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Climate change and mountain water resources: overview and recommendations for research, management and politics

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Abstract

Mountains are essential sources of freshwater for our world, but their role in global water resources could well be significantly altered from anticipated climate change. How well do we understand these changes today, and what are implications for water resources management and for policy?

With these questions in mind, a dozen researchers – most of them with experience in collaborating with water managers – from around the world assembled for a workshop in Göschenen, Switzerland on 16–19 September 2009 by invitation of the Mountain Research Initiative (MRI). Their goal was to develop an up-to-date overview of mountain water resources and climate change and to identify pressing issues with relevance for science and society.

This special issue of Hydrology and Earth System Sciences assembles contributions providing insight into climate change and water resources for selected case-study mountain regions from around the world. The present introductory article is based on analysis of these regions and on the workshop discussions. We will give a brief overview of the subject (Sect. 1), introduce the case-study regions (Sect. 2) and examine the state of knowledge regarding the importance of water supply from mountain areas for water resources in the adjacent lowlands and anticipated climate change impacts (Sect. 3). From there, we will identify research and monitoring needs (Sect. 4), make recommendations for research, water resources management and policy (Sect. 5) and finally draw conclusions (Sect. 6).

1 Introduction

On a global scale, mountains contribute disproportionately high runoff, provide a favourable temporal redistribution of winter precipitation to spring and summer runoff and reduce the variability of flows in the adjacent lowlands (Viviroli et al., 2003; Viviroli and Weingartner, 2004). These mountain water resources are indispensable for irrigation, industry and drinking water supply as well as for hydropower production both upstream and downstream. The vital role of mountains has recently been touched upon by several benchmark reports such as the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) (Solomon et al., 2007; Parry et al., 2007) and the associated technical paper on climate change and water (Bates et al., 2008), the Stern Review (Stern, 2007) and the Third United Nations World Water Development Report (UN WWDR3) (WWAP, 2009).

Although the IPCC AR4 projections suggest an increase in global average precipitation, a decrease in precipitation and thus runoff is expected in most regions where the relation of water supply to water demand is already critical today (Solomon et al., 2007). This concerns especially the subtropical climate zone where both vulnerability to water scarcity and dependence on mountain water resources are high (Viviroli et al., 2007). Furthermore, the IPCC Technical Paper on Climate Change and Water (Bates et al., 2008) states with high confidence that global warming will cause changes in the seasonality of river flows where much winter precipitation currently falls as snow. This notion is in agreement with trends already observed in mountain regions; most clearly in the North American Cordillera (e.g. Stewart et al., 2005; Maurer et al., 2007, Déry et al., 2009a, b; for a comprehensive overview see Stewart, 2009). Glacier-related changes in runoff usually include increased runoff from enhanced ice melt, while water yield will decrease in the long term. Such changes have recently been summarised by Casassa et al. (2009) for the major mountain ranges of the world on basis of observations from recent decades.

The combination of shifts in seasonality and changes in total runoff are likely to have consequences for future water availability, increasing the challenges for management of water resources originating in mountains. Current management regimes based on historic climate and hydrological variability will likely be inadequate, yet better methods based on process understanding remain hampered by our limited understanding of both projected climate change and hydrologic response.

Coping with these anticipated changes requires effective and integrative water resources management. As a prerequisite, it is necessary to determine reliably the location, extent, dependability and quality of water resources, as well as the human activities that affect those resources (cf. Young et al., 1994). At the same time, it is essential that these findings be useful for water managers in order to pave the way for their implementation in water resources management practice.

2 Introduction of case-study regions

This overview article is based on a number of case study regions that also make up the contributions to this special issue. Although it is not possible to draw a complete picture for all mountain regions of the world, we believe that our choice of case-studies forms a solid basis for identifying typical problems concerning climate change and management of water resources with focus on mountain areas.

The regions studied are listed in Table 1, and Fig. 1 indicates the location of the regions on a world map. Also shown in Fig. 1 is the significance of mountain areas for downstream water resources, which is quantified here by the index for Water Resources Contribution (WRC) after Viviroli et al., 2007. WRC is the ratio of lowland water availability (surplus or deficit) to water supply (only surplus is considered, see below) from mountains and identifies the importance of a mountain raster cell for water resources supply in the hydrologically related lowland area.

A more in-depth characterisation of the regions studied is provided in Fig. 2 on the basis of the following metrics:

- Water stress: Dynamic Water Stress Index (DWSI) as introduced by Wada et al. (2010), averaged over cells of 0.5°×0.5°. DWSI is based on the well-known Water Stress Index (WSI) which expresses how much of the available water is taken up by the demand. DWSI extends WSI by considering duration, frequency and severity of water stress over a period of 44 years (1958 to 2001). Values above 0.2 indicate medium water stress, and above 0.4 indicate high water stress. The dot indicates the mean value for the entire region (including the lowland portions), and the grey bars indicate the range of water stress observed in the entire region.

- Water management capacity: capacity of the water management sector to adapt to projected climate change. We judged 14 questions organised in four thematic blocks: institutional capacity; political conditions; manager competence (education, training and experience); and knowledge transfer with researchers. For each block, a score of 1 means low capacity, and a score of 5 indicates high capacity. The summary score is the average of the scores achieved in the four thematic blocks. The grey bars indicate the range of scores observed in the four thematic blocks.
- Scientific capacity – national: scientific capacity in water resources and climate change available in the respective nation. This is assessed through 11 questions organised in four thematic blocks: boundary conditions (e.g. funding, research centres); competence in research; data availability and access; and state of knowledge. A score of 1 means low capacity, and a score of 5 indicates high capacity. The grey bars indicate the range of capacity observed in the four thematic blocks.
- Scientific capacity – international: Similar to national scientific capacity, only that here, the capacity available for the respective region at international level is assessed.

The main goal of this assessment is to illustrate the level of diversity in both likely water stresses and the capacity to deal with water stress that occur in our case-study regions, thus providing a framework for more detailed assessments and subsequent recommendations. It should be borne in mind that the variation may be large even within a single region, particularly with regard to water stress and water management capacity.

In part (a) of Fig. 2, the capacity of water management to adapt to climate change is plotted against water stress for each region. In general, high physical water stress is found together with low adaptation capacity, which is detrimental for the security and reliability of water supply. Slight deviation from this general trend is found in the Pyrenees (PYR) and the Drakensberg Mountains (DRM) where relatively high average water stress is met by well-developed management capacity. It should be noted that the value drawn for water stress refers to the mean of the entire case-study region, which may mask smaller areas with high water stress. This applies, for example, to Bolivia, Ecuador and Peru which were chosen to represent the Tropical Andes (ANT). The average water stress computed for this region is 0.15, while the arid parts of the region (the Andes themselves, including the Pacific slopes as well as the lowlands to the west) show values well above 0.4. Similar reservations apply to the average water stress value for the Karakoram Himalaya (0.29), especially because the Indus Plains – where the majority of the population lives – suffer from even more severe water stress (Archer et al., 2010), frequently with values well above 0.8. The average value for the Pyrenees (0.22) also hides that stress is much higher in the adjacent River Ebro Plain. It is therefore important to consider the value range indicated by the grey bars in Fig. 2 and to bear in mind that the level of water stress is very diverse in some regions. The top left of Fig. 2 shows the central and eastern part of the European Alps (ALC and ALE). In these regions there is a very high level of management capacity and generally low water stress, the latter occurring almost exclusively outside of the actual mountainous region.

Part (b) of Fig. 2 assesses the scientific capacity to deal with climate change questions for our case-study regions. It shows that regions with low national scientific capacity can usually obtain slightly higher research capacity at the international level, most notably in the Tropical Andes (ANT) and the Karakoram Himalaya (HIK). In practice, international scientific support will obviously require appropriate funding which will usually also be of international origin. On the other hand, where there is high national scientific capacity, international scientific capacity usually lags a little behind, although international projects (such as research funded by the EU in the case of the European Alps, ALC and ALE, and the Pyrenees, PYR) may still make the region attractive for international research and lead to a relatively high level of international scientific capacity. The Upper Changjiang region (UCJ) presents an outlier from the aforementioned connection as it has relatively high national scientific capacity but rather poor international capacity. The emerging economic power of China has led to international scientific aid becoming less available as the country is increasingly expected to rely on its own scientific resources.

