TREND OBSERVATORY ON WATER

TREND SHEET

"On thin ice – adapting water resources management to climate change effects on the mountain cryosphere"

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#2

Almost 25% of the world's population depend on mountain cryosphere - glaciers, snow, and permafrost - as their main source of water. But this source is shrinking at unprecedented pace almost everywhere in the world. Climate change effects on mountain cryosphere have already altered some rivers' flows, and impacts on water resources and their uses are expected to further increase in the future. However, the impacts observed vary over regions, seasons and time scales and uncertainties remain in projections of future impacts.

Water resources management, therefore, has to better deal with uncertainties by taking a risk-based approach and adopting solutions that are robust over a wider array of potential future conditions. Moreover, with the disappearance of glaciers and reaching of so called "peak water", more abrupt changes in water availability are projected. With more dramatic impacts of higher temperatures, incremental adaptation may be insufficient and transformational adaptation involving more substantive, systemic changes may be needed.

This Trend Sheet summarises the state of research on climate change effects on the mountain cryosphere and its impact on freshwater resources. It provides examples of approaches that can help deal with uncertainties and reviews emerging insights on how to foster transformation.

Content

Definition of terms

Cryosphere – The components of the Earth System at and below the land and ocean surface that are frozen, including snow cover, glaciers, ice sheets, ice shelves, icebergs, sea ice, lake ice, river ice, permafrost and seasonally frozen ground. [5]
Peak water – Peak water refers to the year when annual runoff from the initially glacier-covered area will start to decrease due to glacier shrinkage after a period of melt induced increase in runoff. [3]
Resilience – The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. [5]
Risk – The potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as from human responses to climate change. [5]
Transformational adaptation – Adaptation that changes the fundamental attributes of a social-ecological system in anticipation of climate change and its impacts […] characterised by system-wide change or changes across more than one system, by a focus on the future and long-term change, or by a direct questioning of the effectiveness of existing systems, social injustices and power imbalances.[5]
Vulnerability – The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. [5]
Water Tower – In the context of hydrology, used as a symbolic term for a mountain area to describe the water storage and supply that mountain ranges provide to sustain environmental and human water demands downstream.

Why this Trend Sheet?

What trend do we observe?

The mountain cryosphere – glaciers, snow, permafrost, and ice in mountain areas – is vanishing almost everywhere in the world due to climate change. Many glaciers are expected to disappear until the end of the 21st century, especially in regions with mostly smaller glaciers and relatively little ice cover. This trend is expected to further accelerate over the next decades due to anthropogenic climate change.

Why is this trend important for water practitioners in development cooperation?

- **Almost 2 billion people worldwide depend on mountain cryosphere as their main source of water.** The mountain cryosphere and high-altitude montane ecosystems form natural 'water towers' that provide and regulate freshwater resources for people living in the mountains as well as downstream.
- **Climate change effects on mountain cryosphere significantly impact on water availability, quality and timing of flows – but the impacts vary over regions, seasons and time scales and uncertainties remain in future projections.** Water managers have long developed approaches to deal with too much and too little water as well as climate variability. Climate change, however, adds another layer of uncertainty and may cause more rapid changes.
- **More uncertain and assumed dramatic impacts of climate change may turn current adaptation practices inappropriate.** Adapting water resources management incrementally to changing conditions may be insufficient, instead more substantive, systemic changes (transformational adaptation) will be required to maintain long term resilience.

What is new?

Glaciers are shrinking even faster than thought before, almost everywhere in the world, as improved methods and data coverage of satellite and in situ observations have shown [1].
Recent research highlights that the world's most important **water towers are also among the most vulnerable to climatic and socio-economic changes** [2].
New insights are emerging on how to deal with uncertainties and profound changes through adaptation measures. Approaches of risk-based management have recently been adapted for better use in water planning, and ongoing research on transformational adaptation is providing first insights on how to bring about more systemic change.

Mountain cryosphere – water towers for billions of people worldwide

High mountain areas worldwide form natural 'water towers' that constitute an important component of the hydrological cycle and a significant freshwater source for many people in the world. This refers to the people living in the mountains but also to those living in downstream regions, particularly in arid and semi-arid zones. In high mountain areas, water often occurs as frozen components of the ecosystem, the so-called cryosphere (including snow, glaciers, permafrost, lake and river ice). Glaciers and snow store water during cooler precipitation periods and release it as meltwater in the warmer and drier seasons. The cryosphere thus functions as a seasonal and/or long-term water storage that can bridge arid periods and act as an important buffer for water supply to human settlements, agriculture, hydropower and natural ecosystems, particularly in vulnerable drought-prone regions. Cryospheric water towers provide water supply to an estimated 1.9 billion people, i.e. almost 25% of the global population [2]. The most important water towers in this regard, unfortunately, are also among the most vulnerable to climatic and socio-economic change (see Box 1).

