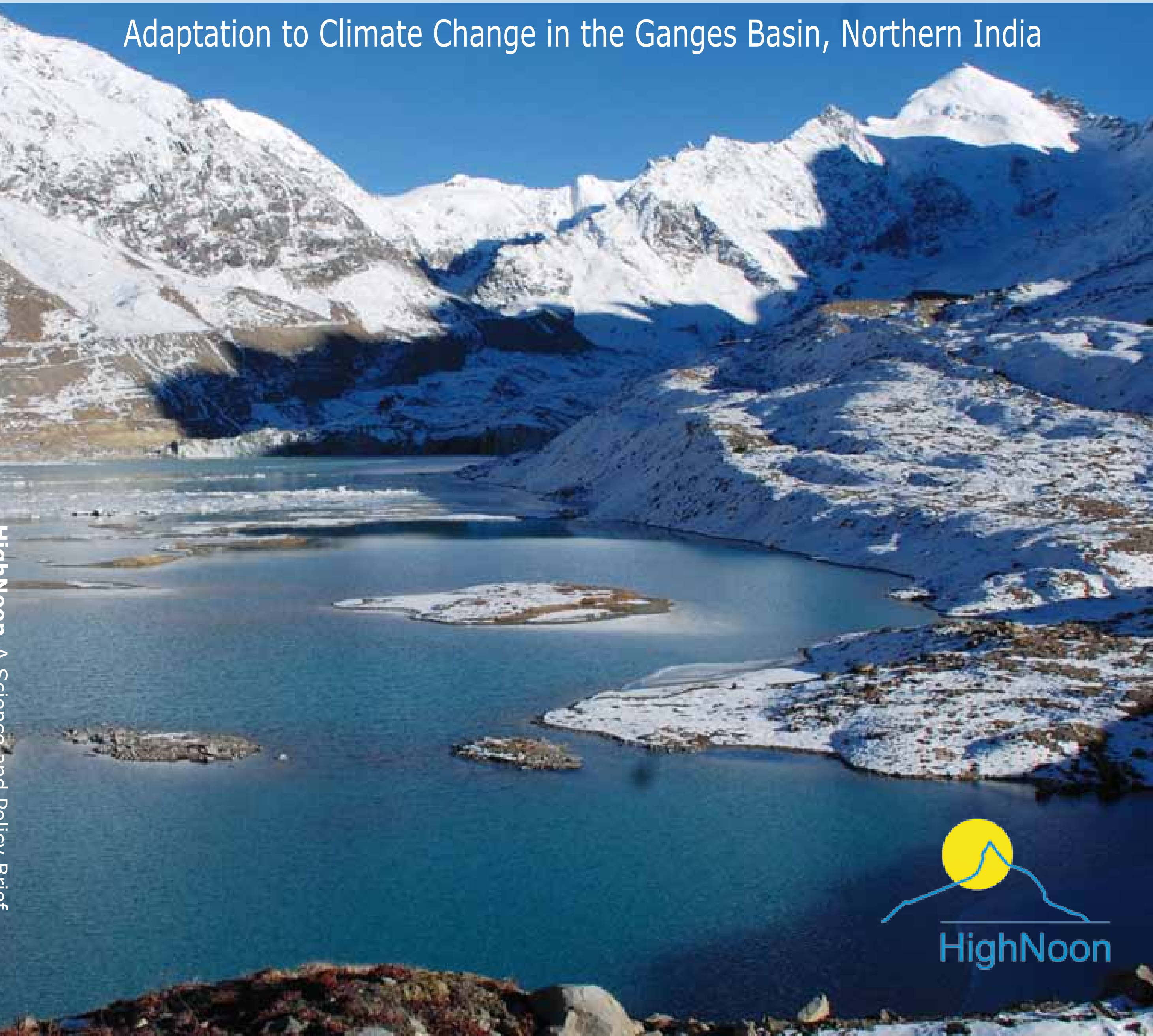
HighNoon
A Science and Policy Brief

Adaptation to Climate Change in the Ganges Basin, Northern India



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April 2012

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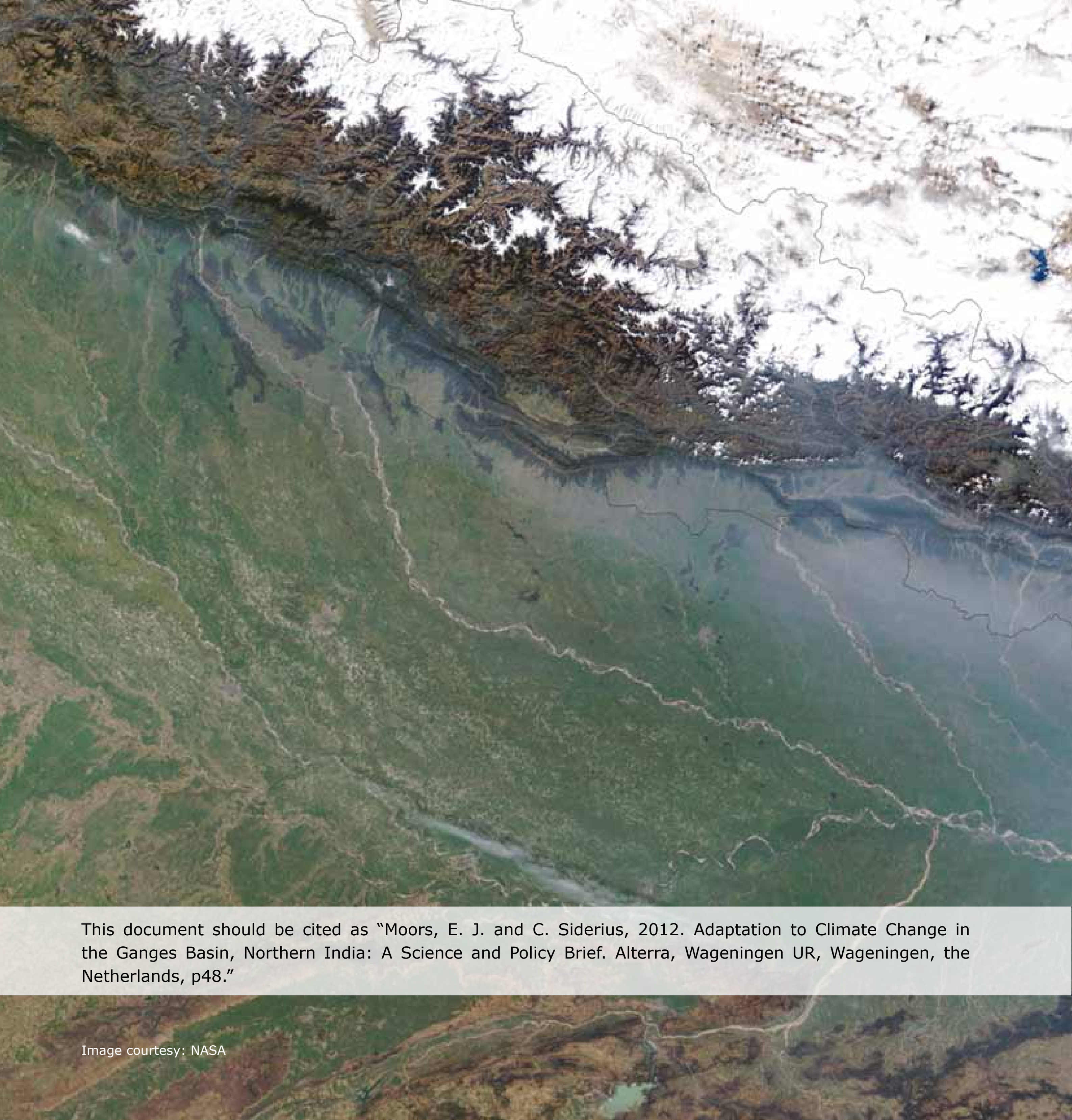

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Image courtesy: NASA

Foreword

Millions of people live in the Ganges basin and depend on water resources derived both from melting snow and ice in Himalayan headwaters and from monsoon rainfall over most of the basin area. Retreating glaciers, changing monsoon patterns, and declining groundwater levels coupled with increasing population, enhanced demand for water for irrigation, developing industrialization, and demand for hydropower are likely to place water resources under considerable stress as the 21st century unfolds.

The urgency of these threats was recognized in 2007, when the impact of climate change on water resources was identified as one of the important areas for EU–India research collaboration. As a result, funds within the European FP7 research programme were made available to initiate the HighNoon project.

HighNoon focussed on the development of adaptation measures in Northern India and is a collaborative effort between European, Indian, and Japanese partner institutes. It is coordinated by Alterra, Wageningen UR, in the Netherlands.

The project has focussed on the development of improved understanding of the biophysical and the social system, at present and in future. The involvement of stakeholders at different levels, ranging from individual farm level to national government, makes the outcomes of the selected adaptation options of great value.