Part (c) of Fig. 2, finally, is a synthesis of parts (a) and (b) and compares maximum scientific capacity available at national or international level with water management capacity to adapt to climate change. It shows that for some regions, scientific capacity (national or international or both) is clearly higher than water management capacity, which points to a need for the better implementation of scientific findings into water management practice. This is most prominent for the Pacific Northwest (PNW) but also occurs in the East Mediterranean region (EM), the Upper Changjiang region (UCJ), the Karakoram Himalaya (HIK), the Drakensberg Mountains (DRM) and the Pyrenees (PYR). In the case of the Pacific Northwest (PNW), both high scientific capacity and high water management capacity are actually present, but science is not integrated with the management community. In spite of sophisticated infrastructure and management systems, the capacity to deal with climate change impacts is limited as soon as it exceeds the natural variability (see Hamlet et al., 2010). This illustrates that inflexibility and resistance to change are even possible in highly developed and successful management systems and may become an obstacle to effective adaptation. In contrast, the management systems that have resulted in areas of relatively high water stress may be much better able to cope with droughts because they are already common events (Hamlet et al., 2010).

The diversity of settings observed in our cross-section of regions calls for a regionally and sometimes even locally differentiated view to future management. At the same time, the detrimental concurrence of high water stress and low management capacity seems to be a common problem that urgently calls for improvements in research, monitoring, management and information exchange, which we will address in Sects. 4 and 5 of this article. For more subtle distinctions, several categories would need to be separated, such as access to infrastructure, management capacity in the context of climate variability, ability to assess future impacts and devise appropriate adaptation strategies or capacity to implement change.

3 State of knowledge

As a basis for identifying research and monitoring needs (Sect. 4) and making recommendations (Sect. 5), we first need to discuss the state of knowledge on provision of runoff from mountains (supply), consumption of water in the lowlands (demand) and options for balancing demand and supply. This will enable us to discuss what kind of information is needed to answer the questions raised by water resources management and planning and how it can be obtained and disseminated.

3.1 Water supply (runoff from mountains)

3.1.1 Present state

Viviroli et al. (2007) recently presented a comprehensive overview of the role of mountains in water supply. On the basis of global runoff fields (Fekete et al., 2002), a mountain typology (Meybeck et al., 2001) as well as further data on population distribution and climate zones, they derived a set of global maps at a resolution of $0.5^\circ \times 0.5^\circ$, revealing that 23% of mountain areas world-wide are essential for downstream region hydrology in the earth system context, while another 30% have a supportive role. When the actual lowland water use is considered explicitly, 7% of the global mountain area has an essential role in water resources, while another 37% provides important supportive supply (Fig. 1). This is of special importance in arid and semiarid regions where the vulnerability to seasonal and regional water shortages is high. Moreover, mountains in the arid zone clearly deliver a disproportionate share of total discharge (66.5%) when compared to their share of total area (29.8%). Critically important mountain regions are found in the Middle East, South Africa, parts of the Rocky Mountains and the Andes. The importance of mountain water resources from the western part of the Himalaya and from the Tibetan Plateau is particularly marked because these regions partly compensate considerable lowland water deficits (Archer et al., 2010).

Snowmelt plays a major role in seasonal runoff patterns and water supply outside of the humid tropics. This was recently shown by Barnett et al. (2005) who used the output of a macro-scale hydrological model with a resolution of $0.5^\circ \times 0.5^\circ$ to assess the ratio of accumulated annual snowfall to annual runoff. The authors also compared the simulated annual runoff to the capacity of existing reservoirs, which served to identify cases where sufficient reservoir storage capacity is available to buffer seasonal shifts in runoff caused by earlier snowmelt (see also Sect. 3.1.5). In their analysis, Barnett et al. (2005) found that about one-sixth of the world's population lives within snowmelt-dominated catchments with low reservoir storage, this domain being potentially vulnerable to shifts in runoff caused by climate change impacts on seasonal snow. A critical region, for example, is the Western Himalaya where a modelling study for the Satluj River basin (a tributary to the Indus River) by Singh and Jain (2003) suggests that about 75% of the summer runoff is generated from snowmelt. On the neighbouring Jhelum River basin, Archer and Fowler (2008) show a similar dependence of summer runoff on preceding winter snowfall.

The significance of glaciers to water supply depends principally on the proportion of catchments that they occupy (i.e. the greater the distance from glaciers, the smaller their influence, cf. Zappa and Kan, 2007; Koboltschnig et al., 2008; Kaser et al., 2009; Lambrecht and Mayer, 2009; Koboltschnig et al., 2010). Therefore, globally valid statements about this significance are not possible. It is also often difficult to make a quantitative distinction between the contribution from melting of seasonal snow and from glaciers, even though nival melt from lower elevations generally precedes the glacial contribution from higher elevations (Weingartner and Aschwanden, 1992). The recent controversy on rates of melting of Himalayan glaciers (see IPCC, 2010 and Sect. 3.1.3) is placed in perspective by preliminary results by Armstrong and Racoviteanu (2009) who found that the annual contribution of glacier melt water to streamflow in the Nepal Himalayas represents 2–3% of the total annual streamflow volume of the rivers of Nepal and that seasonal contributions are not likely to exceed 2–13% of the total annual flow volume measured at lower altitude hydrometric stations (see also Alford, 2008). For the Indus River basin, situated in a drier climatological region, the glacial regime plays an important role in the high-altitude catchments, but its influence decreases strongly toward the margins of the mountains (Archer et al., 2010). In contrast, proportional flow from glaciers over large areas in the tropical Andes is much higher because the mitigatory influence of snow is limited (see Sect. 3.1.3).

Glaciers may provide a smoothing effect for water resources by complementing irregular runoff from highly variable summer precipitation with much more stable melt runoff (see e.g. Hock et al., 2005). With reference to studies from the Cascade Mountains (Fountain and Tangborn, 1985) and the Alps (Chen and Ohmura, 1990), Casassa et al. (2009) conclude that a minimum coefficient of variation in summer runoff is reached with a share in glaciated area of about 40%. In addition, glaciers reduce the interannual variability of summer flows with their long-term buffering function (Zappa and Kan, 2007).

3.1.2 Past trends in mountain runoff

Trend analyses over the historic record are very difficult for both mountainous and lowland areas. Results depend heavily on the methodology implemented and the timeframe of the study (see e.g. Radziejewski and Kundzewicz, 2004), and the high variability of precipitation and temperature often lead to inconclusive findings. Particular challenges are imposed by interannual and cyclic variations in precipitation and mountain snowpacks that are caused by large-scale circulation modes such as the El Niño – Southern Oscillation, the Eurasian Pattern, the North Atlantic Oscillation, the North

Pacific Oscillation, the Pacific North American Pattern, the Pacific Decadal Oscillation and the Indian Monsoon to name but a few. Some studies have removed interannual variability due to natural climate modes from time series, allowing for more reliable trend detection (Vuille and Milana, 2007), but the relatively short time span of most data records (typically a few decades) remains a major impediment to the detection of conclusive trends.

For mountain areas, trend detection is assumed to be easier due to the high climatic sensitivity of these environments, although much depends on the particular frame of a trend study (see also Sect. 4.1.7). For Switzerland, Birsan et al. (2005) identified changes in streamflow since 1930, with increases in winter, spring and autumn, which the authors attribute tentatively to a shift from snowfall to rainfall and increased and earlier snow melt due to a rise in air temperature. These streamflow trends were found to be positively correlated with mean basin elevation (and strongest for medium flows), thus suggesting that mountain basins are among the most vulnerable environments in terms of climate-induced streamflow changes. In summer, however, when most runoff is provided on an annual basis, both decreasing and increasing trends are observed. The heterogeneity of these trend signals is illustrated by the recent analysis by Barben et al. (2010) for Switzerland. For the French part of the Alps, Renard et al. (2008) detected a trend towards earlier snowmelt. For the western United States, a number of studies found that more precipitation is falling as rain instead of snow in winter, and that snow melt occurs earlier (e.g. Hamlet et al., 2005; Mote et al., 2005; Knowles et al., 2006). As regards the associated changes in runoff (Dettinger et al., 1995; Cayan et al., 2001; Regonda et al., 2005; Stewart et al., 2005), Barnett et al. (2008) were successful in identifying an anthropogenic “fingerprint” by using a multivariable detection and attribution methodology (see also Hamlet et al., 2010). Particular difficulties apply however to trend analyses in the mid-elevations of the semi-arid and arid climate zones. In these critical regions, the natural runoff pattern of most of the large streams has been altered, largely by dams or diversions (cf. Döll et al., 2009), which makes it difficult to assess changes in the natural response of amount and timing of streamflow (cf. Stewart, 2009).

Although changes in temperature and precipitation certainly have the biggest impact on streamflow from a global viewpoint, it should be borne in mind that other factors can also effect changes in streamflow in some regions. In Mediterranean mountains such as the Pyrenees, for example, depopulation and subsequent land abandonment have led to vegetation growth which has been the main driver for reduced runoff generation and decreasing streamflow (Begueria et al., 2003; López-Moreno et al., 2008).