Due to the remoteness of mountain areas, monitoring networks are often insufficiently dense and fieldworks complicated, which compromises management today and projections of future changes. While improvements in observation systems and model developments have advanced scientific understanding of cryosphere change over the past years, meteorological, hydrological, climate and cryosphere observations in mountain regions remain scarce. Moreover, **mountain systems and water towers often stretch beyond national borders, therefore requiring transboundary cooperation and data sharing** for sustainable resources management. In October 2019, the World Meteorological Organisation (WMO) at its High Mountain Summit has therefore issued a call to action to increase international efforts in high-mountain observation. Uncertainties, however also relate to the socio-economic development and thus water demand in mountain and downstream areas.

Box 1 - The Water Tower Index

The Water Tower Index, recently developed by an international group of researchers, ranks all cryospheric water towers by importance in terms of their water supplying role and the downstream demand from ecosystems and society. The research also assessed vulnerability of water towers, assuming that this depends on water stress (ratio of total water withdrawals to the available renewable surface and groundwater supplies), governance, hydropolitical tension and future climatic and socio-economic changes.

The Indus, Tarim, and Amu Darya water towers in Asia score highest in importance and vulnerability, worldwide. In South America, the Chile-Patagonia-South and Negro water towers also score high in both terms, importance and vulnerability. [2]

How do climate change effects on mountain cryosphere impact freshwater resources?

Mountain cryosphere is highly sensitive to climate change and impacts are already becoming obvious: low-elevation snow cover, glaciers and permafrost show a general decline since the mid-20th century, although annual variability and regional differences are large. Mountain cryosphere is projected to continue declining in almost all regions throughout the 21st century. [3] Cryosphere decline may be further intensified by local climate feedbacks: as the reflecting white snowcover declines, absorption of incoming solar radiation is increased, which in turn leads to more warming, the so-called snow albedo feedback.

Climate change effects manifest in slow-onset changes in the amount and seasonality of river runoff as well as hydrological extremes, floods in particular. **In recent decades, climate change effects on snow and glaciers have already altered the amount and seasonality of runoff in snow-dominated and glacier-fed river basins and these effects are projected to further increase in the future.** As glaciers melt, summer and annual water runoff typically first increases for some years or decades until a point in time, called peak water, beyond which runoff steadily declines due to glacier shrinkage. Despite regional variability, **average annual runoff from glaciers will have reached a peak that will be followed by declining runoff, at the latest by the end of the 21st century in all regions** [3]. Water management therefore needs to prepare for decreasing flows after some decades of increased water availability (see Box 2).

Future changes in mountain cryosphere are projected to affect water resources and their uses, such as irrigated agriculture and hydropower in high mountain areas as well as in lowlands downstream. However, the cause effect relationships are complex and **impacts differ significantly between seasons and among regions, and therefore require regional impact analyses.**

The state of research on climate change effects in the mountain cryosphere as well as associated impacts, risks and adaptation measures have recently been synthesised in a dedicated chapter of the Intergovernmental Panel on Climate Change (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC). The most relevant insights for water resources management are summarised below.

- **Summer and annual runoff has increased in several glacier-fed rivers, due to intensified glacier melt, but decreased in others where glaciers are already vanishing.** As glaciers melt, summer and annual water runoff typically first increases for some years or decades until a point in time, called peak water, beyond which runoff steadily declines due to glacier shrinkage. Many glaciers have already reached peak water, and according to a recent study this concerns e.g. 82–95% of the glacier area in the tropical Andes and 55–67% in Central Europe and the Caucasus [4]. **Summer runoff is predicted to decline over the 21st century in many basins**, for example in High Mountain Asia and the tropical Andes due to less snowfall and decreases in glacier melt after peak water. Peak water will generally occur earlier in regions with little ice cover and smaller glaciers, such as e.g. the European Alps and the Caucasus.

- **Winter runoff has increased in recent decades and is projected to further increase in many rivers over the 21st century**, due to more precipitation falling as rain instead of snow and increased winter snowmelt in a steadily warming climate.