HighNoon leaves a clear legacy of datasets that will be made available to the whole research community in India and Europe. These datasets include, amongst others, an up-to-date inventory of the state of Himalayan glaciers, and regional climate projections at an unprecedented resolution. By installing a recording station to measure river flow at a high elevation site close to the East Rathong Glacier, HighNoon contributes to the much-needed improvement of data coverage.

In addition, HighNoon has created a European-Indian-Japanese group of knowledgeable and experienced researchers working at the interface between the physical sciences of climatology, glaciology, and hydrology with the social sciences. These scientists together with the participants of the HighNoon Spring School(s) will go on to influence international research projects for years to come, underpinning the development of evidence-based inter-governmental policy-making.

Eddy Moors, HighNoon Coordinator

Major findings and recommendations for policy makers

Major findings

- Gradual wide-spread **warming** over northern India is projected by Regional Climate Models (RCM). Temperatures in the Ganges basin are expected to increase by an average of about 2 °C by 2050 and 4 °C by 2100, being more pronounced over **mountainous areas**.

- Annual total **precipitation** changes across northern India are less certain. Against a backdrop of considerable decadal variability, the slight increase in precipitation to 2050 indicated by the RCMs is unlikely to be significant.

- **Regional differences** in projected precipitation levels suggest a small decrease to be more likely towards the west of the Ganges basin by 2100, but an increase more likely towards the east.

- High intensity precipitation events are projected to increase in the Ganges basin. The intensity of **flood events** in the basin is expected to successively increase after 2050. Increased flooding intensity can result in enhanced **sediment erosion**, which will consequently reduce storage capacity of the reservoirs towards the end of the century.

- The expected continuation of **glacier shrinkage** in most parts of the Himalayan mountain ranges is confirmed by innovative modelling of glaciers at a large scale within RCMs, but with some increase in the western Himalaya and Karakoram.

- It is unlikely that the next decades will see dramatic changes in total runoff, but continued glacier recession will lead to changes in the **seasonal pattern** of runoff in upstream basins, with changes in both timing and amount **of snow melt** likely to affect flow in spring months, at times when other sources of runoff are scarce.

- Within India, several lakes located in Sikkim threaten downstream villages with **Glacier Lake Outburst Floods (GLOFs)**. Glacier lakes studied in the states of Jammu and Kashmir and Himachal Pradesh are thought to present a minor risk to downstream regions.

- **Drought** conditions are expected to be exacerbated by 2050 as a result of higher temperatures and fewer rain days.

- Yields of existing varieties of both **rice and wheat** are projected to decline, with greater reductions in upstream regions, as negative impacts of higher temperatures offset positive effects of higher carbon dioxide concentrations. Downstream, in and around the Ganges delta, rice and wheat production might improve slightly, if precipitation increases.

- **Stakeholders** report increases in temperatures across the Ganges basin, nights becoming warmer, winters being shorter, greater variability in rainfall, and extreme events, mostly related to drought, becoming more frequent.

- Within the same state, stakeholder discussions showed commonality concerning **perceived vulnerability** across state, district, and community levels.

- In upstream regions, where stakeholders expect climate change to increase flood risk, **adaptation measures** to prevent flood damage are highly prioritized. In mid and downstream regions of the Ganges basin, stakeholders anticipate droughts and lowering of the water table, leading them to prioritize measures to maintain groundwater levels, and to develop water harvesting and water use efficiency.

Recommendations

- Rates of melt and accumulation of Himalayan glaciers are still not well understood. More research is needed on **benchmark glaciers** so as to better understand their dynamics, evolution, and response to climate change.

- The network of **benchmark glaciers** for sustained measurements should be extended to represent the large diversity of Himalayan glacier environments so as to allow better prediction of future meltwater yields.

- Using the identification of critical glacier lakes, lake monitoring and installation of **early warning systems** must now be developed.

- Further research is needed to understand regional and global mechanisms driving the **Indian Monsoon** to improve precipitation in climate models. Such understanding will also help in daily and seasonal forecasting of precipitation, useful for tackling floods and droughts alike.

- When limited in financial resources, invest either in regional climate models for spatial detail or in multiple general circulation models for spread in **emission scenario outcomes**.

- To support decision making on climate change adaptation, **climate science information** needs to be made available to **stakeholders at all levels**, in an understandable format and at a scale and detail, which is relevant to stakeholders.

- Robust climate adaptation decision making, needs to account for both the **uncertainty** in future climate projections and for **natural climate variability**, which may lead to short-term variation in climate.

- At present, adaptation measures in India are planned at national and state level, not taking into account the physical boundaries of water systems. To prevent adverse effects in other parts of the river basin, planning should be tailor-made at the **river basin scale**.

- To increase resilience, adaptation plans should be made **locally specific**. Enabling the exchange of case studies and good practices will facilitate the development of robust solutions.

- Large scale water storage for agriculture is not a viable option for mid and downstream of the Ganges basin, partly due to topography. Focus should rather be on more **local distributed storage**. That would also help in inducing natural recharge to replenish the ever reducing groundwater.

- Recent scientific developments have led to an increase in skill in long-term forecasting on the seasonal, annual, and decadal scales. These forecasts may provide important information to decision makers. Further development of these **forecasting skills** should be encouraged.

- To enable quantification of cost and benefit analysis of adaptation options, more empirical research is needed integrating **participatory qualitative methods** and **quantitative model-**based outcomes.

- Common knowledge could be increased by supporting comparison, evaluation, and **monitoring of approaches**.

- A platform for the **exchange of information** and good practices regarding climate adaptation is recommended.

- Making bio-physical and socio economic **data available** to the research community will greatly decrease the uncertainty in research outcomes and consequently increase the value of these research results for society.

- Results from the HighNoon project could be transferred to other countries trying to achieve the **Millennium Development and Sustainability Goals** by Green Economic Growth.

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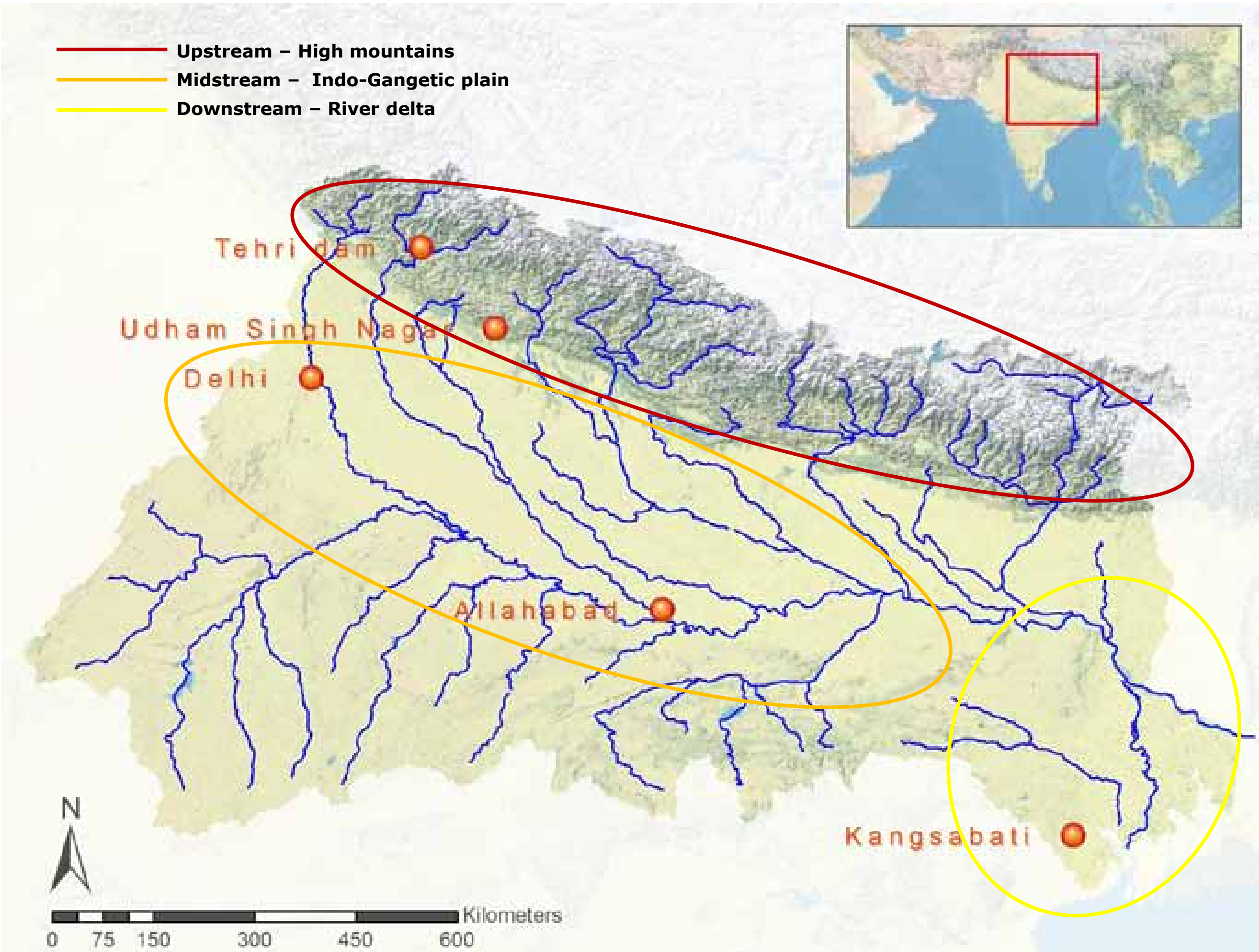


The Ganges basin with the HighNoon case study sites upstream (Tehri dam, Udham Singh Nagar), mid-stream (Delhi, Allahabad), and downstream (Kangsabati)

Introduction

"Adaptation to Changing Water Resources Availability in Northern India with Himalayan Glacier Retreat and Changing Monsoon" (HighNoon) is an EU-funded project (2009–2012) carried out as a collaboration between European, Indian, and Japanese partner institutes.