3.1.3 Climate change projections

Scenario projections for the impacts of climate change on precipitation and runoff are subject to large uncertainties at the global scale. This is apparent from the results of different GCMs which are not consistent everywhere in the sign of change – and where they are, the magnitude of change is often very different (Bates et al., 2008; Stewart, 2009; see also Buytaert et al., 2009). Climate change scenario projections are particularly difficult for mountain areas owing to the difficulties in modelling regions with marked topography (see Sects. 3.1.4 and 4).

Bates et al. (2008) ascertain the "very robust" finding that warming would lead to change in the seasonality of snowmelt-dominated rivers and that snow-dominated regions are particularly sensitive to changes in temperature. Depending on altitude, early snowmelt may lead to more frequent spring flooding at the local scale, and summer irrigation water shortages may occur in regions that are dominated today by nival regimes. Large changes are expected especially at low latitudes, e.g. in south-east and central Asia (Parry et al., 2007). In regions where dependence on glacier runoff is high, shifts in seasonality and decreases in the amount of glacial melt will cause a reduction in water availability as well as reducing the buffering effect of glacier runoff during the dry season (e.g. in the Tropical Andes, see Vuille et al., 2008; Coudrain et al., 2005, or in central Asia, see Hagg and Braun, 2005). Owing to the limited research available at present, projections regarding the future state of glaciers are however difficult and subject to errors. This was recently shown by the controversy about the false IPCC statement that the Himalayan Glaciers could disappear by 2035 at present warming rates (see Bagla, 2009; IPCC, 2010; Schiermeier, 2010; see also Sect. 3.1.1). In addition, research concerning the future state of glaciers must go beyond focusing on surface air temperature and must also consider global shortwave radiation (Huss et al., 2009) or, in the case of tropical glaciers, atmospheric moisture (Mölg et al., 2006).

Considering the present state and anticipated changes, a number of regions are particularly vulnerable to changes in mountain runoff and subsequent deterioration of water resources supply in the adjacent lowlands.

- Viviroli et al. (2007) identify vulnerable regions where a high dependence on mountain runoff in the lowlands coincides with anticipated decrease in precipitation and growth in population. This applies mainly to river basins in the subtropical and wet-dry tropical climate zones where the capacity to adapt to changes is also low. Particularly vulnerable regions encompass great parts of the large Himalayan river basins that are, according to recent population data (ORLN, 2002), home to over 1.3 billion people today, but also the Middle East (e.g. Euphrates and Tigris River basins), North, East and South Africa as well as the dry parts of the Andes (in the central and northern Andes: the western side and the highlands; in the southern Andes: the eastern side).

- The UN WWDR3 (WWAP, 2009) mentions two mountain-related systems where high vulnerability meets limited possibility of adaptation. The first are snow melt systems such as the Indus River basin, the Ganges-Brahmaputra River basin and Northern China. The second are the semi-arid and arid tropics with limited snow melt and limited groundwater like parts of the Indian subcontinent, Sub-Saharan Africa and Southern and Western Australia. The reasons for the vulnerability of these systems vary strongly from region to region and encompass a number of anticipated changes, such as unfavourable changes in the amount and timing of runoff, rainfall variability, groundwater tables, population growth and food demand. Similarly diverse are the factors that limit adaptability, such as limited capacity to further extend the existing infrastructure, water resources that are already overallocated or a lack of public funds.

3.1.4 Representation of mountains in climate and hydrological models

Climatological and hydrological modelling are important tools for laying the foundations for successful and sustainable water management. Insight into important processes of mountain areas is achieved through process-oriented hydrological modelling exercises with focus on snow and glacier melt. A number of such studies have been conducted for meso-scale catchments in the European Alps (e.g. Gurtz et al., 2003; Verbunt et al., 2003; Zappa et al., 2003; Schaefli et al., 2005; Horton et al., 2006; Lehning et al., 2006; Huss et al., 2008; Koboltschnig et al., 2008; Magnusson et al., 2010), the Scandinavian mountains (Hock, 1999; Hock and Holmgren, 2005), the Rocky Mountains (e.g. Letsinger and Olyphant, 2007; Stahl et al., 2007; Comeau et al., 2009; DeBeer and Pomeroy, 2009; see also overview by Bales et al., 2006) and the Western Himalaya (e.g. Singh and Bengtsson, 2003; Singh and Jain, 2003; Rees and Collins, 2006; Konz et al., 2007; Akthar et al., 2008). Global macro-scale studies (e.g. Barnett et al., 2005; Adam et al., 2009) are equally important in providing the bigger picture.

Climatological and hydrological modelling is, however, particularly challenging in mountain environments for two reasons. First, the pronounced spatial and temporal heterogeneity of conditions in mountain areas calls for high model resolutions and thus also for detailed physiographic information (e.g. soil and land use types). The latter is usually only available for limited areas, which restricts the availability of reliable modelling efforts mostly to case studies at the meso scale. Second, relevant processes in mountain areas are not understood sufficiently. This concerns especially orographic precipitation and snowfall, which are among the most difficult variables to simulate in climate models, even at high spatial and temporal resolutions. Another area of uncertainty concerns the magnitude of the feedback effects (see Sect. 4.1.6) and their influence on the energy balance. Due to the limited process understanding, formulation of such effects varies substantially between individual models. Furthermore, the interaction between climate change and vegetation and its effect on the hydrological cycle is also not fully understood. Altogether, the impact of climate change on the water cycle in mountainous regions – particularly on snow and ice – is highly non-linear and requires much more detailed research. Especially when using macro-scale models, the increasing size of the area studied requires more straight-forward approaches, limiting the level of detail and process representation. Interpretation of such macro-scale models for local changes is therefore not possible yet, and seasonal changes should also be interpreted with great care.

3.1.5 The role of reservoirs

In view of the colossal magnitude of water engineering today (see Vörösmarty and Sahagian, 2000), the role of dams and reservoirs needs to be considered when discussing present and potential future water supplies. The number of reservoirs worldwide is impressive: The World Register of Dams (WRD) (ICOLD, 2003) lists around 50 000 medium- or large-size dams (figures vary depending on dam height and capacity criteria), and according to the UN WWDR3 (WWAP, 2009), 270 additional dams of 60 m height or larger were planned or under construction as of 2005. As regards storage capacity, Chao et al. (2009) have shown on the basis of an augmented and improved version of the WRD that a total of 10 800 km^3 of water has been impounded on land to date. A smaller database by UNEP (2003) that lists dam purpose data for 1021 major reservoirs reveals that 55% of dams are at least partly or even fully used for water supply or irrigation or both. This function involves mostly a redistribution of seasonal maximum flows towards times of maximum water demand (typically the high agricultural demand in spring and early summer) and a stabilisation of water supply.

Since dams can take on a role that is similar to that of the temporary storage of water in snow and ice, it is of course possible to compensate climate-change induced shifts in runoff regime by building additional dams, at least to a certain degree. This way of handling changes however faces a number of problems and questions:

- The economic feasibility of this mitigation strategy is questionable for many regions of the world, owing to the extremely high investments necessary. In addition, building large dams may require resettlement of a large number of people (about 1.2 million local residents in the case of the Three Gorges Dam at the Changjiang River in China) and flooding of archaeological heritage (such as in case of the Ilisu dam at the Tigris River which would drown the ancient town of Hasankeyf and further archaeological heritage).

- Building additional dams is hardly an option in regions that have already developed excessive impoundment infrastructure, such as in the Columbia River basin which features 14 major dams alone in the main river branch and about 250 dams in the entire catchment.

- Alteration of amount and variability of river flow causes a number of environmental impacts downstream such as changes in river ecology (boosted through the concurrent fragmentation of rivers, see WWAP, 2009) or intrusion of saltwater from the sea into aquifers (for example on the lower Indus, see Archer et al, 2010). In addition, the erosive capacity of downstream flows may be increased due to an imbalanced sediment budget, causing damages to river banks infrastructures (Kondolf, 1998).

In many cases, the above concerns have led to public opposition to the construction of new dams, delaying projects considerably and, in extreme cases, even bringing projects to a halt. In Spain, for example, most of the plans for building new dams are stuck in the law courts, as progress is each of the ongoing or planned hydraulic projects requires open public debates and long citizen's participation processes. Similarly, plans for transferring water from the Tagus and the Ebro River basins to Mediterranean areas have faced strong social and political opposition (Ibáñez and Prat, 2003). Another example is Pakistan which, in spite of two large dams (Tarbela and Mangla) on the mountain rim, has limited storage in comparison with world standards (World Bank, 2005). In terms of storage capacity, Pakistan has 150 m^3 per capita compared with the United States and Australia with over 5000 m^3 per capita. Successive attempts to develop major new reservoirs on the Indus have met with strenuous political as well as environmental objections.

In addition, it should be borne in mind that the lifespan of most reservoirs is limited due to sedimentation. With the reduction of storage volumes, the stabilising effect on water supply will diminish significantly over the decades.