- **Spring peak runoffs have shifted in timing towards earlier spring due to earlier snowmelt and is projected to occur up to several weeks earlier in the year by end of the 21st century**, in many snow dominated river basins around the world. This may result in water scarcity in summer and thus in critical times for irrigation.

- **Rain-on-snow floods**, i.e. floods originating from the combination of rapidly melting snow and intense rainfall, have increased over the last decades at high elevations in winter and decreased at low elevations in spring. Rain-on-snow events are some of the most damaging floods in mountain areas, and their frequency is projected to increase and occur earlier in spring and later in autumn at higher elevation and to decrease at lower elevation.

Box 2 - Melting glaciers make the desert bloom in Peru – but for how long

Increased melting of glaciers and snow can be a welcome additional supply of water in dry areas. However, as peak water is going to be reached soon in many glacier-fed basins in the world, this water supply is not sustainable in the long-term. In Peru's arid north, the government has started a huge infrastructure project in the 1980s, bringing irrigation water from melting glaciers in the Andes Cordillera Blanca to the desert by constructing a 154 km canal (projected to extend to 267 km with completion of Stage III).

The **Chavimochic irrigation project** diverts up to 105 m3/s from the Santa River for agriculture in adjacent watersheds on the arid coastal plain. After Stages I and II of Chavimochic, approximately 81,000 ha have come under cultivation, producing high- value export-crops.

The project simultaneously provides much of the coastal city of Trujillo's potable water supply. The project has thus created livelihoods for thousands of people through irrigated agriculture, further providing clean drinking water and electricity from hydropower.

The livelihoods of hundreds of thousands of people have become dependent on an insecure water supply. However, already now flows are decreasing and less reliableas glaciers in the Andes are shrinking, and it is estimated that by 2050 much of the icecap will be gone. **A fundamental change towards longterm sustainable water resources management - and development in the region in general - is urgently needed!**

Other climate change impacts

- **Climate change effects on mountain cryosphere may affect occurrence of natural hazards.** Over the past decades glacier retreat and permafrost thaw have decreased the stability of mountain slopes, and the number and area of glacier lakes has increased in most regions. Glacier lake outburst floods (GLOFs), landslides and snow avalanches, are projected to occur in new locations or different seasons. Related risks may be further exacerbated by unsustainable land-use management and deforestation.

- **Sediment transport in rivers fed by mountain cryosphere is expected to increase as a result of more frequent flood events and increased erosion** due to permafrost reduction and glacier retreat. While sediment transport supplies mountainous and downstream ecosystems and agricultural soils with important nutrients, increased sediment loads may impact hydropower facilities and water supply systems as well as cause siltation of wetland areas. However, there is still limited understanding of the effects of changes in the cryosphere on sediment flux in mountain areas.

- **Changes in the mountain cryosphere will influence water quality.** Besides changes in nutrient content from sediment transport, release of heavy metals, particularly mercury, and other legacy contaminants currently stored in glaciers and permafrost will affect water quality. This may pose a potential threat to freshwater biota, household use and irrigation, especially where glaciers are subject to substantial pollutant loads such as in High Mountain Asia and Europe.

Opportunities of climate change effects in mountain cryosphere

Changing climate is projected to bring along substantial adverse effects for people living in and downstream of mountain cryosphere. However, there are also some opportunities that could be seized if managed wisely.

- **Making sustainable use of increased glacier runoff.** Peak water annual runoff from glaciers can substantially exceed the annual runoff generated before the glacier started to retreat. In a global study, it was projected that peak water annual runoff will increase by more than 50% relative to 1980–2000 in some basins [4]. This excess water can be used in different ways, such as for hydropower or for increasing irrigation in agriculture. In Iceland, for example, the National Power Company was able to increase hydropower production capacity by making use of increased run-off from melting glaciers. There is, however, a danger in relying on increased water availability in the long term. Strategic water resources planning needs to cater for strategies to deal with decreasing flows after peak water has been reached (see Box 2).

- **Shifting to crops that generate more income or support local food security.** Increasing temperatures in mountain areas often allows to extend cropped areas to higher altitudes and/or to cultivate crops that do not grow in very cold climate, providing new or increased opportunities for local food security and income generation. Shifting to less water-intensive crops in response to reduced water availability has, in some cases, also come along with co-benefits, for example production of more nutrient rich crops that support local food security.