The concerns

The monsoon precipitation in the Indo-Gangetic plain and the growth and melt of the snow and ice cover in the Himalaya control the hydrological system of northern India. Climate change is expected to modify these phenomena. That in turn will have short-term as well as long-term impacts on the hydrological systems, including snow cover, glaciers, groundwater and surface water resources, as well as water use by natural and agricultural ecosystems.

These impacts will be especially profound in the perennial river basins, Ganges, Indus, and Brahmaputra, where snow and glacier melt form an important part of the rivers' flow. Increased melting of snow and glaciers could lead to changes in timing and magnitude of flows. In addition, the presence of snow cover and timing of snow fall on the Himalaya and the Tibetan plateau also influence the monsoon.

Previous research showed great uncertainty in changes in melt water quantities, as well as possible alterations in precipitation patterns because of changes in the monsoonal circulations. The retreat of glaciers and a possible change in monsoon precipitation and pattern will have a great impact on the temporal and spatial availability of water resources in northern India. The pace and magnitude of these changes will also determine the type of adaptation needed.

The aim

The principal aim of the HighNoon project was to assess the impact of Himalayan glacial retreat and possible changes in the Indian summer monsoon on the spatial and temporal distribution of water resources in northern India. The project further aimed to provide recommendations for appropriate and efficient strategies that strengthen the cause for adaptation to hydrological extreme events through a participatory process. The main aspects of the research programme were:

- Developing scenarios for snow melt and monsoon patterns based on improved regional climate simulations.
- Developing realistic regional socio-economic scenarios and assess the changing water resources using regional models.
- Providing new methods for the prioritization of adaptation measures to be used for the selection of adaptation options.
- Participative development of specific multi-sector adaptation measures in consultation with stakeholders.

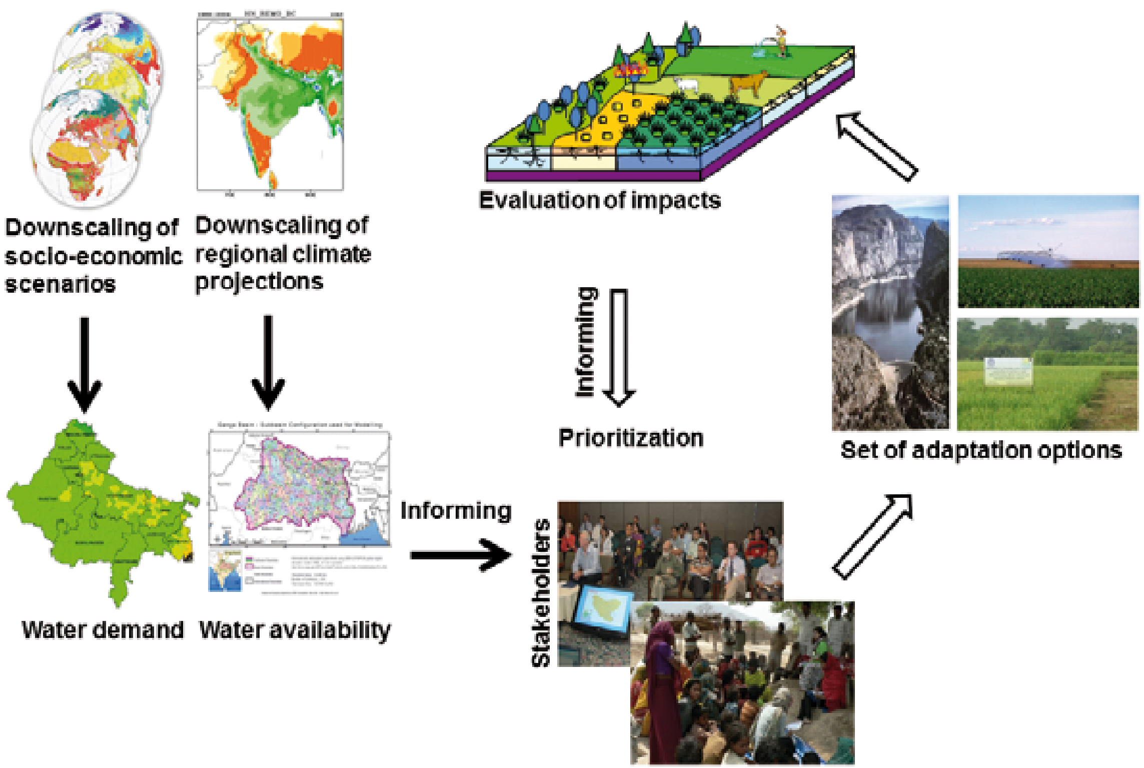
The methods

HighNoon applied a transdisciplinary research approach to climate change adaptation. Knowledge on climate change and climate variability of stakeholders at different levels was integrated with scientific knowledge derived from improved regional climate modelling and socio-economic scenario development.

The HighNoon approach integrated biophysical and socio-economic data to develop knowledge on water availability and demand and iteratively involved stakeholders to develop acceptable and robust adaptation options.

Besides data and tools developed within the HighNoon project, it made use of available existing data and a suite of modelling tools at different spatial scales; from Global Climate Models (GCMs) to basin scale hydrological models to dam-burst models.

HighNoon was built on large pre-existing EU and Indian projects, components of bilateral cooperation programmes, and the IPCC.



Changes

Glaciers

Glaciers are important water resources in that they moderate year-to-year variability of runoff. In warm dry years, enhanced ice melt contributes to flow when direct runoff from precipitation is in short supply, whereas in cool wet years, reduced ice melt results from snow on the glacier surface raising albedo. However, this reduction is offset by runoff from the additional precipitation.

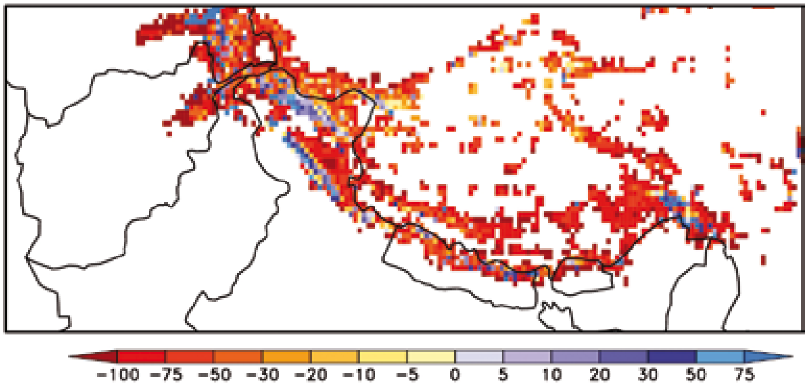
As glaciers lose mass, an additional component of runoff, the deglaciation discharge dividend, is added to flow, so that annual discharge can exceed annual precipitation.

Estimates of glacier areas and volumes of ice in the Himalaya have been reassessed largely by remote-sensing methods, giving totals of 22.829 x 10^3 km^2 of glacier cover, and between 1071 and 2431 km^3 of ice along the Himalayan arc.

Glacier area reductions have been varied, but losses appear to be in the range 0.1 to 0.9% per annum over periods of about 40 years. All models project mass losses in coming decades that are substantial for most parts of the Himalaya, but consistently fall well short of complete region-wide glacier disappearance.

Incorporating glacier cover into RCMs has been achieved and initial results from REMO show considerable glacier shrinkage in some grid cells, but increases in area in the western Himalaya and Karakoram ranges.

The deglaciation discharge dividend cannot be sustained indefinitely, and, as glaciers decline or should glaciers ultimately disappear, flow will be reduced and runoff variability increased to reflect solely future amounts and variability of precipitation.



Change between 1989 and 1998 in glacier cover as a percentage for each grid box area, calculated with a novel glacier parameterization scheme incorporated into the REMO RCM over the South Asian model domain as shown.