Finally, water management strategies and associated dam operation rules can also have a large impact on water supply available. In view of anticipated changes in supply and demand, water management is particularly challenging and requires sound and reliable projections of inflow (cf. Milly et al., 2008). There are already historic examples where water management strategies have been based on a false premise of unrealistically high supply since planning was based on periods of exceptionally high water supply. A prominent case is the Colorado River basin where the average annual reliable flow used for establishing water rights of states within the Colorado River Compact was overestimated because the short observational record turned out to cover the wettest period in 400 years and did not represent the strong decadal and longer variations in streamflow (Pulwarty et al., 2005; Woodhouse et al., 2006). Another significant example is the Grande Dixence hydropower scheme in the Swiss Alps with the highest dam in the world to date. The dam was dimensioned on basis of measurements from 1920 to 1953 which was a period with some exceptionally warm summers, leading to notable release of water from glaciers (see also Huss et al., 2009) and therefore overestimation of long-term average inflow (Bezinge, 1981).

3.2 Water demand (consumption in lowlands)

When considering water resource questions, we must also consider water demand. As demand is largely outside of mountain regions, a detailed investigation of future demand is beyond the scope of this paper, and is in any event subjected to an even greater number of uncertainties due to population and technology than are supply projections.

3.2.1 Agriculture

According to the UN WWDR3 (WWAP, 2009), roughly 70% of global water withdrawals are used for irrigated agriculture today. Therefore, future water demand for food production will potentially have the biggest impact on overall water demand. A critical mountain-related issue is that seasonality of agricultural demand is usually not accounted for sufficiently. In critical regions, however, vulnerability to water stress will increase markedly if seasonality of mountain runoff changes and the demand peaks are currently attenuated by mountain runoff. Agriculture is especially vulnerable because it benefits from spring and summer runoff from mountains right at the time when demand for plant growth is biggest.

Three factors are decisive in this context. First, population dynamics will alter the patterns of regional demand, with strong increases expected in downstream regions that already today exhibit high demand. The growing demand caused by population increase is projected to exceed even changes induced by climate change in some regions (see also Vörösmarty, 2000), including areas like the Middle East or South Asia which benefit today from mountain runoff (Viviroli et al., 2007; Archer et al., 2010). Second, dietary habits might also have considerable influence, especially the trend towards higher shares in meat consumption which means that more water is required to produce the same calorific value. According to Molden (2007), global average meat consumption will rise from 37 kg per capita per year in 2000 to 48 kg in 2050. A particularly strong increase is expected in East Asia where economic growth will boost annual meat consumption to the level of OECD countries. This is equivalent to an almost twofold increase between 2000 and 2050. Third, it should be borne in mind that rising temperatures will increase evaporative demand and thus might reduce crop yields, such as anticipated for the Lower Indus plains where projections suggest a reduction of wheat yields in most climatic zones (Sultana et al., 2009) although partly compensated by the direct enhancing effect of increasing CO_2 on crop yields.

Besides the aforementioned main drivers, a number of further factors influence water demand for food production. However, these are highly uncertain and difficult to predict as regards both their future development and their overall impact. These include development of water-saving plant species through genetic engineering, shifts in plant composition of agricultural areas as a natural reaction to climate change or as deliberate adaptation by farmers to agricultural policy (e.g. subsidies for certain farming schemes or certain regions) or energy policy (e.g. subsidies for biofuels).

3.2.2 Hydropower

Although hydropower does not represent a consumptive water use, it affects runoff seasonality in the case of reservoir storage and, moreover, creates considerable challenges for water resources management in terms of reservoir operation for water allocation and risk management. The construction of a large number of additional dams is anticipated with economic development and the associated increase in energy demand. A further incentive for building dams stems from the low CO_2 emissions associated with hydropower: in its World Energy Outlook 2008, International Energy Agency (IEA, 2008) draws a scenario with more than doubling of current hydropower capacity until 2030 to meet climate goals.

Vast unused potential for hydropower production is present in Africa, developing Asia, Latin America, China, India and Russia (IEA, 2006). In the Yalong River, a branch of the Changjiang River's mountainous upstream area, for example, plans foresee construction of 21 new reservoirs during the next 15 years. Moreover, use of air conditioning may become more widespread and frequent in industrialized countries, owing to the rising air temperatures. The resulting increase in summer energy demand may pose problems in regions where no or insufficient reservoir volumes are available, especially when summer runoff is decreasing at the same time (e.g. in the Pacific Northwest of the United States).

3.3 Balancing demand and supply

Already today, there are extended regions that are experiencing water stress and, at the same time, depend at least to some degree on mountain water resources. Examples are found in Southwest US, the Pacific side of the Tropical Andes, South Africa, parts of the Mediterranean, the Middle East, large parts of Asia and Southeast Australia (see WWAP, 2009). In all of these cases, solutions are urgently required to prevent the detrimental consequences of water stress. This requires, above all, a paradigm shift to a water resources management that orients itself not by the water demand but by the limits of the supply and thereby considers all of the decisive factors across the entire river basin.

In most cases, it will not be possible to greatly increase available water resources to reduce water stress. Desalinisation might be an option with further technological progress and lowering cost (Zhou and Tol, 2005), but its use is currently limited to energy-rich regions. Practical problems apply also to alleviation of regional water demand by importing food and thus also the water that was used to grow it (so-called virtual water, cf. Allan, 2003). Although analyses of the international trade of virtual water reveal impressive quantities of water transferred (Chapagain et al., 2006), it seems unrealistic as a solution for the regions most urgently in need in the face of the global inequalities in power and capital (cf. Meek and Meek, 2009). In some regions, it might however be possible to reduce water stress by improving water quality. In the Andes, for instance, sewage treatment plants do not exist in most places, and much of the streamflow eventually becomes polluted and is thus lost for human consumption and food production (or causes serious health issues like Cholera outbreaks if used nevertheless). Furthermore, temporal reallocation of runoff might be improved by long-term basin planning and through integrated operation of multiple reservoirs, such as in China.

From the present point of view, the most promising option to re-balance supply and demand seems to be reducing demand. For regions with low or medium economic development and high dependence on irrigated agriculture, this may be achieved by implementing more efficient and thus water-saving irrigation techniques. For Pakistan, for example, the World Bank (2005) notes the "hopeful fact" that there is much scope for increasing productivity given the low crop yields (e.g., wheat yield per unit of water in Pakistan is 50% of that in the Colorado Basin). Where economic development is already high, reduction of demand can be achieved by technological measures in irrigation (see e.g. FAO, 2002), reuse of treated waste water, specific legislation (e.g. prohibit irrigation of certain crops and excessive private water use during drought periods) and awareness-rising (e.g. campaigns for households).

4 Research and monitoring needs

In identifying research needs with a view to water resources management, we should prioritise issues that have the highest potential for improving runoff projections. In our view, the highest priority is to improve projections of precipitation, not only regarding amounts, but also spatial distribution, resolution and temporal variability. Considering that the General Circulation Models (GCMs) represented in the IPCC AR4 are not even able to provide certainty about the sign of projected changes in many regions, problems with all other components of the hydrological cycle are likely to be dwarfed by these uncertainties. Further issues of relevance concern better estimation of snow water equivalent, more detailed soil information and better monitoring and modelling of evapotranspiration. In the regions that were studied as a basis for this article (cf. Sect. 2), aforementioned priority ranking is almost universal, with only a few minor differences that apply to the relative position of the lower priorities. These and a few more research priorities in process knowledge will be discussed below.

4.1 Research priorities

4.1.1 Improving precipitation projections

Thinking about improvements in precipitation projections quickly brings us to climatological downscaling and its particular advantages in mountainous regions where the accurate representation of spatio-temporal variability of precipitation is a huge challenge. GCMs are run at a very coarse resolution (~300 km×300 km grid cells) and are therefore not able to reproduce high-resolution features and mountain-specific effects like orographic forcing and rain-shadowing. To model such mountain-induced circulation patterns it is necessary to run limited-area models or to dynamically downscale GCMs using Regional Climate Models (RCMs). Since running RCMs is extremely computationally intensive, however, statistical downscaling (SD) is frequently used as an alternative. Statistical downscaling normally fits an empirical relationship between local observations and regional climate features (e.g. circulation patterns, pressure fields etc.) using historic data and then assumes that this relationship can be used to estimate future changes in local climate from the same regional features modelled using global or regional climate models. Although the results of SD are not based on physical process modelling, they often provide equally reliable results (Fowler et al., 2007). SD has, for instance, great potential in the Andes where temporal precipitation variability is highly correlated with large-scale upper air flow which can be adequately simulated in GCMs (Garreaud et al., 2003). Finding the most appropriate downscaling method is not always straightforward, and the choice depends on the temporal and spatial scale in focus. It should however be borne in mind that the choice of the driving GCM generally introduces the largest uncertainty and, together with the choice of emission scenario, is even more decisive for the results than the downscaling method used (Fowler et al., 2007). Therefore, a probabilistic approach should be pursued, using multi-model ensembles of GCMs and downscaling methods to allow the largest uncertainties in future projections of climate change to be explored adequately.

