agricultural lands in the year 2000, Ramankutty et al., 2008

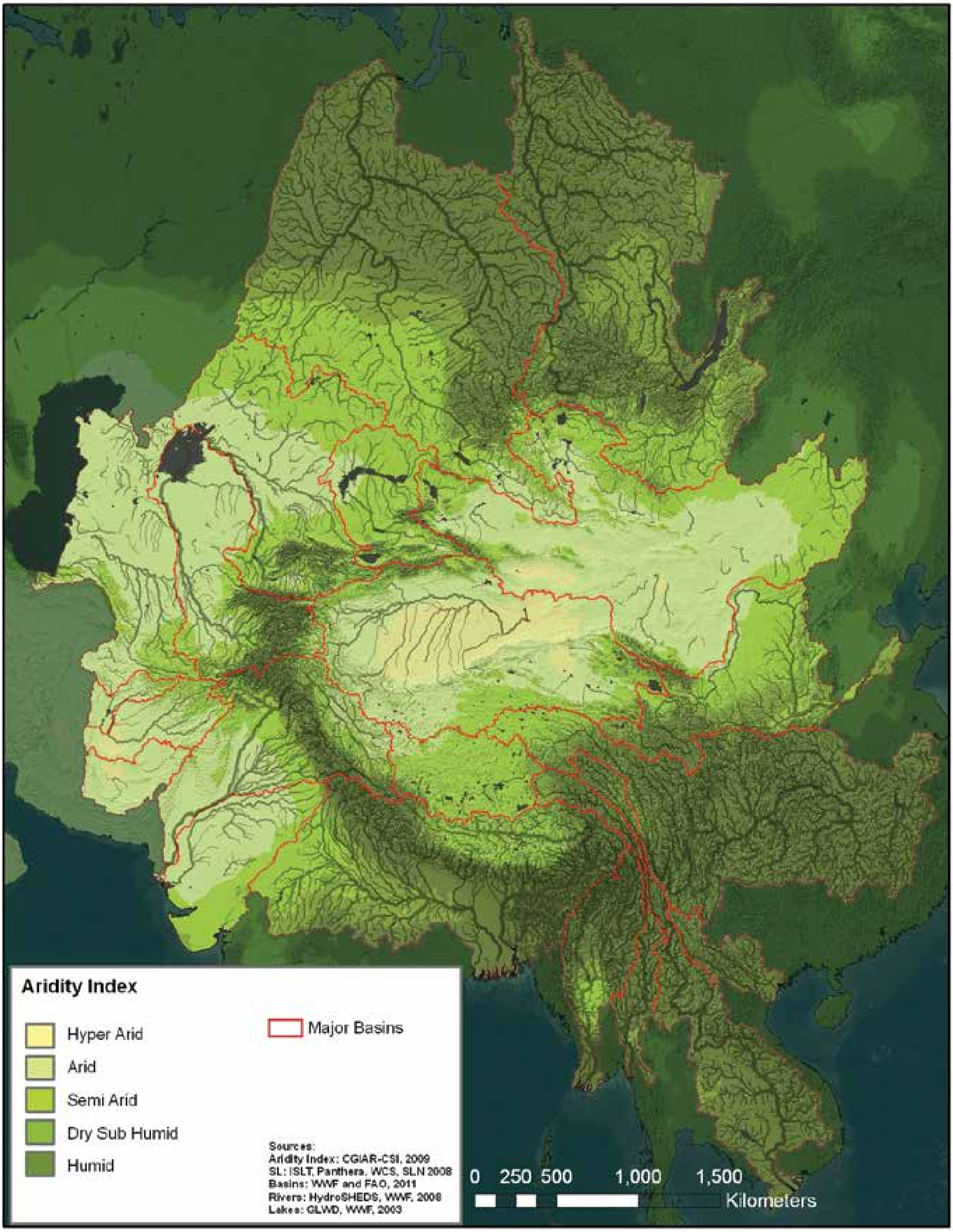
Extent—Major basins overlapping with the snow leopard range

15-s Hydrosheds, FAO/WWF, Lehner et al., 2008, and **ISLT, Panthera, SLN, WCS,** Beijing, China, 2008

Snow leopard range

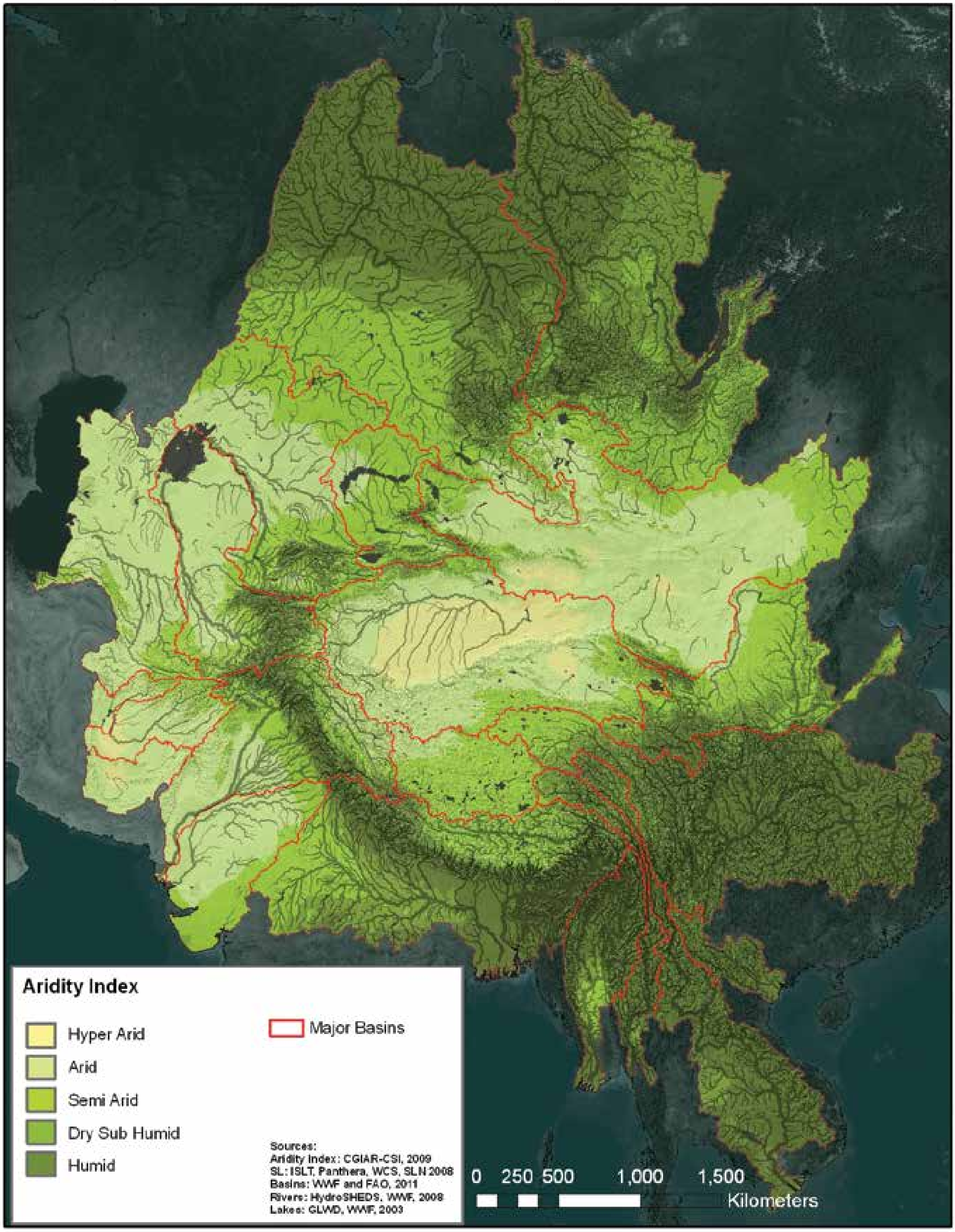
ISLT, Panthera, SLN, WCS, Beijing, China, 2008

Aridity Index



Sources:
Aridity Index: CGIAR-CSI, 2009
SL: ISLT, Panthera, WCS, SLN 2008
Basins: WWF and FAO, 2011
Rivers: HydroSHEDS, WWF, 2008
Lakes: GLWD, WWF, 2003