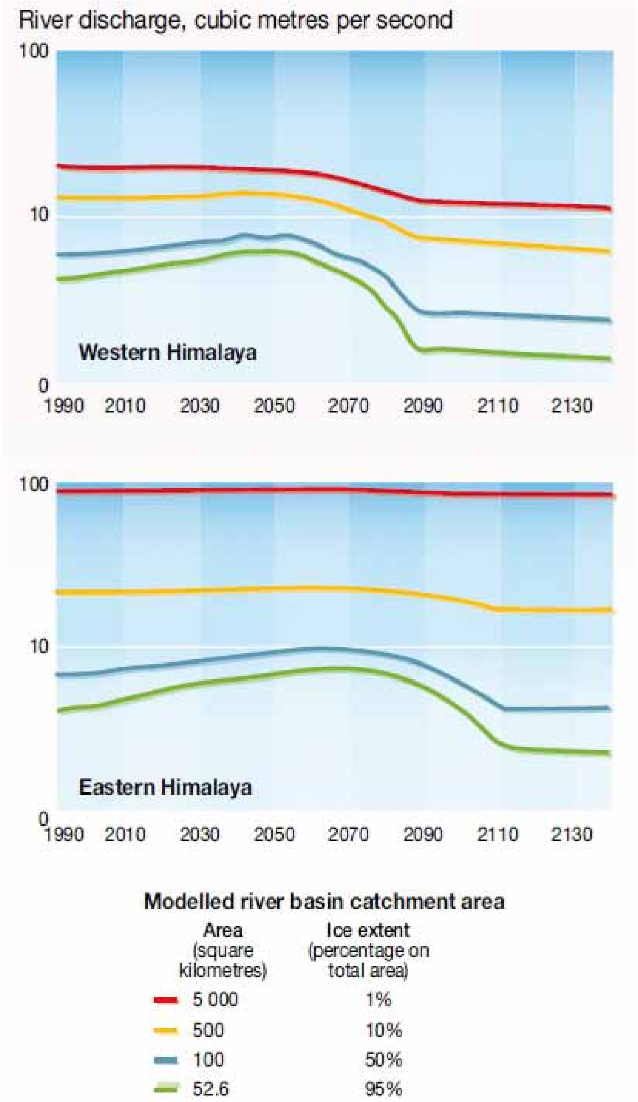
Ice, snow, and runoff in mountainous catchments

The common perception of an initial increase in runoff as glaciers retreat, followed by a sharp decrease in runoff as glaciers disappear needs further refinement. As runoff from a glacier is a function of energy input and glacier area, warmer conditions lead to enhanced melt until, depending on the relationship between ice thickness and area, glacier area reduction starts to offset continuing increases in heat availability, and flow declines.

In headwater catchments in the **western** Himalaya of the Ganges basin, runoff may first slightly increase. From mid-century, however, river flow in the drier areas will decrease, but by what amount is difficult to assess without knowledge of glacier area-thickness relationships.

In drier **western to central areas** of northern India, where monsoon rainfall has a smaller contribution to flow downstream than further east, runoff is likely to decline both in headwaters and downstream in the latter part of the century.

Summer monsoon snowfall in the **central to eastern** Himalaya in the Ganges basin tends to reduce glacier melt runoff whilst downstream simultaneous rainfall over wide swaths of the lowlands enhances discharge. Increasing temperatures will raise the elevation above which snow falls, but this height is difficult to predict from RCMs. In such areas of the central to eastern Himalaya, in mountain basins with relatively high levels of glacier cover, river flow might first be expected to increase to the 2050s, before decreasing to levels lower than today by about 2100. Downstream, however, flow will generally be maintained by substantial amounts of monsoon rainfall occurring over large portions of the catchment areas.



Impact of glacier shrinkage on runoff in two conceptual river basins representing the Western and Eastern Himalayas

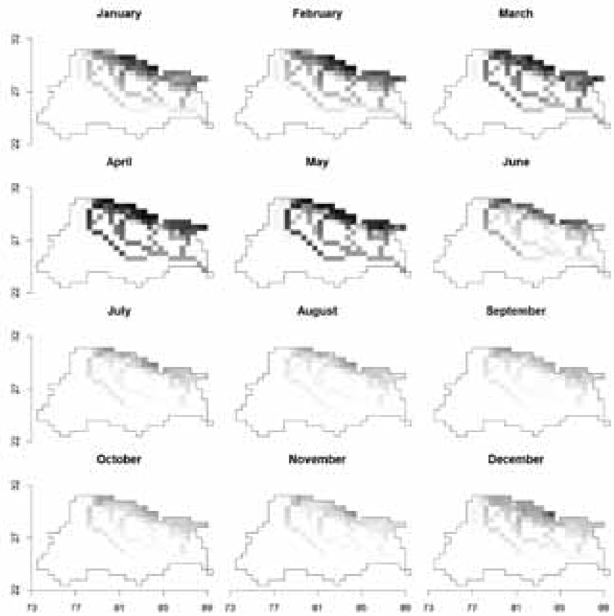
Contribution of ice and snow melt to water resources in the Ganges Basin

Timing of snow melt in mountainous sub-basins will depend on spring temperatures, both through determining the length of season during which precipitation accumulates as snow and through energy availability for melting accumulated snow pack. As temperatures warm, snow melt is likely to occur earlier in spring.

For the entire basin, the contribution of snow and ice melt to the total discharge of the Ganges was estimated, using a multi-model approach, to be between 1 and 5% of annual basin runoff. Snow melt, however, provides a significant proportion of runoff in spring months, a period in which other sources of runoff are scarce, with up to 38% of the total flow in the Ganges being derived from snow in spring months.

It is unlikely that dramatic changes in total runoff will occur in the next few decades, but continued glacier area reduction will modify the seasonal pattern of runoff, especially in upstream highly-glacierized basins.

Overall, reducing glacier dimensions through the 21st century are likely to have less of an impact on river flows with distance downstream from glaciers in areas strongly influenced by monsoonal rainfall.



Snow melt contribution to runoff (%) in the Ganges basin, averaged over the different months for the whole basin, based on an ensemble of VIC, LPJmL, JULES, and SWAT model runs for the period 1971–2000 (white = 0%, black = 100%)

Monsoon precipitation

The Indian summer monsoon is expected to become more important for future water resources management in the Ganges basin, especially as groundwater resources currently used for supporting agriculture and domestic use become scarcer. Future changes in monsoon precipitation amounts and timing are therefore of high importance to the region.

Earlier Global Circulation Model projections were highly contradictory for the Indian subcontinent, projecting both increases and decreases in precipitation. None of these models fully represented Himalayan topography and several were unable to describe the monsoon precipitation.

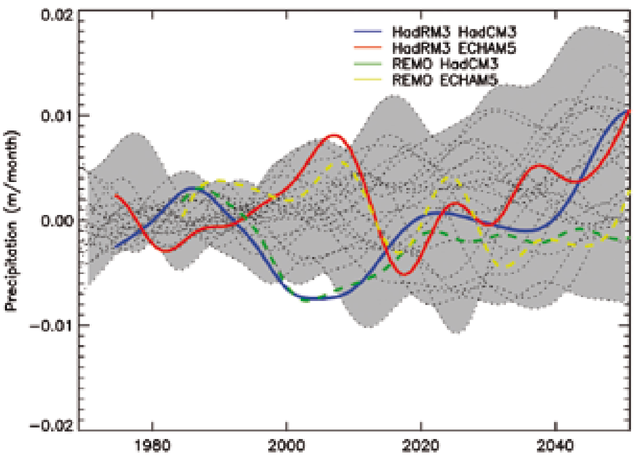
HighNoon has produced an ensemble of four Regional Climate Model (RCM) projections at 25 km resolution for the Indian Subcontinent. These are the most detailed simulations available till date. The RCMs used by HighNoon are able to simulate the monsoon dominated climate in and around the Himalayas and reflect the role of the steep topography on moisture transport fluxes.

The RCM projections show still a considerable uncertainty, in line with the earlier Global Circulation Model predictions, with future precipitation projections ranging from a small decrease through no change to a relatively large increase.

Though overall the simulations tend towards an increase in future precipitation, there is a substantial natural climate variability with decade- long periods of increasing precipitation followed by equally long periods of decreasing precipitation. This makes the increase not significant.

The future precipitation in the monsoon months of June, July, August, and September shows a similar wide range.

In some areas, the projections show a tendency to increased high intensity rainfall events, and a decrease in the number of rainfall days. Variation within the basin results from a small decrease in rainfall by 2100 being more likely in the west and an increase more likely in the east.



Change in annual precipitation relative to 1971–2000 simulated by the IPCC AR4 Models (Grey) and the HighNoon Regional Climate Models under the SRES A1B scenario. The data are smoothed to show the decadal climate variability.