In the context of mountain water resources, with their often pronounced seasonality, air temperature also has an important impact on runoff. Compared to precipitation, the downscaling of temperature is however much more straight-forward. The accurate representation of precipitation is, at first glance, not as important for high elevation basins where the runoff seasonality is controlled by snow and ice melt and, hence, predominantly by air temperature. However, since much of the summer runoff is provided by the melting of the previous winter snowfall, when it comes to the future behaviour of glaciers and their role in providing meltwater during summer months, reliable projections are required for both air temperature and the temporal and spatial distribution of precipitation. For example, it has recently been suggested that glaciers in the Karakoram are showing a tendency of mass increase that is in opposition to the trend of rapidly retreating glaciers in the Himalaya (Hewitt, 2005). This may have been caused by a general increase in winter precipitation (as snow) at the confluence of the Westerlies and the southwest Asian Monsoon (Archer and Fowler, 2004). In spite of rising temperatures, altitudes that are still located above the snowline may receive more winter snowfall, leading to glacier mass accumulation (Bishop et al., 2008). Or it may be a result of falls in summer temperature, reducing the amount of melt from snow and ice and reducing the concurrent summer flow in the high tributaries of the Indus (Fowler and Archer, 2006).

Overall, much research on downscaling is still needed for the Tropics and the developing world. These regions have been rather neglected so far in spite of the importance that more reliable information on climate risk has for development and adaptation planning where economic growth is already severely hampered by climate variability and change (Fowler and Wilby, 2007). Research should also not stop after examining downscaling in the context of climate change but move on to assessing the impacts on hydrology and provide advice for stakeholders and managers for dealing with water adaptation to climate change (Fowler and Wilby, 2007). Following Koutsoyiannis et al. (2009), we argue that the uncertainties related to predicting the future availability of water resources requires a more intensive dialogue between climatologists and hydrologists.

4.1.2 Snow water equivalent

Seasonal snow has a considerable effect on the water balance of many rivers (cf. Barnett et al., 2005). To date, however, the snowpack is represented only in strongly simplified manner in macro-scale hydrological models (Widén-Nilsson et al., 2009). For better estimation of possible future shifts in runoff seasonality, more reliable estimates of Snow Water Equivalent (SWE) are required as a basis for improving our models or at least for calibrating the snow sub-model more rigorously. This improvement mainly calls for better observation techniques and a widespread use of them in monitoring. Besides ground-based point samples (e.g. from snow pillows), space and airborne estimates are of particular interest because they are more representative of an area:

- The advanced passive microwave scanning radiometer on board of the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) Aqua satellite currently provides global spaceborne estimates of SWE. The scattering effects of snow cover are related empirically to snow-cover depth and water content based upon field measurements. Daily, 5 day maximum and monthly mean SWE estimates are available at a spatial resolution of 25 km from 19 June 2002 to the present. Sources of error include variations in snow crystal size, snow detection in mountainous terrain, wet snow discrimination and snow mapping in densely forested areas (NASA, 2006). More detailed SWE data might be retrieved from the COld REgions Hydrology high-resolution Observatory (CoReH2O). The observatory is a candidate mission for the European Space Agency (ESA) Earth Explorer Programme due for launch in the first half of the forthcoming decade (ESA, 2008). CoReH2O utilises twin frequency Synthetic Aperture Radars (SARs) with an emphasis on, among other things, parameterisation of snow and ice processes as represented in hydrological numerical weather forecasting models as well as climate research applications and validation of hydrological and coupled land-atmosphere models (Rott et al., 2008).

- SWE estimation at regional scale is possible via airborne gamma radiation sensing as developed and maintained in the United States by the National Oceanic and Atmospheric Administration (NOAA) National Operational Hydrologic Remote Sensing Center (NOHRSC). The method uses the attenuation of the terrestrial radiation signal by water mass and, given a realistic estimate of soil moisture in the upper 20 cm (eight inches) of soil, allows determination of total above ground moisture, i.e. SWE (Carroll, 2001). Flight lines are approximately 16.1 km (10 miles) long and 1.6 km (1 mile) wide, while the aircraft flies at about 150 m (500 feet) above the ground. The NOHRSC uses SWE data from these surveys operationally, for example, for issuing water supply and flood forecasts.

The effort of SWE estimation can be reduced considerably if snow depth is used as a surrogate. This method requires a reliable model for snow density, such as that proposed recently by Jonas et al. (2009) for the Swiss Alps as a function of season, snow depth, site altitude, and site location. Such a model requires extensive series of measured snow densities and snow depths. Jonas et al. (2009) used more than 11 000 such measurements, taken at 37 sites over past 50 years.

Snow distribution, in contrast, can already be estimated now from remote sensing. In addition, advanced image processing algorithms are available to estimate the fraction of snow cover within individual pixels (Foppa et al., 2007), which help to characterise better the discontinuous and heterogeneous distribution of snow cover in mountainous regions.

4.1.3 Soil information

The lack of soil information at an adequate resolution is a universal problem in hydrological modelling. Soil properties are usually mapped poorly and at a coarse resolution only, and there will likely be no major improvement in the near future, owing to the high cost and low scientific recognition of extensive field campaigns. The problem is amplified in mountain regions with their high heterogeneity of conditions for pedogenesis. Further development and implementation is also required in interpretation of existing soil maps with view to hydrological processes (e.g. Schmocker-Fackel et al., 2007).

The situation is a little better for land cover which can be derived with reasonable accuracy and effort from remote sensing information. Aerial photography, which provides better data at present, is very costly.

4.1.4 Evapotranspiration and sublimation

Considerable difficulties apply to evapotranspiration (ET) and its behaviour under a changing climate. On the one hand, observed values of ET are usually very scarce, especially in dry climates where direct measurements are also quite difficult. On the other hand, the present state of ET is not necessarily meaningful for the future since changes in processes could exert significant influence. The suppression of plant transpiration due to reduced stomatal aperture with increasing CO_2 levels (see e.g. Gedney et al., 2006a; Betts et al., 2007) could, for example, counteract the general trend for higher evaporation at the global level. Better representation of soil-plant-atmosphere exchange in climate models and improved treatment of the energy budget are therefore important tasks for research.

The magnitude of changes in ET and their impact on hydrology depend very much on the specific environment. In glaciated catchments in the Andes, for example, sublimation has a bigger impact on water resources than ET. Moreover, possible changes in land use may also be important for ET, no matter whether they are caused by climate change, migration, economic development, or altered land use practice. In the Pyrenees, a significant increase in ET is expected due to the growth of vegetated area, caused by abandonment of agriculture and grazing and a rise of the tree line. In regions where shrub and forest growth are dominant, the impact of increased ET may even outweigh other climate-change related effects.

4.1.5 Groundwater

Although groundwater recharge is not a specific mountain process, replenishment of aquifers at the mountain front can be important, and is even dominant in many basins in arid and semiarid climates (Wilson and Guan, 2004). Recharge of the Atacama Desert aquifer, for example, has been shown to be fed mainly from rainfall and snowfall in the high Andes (e.g. Houston et al., 2002). Groundwater in the lower Indus plains is significantly recharged by leakage from irrigation canals fed from the Indus River and therefore also dependent on mountain sources (Archer et al, 2010). To provide a better overall picture, it is crucial to improve process knowledge about groundwater flows or at least quantitative data about the extent and renewal rate of large aquifers. Detailed knowledge that is missing today concerns groundwater interaction with surface water as well as the dependence of groundwater on natural vegetation, land management and abstraction. This also concerns mechanisms, influences and rates of recharge at the mountain front. A better understanding of the relevant processes would help to improve assessment of climate change impacts on groundwater (see e.g. Döll, 2009; Goderniaux et al., 2009; Kundzewicz and Döll, 2009), and it might also be an important step towards exploring active management of groundwater resources (such as artificial groundwater recharge).

4.1.6 Enhanced warming and feedback mechanisms

We conclude our presentation of research priorities with remarks on the enhanced warming that is assumed for high elevations as a consequence of energy budget and related feedback mechanisms in mountain areas. The issue of enhanced warming is vital for determining speed and extent of potential changes in seasonal to multidecadal water storage in the form of snow and ice (Messerli et al., 2004).