Aridity Index Under 2 Degrees Temperature Rise



Sources:
Aridity Index: CGIAR-CSI, 2009
SL: ISLT, Panthera, WCS, SLN 2008
Basins: WWF and FAO, 2011
Rivers: HydroSHEDS, WWF, 2008
Lakes: GLWD, WWF, 2003

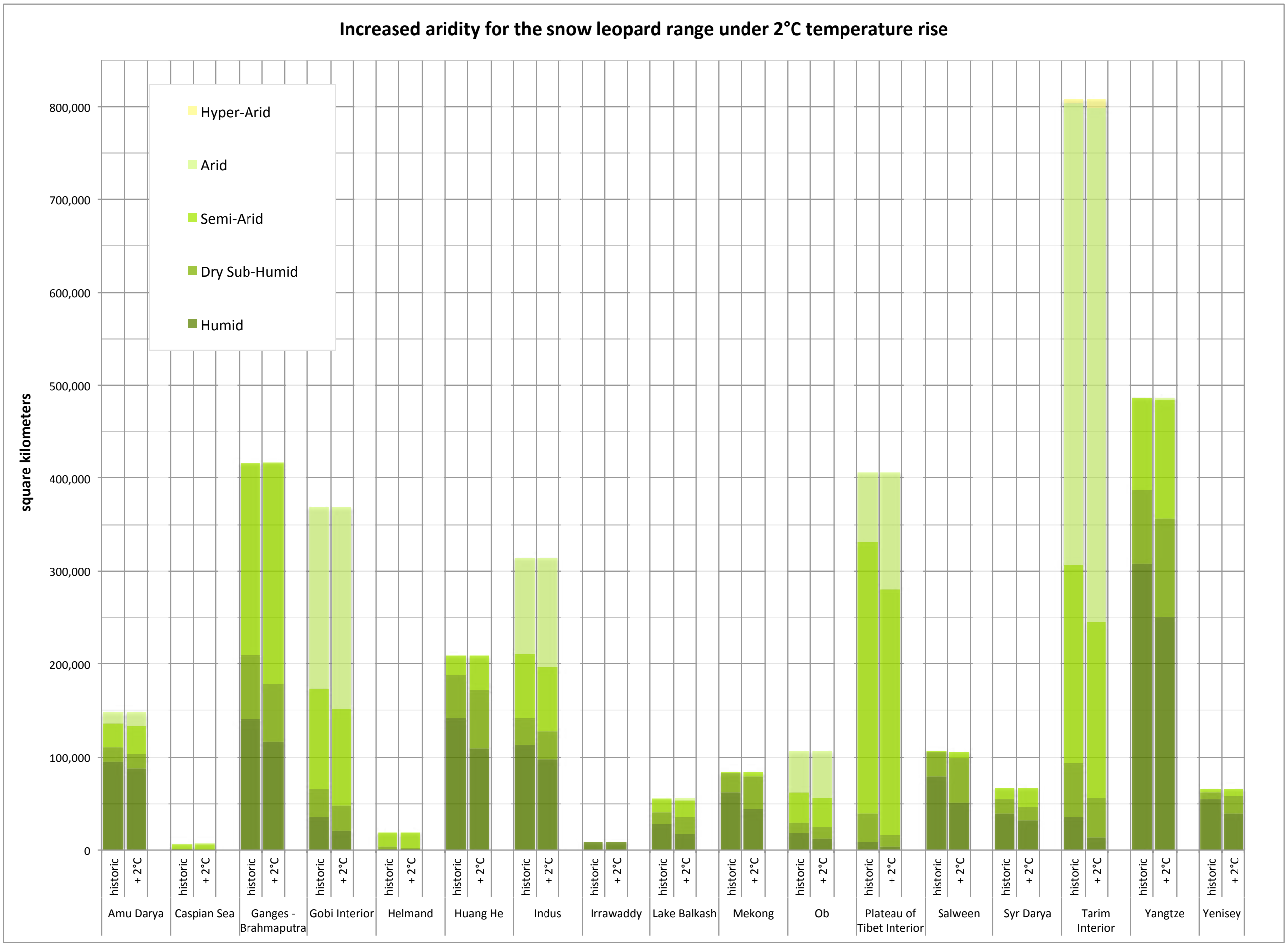
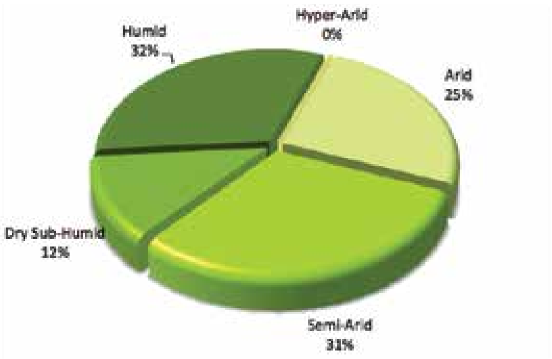


Figure 15. Increased aridity for the snow leopard range under 2°c temperature rise.

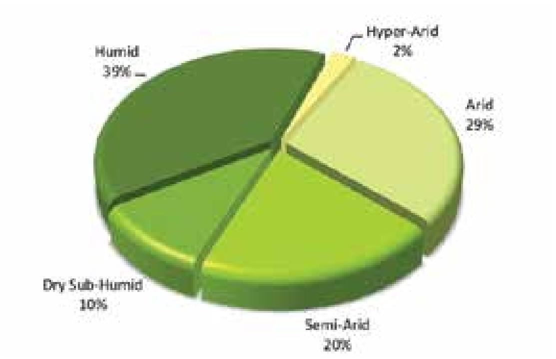
This graph indicates that some of the eastern basins (Mekong, Halween, Huang He, Yangtze) may lose a considerable amount of humid area under a 2° temperature rise. On the other hand, the western basins (Indus, Amu Darya, Syr Darya) would not shift considerably toward greater aridity, making them perhaps more stable under climate change than the eastern basins.

ARIDITY INDEX UNDER 2 DEGREES TEMPERATURE RISE

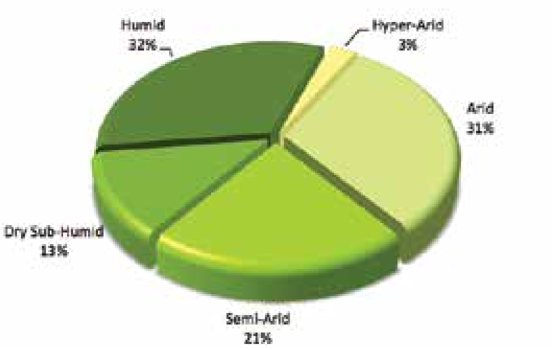
This map shows aridity shift under a presumed 2°C increase in temperature. Patterns of aridity do not change remarkably. It is particularly important to note the 8% decrease in humid lands (in favor of semi-humid), and that the hyper-arid zone does not expand into the snow leopard range. This shift may be good for snow leopards, but less so for water provision.



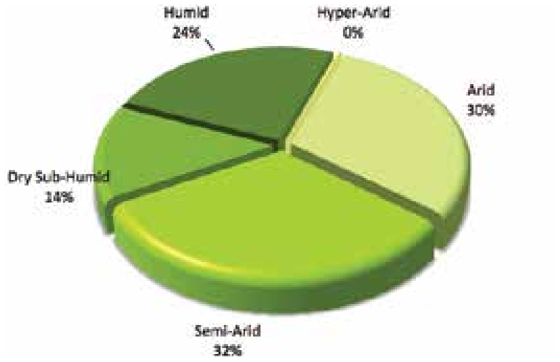
Normal aridity distribution of the entire region (across the major basins that drain from the SL range)