CHANGES

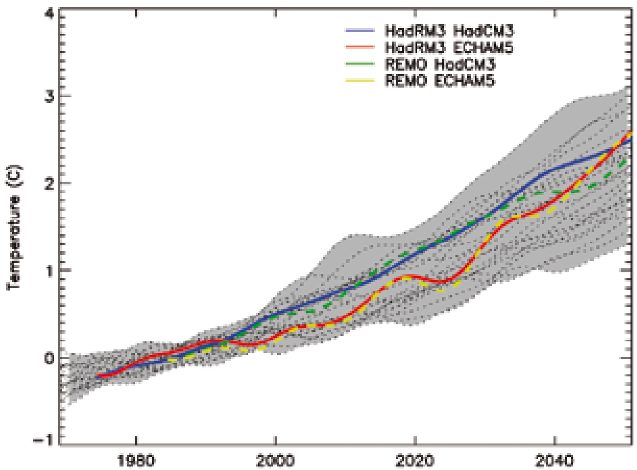
Temperature

India is already experiencing yearly recurring periods of high temperatures and heat stress especially in the months just before the onset of the monsoon.

The trend in temperature for the region is more consistent than the trend in precipitation, with all the Global Circulation Models already showing a steady increase. Analysis of the HighNoon Regional Climate Models shows that the region is expected to warm at a faster rate than the global mean.

Under the studied SRES A1B scenario, temperatures are projected to increase by 1.5 to 3 °C by 2050, 2 °C on average between the RCM ensemble members. Post 2050, the temperatures are expected to keep rising, by 4 °C on average, particularly if no global climate mitigation policy is enacted.

The warming is most pronounced over the mountainous regions. Reasons are that land warms faster than oceans so the Himalayan region warms faster than the global mean. In addition, reduction in seasonal snow decreases the albedo, exacerbating the warming signal.



Change in annual mean temperature relative to 1971–2000 simulated by the IPCC AR4 Models (Grey) and the HighNoon Regional Climate models under the SRES A1B scenario. The data is smoothed to show the decadal climate variability.

CHANGES

Hazards and vulnerability

Agriculture

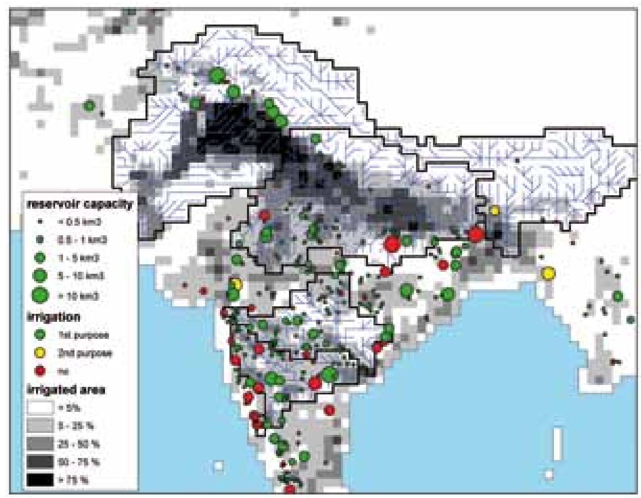
India's population and economy is growing and transforming rapidly. The aim is to increase productivity and expand agricultural area where possible to produce the food needed. However, the potential for this increase is questionable, with water resources becoming an ever larger constraint.

Within HighNoon, a framework was developed to make an integrated, spatially explicit analysis of water availability for future agriculture, thereby projecting both changes in the demand and supply of water. This framework can be used to quantify where adaptation is most beneficial.

HighNoon estimates that the current annual water withdrawals for irrigation in the Ganges basin are around 375 km^3. More than 50% of this water is taken from groundwater reserves. These extractions cannot be sustained indefinitely in the future. Around 50 km^3 per year is supplied by human build reservoirs and this water accounts for 10% of the irrigated crop production in the Ganges.

HighNoon shows that increasing the storage capacity in large reservoirs in this basin will not reduce the pressure on groundwater resources. To ensure future food production, measures that decrease the irrigation water demand, e.g. improving the efficiency of irrigation systems, or increasing the productivity of rainfed agriculture, were evaluated to be a better strategy.

The impact of climate change on agricultural production was further studied through detailed crop modelling. Results show that increasing temperatures, changing rainfall, and increased CO_2 concentration will affect agricultural production of rice and wheat in upper, middle, and lower sections of the Ganges Basin. The general trend is towards decreased agricultural production in all three basin sections, but especially impacting the upstream part. With the existing crop varieties, higher temperature impacts offset the positive effects of higher carbon dioxide concentrations.



Schematization of major river basins used to calculate agricultural water availability and demand (used for the LPJml – WaterWise models)

It was also found that large-scale irrigation influences rainfall in the Ganges. Moisture that evaporates from the land is transported downwind, where it falls as rain again. During the winter months, the large majority of moisture was transported away from the land towards the Indian ocean. However, during the March-April-May period, 20% of the evaporation from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the Ganges river basin returns as precipitation in the Ganges river basin, and can potentially be re-used. This amounts to about 5% of precipitation annually, with peaks of about 10% during the pre and post-monsoon periods.

Drinking water

Socio-economic change will multiply the demands for drinking water. For example, the population of India's national capital region, Delhi, is increasing rapidly with annual growth rates of almost 4%. Domestic water demand also has a direct positive relationship with the standard of living. The further increase in demand can be associated with a decrease in poverty rates since 1951.

HighNoon down-scaled the socio-economic scenarios for Delhi and all the districts within the Ganges basin to estimate future water demand. Poverty is further expected to go down in the next few decades, leading to higher demand. In addition, industrial water demand in Delhi is expected to almost double in the coming decade to more than 30% of overall demand.

HighNoon also assessed the vulnerability of Delhi's drinking water sector. Surface water contributes to over 86% of Delhi's total drinking water. Drinking water is sourced from the Yamuna River, Bhakra storage, and Upper Ganges canal downstream from the studied Tehri dam – all of which are climate sensitive.

Especially the reservoirs in the upper mountainous regions, like the Tehri dam, will become more vulnerable to the variability and irregularities of the monsoon when the contribution of glacier melt is expected to decrease in the second half of the century.

Water management

Water allocation over the different sectors and between upstream, mid-stream, and downstream users is a difficult task and will always remain so, even if annual rainfall would slightly increase in the future. An increased demand from industry, agriculture, and households along with slow improvement in water use efficiency in agriculture will not make the puzzle any easier to solve.

In HighNoon, impact models were further developed for the basin. Flow series and moisture conditions obtained from the models are used to analyse the changes in the flood and drought conditions under different climate and water allocation scenarios. These results feed directly into the NATCOM program of Government of India.

HighNoon results show that the intensity of the flood events in the basin is expected to successively increase after 2050. The drought conditions in future are expected to deteriorate by 2050 due to a reduction in rainy days and higher temperatures.

The natural variability in the climate system of the Ganges basin is very important to water resources adaptation plans. They need to be robust to uncertain multi-decadal climate change as well as decadal periods of both increasing and decreasing water resource availability. During the course of the project, Indian Highnoon partners were actively involved in developing State Adaptation Action Plans for several states within the basin.

Hydropower

India's energy demand is expected to increase significantly in the coming decades. Part of this demand will have to be met by hydropower.

Given the latest regional climate scenarios, hydropower plants located in the Himalaya will be subject not only to changing quantities of melt water, but also to varying characteristics of flow. Investment decisions for dams will have to consider these future changes, as flows in the second half of the century may become inadequate to fill reservoirs to the optimal capacity.

Both existing and yet-to-be-constructed hydropower installations will have to respond to changing discharge characteristics. A shift from snowfall to rainfall and earlier melting of snow due to higher temperatures will increase seasonality flow over the year. HighNoon research furthermore suggests that as discharge generally increases with warming and thereby diurnal range of flow in summer expands. This will necessitate modification and/or relocation of structures.

The HighNoon model studies indicated that sediment load is likely to increase because of enhanced precipitation intensities. This shall reduce the capacity of the reservoirs.

In the case of Delhi, power supply was considered only marginally vulnerable to climate change. Despite climate change affecting the water storage upstream, Delhi's large bargaining power and connection to the national power grid can supply it with power from other sources, if needed.

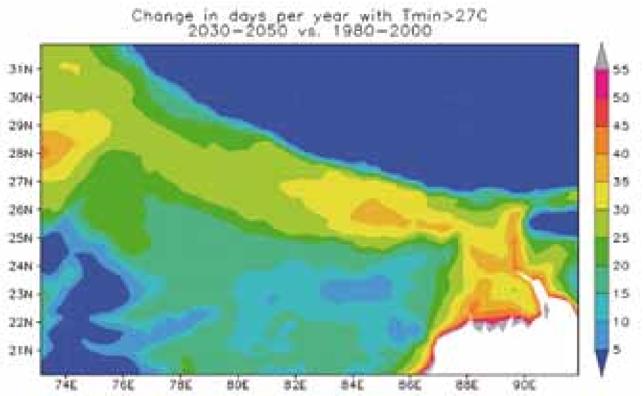
Health and heat waves

The threshold of 27 °C for the minimum night-time temperature is considered a critical limit above which humans are not able to recuperate effectively.

Prolonged periods with night-time temperatures above this threshold will have a negative impact on the health of humans, especially vulnerable groups, such as elderly and sick people as well as young children.