There are two relevant feedback mechanisms. First, depletion of snow and ice covered areas reduces surface albedo and thus leads to an increased absorption of shortwave radiation. Owing to its close connection to the seasonal snowpack, this effect is strongest in winter and spring of the mid latitudes (Giorgi et al., 1997) and has considerable influence on temperature trends in mid elevations that are located near the annual 0 °C isotherm (Pepin and Lundquist, 2008). Second, decreasing cloud cover at high elevations increases incoming solar radiation, forming a cloud-radiation feedback cycle. This feedback was discussed for the Tibetan Plateau by Duan and Wu, 2006 and Liu et al., 2009 and is also likely to have occurred in the European Alps (Auer et al., 2007). In addition to these feedbacks, mountains are more directly exposed to the middle troposphere where the enhanced hydrologic cycle will augment the release of latent heat, leading to enhanced warming in high mountain regions, primarily in the tropical latitudes (Bradley et al., 2004 and 2006).

Closer examination however reveals that there is no definitive consensus about enhanced warming at high elevations and the physical mechanisms involved. While numerous studies have found clear evidence of enhanced warming in 20th century observations (Beniston and Rebetez, 1996; Diaz and Bradley, 1997; Shresta et al., 1999; Liu and Chen, 2000; Diaz et al., 2003; Diaz and Eischeid, 2007) or numerical experiments with climate change scenarios (Giorgi et al., 1997; Fyfe and Flato, 1999; Snyder et al., 2002; Chen et al., 2003; Bradley et al., 2004; Urrutia and Vuille, 2009) or both (Liu et al., 2009), other studies have not led to uniform confirmation (Nogués-Bravo et al., 2007), were inconclusive (Pepin and Seidel, 2005) or even contradictory (Vuille and Bradley, 2000). Contradictory results have even been found for the same region. The European Alps are such an example: Beniston and Rebetez (1996) examined 15 years of temperature minima observations across Switzerland and found a very significant altitudinal dependency of warm and cold anomalies, with a positive altitude gradient for warm winters and a reverse anomaly for cold winters. Auer et al. (2007), in contrast, did not detect enhanced warming (or cooling, for that matter) in their comprehensive study which encompasses the entire Greater Alpine Region and features temperature records that extend back as far as to 1760. They rather found that the entire alpine region has experienced a warming twice as high as the global or Northern Hemispheric average since the late 19th century, and the data suggest that this was most likely caused by reduced cloudiness. Further contradictions have been pointed out for the Rocky Mountains (Pepin and Losleben, 2002; Diaz and Eischeid, 2007) and the Tibetan Plateau (Liu and Chen, 2000; You et al., 2008).

It is concluded that detection of altitude gradients in warming is not straight-forward as such gradients depend on latitude, region, scale, timeframe and methods and are disturbed by local-scale effects such as the high variability of temperatures as well as gradually occurring changes in land cover and patterns of aerosol emission and transport (see discussion by Liu et al., 2009). Further bias is introduced because many high-elevation climate gauging sites are located in valleys, mixing up the effects of topography and elevation (Pepin and Seidel, 2005). Pepin and Lundquist (2008) argue that high elevation measurements are still of high value for early detection of increasing temperatures, although maybe not because of enhanced warming but rather because summit locations are more directly influenced by the free troposphere and lack the surface complexities of lower elevations which cause significant “noise” in temperature trends. With the help of principal component analysis, Böhm et al. (2001) found that the data from remote places on mountain peaks in high-level alpine areas may well represent “climatic background information” right in the centre of densely populated Europe.

In view of the large uncertainties and the importance for determining the vulnerability of mountain areas towards a changing climate, a more detailed representation of energy budgets and feedback mechanisms in models is urgently needed.

4.2 Importance of environmental monitoring

In view of the research needs described above, we should not forget that environmental monitoring is an indispensable prerequisite for improving our understanding of all components of the hydrological cycle (Kundzewicz et al., 2008). This is especially true for high altitudes where large temporal variability and spatial heterogeneity of processes call for even more extensive and long-term monitoring efforts.

4.2.1 Variables of interest

One of the most important variables to be gauged in mountainous areas is precipitation. The corresponding networks are usually biased towards lower elevations (see following Sect. 4.2.2), and the combination of considerable measurement errors (especially with regard to snow) and local-scale orographic effects further decrease the reliability of present estimates (Neff, 1977; Legates and DeLiberty, 1993; Sevruk, 1997; Sevruk et al., 1998; Adam et al., 2006). Remote sensing or weather radar, although valuable for complementing precipitation estimates, are not likely to become reliable surrogates in the near future since conversion of sensor data remains difficult. In addition, calibration of such techniques will inherently remain subject to the availability of steady and reliable ground truth gauge observations.

Another important component subject to significant lack of data is snow. Although it has been possible to improve the availability of snow cover data thanks to remote sensing (e.g. Armstrong and Brodzik, 2005; Armstrong et al., 2005; Foppa et al., 2007; Parajka and Blöschl, 2005), more detailed information is still required on snow water equivalent (SWE). More extensive field monitoring of SWE would be of high value for validating hydrological models and could be used for developing and testing independent SWE reconstruction models on the basis of remote sensing information as demonstrated by Molotch (2009) (see also Sect. 4.1.2).

Significant data gaps apply to glacier mass balance, which is central for evaluating corresponding models. Changes in mass balance are however much more difficult to determine than changes in glacier length. Due to the logistical challenges involved, the sample of glaciers with mass balance monitoring is biased towards the morphologically simple and more accessible glaciers, as well as towards the Northern Hemisphere and in particular Europe. In addition, only few records date back to the mid 20th century. In view of this, the work of the scientific glacier monitoring networks such as the World Glacier Monitoring Service (WGMS) (Zemp et al., 2008) is highly important for collecting and disseminating standardised data on glacier changes worldwide.

Large gaps are also present in streamflow measurement, especially as regards records that capture seasonal melt of snow and ice. In its function as the integrative hydrological response from a catchment, streamflow is obviously central for enabling trend studies (e.g. Peel and McMahon, 2006 and Gedney et al., 2006b) as well as for verifying and improving models which can in turn be used for making predictions in ungauged catchments (PUB initiative, see Sivapalan et al., 2003). Today, monitoring data is available for only two thirds of the actively drained land surface area (Dai and Trenberth, 2002), and these records vary widely in length, frequently contain gaps and are, in addition, subject to biases from diversions and reservoir storage. Remotely sensed data might serve to reduce error and uncertainty in models for ungauged basins but is no substitute for a dense in situ gauge network (Neal et al., 2009).

While the importance of gauging further variables such as ET, groundwater level and water quality was already highlighted in the preceding section, water consumption needs better quantification. Archer et al. (2010) note the difficulty of effective management of the Indus Basin Irrigation System in the absence of a licensing system for groundwater, inadequate measurement of distributary offtakes, high leakage losses from irrigation channels and pipelines to groundwater and illegal abstractions. Such unregulated water transfers, which are not uncommon, may constitute a high percentage of total consumption.

4.2.2 Representativeness for high altitudes

As indicated in the preceding section, variability and heterogeneity of processes in mountain areas are faced with a lack of instrumental records for high altitudes. This will be illustrated below in more detail for two key hydrometeorological variables, namely runoff and precipitation.

Figure 3 characterises the global situation by showing the altitudinal distribution of runoff gauge data accessible via the Global Runoff Data Centre (GRDC) (GRDC, 2009) and precipitation gauge data available from the Global Precipitation Climatology Centre (GPCC) (GPCC, 2010). The two archives are among the largest and most respected sources of runoff and precipitation data on the global scale. Station altitudes, although reported for many stations in both catalogues, cannot always be considered reliable and were derived from the $0.5' \times 0.5'$ resolution global digital elevation model GTOPO 30 (USGS, 1996) with help of the reported station location. Stations were included in the analysis on condition that they provide data in daily resolution for at least 10 years, and that their altitude could be determined from GTOPO 30, which was the case for 6541 GRDC stations and 48 841 GPCC stations. The altitudinal distribution of the hydrometeorological network is compared with the hypsography of the global land surface area (without Greenland and Antarctica) which was also derived from GTOPO 30. For the GRDC runoff station archive, the majority of stations are located below 300 m a.s.l., and under-representativity is observed for altitudes above 1500 m a.s.l. It should be noted however that the runoff gauge location analysed refers to the basin outlet, while the respective runoff measurements apparently integrate information from the entire basin which also spans to higher altitudes. Representativeness of the GPCC precipitation archive is surprisingly good when looking at the entire altitude range, with only altitudes below 100 m a.s.l. being overrepresented. The inset of Fig. 3 shows, however, that altitudes above 2500 m a.s.l. are slightly underrepresented, and those above 3500 m a.s.l. increasingly underrepresented.