Normal aridity distribution in the snow leopard range



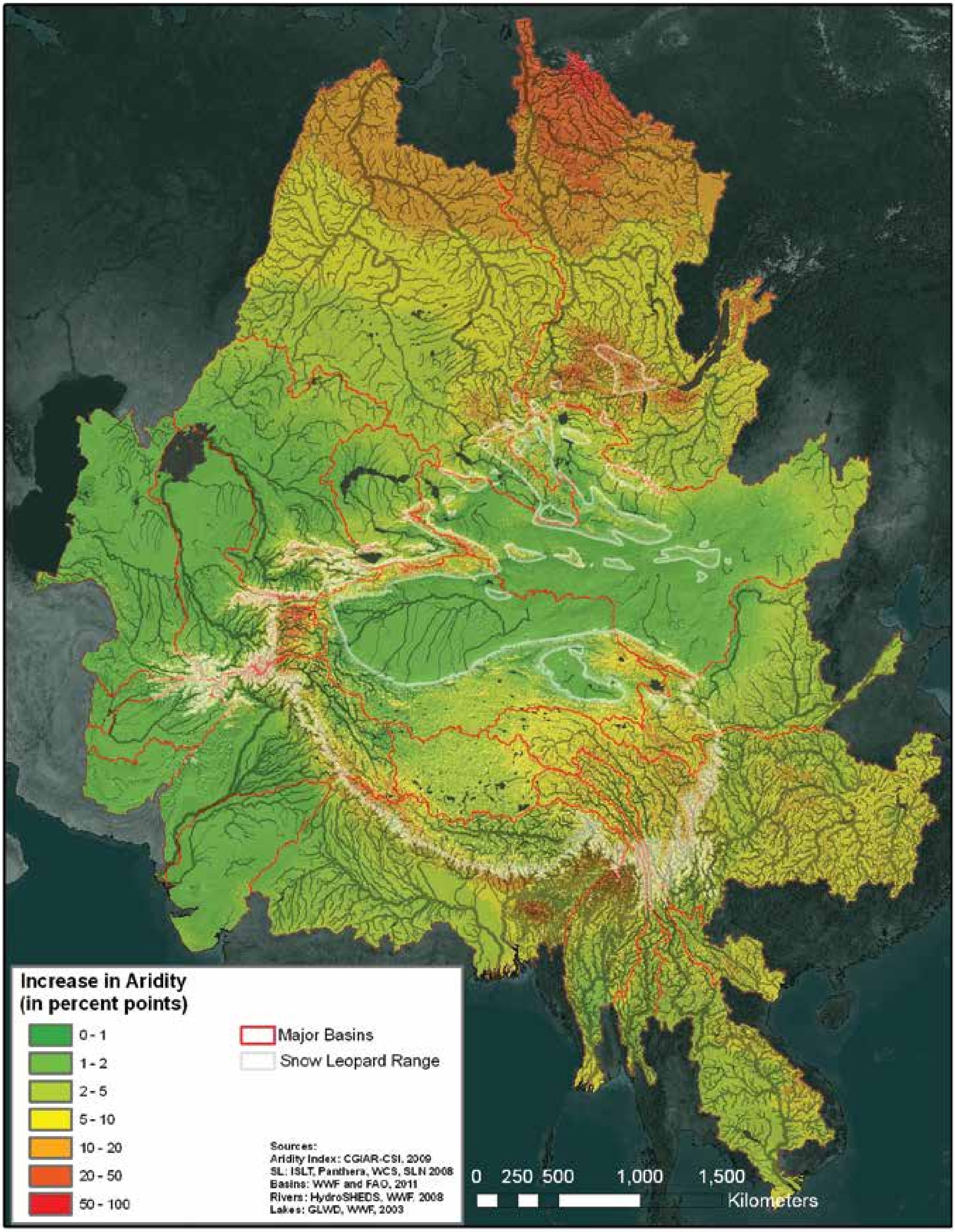
Aridity distribution of the entire region (across the major basins that drain from the SL range) under 2°C temperature rise



Aridity distribution in the snow leopard range under 2°C temperature rise

Under future conditions, arid conditions would become more prevalent in the snow leopard range, and humid conditions may decrease by about 8%. But there is no anticipated expansion of hyper-arid areas in this zone. Throughout the major basins, more arid zones (arid, semi-arid, and hyper-arid) may expand by about 4%.

Increase in Aridity Index Under 2 Degrees Rise



Sources:
Aridity Index: CGIAR-CSI, 2009
SL: ISLT, Panthera, WCS, SLN 2008
Basins: WWF and FAO, 2011
Rivers: HydroSHEDS, WWF, 2008
Lakes: GLWD, WWF, 2003

INCREASE IN ARIDITY UNDER 2 DEGREES TEMPERATURE RISE

This map shows the change in aridity (%), illustrating that the most dramatic changes in aridity are taking place inside the humid class. But this is also because it is the widest class, covering everything over 0.65 in the aridity index.

Methods:

Aridity is recalculated by first recalculating annual potential evapotranspiration in response to a 2° temperature rise (Trabucco, et al, 2009). Next, we recalculated aridity *(Aridity Index = Mean annual precipitation / Mean annual PET),* keeping rainfall and other components of PET the same. This therefore does not show actual aridity under climate change, but sensitivity of aridity to temperature rise.

Data sources:

Aridity

Global Aridity Index, CGIAR-CSI, Trabucco et al., 2009

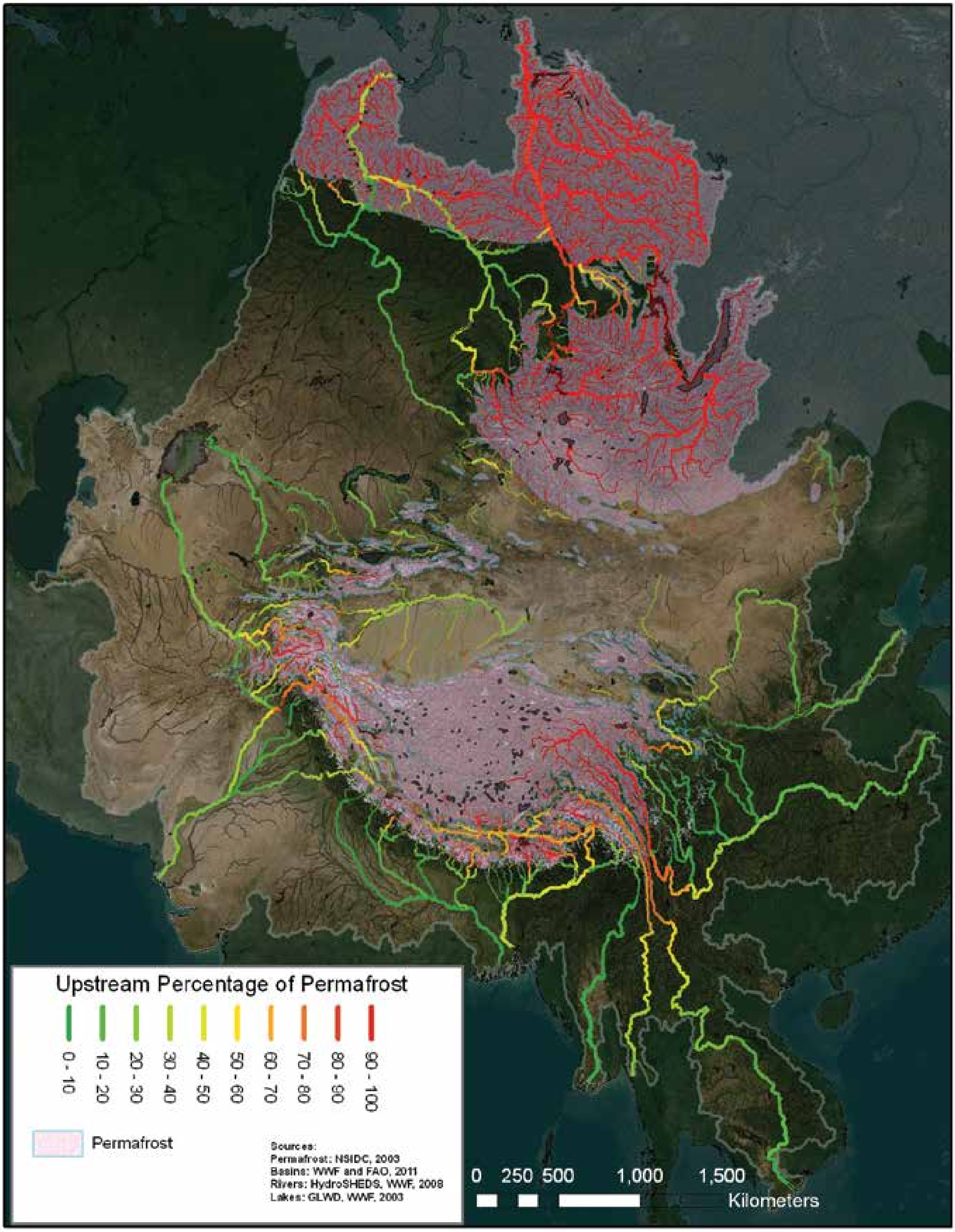
Hydrography

HydroSHEDS, 30s and 5 min resolution, WWF, Lehner et al., 2008

River basins

HydroBasins, FAO and WWF, 2011

Upstream Influence of Permafrost



Sources:
Permafrost: NSIDC, 2003
Basins: WWF and FAO, 2011
Rivers: HydroSHEDS, WWF, 2008
Lakes: GLWD, WWF, 2003

UPSTREAM INFLUENCE OF PERMAFROST

This map depicts rivers according to the total amount of upstream permafrost. Any river that is on, or has a significant amount of its upstream on permafrost, is likely to undergo hydrological change based on retreating and shrinking permafrost. While there is considerable uncertainty around what will change, rivers on permafrost should be managed to anticipate potentially changed flows during and following melting.