The HighNoon climate projections show where and when such prolonged conditions will occur.

The development of adaptive housing to reduce in-house temperatures is recommended for these regions.



Change in number of days per year for which the minimum daily temperature exceeds 27 °C, a critical threshold for humans and animals

HAZARDS AND VULNERABILITY

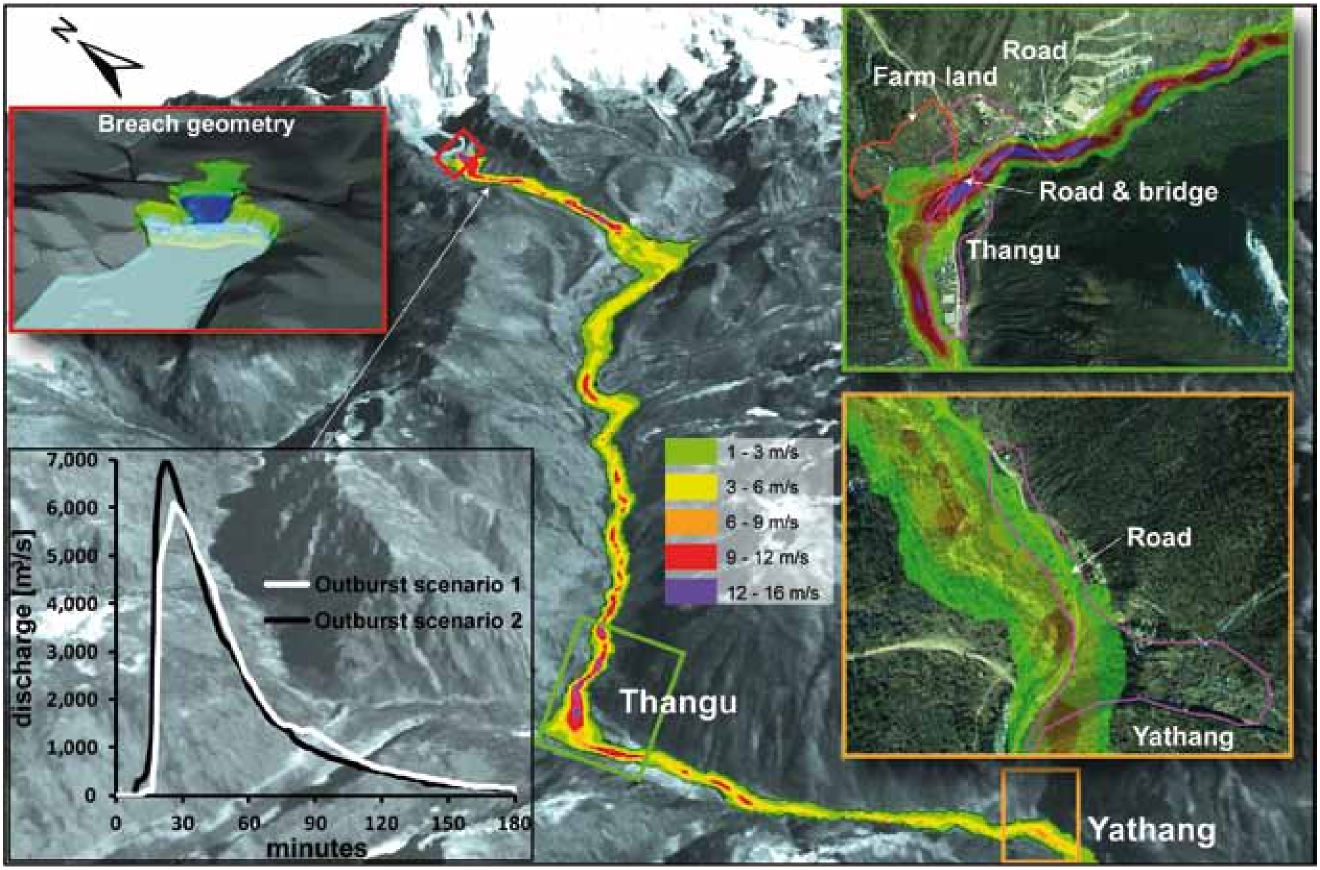
Hazards of glacier lakes

Glacier lake hazards, especially lake outburst probabilities, outburst magnitudes, and damage potentials were evaluated within HighNoon for selected high-risk lakes in the Indian Himalayas.

The case study glacier lakes in the states of Jammu and Kashmir and Himachal Pradesh were found to present moderate risks to downstream villages, whereas in Sikkim the case study lake severely threatens downstream locations.

HighNoon consultations found that the awareness about the existence and the potential hazard of the investigated lakes is hardly present in the villages downstream.

Combining high resolution imageries, a sophisticated dynamic modelling approach, and field work, a lake outburst scenario for Shako Cho Glacier Lake in Sikkim was studied. The results include an estimation of flow extent, the lake outburst hydrograph, breach geometry, and flow velocities at potential impact areas in Thangu and Yathang village.



Perceptions on vulnerability

Changes in climate and climatic hazards in the recent past are felt to be increasing by stakeholders, especially in the last 5 to 10 years. Reported observations in the HighNoon consultations include increases in summer temperatures, shorter, but also more severe winters, more frequent and severe occurrence of fog, decrease in winter rainfall, delays in the onset of the monsoons, more erratic rainfall distribution, and increased and more frequent incidences of extreme events like floods and droughts.

Within the same state, the results of discussions across state, district, and community level showed a large commonality among the perceived hazards. While stakeholders at the state and the district level recognized climatic changes over a span of 10–15 years, stakeholders at the community level professed these changes observable over the past 5–10 years.

In the upstream areas, at the community level, the year round availability of water for irrigation in the region allowing the farmers to cultivate different types of high value crops was highlighted as being a reason for farmers' prosperity. Loss of cultivable land and property due to floods was highlighted as primary concerns. Landless laborers who have close proximity to the flood plains were identified as the most vulnerable groups due to high exposure to extreme conditions of floods. At the district level, over-abstraction of groundwater in the current day context was discussed as the main reason contributing to vulnerability in the future.

In the mid-stream areas of the basin where agriculture is mainly rain fed, lack of water resources for irrigation and subsequently declining returns from the agriculture sector were primary concerns at the community level. More frequent and intense droughts lead to migration of farmers in order to supplement their income. At the state level, it was observed that such detrimental impacts on agriculture and returns from the sector would lead to disenchantment with agriculture as an occupation. A significant decrease in the total food production, changes in the crops selected for cultivation in response to bio-physical stresses, and reduced productivity of reservoir-based hydro-power plants were also flagged as important concerns that would add to present and future vulnerability to climate change.

In the downstream areas, decline in water availability and limited access to scarce resources, in general were perceived as causes for vulnerability by the community. At the district level, reasons were related to the prevalence of largely subsistence-based rainfed agriculture and the perceived decrease in winter rainfall, delays in the onset of the monsoons and more erratic rainfall distribution. At the state level, degradation of forest resources and limited ground water availability for drinking and irrigation was highlighted as reasons to aggravate the vulnerable situation of the communities.

	Upstream	Mid-stream	Downstream
Community Level	1. Monitoring of sand mining from river banks (Anticipatory) 2. Construction of stone embankments (Preventive) 3. Afforestation 4. Livelihood diversification 10. Capacity building for more efficient farming practices	1. Water harvesting structures like ponds/ water storage 2. Drip/Sprinkler Irrigation systems 3. Agro-forestry 4. Crop diversification 5. Afforestation	1. Awareness camps 2. Rain water harvesting 3. Organic farming 4. Integrated farming 5. Short duration varieties 6. Afforestation 7. Deep tube-wells
District Level	1. Public awareness for needs and methods for water conservation 2. Monitoring sand mining from river banks 3. Better forecasting systems 4. Limiting cultivation of summer rice 5. New varieties under crop insurance schemes 6. Livelihood diversification 7. Strengthening of embankments 8. Promotion of agro-forestry 9. Afforestation with less economically viable trees 10. Relocation of people from flood plains	1. Afforestation or large scale plantations 2. Promoting new technologies like sprinkler irrigation with demonstration 3. Field bunding 4. Use of heat-tolerant and drought-tolerant crop varieties 5. Lining of canals in water scarce areas 6. Construct soak-pit around all hand pumps	1. Checking dams 2. Surface water bodies 3. Field bunding 4. Crop diversification 5. Integrated farming 6. Organic farming
State Level	1. Participatory Integrated watershed management* • Increasing storage structures (village ponds, tanks, reservoirs) • Creation of markets for agri-business development • Capacity building of communities and local governments 2. Increasing green cover through afforestation (*Uttarakhand State Watershed Management Directorate)	1. Increasing storage capacities 2. Livelihood diversification, for example through agro-forestry 3. Improved crop varieties 4. Afforestation 5. Lining of canals	1. Traditional rainwater harvesting 2. Check dams 3. Increasing forest cover 4. Artificial groundwater recharge 5. Better crop varieties 6. Weather information forecasting 7. Wastewater reuse

Table listing the priority in adaptation options at community, district and state levels for three case study sites in upstream, mid-stream and downstream in the Ganges basin.