The characteristics of the precipitation gauge network are broken down into network density per continent in Fig. 4. Europe clearly has the densest network (0.13 stations per 100 km^2/791 km^2 per station), although with a marked centroid around 500 m a.s.l. and a subsequent decrease with higher altitudes. The lowest density is present for Asia (0.02 stations per 100 km^2/5633 km^2 per station), which exhibits even lower values above 2500 m a.s.l. (0.004 stations per 100 km^2/26 692 km^2 per station). Africa and South America possess their highest densities at intermediate and high altitudes (1600–2600 m a.s.l. and 1700–3500 m a.s.l., respectively), although it should be noted that the densities are clearly lower than for Europe and the absolute number of high altitude stations is very low for Africa. North America about follows the global average with a relatively steady decrease of network density with altitude. High and very high altitudes are therefore mainly represented by the 292 South American stations that are located above 3 000 m a.s.l. These make up 73% of the global network above this altitude, although South America possesses only 23% of global land surface area above 3000 m a.s.l. outside of Greenland and Antarctica. Note that the WMO (1994) recommendation of 0.4 stations per 100 km^2 (250 km^2 area or less per station) for mountainous areas is clearly missed in this continental analysis. WMO recommendations for plains and hills (0.17 stations per 100 km^2) as well as for coastal areas (0.11 stations per 100 km^2) are only met in Europe and Australia. A similar analysis for runoff was not made because the sample of stations per continent was considered to be too small, with a total of only 70 stations above 2000 m a.s.l. representing an area of 7.7×10^6 km^2.

Above figures are by no means intended to criticise the highly important work of hydrometeorological surveys and even less that of data collection and distribution centres like GRDC and GPCC. They rather illustrate that improvement of monitoring at high altitudes is indeed an important and necessary task if we want to enhance the data base for understanding processes in mountain areas. In particular, Asia should be a priority because of its extensive high-elevation areas that are inadequately monitored and at the same time highly significant for downstream hydrology and water resources (cf. Sect. 3.1.1).

The global and continental overview presented here is, of course, a simplification and does not necessarily express regional or local characteristics. Therefore, a similar analysis was performed for Switzerland, representative of a region characterised by marked relief and at the same time possessing one of the world's densest hydrometeorological networks. Figure 5 compares the hypsographic curve derived from the Swiss Digital Elevation Model at resolution 0.1×0.1 km^2 (FSO, 2003) with the altitudinal distribution of 568 runoff gauges (FOEN, 2009) and 608 precipitation gauges (MeteoSwiss, 2005) which have recorded data for at least 10 years and at least in daily resolution. The gauging network is generally very representative for intermediate altitudes, the most frequent altitude band of 400–500 m a.s.l. is clearly overrepresented. Above an altitude of 1500 m a.s.l., where snow and ice melt processes are dominant in the runoff regime (Viviroli and Weingartner, 2004), 37% of total surface area is however represented by only 7% of the runoff and 10% of the precipitation gauge networks. The density of the runoff observation network is 1.37 stations per 100 km^2 which is well above the minimum density of 0.1 stations per 100 km^2 (1000 km^2 area or less per station) recommended by WMO (1994) for mountainous regions. The recommended density is, however, only met for altitudes up to about 2100 m a.s.l. This seems acceptable when considering that a dense network would not make sense for much higher altitudes where snow and glacier cover dominate. For precipitation, the WMO recommendation of 0.4 stations per 100 km^2 for mountainous regions is met in Switzerland on average with 1.47 stations per 100 km^2. The recommendation is still closely met on average for the entire territory above 1500 m a.s.l. with 0.38 stations per 100 km^2, but is missed for altitudes above 2000 m a.s.l. which still make up 24% of the country's total area.

4.2.3 The way forward

The general lack of observational data is detrimental in mountains of the arid and semi-arid zones of the Tropics, Subtropics and Mediterranean region where dependence on mountain runoff in the adjacent lowlands is highest. In spite of this, the sparse hydrological, climatological and glaciological monitoring networks that exist today face a tendency for reduction in numbers due to the high operating cost of measuring stations in remote mountain areas with their harsh environmental conditions. This tendency must be reversed. Furthermore, public access to measured data must be improved, above all in regions of frequent water-scarcity where its dissemination is often prohibited for political reasons, especially in South Asia.

How can the tendency of shrinking observation networks be reversed? An interesting example is found in the Andes where participatory environmental monitoring is actively being explored as an important component of regional development. Data on precipitation and river flow are collected by farmers who are then able to improve irrigation schedules and water supply systems. The data collected are also essential for negotiating compensation for environmental services which can help diversify local incomes and make farmers more resilient to the anticipated effects of climate change (Buytaert et al., 2006). In order to secure continuity of observations in the long term and allow effective dissemination of data, however, it would be important to link such valuable initiatives into official networks at the regional or national level.

5 Recommendations to improve mountain water resources management

On basis of the state of knowledge and the research needs identified, we will now provide some recommendations concerning how advancements in the management of mountain water resources under climate change can be achieved in the fields of research, management and policy, as well as through their interactions.

5.1 Recommendations for research

An important point for scientists is to improve the utility of their research for water managers, i.e. *“translating (. . .) science into practical measures that can be taken up and used at the point of delivery of adaptation”* (Fowler and Wilby, 2007). One of the most crucial prerequisites for this is to understand that water managers require models that provide answers for the integrated system of water supply and demand, while scientists focus on models that advance process understanding. Owing to their responsibility for ensuring reliable supply, their focus is usually on establishing safe and reasonable management measures, and therefore, they cannot accept assumptions but rather pursue a risk-adverse approach. Uncertainties and the reasons for their existence must thus be addressed clearly, and it is also necessary to clarify that scenario projections are not exact predictions but instead provide a plausible range of possible future system states (Kundzewicz et al., 2009). Moreover, model results should always be accompanied by a probability range (e.g. from using model ensembles), and interpretation of these ranges must be assisted. Emphasis should also be put on future changes in the variability of water resources which, unlike variability itself, may pose serious problems if not addressed in management strategies. Indeed, since water managers are more interested in short-term impacts rather than in long-range climate change projections (e.g. for the 2080s as commonly provided by the climate modelling community), the onus should be on better capturing seasonal and decadal variability within climate models and thus downscaled temperature and precipitation time series (Fowler and Wilby, 2007). Although the scenario context and the data for projections should always be revealed, adaptation decisions may be facilitated by limiting the level of detail to what is necessary and by providing conceivable management options. In all of this, scenario projections should also be made for the near future (e.g. 2010–2035) in order to facilitate a continuous development of management practises. Impact of academic research on management practice could be improved further by publishing results in regional and national open-access water management journals.

In order to improve communication with managers, a common language should be sought which circumvents ambiguities that are caused by the different professional backgrounds (“regime”, for instance, can be interpreted as a hydrological or a legal term). Regular discussion meetings can quickly clear up such misunderstandings. Communicating results by means of comparison with experience might also be helpful in bridging gaps, e.g. by adding that the situation observed during a recent heat wave might occur every few years for a medium warming scenario in 2050 and could correspond to the average conditions in 2050 for a strong warming scenario (presented like this in Switzerland with reference to the 2003 heat wave in Europe, see OcCC, 2007). Furthermore, experience has shown that successful transfer of know-how must be based on a continuous, long-term and peer-to-peer relationship between researchers and practitioners.

Another significant issue concerns the relationship of science and policy, which can be a difficult one in the sometimes heated debate about climate change and its impacts. To ensure the credibility and integrity of science, it is important to think about what role scientists should take on and how they should communicate results and the associated uncertainties (von Storch, 2009). What seems to be underrepresented today is a science that provides a bandwidth of probable futures and, even more importantly, presents the implications of different decisions including their efficiency and costs, drawbacks and advantages (see Pielke Jr., 2007, in particular the role he describes as a "Honest Broker of Policy Alternatives"). In doing so, it is absolutely essential that scientists address the complexity in the corresponding impact pathways and communicate the related uncertainties in a comprehensible manner. On the basis of such projections, decision makers must finally perform a comprehensive balancing of ecological, social and economic interests, with further support from scientists as necessary. This seems even conceivable for regions with poor scientific capacity if local decision-makers recognise the need for scientific support and are able to find appropriate expertise outside of the region at international level.

The complexity of climate change issues in mountain areas makes it nearly impossible for an individual researcher to represent all of the relevant areas of expertise. This strongly calls for scientists to engage in interdisciplinary research and to commit to acting on advisory boards and similar scientific bodies.

In addition to the above points, researchers should not cease to point out the vital importance of long-term monitoring to politicians and practitioners and work towards securing funding for measuring, analysing and archiving data, with particular emphasis on high altitudes (see Sect. 4.2). Common criticisms – that monitoring is not "real science" or that most data are never used (see Lovett et al., 2007) – need to be countered with sound and purposeful consideration of parameter selection, quality control, long-term archiving, implementation in research programmes and international data exchange. The importance of data in the context of water resources management needs to be emphasised because the absence of evaluation of models with real-world data and the associated lack of credibility is a key barrier in transferring scientific results to water managers. Establishing data exchange networks and digitising historical data could be further steps towards an improved verification of climatic and hydrological models with a focus on mountain areas and climate change.