Data sources:

Permafrost

Circum-Arctic of Permafrost and Ground-Ice Conditions v2, Brown et al., 2002

Greater snow leopard range

Combination of High Asia (>3,000 m) and Snow Leopard Range maps, ISLT, Panthera, SLN, WCS, 2008 and HydroSHEDS 15s Void-filled DEM, WWF, Lehner et al., 2008

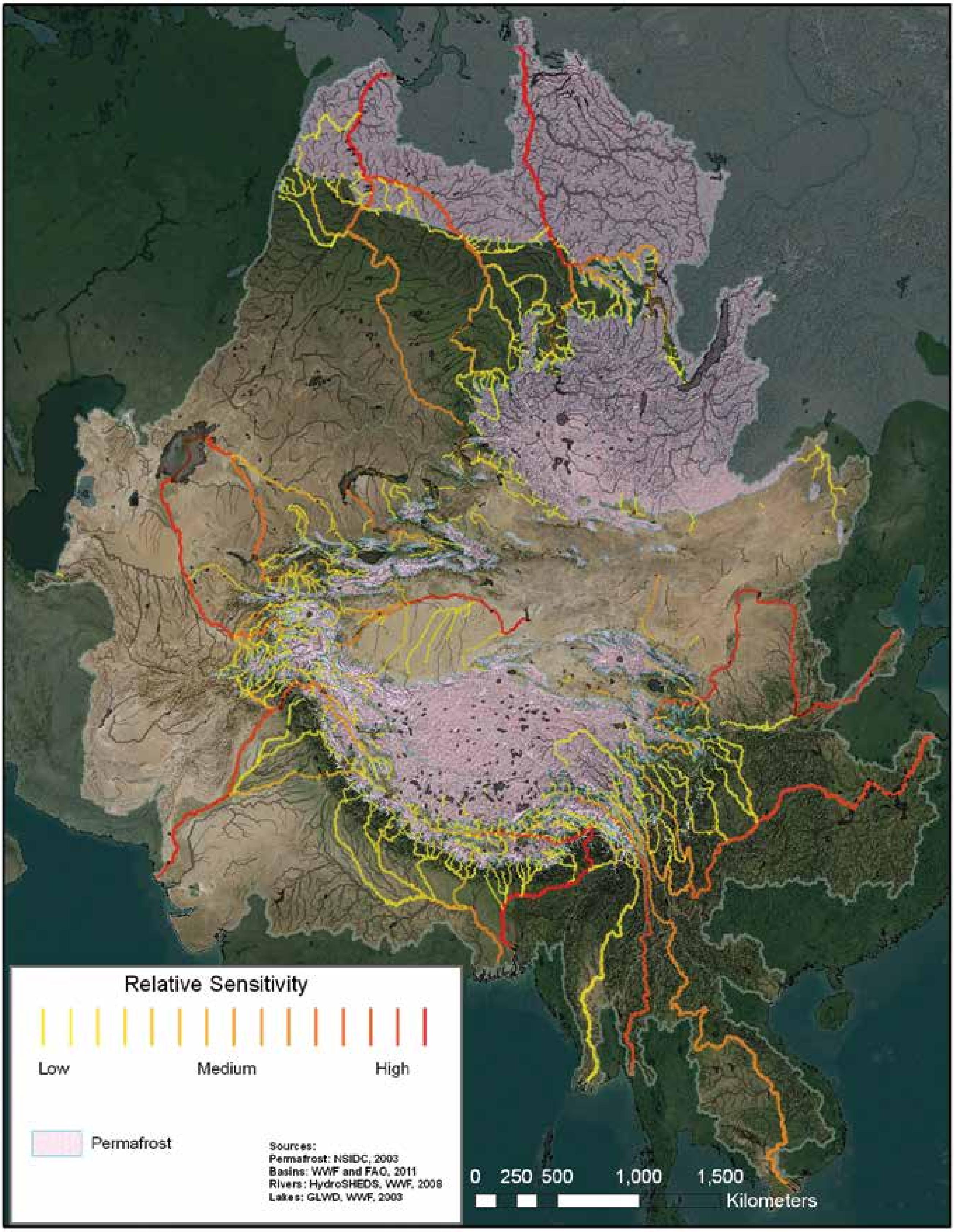
Hydrography

HydroSHEDS, 30s and 5 min resolution, WWF, Lehner et al., 2008

River basins

HydroBasins, FAO and WWF, 2011

River Sensitivity to Permafrost Retreat



Sources:
Permafrost: NSIDC, 2003
Basins: WWF and FAO, 2011
Rivers: HydroSHEDS, WWF, 2008
Lakes: GLWD, WWF, 2003

RIVER SENSITIVITY TO PERMAFROST RETREAT

While permafrost degradation is a complex multi-dimensional process over seasons and years, the most basic changes that can be related to permafrost degradation are based on its potential for disappearance and retreat. This map shows river sensitivity to permafrost retreat, assuming the current circumference of permafrost territory is more susceptible to retreat. Here, we counted the number of streams and rivers that cross the boundary from permafrost to downstream (or vice versa), as an indication of which systems may be most sensitive to permafrost retreat.

Data sources:

Permafrost

Circum-Arctic Map of Permafrost and Ground-Ice Conditions, v2, Brown et al., 2002

Greater snow leopard range

Combination of High Asia (>3,000 m) and Snow Leopard Range maps, ISLT, Panthera, SLN, WCS, 2008 and HydroSHEDS 15s Void-filled DEM, WWF, Lehner et al., 2008