Priorities in adaptation options

Based on their perceived vulnerabilities to climate change, the stakeholders at the state, district, and community level identified and prioritized a set of sectoral, multi-sectoral, and cross-sectoral adaptation measures. The arguments were largely drawn from stakeholders' experiences on how these or related options had fared in the past. Some criteria were based on the understanding of the nature of climate change problem, the uncertainty it presents, and the need for anticipatory action or preparedness.

Differences in vulnerability were reflected by differences in priorities set by stakeholders at different levels and across case studies. Flood protection management scored high in the upstream case study while water conservation and storage and livelihood diversification were considered most important in drought prone mid-stream and downstream case studies. The options proposed were mostly 'green measures', small-scale options at field level targeting agricultural water management and a better use of rainfall. Large-scale 'blue measures', which consists of large scale infrastructural options like storage dams, were seen as less viable for the Ganges basin.

Across case studies in general, stakeholders at the state and the district levels identified cost as an important criteria for prioritizing adaptation options. High cost options like strengthening of embankments were low on priority for district-level stakeholders in the upstream case study, though its immediate benefits were acknowledged. Relocation of people from flood plains was least preferred and least feasible due to the high associated costs and low social acceptability.

At higher stakeholder levels, in most cases, the preference was for options that are in alignment with existing schemes and programmes, such as widening scope and delivery of crop insurance. However, some suggestions that were in alignment with existing schemes were still ranked low due to feasibility issues. For example, state level stakeholders in the mid-stream case study ranked afforestation initiatives low on the preference list since they were not ecologically feasible.

Priorities set by communities revealed that there was a clear preference for options providing immediate benefits and addressing current risks. For instance, communities highlighted the need for storage structures for water as a priority, vis-à-vis measures like afforestation, which encompass longer time to realize perceivable benefits. Social acceptability was another guiding factor in identifying preferences. Although an option like changing current cropping practices like shifting from summer rice cultivation to less water intensive crops (vegetables, pulses) was emphasized at the district level, it ranked low on acceptance by communities where actual implementation had to take place.

Options that require farmers to adopt new techniques and practices were ranked low, because of the existing gaps in capacity and their lack of confidence in supporting institutions that could, provide the required awareness, training, and demonstration.

Tools and inventories

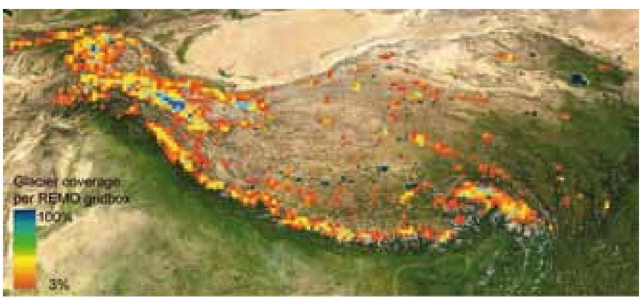
Glacier inventory

HighNoon collected glacier outlines from various databases and compiled a comprehensive inventory of the best available glacier data for the Himalaya.

For the entire Himalaya, including regions in the western Himalaya that have not been covered by the global glacier databases until today, new outlines were created by remote sensing techniques. Initial estimates of volumes of ice stored in the Himalayas were subsequently derived.

Regional Climate Models, such as applied within the HighNoon project, can use these glacier areas and glacier volumes, which will allow a dynamic coupling of glaciers with climate.

Furthermore, the dataset can be used as a benchmark against which future changes in glaciers can be compared.



Glacier areas coverage over the whole Hindu-Kush-Karakoram Himalaya mountain ranges, gridded for use in the REMO climate model

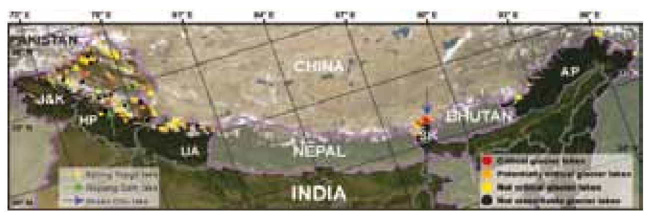
Glacier lake inventory

HighNoon presents a first area-wide glacier lake inventory for the Indian Himalayas, including a qualitative lake classification.

Glacier lake hazards and glacier lake distributions are investigated in many glaciated regions of the world, but comparably little attention has been given to this topic in the Indian Himalayas.

A total of 251 glacier lakes larger than 1 hectare were detected in the five states spanning the Indian Himalayas. Lake distribution pattern and lake characteristics were found to differ significantly between different regions, with most critical lakes lying in Sikkim.

The lake classification can be used to select the most critical areas and target investments in early warning systems. Furthermore, it provides an indication of erosion risk, which is of interest for the hydropower sector.



Glacier lake inventory with mapped and classified glacier lakes >1 ha over the entire Indian Himalayas. Three critical glacier lakes for which a detailed risk assessment was carried out are indicated by arrows.

Agricultural forecasting tool

In HighNoon, the potential of using short-term weather forecasts to increase irrigation efficiency in rice cultivation, as a potential adaptation option to future climate change, was explored.

Field tests and modelling revealed that basing the decision to irrigate rice on short-term weather forecasts could reduce water application by 17%–60%, if 5 days rainfall forecasts would be very accurate. Modelling showed that using accurate forecasts under future climate conditions can potentially lead to an additional saving of irrigation water.

Skill in forecasting future weather and climate in India, on the short (days), medium (seasons), and long term (decades) is improving. However, at present, forecasts issued by the Indian Meteorological Department (IMD) for West Bengal, the region observed, are not accurate enough to achieve the desired water savings.

The HighNoon approach combines weather forecasting with site specific modelling of soil moisture, nutrient status, and crop water stress. This creates a more tailor-made advise for both small- and large-scale farmers.

Indicator framework tool and water resources GIS server

In the HighNoon project, an indicator framework has been developed to summarize and visualize the impact of climate change on different sectors. The framework characterizes the baseline and future water resources and livelihood status. Main indicators for a variety of stresses for the three case study sites are summarized below.

Indicators	Season	USN	Allahabad	Kangsabati
Agricultural water stress	PreMonsoon	High	High	High
	Monsoon	Moderate	Moderate	Moderate
	Post Monsoon	High	High	No Stress
	Winter	Strong	Strong	Strong
Irrigation requirement / crop water deficit	PreMonsoon	Low	Low	Moderate
	Monsoon	Strong	High	Moderate
	Post Monsoon	Strong	Strong	Moderate
	Winter	Strong	Moderate	Moderate
Blue water flow / natural water resources	PreMonsoon	Strong	Strong	Strong
	Monsoon	Low	Low	Low
	Post Monsoon	Moderate	Moderate	Moderate
	Winter	High	Strong	Strong
Green water flow / crop water requirement	PreMonsoon	Moderate	Strong	Moderate
	Monsoon	Low	Low	Low
	Post Monsoon	Moderate	Moderate	Moderate
	Winter	Strong	Moderate	Strong
Green water storage / soil moisture	PreMonsoon	Moderate	Strong	Moderate
	Monsoon	Low	Low	Low
	Post Monsoon	Moderate	Low	Low
	Winter	Low	Moderate	Moderate

No Stress | Low | Moderate | High | Strong

The use of indicators in the water sector has become more important in recent years, and legislations have given prominence to use indicators as evaluation and management tools.

The indicator framework can be used by policy makers to target their attention and resources to specific sectors and areas. It helps in identifying adaptation measures as well as in evaluating impacts of proposed adaptation measures.

A user friendly interface has been developed for deployment of the indicator framework. The NATCOM Hydrological Information System is an interactive website where model results and analysis of climate change research are presented, amongst others from HighNoon. It covers not only the Ganges but all of India's river basins.

Easy viewing and querying of the outputs of the indicator framework for the case study sites of the Ganges basin have been provided at:

http://gisserver.civil.iitd.ac.in/HighNoon/HighNoon.aspx

Data

By making the data generated by HighNoon, available to other researchers, HighNoon hopes and expects that these datasets will be used by the wider community. This will further help support defining better adaptation strategies.

The HighNoon main datasets are:

i) Climate data from 4 Regional Climate Model runs using a single scenario (A1B). Two model runs cover the period 1989 to 2050, while the other two model runs cover the period 1970 to 2050. Typically, daily data are available for: radiation, temperature, relative humidity, precipitation, snowfall and wind. The spatial resolution is 0.25 degree (~25 x 25 km). These data are available for the following domain:
   - Bottom left: 20.125 N, 73.125 E
   - Top right: 31.875 N, 91.875 E

ii) An inventory of the snow and ice area and volumes for the Himalaya region.