Further Reading

Huss et al 2017 "Toward mountains without permanent snow and ice"

UNESCO 2018 "The Andean glacier and water atlas: the impact of glacier retreat on water resources"

SDC Climate Change and Environment Network 2019 "The Climate-Cryosphere-Water Nexus in Central Asia"

Bloch et al 2019 "Status and Change of the Cryosphere in the Extended Hindu Kush Himalaya Region"

Adapting water management to uncertain change in mountain areas

Existing water resources management approaches developed to address variability in water availability and hydrological extremes can be a good starting point for adapting to changes in mountain cryosphere. Water resources management has always had to deal with climate variability and conditions of too much or too little water. Several handbooks and information platforms provide general guidance, e.g. the UNEP/DHI "Practitioners Guide to Adaptation Technologies for Increased Water Sector Resilience". In some cases, leveraging indigenous knowledge and reviving traditional practices of mountain communities can reveal sustainable solutions. An example from Peru is the restoration of ancient terraces and channels following designs from the Inca times. The channels capture water from waterways during times of high runoff and distribute it to areas where it can infiltrate into the ground to later feed springs further down in the mountains.

Increasing storage capacity can help address reduced natural storage provided by glaciers and snowpacks in mountains. Storage solutions range from development and sustainable management of reservoirs, via micro dams or ponds built by communities, to improving natural storage in mountain wetlands and land use practices that keep moisture in the soil. The ICIMOD report "Water Storage - A strategy for climate change adaptation in the Himalayas" discusses related challenges and opportunities in the Himalayas. More recently, approaches for storage of water in artificial glaciers have been developed in Ladakh, India, but their long-term sustainability is questioned (see e.g. glacierhub.org). In transboundary river basins, cooperation of riparian states can help increase effectiveness of water storage as it is often more effective to store water for downstream use in upstream countries, e.g. in wetlands or multi-purpose dams.

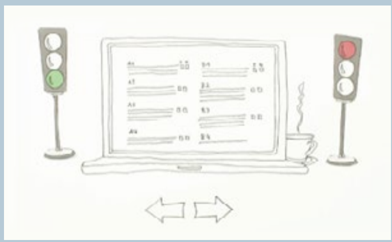
In the face of rapidly changing cryosphere and remaining uncertainty, however, water resources management and planning needs to be based on integrated assessments of climate related risks. The effects of climate change on mountain cryosphere are expected to further increase in the future, yet impacts on water resources will vary over regions, seasons and time scales. While regional climate and hydrological modelling can help inform water resources management, projections come along with significant uncertainties. Uncertainties not only remain in projections of future climate change impacts on freshwater resources, but also related to future socio-economic conditions that shape water dependency and vulnerability to climate change. Risk assessments therefore need to integrate projections of regional climate change effects and socio-economic developments. Several tools and guidance documents for climate risk and vulnerability assessments have been developed but need to be used more broadly in water resource management planning (see Box 3). Data availability is often a challenge in risk assessments. In transboundary settings, this is further complicated if relevant data is not shared among riparian countries.

Measures to increase resilience to climate change effects on mountain cryosphere have to deal with remaining uncertainties and account for residual climate risks. While risk assessments help to better factor in uncertainties related to future conditions, they cannot eliminate these uncertainties. Therefore management of water resources that depend on mountain cryosphere needs to take a risk-based approach and adopt robust solutions that perform well over a wide range of climate (and non-climate) scenarios, and/or are flexible enough to be easily adapted to changing conditions. Robust strategies include:

- **Multiple-benefit solutions, or so-called no-regret solutions,** that provide benefits irrespective of negative climate change impacts, such as water demand management, or conservation of wetlands for water storage with co-benefits for mountain biodiversity and livelihoods. Ecosystem-based approaches for adaptation have proven to provide great potential as resilient solutions bringing multiple benefits.

- **Reversible or flexible solutions** that can be adapted to changing conditions, at a relatively low cost, for example to decreasing water flows after peak water. Governance approaches are often more easily adaptable than hard infrastructure, such as water pricing to incentivise more efficient water use in times of water shortage.

Box 3 - Melting glaciers make the desert bloom in Peru – but for how long



The **Climate, Environment and Disaster Risk Reduction Integration Guidance** (CEDRIG) tool developed by the Swiss Agency for Development and Cooperation (SDC) helps to systematically integrate climate, environment and disaster risk reduction into development cooperation strategies, programs and projects. It factures in risks for development action as well as possible negative or positive impacts caused by development actions, e.g. increasing vulnerability and thus 'doing harm'.