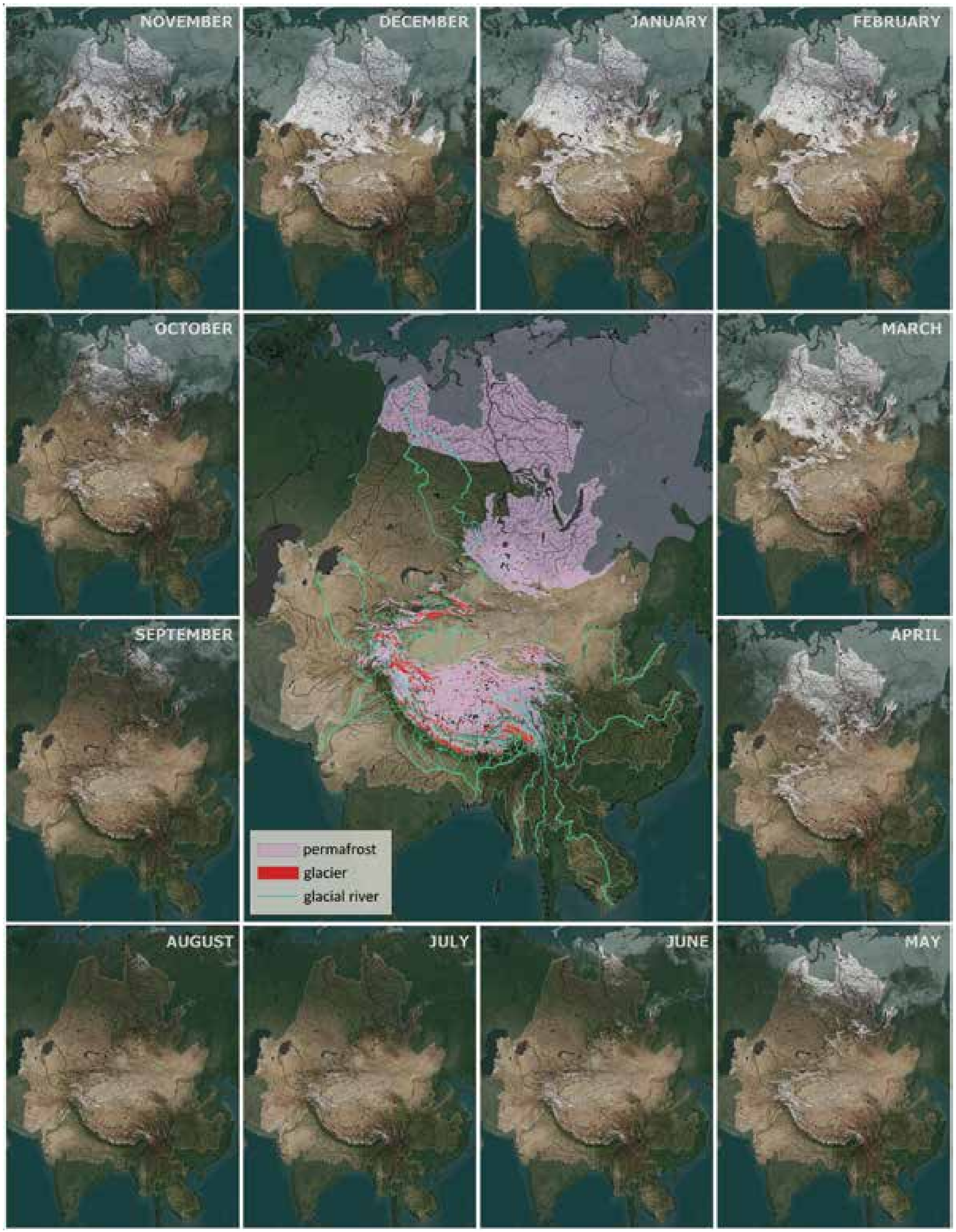
Hydrography

HydroSHEDS, 30s and 5 min resolution, WWF, Lehner et al., 2008

River basins

HydroBasins, FAO and WWF, 2011

Monthly Cryosphere Extent



This map shows the monthly extent of the cryosphere, including glacier, permafrost, snow and ice. Permafrost is not visible from space.

LIST OF LITERATURE

Aizen, V B, E M Aizen, and V a Kuzmichonok. 2007. "Glaciers and Hydrological Changes in the Tien Shan: Simulation and Prediction." *Environmental Research Letters 2* (4) (October 30): 045019. doi:10.1088/1748-9326/2/4/045019. http://stacks.iop.org/1748-9326/2/i=4/a=045019?key=crossref.7aefb875991380b928985e7496730aff.

Aizen, Vladimir B, Elena M Aizen, and M M John. 1996. "Of Hydrology Precipitation , Melt and Runoff in the Northern Tien Shan" 186: 229–251.

Ale, Som B, Bhaskar S Karky, Priscilla Allen, and Dennis Macray. 2002. "Contributed Papers to the Snow Leopard Survival Strategy Summit May 2002 Prepared by the International Snow Leopard Trust Table of Contents" (May).

Anderson, M. G., C.E. Ferree. 2010. "Conserving the Stage: Climate Change and the Geophysical Underpinnings of Species Diversity." *PloS One* 5 (7).

Argerich, a, S L Johnson, S D Sebestyen, C C Rhoades, E Greathouse, J D Knoepp, M B Adams, et al. 2013. "Trends in Stream Nitrogen Concentrations for Forested Reference Catchments across the USA." *Environmental Research Letters* 8 (1) (March 1): 014039. doi:10.1088/1748-9326/8/1/014039. http://stacks.iop.org/1748-9326/8/i=1/a=014039?key=crossref.3217949ec712e5f36885b6dd262dfebb.

Bai, Yongfei, Jianguo Wu, Qi Xing, Qingmin Pan, Jianhui Huang, Dianling Yang, and Xingguo Han. 2008. "Primary Production and Rain Use Efficiency across a Precipitation Gradient on the Mongolia Plateau." *Ecology* 89 (8): 2140–2153. http://www.ncbi.nlm.nih.gov/pubmed/18724724.

Bai, Z.G., D.L. Dent, L. Olsson, and M.E. Schaepman. 2008. "Global Assessment of Land Degradation and Improvement. 1. Identification by Remote Sensing." ... : *International Soil Reference* .... ftp://ftp.unccd.int/disk1/Library/Full Text 2011-2012 Full Text Publications/GLADAreport 2008_01_glada international_rev_nov 2008.pdf.

Bai, Z.G., Dent, D.L., Olsson, L. and Schaepman, M.E. 2008. "Proxy Global Assessment of Land Degradation." *Soil Use and Management* 24: 223–234.

Bajracharya, Samjwal Ratna, Pradeep Kumar Mool, and Basanta Raj Shrestha. 2008. "Global Climate Change and Melting of Himalayan Glaciers." *In Melting Glaciers and Rising Sea Levels: Impacts and Implications*, edited by Prabha Shastri Ranade, 28–46. The Icfai's University Press.

Bruijnzeel, L.A., and C.N. Bremmer. 1989. "Highland - Lowland Interaction in the Ganges Brahmaputra River Basin". Kathmandu: ICIMOD.

Center for International Earth Science Information Network (CIESIN)/Columbia University, International Food Policy Research Institute (IFPRI), The World Bank, and Centro Internacional de Agricultura Tropical (CIAT). 2011. "Global Rural-Urban Mapping Project, Version 1 (GRUMPv1): Population Density Grid."

Chen, Xi, Jie Bai, Xiaoyu Li, Geping Luo, Junli Li, and B Larry Li. 2013. "Changes in Land Use/land Cover and Ecosystem Services in Central Asia during 1990–2009." *Current Opinion in Environmental Sustainability* 5 (1) (March): 116–127. doi:10.1016/j.cosust.2012.12.005. http://linkinghub.elsevier.com/retrieve/pii/S1877343513000031.

Chen, Xi, Bai Lian Li, Qin Li, JunLi Li, and Saparnov Abdulla. 2012. "Spatio-Temporal Pattern and Changes of Evapotranspiration in Arid Central Asia and Xinjiang of China." *Journal of Arid Land* 4 (1) (January 6): 105–113. doi:10.3724/SP.J.1227.2012.00105. http://pub.chinasciencejournal.com/article/getArticleRedirect.action?doiCode=10.3724/SP.J.1227.2012.00105.

Christensen, L., M.B. Coughenour, J.E. Ellis, and Z.Z. Chen. 2004. “Vulnerability of the Asian Typical Steppe to Grazing and Climate Change.” *Climatic Change* 63 (3): 351–368. doi:10.1023/B:CLIM.0000018513.60904.fe. http://dx.doi.org/10.1023/B:CLIM.0000018513.60904.fe.

Crimmins, Shawn M, Solomon Z Dobrowski, Jonathan a Greenberg, John T Abatzoglou, and Alison R Mynsberge. 2011. “Changes in Climatic Water Balance Drive Downhill Shifts in Plant Species’ Optimum Elevations.” *Science* (New York, N.Y.) 331 (6015) (January 21): 324–7. doi:10.1126/science.1199040. http://www.ncbi.nlm.nih.gov/pubmed/21252344.

Davies, J., Poulsen, L., Schulte-Herbrüggen, B., Mackinnon, K., Crawhall, N., Henwood, W.D., Dudley, N., Smith, J. and Gudka, M. 2012. *Conserving Dryland Biodiversity*. *Biodiversity*. IUCN, UNEP-WCMC, UNCCD. http://www.tandfonline.com/doi/full/10.1080/14888386.2014.942752.

Diffenbaugh, Noah S., and C.B. Field. 2013. “Changes in Ecologically Critical Terrestrial Climate Conditions.” *Science* 341 (6145): 486–492.

Diffenbaugh, Noah S., Martin Scherer, and Moetasim Ashfaq. 2012. “Response of Snow-Dependent Hydrologic Extremes to Continued Global Warming.” *Nature Climate Change* 3 (4) (November 11): 379–384. doi:10.1038/nclimate1732. http://www.nature.com/doifinder/10.1038/nclimate1732.