More information on datasets, tools and inventories can be found on the HighNoon website:

http://www.eu-highnoon.org

Measurement station

Installing an Ott Logosens datalogging system allows continuous measurement of river flow at a high elevation site downstream of East Rathong Glacier, Sikkim, in north-east India. Selected as a benchmark glacier, water depth at the gauging station on the proglacial stream is recorded using a pressure transducer. Water temperature and conductivity sensors allow monitoring of water quality at 30 minute intervals. Attached to the same datalogger, mast-based sensors monitor 2m air temperature and incoming radiation. The station is powered by solar panels and is programmed to run for 4 months without attention, ideal for the remote nature of the site.

The station will be maintained after the lifetime of the HighNoon project, thereby contributing to accumulation of consistent, long-term datasets in a region where otherwise information is sparse.

HighNoon, thus, contributes to the much-needed improvement of hydrometeorological data collection in the Himalayan region.

Knowledge capacity building

A 5-day HighNoon Spring School on "adaptation to changing water resources and water demand with glacier retreat and changing monsoon pattern" was organized by the HighNoon team as part of the capacity building activities. The curriculum included:

- Regional Climate Modelling
- Glacier / snow melt
- GLOFS
- Water resources
- SWAT modelling exercise
- Hands-on exercise GIS tool
- Risks and vulnerability of agriculture and the use of climate forecasting to deal with climate change
- Modelling the global water cycle: experience from the WATCH project
- Development and use of socio-economic scenarios
- Uncertainty role play
- Assignment: implementation of adaptation
- Communication of uncertainty
- Stakeholder involvement
- Policy implications at different scales

Over 30 PhD students and early career professionals attended the Spring School at the Indian Institute of Technology, Delhi campus. The intention is to establish the Spring School as a yearly event within the South Asian region.

Implementation

Implementation of adaptation is mainly about enhancing available technology as opposed to developing new technology. Most technologies, like improved varieties or rainwater harvesting structures, are already part of existing rural or urban development schemes. With relatively simple measures their effectiveness, and adaptive nature, can be improved.

We call this 'SmartWater' measures of which several are tested by the HighNoon partners in recent years. These measures are a shell around a technical solution, offering information, control, and flexibility to users with regard to water availability and use. This shell enables users to plan, evaluate, and adjust their practices, if needed, and, thus, to adapt.

SmartWater for Agriculture I - Improved nutrient application

Better nutrient management is essential to increase productivity of India's agriculture. However, the expected increase in rainfall variability will make it more difficult to apply fertilizers at the right time. On controlled field sites at IIT Kharagpur targeted, weather-dependent nutrient applications are tested with a combination of new rice varieties. A tool is developed to enable rapid decisions when to apply nutrients using IMD forecasts and to measure and evaluate the effect. Implementation of this SmartWater measure will require cooperation with national and regional institutes that develop and produce forecasts, including IMD, NCMRWF, and ISRO, as well as KVK's to tailor forecasts to the needs of farmers.

SmartWater for Agriculture II – Flexible use of water harvesting reservoir

One of the preferred adaptation options from the HighNoon stakeholder consultations is the storage of rainfall runoff in water harvesting structures, an ancient Indian method. However, traditional systems do not always offer the flexibility and water delivery security needed now and in future. In selected agricultural fields, the adaptive capacity of farmers in small reservoir supported irrigation schemes was improved. The traditional outlet of the reservoir was replaced by a SmartWater outlet, including a flexible gate, measurement weir, and rainfall gauge. With this outlet the outflow could be regulated, allocated, and monitored, allowing for a more flexible use of water, combining rainfall, reservoir stored water and groundwater. This resulted in an increased cropping area of almost 60% and a reduced vulnerability to

year-to-year rainfall variability. Implementation of this SmartWater measure will require: cooperation with government or local authorities, (depending on the size of the reservoirs), upgrading of control structures, and training of Water User Associations.

SmartWater for Hydropower – Adaptive water intakes

Hydropower plants located in Himalayan basins will be subject not only to changing quantities of available melt water, but also to varying flow characteristics. Investment decisions for new dams will have to consider future changes in flow, both for design and for the period of return on investment. In the third to fourth quarter of this century, flows may become inadequate to fully fill reservoirs to their capacity. Therefore, both existing and yet-to-be-constructed hydropower installations will have to respond to changing discharge characteristics. From experience in mountain ranges elsewhere, e.g. Europe, HighNoon partners found that as discharge generally increases with warming, diurnal range of flow in summer expands. On days with higher flows, some of the melt water is lost as flows exceed design capacity of water intakes, necessitating modification and/or relocation of structures. In HighNoon, a method was developed to estimate the future contribution to runoff of snow and glacier melt and the daily variations, based on upstream catchment size, snow cover distribution over time/elevation, and percentage glaciation. Using this information, hydropower intakes can be designed, taking into account expected site-specific future changes in runoff. Implementation for individual hydropower plants will require cooperation between hydropower companies and climate researchers.

Creating ownership of SmartWater technologies

Implementation should assist in building local capabilities in the operation and maintenance and management of the interventions. Before implementation, it is essential to create the right enabling conditions. These conditions would largely include creating capacity of institutions and communities by involving them in the further development of the adaptation options and in the monitoring of the benefits that will be generated after implementation. Such an approach would increase the ownership of these initiatives by the community and would be important for self-sustaining these initiatives after the implementation activities are completed.

Future research challenges

To improve embedding of research results in society and to further promote science, HighNoon organized a number of events bringing together NGO's, civil society organizations, policy makers, and scientists:

- *Open science seminar "Future of water resources in India under a changing climate" New Delhi, May 13–14, 2009;*
- *Roundtable discussion "Bi- and multilateral Indo-European cooperation on climate research and innovation", New Delhi, November 28, 2011;*
- *Trans-Himalayan workshop "Glaciers, snow melt, and runoff in the Himalayas" Kathmandu, Nepal, February 6–7, 2012;*
- *Special event "Adapting to the changing climate and water resource availability in the Ganges basin". 12th Delhi Sustainability Development Summit, New Delhi, February 2–4, 2012;*
- *HighNoon Open science and policy seminar "Climate change and adaptation", New Delhi, April 4, 2012.*

From our research experience and the discussions held during these events, gaps were recognized on three main topics: "glaciers, snow, and runoff", "extremes", and "adaptation". The following issues were mentioned to improve on the present shortcomings:

Gaps – Glaciers, snow, and runoff

- More continuous monitoring of representative benchmark glaciers
- Additional benchmark catchments taking glacier, snow, and runoff divides into account
- Focus on seasonality and inter-annual variability

Gaps – Extremes of precipitation and temperature

- Collect measurements at more extreme (e.g. higher altitudes) locations under more extreme conditions
- Develop regional climate projections from more extreme emission scenarios
- Move from analysing averages to extremes (and variability in extremes)
- Increase detail in terms of spatial and temporal resolution when it comes to impacts especially in urban areas

Gaps – Adaptation

- Promote collaboration to enable comparison, evaluation, and monitoring of approaches, e.g. adjust www.climate-adapt.eu, for India
- Develop regional climate services
- Undertake integrated assessments that allow for planning in adaptation
- Integrate policies to prevent mal-adaptive effects
- Communicate scientific information and uncertainty in planning for adaptation

In addition, the health and environmental implications of widespread pollution, with longer duration of low flows, will only be exacerbated with higher temperatures in the future asking for water management to integrate both water quantity as well as quality.

Colophon

Adaptation to Climate Change in the Ganges Basin, Northern India | A Science and Policy Brief

Editors: David Collins, Fokke de Jong, Eddy Moors, Roshni Sengupta, Christian Siderius, Naeema Jihan Zinia

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Contributors: Sneha Balakrishnan, Suruchi Bhadwal, Ajay Bhave, Shreya Bhattacharya, Hester Biemans, David Collins, Saptarishi Das, A.P. Dimri, Sambita Ghosh, A.K. Gosain, Annemarie Groot, Christian Hügel, Claire Jacobs, Pankaj Kumar, Rishu Kumar, G.J. Lingaraj, Camilla Mathison, Arabinda Mishra, Ashok Mishra, Neha Mittal, Eddy Moors, Sreeja Nair, Sandhya Rao, Jeff Ridley, Christian Siderius, Puja Singh, Tanya Singh, Nies Springer, Markus Stoffel, Catharien Terwisscha van Scheltinga, Andy Wiltshire, Raphael Worni, Tetsuzo Yasunari.

Partners:

- Alterra – Wageningen University and Research Centre, The Netherlands
- The Energy and Resources Institute, India
- UK Met Office, UK
- University of Salford, UK
- Indian Institute of Technology, Delhi, India
- University of Geneva, Switzerland
- Max Planck Institute for Meteorology, Germany
- Indian Institute of Technology, Kharagpur, India
- Nagoya University, Japan

Contact:
Dr Eddy Moors, Project Coordinator
Alterra, Wageningen UR,
PO Box 47, 6708 PB Wageningen, The Netherlands
Tel.: +31 317 486 431
E-mail: eddy.moors@wur.nl

HighNoon

www.eu-highnoon.org

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SEVENTH FRAMEWORK PROGRAMME