More recently, the **Climate Risk Informed Decision Analysis** (CRIDA) approach was designed by UNESCO and partners for water resource planning and management, in particular. It provides guidance for evaluating future uncertainties related to a changing climate, demographics, environment or economics, and for decision-making in face of residual risks.

Further Reading

Matthews et al. 2019 "Wellspring: Source Water Resilience and Climate Adaptation", (see Annex2 for examples of robust and flexible solutions providing multiple benefits, and Table 1 for examples of nature-base solutions to address impacts from decreasing glaciers and snowpacks.)

Mishra et al. 2017 "Building Mountain Resilience- Solutions from the Hindu Kush Himalaya", (incl. approaches for sustaining natural resources, changing behaviours and practice, and improving governance and services)

Nüsser et al. 2019 "Socio-hydrology of Bartificial glaciers^ in Ladakh, India: assessing adaptive strategies in a changing cryosphere"

United Nations Development Programme 2015 "Making the Case for Ecosystem-Based Adaptation. The Global Mountain EbA Programme in Nepal, Peru and Uganda."

Need for more transformational change

Continuing temperature increase will fundamentally change high mountain cryosphere and montane ecosystems. This is expected to cause profound alteration of the hydrologic regime in dependent basins as glaciers disappear irreversibly. Moreover, as some mountain areas are more susceptible to warming than the global average, climate change impacts may indeed be much more severe than currently expected. For example, increasing temperatures may turn montane ecosystems including glaciers and snowpacks into wetlands, bare ground, or grasslands; and river basins currently fed by glaciers and snow may shift to a rain-fed hydrology. Extreme climate change scenarios (high-end scenarios) can illustrate the consequences. In order to adapt to high-end climate change, **it is vital that water managers also consider uncertain, but potentially high-risk, scenarios of the future.**

Rapid and irreversible change to mountain cryosphere will likely render incremental adaptation of water resources management insufficient. Instead more substantive, systemic changes may be needed, so called transformational adaptation. For example, when reduced water availability in mountain areas can no longer be addressed merely by improved storage and increasing water use efficiency, after peak water has been reached and glaciers disappear. As water resources get ever scarcer, farmers, for example, may have to substantially change their farming systems to use water more effectively (not only more efficiently) to generate income, e.g. by planting highly drought resistant crops, by changing livelihoods to pastoralism or ecotourism, where possible, or even by moving downhill for search of wage labor. **In adaptation planning, decision makers should anticipate radical climate change impact, assess at what point transformational approaches are needed, and prepare for it.**

However, there is still substantive need to develop and better study transformational adaptation measures. There are yet limited case studies and good practice examples of transformational adaptation, especially in mountain areas. Current research, shows that the main challenges in achieving transformational adaptation are overcoming technical path dependencies and bringing about institutional and societal change. One way to address these challenges is adopting a coordinated sequence of rather incremental adaptation measures, so called transformative pathways, eventually leading to transformational change.

Further Reading

Fedele et al. 2019 Nature-based Transformative Adaptation: a practical handbook

Carter et al. 2018 Transforming Agriculture for Climate Resilience: A Framework for Systemic Change

References

[1] Zemp, M. et al., 2019: Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. Nature, 568(7752), 382–386 doi:10.1038/s41586-019-1071-0

[2] Immerzeel, W. W. et al., 2019: Importance and vulnerability of the world's water towers. Nature, 577 https://doi. org/10.1038/s41586-019-1822-y

[3] Hock, R., et al., 2019: High Mountain Areas. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

[4] Huss, M. and R. Hock, 2018: Global-scale hydrological response to future glacier mass loss. Nat. Clim. Change, 8(2), 135–140, doi:10.1038/s41558-017-0049-x

[5] IPCC, 2019: Annex I: Glossary [Weyer, N.M. (ed.)]. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

The "**Trend Observatory on Water**" of the Swiss Agency for Development and Cooperation (SDC) aims at informing the RésEAU, SDC's Water Network, and interested parties about relevant emerging trends and innovative approaches for development cooperation in the water sector. Initiated by SDC's Global Programme Water and run by adelphi, it analyses how major global trends can affect water resources and management practices in the future. Through various communication formats and its website https://hazu.swiss/deza/trend-observatory-on-water it aims to raise awareness of opportunities that arise for more sustainable solutions, but also of the risks and challenges that might come along with them.

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