Dobrowski, S. Z., S. M. Crimmins, J. a. Greenberg, J. T. Abatzoglou, and a. R. Mynsberge. 2011. “Response to Comments on ‘Changes in Climatic Water Balance Drive Downhill Shifts in Plant Species’ Optimum Elevations.’” *Science* 334 (6053) (October 13): 177–177. doi:10.1126/science.1205029. http://www.sciencemag.org/cgi/doi/10.1126/science.1205029.

Farley, Kathleen a., William G. Anderson, Leah L. Bremer, and Carol P. Harden. 2011. “Compensation for Ecosystem Services: An Evaluation of Efforts to Achieve Conservation and Development in Ecuadorian Páramo Grasslands.” *Environmental Conservation* 38 (04) (November 3): 393–405. doi:10.1017/S037689291100049X. http://www.journals.cambridge.org/abstract_S037689291100049X.

Farrington, J.D. 2011. “Impacts of Climate Change on the Yangtze Source Region and Adjacent Areas.”

Forrest J., Wikramanayake E., Shrestha R., Areendran G., Gyeltshen K., Maheshwari A., Mazumdar S., Naidoo R., Shen N., Thapa G.J., Thapa K. 2010. “Planning for Climate Vulnerability in the Snow Leopard Range of Nepal, Bhutan, India, and China.”

Forrest, Jessica L., Eric Wikramanayake, Rinjan Shrestha, Gopala Areendran, Kinley Gyeltshen, Aishwarya Maheshwari, Sraboni Mazumdar, Robin Naidoo, Gokarna Jung Thapa, and Kamal Thapa. 2012. “Conservation and Climate Change: Assessing the Vulnerability of Snow Leopard Habitat to Treeline Shift in the Himalaya.” *Biological Conservation* 150 (1) (June): 129–135. doi:10.1016/j.biocon.2012.03.001. http://linkinghub.elsevier.com/retrieve/pii/S0006320712001437.

Frei, Allan, Marco Tedesco, Shihyan Lee, James Foster, Dorothy K. Hall, Richard Kelly, and David A. Robinson. 2012. “A Review of Global Satellite-Derived Snow Products.” *Advances in Space Research* 50 (8) (October): 1007–1029. doi:10.1016/j.asr.2011.12.021. http://linkinghub.elsevier.com/retrieve/pii/S0273117711008611.

Gao, Ying Zhi, Qing Chen, Shan Lin, Marcus Giese, and Holger Brueck. 2011. “Resource Manipulation Effects on Net Primary Production, Biomass Allocation and Rain-Use Efficiency of Two Semiarid Grassland Sites in Inner Mongolia, China.” *Oecologia* 165 (4) (April): 855–64. doi:10.1007/s00442-010-1890-z. http://www.ncbi.nlm.nih.gov/pubmed/21191799.

Genxu, Wang, Liu Guangsheng, and Li Chunjie. 2012. “Effects of Changes in Alpine Grassland Vegetation Cover on Hillslope Hydrological Processes in a Permafrost Watershed.” *Journal of Hydrology* 444-445 (June): 22–33. doi:10.1016/j.jhydrol.2012.03.033. http://linkinghub.elsevier.com/retrieve/pii/S0022169412002430.

Genxu, Wang, Li Shengnan, Hu Hongchang, and Li Yuanshou. 2009. “Water Regime Shifts in the Active Soil Layer of the Qinghai–Tibet Plateau Permafrost Region, under Different Levels of Vegetation.” *Geoderma* 149 (3-4) (March): 280–289. doi:10.1016/j.geoderma.2008.12.008. http://linkinghub.elsevier.com/retrieve/pii/S0016706108003728.

Governali, C., Rowe, A., Wheelock, A. 2013. “Conserving the Stage for the Future of Biodiversity in High Asia.”

Hatfield, Richard, Jonathan Davies, Abdrahmane Wane, Carol Kerven, Celine Dutilly-diane, Jean Pierre Biber, Juan Luis Merega, Michael Ochieng Odhiambo, Roy Behnke, and Susanne Gura. 2006. “Global Review of the Economics of Pastoralism.”

Heiner, M., Yunden, B., Kiesecker, J., Davaa, G., Ganbaatar, M., Ichinkhorloo, O., von Wehrden, H., Reading, R., Olson, K., Jackson, R., Evans, J., McKenney, B., Oakleaf, J., Sochi, K., Oidov, E. 2013. “Applying Conservation Priorities in the Face of Future Development: Applying Development by Design in the Mongolian Gobi.”

Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones, and A. Jarvis. 2005. “Very High Resolution Interpolated Climate Surfaces for Global Land Areas.” *International Journal of Climatology 25*: 1965-1978. 25.

Hijmans, Robert J. 2011. “Comment on ‘Changes in Climatic Water Balance Drive Downhill Shifts in Plant Species’ Optimum Elevations’.” *Science (New York, N.Y.)* 334 (6053) (October 14): 177; author reply 177. doi:10.1126/science.1203791. http://www.ncbi.nlm.nih.gov/pubmed/21998370.

Immerzeel, Walter, Jetse Stoorvogel, and John Antle. 2008. “Can Payments for Ecosystem Services Secure the Water Tower of Tibet?” *Agricultural Systems* 96 (1-3) (March): 52–63. doi:10.1016/j.agsy.2007.05.005. http://linkinghub.elsevier.com/retrieve/pii/S0308521X07000777.

Immerzeel, Walter W, Ludovicus P H van Beek, and Marc F P Bierkens. 2010. “Climate Change Will Affect the Asian Water Towers.” *Science (New York, N.Y.)* 328 (5984) (June 11): 1382–5. doi:10.1126/science.1183188. http://www.ncbi.nlm.nih.gov/pubmed/20538947.

Inauen, Nicole, Christian Körner, and Erika Hiltbrunner. 2013. “Hydrological Consequences of Declining Land Use and Elevated CO 2 in Alpine Grassland.” Edited by Richard Bardgett. *Journal of Ecology 101* (1) (January 21): 86–96. doi:10.1111/1365-2745.12029. http://doi.wiley.com/10.1111/1365-2745.12029.

IUCN, and UNEP-WCMC. 2013. “The World Database on Protected Areas (WDPA) (2013 Version).” www.protectedareas.net.

Jackson, Rodney, and R Wangchuk. 2001. “Linking Snow Leopard Conservation and People-Wildlife Conflict Resolution: Grassroots Measures to Protect the Endangered Snow Leopard from Herder Retribution.” *Endangered ...* 18 (4): 138–141. http://www.snowleopardconservancy.org/pdf/Snow Leopard 138-141.pdf.

Jamiyansharav, K., D. Ojima, R.a. Pielke, W. Parton, J. Morgan, a. Beltrán-Przekurat, D. LeCain, and D. Smith. 2011. “Seasonal and Interannual Variability in Surface Energy Partitioning and Vegetation Cover with Grazing at Shortgrass Steppe.” *Journal of Arid Environments* 75 (4) (April): 360–370. doi:10.1016/j.jaridenv.2010.11.008. http://linkinghub.elsevier.com/retrieve/pii/S0140196310003174.

Jin, Huijun, Ruixia He, Guodong Cheng, and Qingbai Wu. 2009. “Changes in Frozen Ground in the Source Area of the Yellow River on the Qinghai – Tibet Plateau , China , and Their Eco-Environmental Impacts.” *Environmental Research Letters* 4 (4). doi:10.1088/1748-9326/4/4/045206.

Jin, Huijun, Ruixia He, Guodong Cheng, Qingbai Wu, Shaoling Wang, Lanzhi Lü, and Xiaoli Chang. 2009. “Changes in Frozen Ground in the Source Area of the Yellow River on the Qinghai–Tibet Plateau, China, and Their Eco-Environmental Impacts.” *Environmental Research Letters* 4 (4) (October 23): 045206. doi:10.1088/1748-9326/4/4/045206. http://stacks.iop.org/1748-9326/4/i=4/a=045206?key=crossref.ac9d3c85d1a8d15cc9f241831fcff11c.

Kang, E, G D Cheng, K C Song, B Jin, X D Liu, and J Y Wang. 2005. "Simulation of Energy and Water Balance in Soil-Vegetation- Atmosphere Transfer System in the Mountain Area of Heihe River Basin at Hexi Corridor of Northwest China." *Science in China Series DEarth Sciences* 48 (4): 538. doi:10.1360/02yd0428. http://219.238.6.200/article?code=02yd0428&jccode=08.

Karnieli, A., U. Gilad, M. Ponzet, T. Svoray, R. Mirzadinov, and O. Fedorina. 2008. "Assessing Land-Cover Change and Degradation in the Central Asian Deserts Using Satellite Image Processing and Geostatistical Methods." *Journal of Arid Environments* 72 (11) (November): 2093–2105. doi:10.1016/j.jaridenv.2008.07.009. http://linkinghub.elsevier.com/retrieve/pii/S0140196308001894.

Kaser, Georg, Martin Grosshauser, and Ben Marzeion. 2010. "Contribution Potential of Glaciers to Water Availability in Different Climate Regimes." *Proceedings of the National Academy of Sciences of the United States of America* 107 (47) (November 23): 20223–7. doi:10.1073/pnas.1008162107. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2996705&tool=pmcentrez&rendertype=abstract.

Klein, Julia A., John Harte, and Xin-Quan Zhao. 2007. "Experimental Warming, Not Grazing, Decreases Rangeland Quality on the Tibetan Plateau." *Ecological Applications : A Publication of the Ecological Society of America* 17 (2) (March): 541–57. http://www.ncbi.nlm.nih.gov/pubmed/17489258.

Kreutzmann, Herman. 2012. "Pastoral Practices in Transition -Animal Husbandry in High Asian Contexts." In *Pastoral Practices in High Asia*.

Lauenroth, William K, and John B Bradford. 2012. "Ecohydrology of Dry Regions of the United States : Water Balance Consequences of Small Precipitation Events" 53 (January 2011): 46–53. doi:10.1002/eco.

Lehner, B., K. Verdin, and A. Jarvis. 2008. "New Global Hydrography Derived from Spaceborne Elevation Data." *Eos, Transactions, American Geophysical Union* 89 (10): 93–94.

Li, Yonghong, Wei Wang, Zhongling Liu, and Shu Jiang. 2008. "Grazing Gradient versus Restoration Succession of Leymus Chinensis (Trin.) Tzvel. Grassland in Inner Mongolia." *Restoration Ecology* 16 (4): 572–583. doi:10.1111/j.1526-100X.2007.00332.x. http://doi.wiley.com/10.1111/j.1526-100X.2007.00332.x.

Lioubimtseva, E., R. Cole, J.M. Adams, and G. Kapustin. 2005. "Impacts of Climate and Land-Cover Changes in Arid Lands of Central Asia." *Journal of Arid Environments* 62 (2) (July): 285–308. doi:10.1016/j.jaridenv.2004.11.005. http://linkinghub.elsevier.com/retrieve/pii/S0140196304002496.

Lioubimtseva, E., and G.M. Henebry. 2009. "Climate and Environmental Change in Arid Central Asia: Impacts, Vulnerability, and Adaptations." *Journal of Arid Environments* 73 (11) (November): 963–977. doi:10.1016/j.jaridenv.2009.04.022. http://linkinghub.elsevier.com/retrieve/pii/S0140196309001220.

Macchi, M;, AM; Gurung, B; Hoermann, and D Choudhary. 2011. "Climate Variability and Change in the Himalayas Community Perceptions and Responses". Kathmandu.

Marchenko, S.S., a.P. Gorbunov, and V.E. Romanovsky. 2007. "Permafrost Warming in the Tien Shan Mountains, Central Asia." *Global and Planetary Change* 56 (3-4) (April): 311–327. doi:10.1016/j.gloplacha.2006.07.023. http://linkinghub.elsevier.com/retrieve/pii/S0921818106001901.

Menzel, L, T Aus Der Beek, T Törnros, F Wimmer, and D Gomboo. 2008. "Hydrological Impact of Climate and Land-Use Change – Results from the MoMo Project." Edited by B Basandorj and D Oyunbaatar. *International Conference on Uncertainties in Water Resource Management Causes Technologies and Consequences WRMMon2008*. IHP.

Mishra, Chardutt, Sipke E. Wieren, Ignas M. a. Heitkönig, and Herbert H. T. Prins. 2002. "A Theoretical Analysis of Competitive Exclusion in a Trans-Himalayan Large-Herbivore Assemblage." *Animal Conservation* 5 (3) (August): 251–258. doi:10.1017/S1367943002002305. http://doi.wiley.com/10.1017/S1367943002002305.

Moore, I.D., R.B. Grayson, and A.R. Ladson. 1991. "Digital Terrain Modeling: A Review of Hydrological, Geomorphological, and Biological Applications." *Hydrological Processes* 5: 3–30.

Olson, David M., Eric Dinerstein, Eric D. Wikramanayake, Neil D. Burgess, George V. N. Powell, Emma C. Underwood, Jennifer a. D'amico, et al. 2001. "Terrestrial Ecoregions of the World: A New Map of Life on Earth." *BioScience* 51 (11): 933. doi:10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2. http://www.jstor.org/stable/1313989.

Olson, Kirk A., Todd K. Fuller, Thomas Mueller, Martyn G. Murray, Craig Nicolson, Daria Odonkhuu, Sanjaa Bolortsetseg, and George B. Schaller. 2010. "Annual Movements of Mongolian Gazelles: Nomads in the Eastern Steppe." *Journal of Arid Environments* 74 (11) (November): 1435–1442. doi:10.1016/j.jaridenv.2010.05.022. http://linkinghub.elsevier.com/retrieve/pii/S0140196310001643.

Pederson, N., C. Leland, B. Nachin, a.E. Hessl, a.R. Bell, D. Martin-Benito, T. Saladyga, B. Suran, P.M. Brown, and N.K. Davi. 2012. "Three Centuries of Shifting Hydroclimatic Regimes across the Mongolian Breadbasket." *Agricultural and Forest Meteorology* (July). doi:10.1016/j.agrformet.2012.07.003. http://linkinghub.elsevier.com/retrieve/pii/S0168192312002377.

Raboin, Matthew L., and Joshua L. Posner. 2012. "Pine or Pasture? Estimated Costs and Benefits of Land Use Change in the Peruvian Andes." *Mountain Research and Development* 32 (2) (May): 158–168. doi:10.1659/MRD-JOURNAL-D-10-00099.1. http://www.bioone.org/doi/abs/10.1659/MRD-JOURNAL-D-10-00099.1.

Ramankutty, N., A.T. Evan, C. Monfreda, and J.A. Foley. 2008. "Farming the Planet: Geographic Distribution of Global Agricultural Lands in the Year 2000." *Global Biogeochemical Cycles* 22. doi:10.1029/2007GB002952.

———. 2010. "Global Agricultural Lands: Pastures, 2000." NASA Socioeconomic Data and Applications Center (SEDAC).

Rasul, Golam, Nakul Chettri, and Eklabya Sharma. 2011. "Framework for Valuing Ecosystem Services in the Himalayas." *Icimod*: 1–18. http://www.cabdirect.org/abstracts/20113136467.html.

Rees, Gwyn, and David N Collins. 2004. "An Assessment of the Impacts of Deglaciation on the Water Resources of the Himalaya, Final Technical Report: Volume 2."

Ren, Haiyan, Philipp Schönbach, Hongwei Wan, Martin Gierus, and Friedhelm Taube. 2012. "Effects of Grazing Intensity and Environmental Factors on Species Composition and Diversity in Typical Steppe of Inner Mongolia, China." *PloS One* 7 (12) (January): e52180. doi:10.1371/journal.pone.0052180. http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3528763&tool=pmcentrez&rendertype=abstract.

Ren, J, R B Alley, I Allison, J Carrasco, G Flato, Y Fujii, G Kaser, et al. 2007. "Observations: Changes in Snow, Ice and Frozen Ground." Edited by S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averyt, M Tignor, and H L Miller. *Changes* AR4 (181): 337–383. doi:10.1016/j.jmb.2004.10.032. http://epic.awi.de/epic/Main?puid=30870&lang=en.

Rodell, M., P. R. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C-J. Meng, K. Arsenault, et al. 2004. "The Global Land Data Assimilation System." *Bulletin of the American Meteorological Society* 85 (3) (March): 381–394. doi:10.1175/BAMS-85-3-381. http://journals.ametsoc.org/doi/abs/10.1175/BAMS-85-3-381.

Salve, Rohit, Erika a. Sudderth, Samuel B. St. Clair, and Margaret S. Torn. 2011. "Effect of Grassland Vegetation Type on the Responses of Hydrological Processes to Seasonal Precipitation Patterns." *Journal of Hydrology* 410 (1-2) (November): 51–61. doi:10.1016/j.jhydrol.2011.09.003. http://linkinghub.elsevier.com/retrieve/pii/S002216941100624X.

Sanderson, E. W., M. Jaiteh, and et al. 2002. "The Human Footprint and the Last of the Wild." *BioScience* 52 (10): 891–904.

Sankey, Temuulen Tsagaan, and et al M. Jaiteh. "Geospatial Assessment of Grazing Regime Shifts and Socio-Political Changes in a Mongolian Rangeland."

Sappington, J. M., K.M. Longshore, and D.B. Thomson. 2007. "Quantifiying Landscape Ruggedness for Animal Habitat Anaysis: A Case Study Using Bighorn Sheep in the Mojave Desert." *Journal of Wildlife Management* 71 (5): 1419–1426.

Schneider, K., J.a. Huisman, L. Breuer, and H.-G. Frede. 2008. "Ambiguous Effects of Grazing Intensity on Surface Soil Moisture: A Geostatistical Case Study from a Steppe Environment in Inner Mongolia, PR China." *Journal of Arid Environments* 72 (7) (July): 1305–1319. doi:10.1016/j.jaridenv.2008.02.002. http://linkinghub.elsevier.com/retrieve/pii/S0140196308000256.

Shan, Tien, Central Asia, Annina Sorg, Tobias Bolch, Markus Stoffel, Olga Solomina, and Martin Beniston. 2012. "Climate Change Impacts on Glaciers and Runoff in" (July): 1–7. doi:10.1038/NCLIMATE1592.

Shrestra, Rinjan. 2007. "Coexistence of Wild and Domestic Ungulates in the Nepalese Trans-Himalaya : Resource Competition or Habitat Partitioning". Norwegian University of Life Sciences.

Sindorf, Nikolai, and Bart Wickel. 2011. "Connectivity and Fragmentation Hydrospatial Analysis of Dam Development in the Mekong River Basin." http://issuu.com/nikolaisindorf/docs/hydrospatial.

Tahmasebi, Asghar. 2012. "Pastoralism under Pressure : Vulnerability of Pastoral Nomads to Multiple Socio-Political and Climate Stresses – The Shahsevan of Northwest Iran."

Trabucco, A., and R.J. Zomer. 2009. "Global Aridity Index (Global-Aridity) and Global Potential Evapo-Transpiration (Global-PET) Geospatial Database". CGIAR Consortium for Spatial Information. http://www.csi.cgiar.org.

UNEP. 2009. "Recent Trends in Melting Glaciers , Tropospheric Temperatures over the Himalayas and Summer Monsoon Rainfall over India."

Wang, Genxu, Wei Bai, Na Li, and Hongchang Hu. 2010. "Climate Changes and Its Impact on Tundra Ecosystem in Qinghai-Tibet Plateau, China." *Climatic Change* 106 (3) (December 21): 463–482. doi:10.1007/s10584-010-9952-0. http://link.springer.com/10.1007/s10584-010-9952-0.

Wang, Huaijun, Yaning Chen, Weihong Li, and Haijun Deng. 2013. "Runoff Responses to Climate Change in Arid Region of Northwestern China during 1960–2010." *Chinese Geographical Science* 23 (3) (May 3): 286–300. doi:10.1007/s11769-013-0605-x. http://link.springer.com/10.1007/s11769-013-0605-x.

Wolf, Adam, and William R L Anderegg. 2011. "Comment on 'Changes in Climatic Water Balance Drive Downhill Shifts in Plant Species' Optimum Elevations'." *Science (New York, N.Y.)* 334 (6053) (October 14): 177; author reply 177. doi:10.1126/science.1204607. http://www.ncbi.nlm.nih.gov/pubmed/21998369.

Yamanaka, T., I. Kaihotsu, D. Oyunbaatar, and T. Ganbold. 2007. "Summertime Soil Hydrological Cycle and Surface Energy Balance on the Mongolian Steppe." *Journal of Arid Environments* 69 (1) (April): 65–79. doi:10.1016/j.jaridenv.2006.09.003. http://linkinghub.elsevier.com/retrieve/pii/S0140196306002813.

Yang, Yuanhe, Jingyun Fang, Philip A Fay, Jesse E Bell, and Chengjun Ji. 2010. "Rain Use Efficiency across a Precipitation Gradient on the Tibetan Plateau." *Geophysical Research Letters* 37 (15): 1–5. doi:10.1029/2010GL043920. http://www.agu.org/pubs/crossref/2010/2010GL043920.shtml.

Yang, Zhao-ping, Yang Hua Ou, Xing-liang Xu, Lin Zhao, Ming-hua Song, and Cai-ping Zhou. 2010. "Effects of Permafrost Degradation on Ecosystems." *Acta Ecologica Sinica* 30 (1) (February): 33–39. doi:10.1016/j.chnaes.2009.12.006. http://linkinghub.elsevier.com/retrieve/pii/S1872203209000882.

Yu, Fangfang, Kevin P Price, James Ellis, and Peijun Shi. 2003. "Response of Seasonal Vegetation Development to Climatic Variations in Eastern Central Asia." *Remote Sensing of Environment* 87 (1) (September): 42–54. doi:10.1016/S0034-4257(03)00144-5. http://linkinghub.elsevier.com/retrieve/pii/S0034425703001445.

Zemmrich, a., M. Manthey, S. Zerbe, and D. Oyunchimeg. 2010. "Driving Environmental Factors and the Role of Grazing in Grassland Communities: A Comparative Study along an Altitudinal Gradient in Western Mongolia." *Journal of Arid Environments* 74 (10) (October): 1271–1280. doi:10.1016/j.jaridenv.2010.05.014. http://linkinghub.elsevier.com/retrieve/pii/S0140196310001564.

Zha, Yong, Jay Gao, and Ying Zhang. 2005. "Grassland Productivity in an Alpine Environment in Response to Climate Change." Area 37 (3): 332–340. doi:10.1111/j.1475-4762.2005.00637.x. http://doi.wiley.com/10.1111/j.1475-4762.2005.00637.x.

Zhang, Geli, Yangjian Zhang, Jinwei Dong, and Xiangming Xiao. 2013. "Green-up Dates in the Tibetan Plateau Have Continuously Advanced from 1982 to 2011." *Proceedings of the National Academy of Sciences of the United States of America* 110 (11) (February 25). doi:10.1073/pnas.1210423110. http://www.ncbi.nlm.nih.gov/pubmed/23440201.

Zhang, JianGuo, YingLi Wang, YunSong Ji, and DeZhi Yan. 2011. "Melting and Shrinkage of Cryosphere in Tibet and Its Impact on the Ecological Environment." *Journal of Arid Land* 3 (4) (September 27): 292–299. doi:10.3724/SP.J.1227.2011.00292. http://pub.chinasciencejournal.com/article/getArticleRedirect.action?doiCode=10.3724/SP.J.1227.2011.00292.

Zhao, Qiudong, Baisheng Ye, Yongjian Ding, Shiqiang Zhang, Shuhua Yi, Jian Wang, Donghui Shangguan, Chuancheng Zhao, and Haidong Han. 2012. "Coupling a Glacier Melt Model to the Variable Infiltration Capacity (VIC) Model for Hydrological Modeling in North-Western China." *Environmental Earth Sciences* 68 (1) (May 24): 87–101. doi:10.1007/s12665-012-1718-8. http://www.springerlink.com/index/10.1007/s12665-012-1718-8.

Zhao, W, S P Chen, X G Han, and G H Lin. 2009. "Effects of Long-Term Grazing on the Morphological and Functional Traits of Leymus Chinensis in the Semiarid Grassland of Inner Mongolia, China." *Ecological Research* 24 (1): 99–108. doi:10.1007/s11284-008-0486-0. http://www.springerlink.com/index/10.1007/s11284-008-0486-0.

USAID
FROM THE AMERICAN PEOPLE

WWF

Why we are here

To stop the degradation of the planet's natural environment and to build a future in which humans live in harmony with nature.

worldwildlife.org/climate