5.2 Recommendations for water resources management

Since our background is mostly in research, we are aware that our limited insight into practical water resources management forbids universally valid and definitive recommendations. We will however attempt to focus a spotlight on the increasingly uncertain future and how to address this with an appropriate management strategy. This issue could also be of particular interest for countries which, to date, lack capacity in water resources management and their related political and institutional frameworks.

In our opinion, there is urgent need to break away from present stationarity-based practices which assume that natural systems fluctuate within an unchanging envelope of variability (cf. Milly et al., 2008). Considering the anticipated changes which may result from climate change, the historical record has become insufficient on its own for predicting supply and demand, even if management systems were originally designed to include risk mitigation. More flexible management and adaptation practices can reduce the risks of failure in supply very effectively (e.g. Ajami et al., 2008), and the benefits are amplified if these practices are implemented into basin-wide water resources allocation and management.

This brings us to the fact that many rivers, lakes and underground water aquifers cross national borders and that there is an increasing potential for conflicts about water resources at the international level (e.g. Euphrates-Tigris, Ganges-Brahmaputra, Indus, Jordan and Nile River basins), and sometimes even reaching the regional level (e.g. Ebro River basin, cf. Sect. 3.1.5). In this context, water resources issues have the potential to serve as an incentive for peaceful cooperation with shared benefits and sustainable development (Wolf et al., 2003). Overall, basin-wide integrated water resources management is nowadays widely accepted and promoted by many international organisations. International basin management organisations such as the International Commission for the Protection of the Rhine (ICPR), the International Commission for the Protection of the Danube River (ICPDR) or the Mekong River Commission

(MRC), to name but a few, can provide an ideal framework for such efforts and promote effective implementation of rules at the national level. Also national commissions such as the Yellow River Conservancy Commission (YRCC) or the Changjiang Water Resources Commission (CWRC) may take on an important role in coordinating basin-wide management within a single country.

In view of the importance of soil and vegetation effects on water yield (e.g. Mark and Dickinson, 2007 for New Zealand and Africa), one should always consider land use in water management schemes, creating Integrated Land- and Water Resources Management (cf. Falkenmark, 2009; Hoff, 2009).

5.3 Recommendations for improving communication between research and management

In many cases, it is unrealistic to expect that water management institutions will be able to employ enough staff to operate sophisticated hydrological models. Adequate resources are typically available only at research institutes which have their own agendas and approaches and lack the continuity required for operational purposes. What can be done, then, to improve the information flow between scientists and water managers and provide a common ground?

Fundamentally, a working relationship between research institutions and management institutions should be developed. Workshops and continuing education seem to be an effective way to facilitate communication between these two parties if such events occur regularly, focus on content of mutual interest and treat both sides as equals. Permanent working groups could take on the task of organising such events.

Another interesting way of establishing successful cooperation was reported by Langsdale et al. (2007). They describe a participatory modelling exercise that was used to support the water resources community of a river basin in British Columbia in evaluating anticipated climate change impacts on a management system. Researchers and practitioners jointly designed an integrated model with the goal of understanding the most important and decisive components rather than aiming at a perfect representation of details. This kind of informal case study enables practitioners to examine management options without actual risk, to understand the specific uncertainties in and limitations of hydrological and climate models and to explore planning as a process of continuous change and adaptation instead of a stationary rule. At the same time, it enables researchers to realise the specific questions and concerns of water resources managers and shows them what kind of results are required by management practice. Involving intermediate professionals from both sides might further facilitate the building of trust and long-term relationships. Initiatives of this kind should be seized upon much more frequently, and management or political institutions should take on a proactive role in initiating them at a regional level. Research institutions should however not be reluctant to point out the need for such joint efforts if they recognise problems on the horizon.

If water resources problems concern more extensive areas and are expected to take on larger dimensions, joint projects can be initiated more effectively by a national government. For the Changjiang River, for example, the Chinese ministry of water resources recently initiated a research project on the integrated operation of multiple reservoirs in the upper river. The project is carried out jointly by research institutes, universities and the river basin management authority, and the intermediate operation rules have turned out to be quite successful so far. In case of an even more extensive need for knowledge, research programmes should be initiated at the national or even international level. In this case, the ministry in charge should seek advice from research institutes and issue a specific call for projects afterwards, ensuring a good mix of science and management. The projects themselves can then be carried out jointly by the research and the management institutes. This has proven to be very successful, for example, in Switzerland (e.g. National Research Programme 31 on Climate Change and Natural Hazards). A mix of administrative and scientific partners with emphasis on relevancy for practical applicability is also required in the EU Interreg IIIB AlpineSpace Programme which features water-related projects such as AlpWater-Scarce (Water Management Strategies against Water Scarcity in the Alps) or AdaptAlp

(Adaptation to Climate Change in the Alpine Space). In the United States, the Regional Integrated Sciences and Assessments (RISA) program was established by the National Oceanic and Atmospheric Administration (NOAA) in the mid-1990s to support research teams that focus on climate issues with relevance for decision and policy makers. A main RISA goal is to achieve results that help society make decisions in the face of climate change. An outstanding example for transdisciplinary, integrative and transboundary global change research is also the GLOWA (Global Change and the Hydrological Cycle) programme launched by the German Federal Ministry of Education and Research (BMBF). Today, GLOWA features cluster projects in Europe (Danube and Elbe Rivers), North and West Africa (Drâa, Ouémé and Volta Rivers) and in the Middle East (Jordan River). The Jordan River cluster is also particularly remarkable in that it brings Jordanians, Palestinians and Israelis together, using a river basin and the common concern of global change impacts as a common platform.

5.4 Recommendations for policy

We conclude our list of recommendations with a number of policy-related issues. Although we may not have the expertise to make pointed recommendations in this field, we wish to raise a few concerns that apply to national policy and politics.

First of all, we observe that the increasing tendency to short-term thinking prevents important problems being tackled in the long term. Political discussions about water resources issues should, however, certainly not only occur in the aftermath of critical situations but receive much more continuous attention.

In regions where the political system is not completely stable, there might also be a need to implement and reinforce existing legislation with respect to water resources. Stronger governance systems are required to address the challenges in water resources management, and even in developed countries, capacity and funding of the responsible institutions have to be strengthened (Gurría, 2008).

With view to institutional organisation, exchange of knowledge between research and management should be facilitated by reducing bureaucratic obstacles, improving efficiency of organisational structures and facilitating collaboration and cooperation among different agencies. In Peru, for example, the hydrologic service was until recently administered by the Ministry of Defence which had little appropriate knowledge of science. This also stresses that hydrometeorological data are often seen as strategically important data that cannot be put in the public domain. Moreover, measurement and management may be divided between several government organisations with limited or untimely data exchange and management coordination: in Pakistan, climatological measurement is primarily the responsibility of the Pakistan Meteorological Department and river flow the responsibility of the Water and Power Development Authority (WAPDA). Management of the Indus Basin Irrigation System is divided between WAPDA for reservoir management and Provincial Irrigation and Drainage Departments for abstraction and distribution. Management can also become ineffective if there are many authorities involved with different objectives and agendas, or where a culture of conflict resolution is lacking. Finally, unprejudiced evaluation of knowledge should be pursued to prevent political instrumentation of selected findings.

As regards the promotion of relevant research, the absence of a framework from which mountain-specific funding can be obtained is a big impediment. In the US National Science Foundation, for example, relevant topics in mountain water resources and climate change are spread across several divisions such as climate dynamics, hydrology, geography and spatial sciences or polar research. In order to promote the integrated assessment of regions, an overarching funding framework should be put in place for mountain research rather than providing funding agencies that focus on individual components of the earth system in mountains. The national or international research initiatives mentioned in the preceding section could complete such a funding structure with particular focus on practice-oriented research. In order to increase the autonomy and flexibility of local management institutions and provincial governments – which often have a higher awareness of regional problems –, it might also be a good idea to provide them with funds subject to use for seeking advice from researchers or initiating cooperation with them. This would complement rather research-oriented funds and facilitate exchange of knowledge. For regions of the globe where a lack of research capacity coincides with limited funding, support is required from abroad, e.g. from cooperation and development agencies at the national level (found in many industrialised countries) or at the international level (e.g. World Bank).

We also believe that current assessment procedures and funding strategies for academic research tend to provide incentives that counteract practice-relevant science. The pressure to focus on high-impact publications and to constantly attract new projects complicates knowledge transfer, and researchers that focus on practice-oriented results risk being accused of "not being scientific". Funding agencies need to better acknowledge and recognise dissemination of knowledge, both for researchers and for managers who are usually very constrained in their time. Interaction and exchange should not be left to the personal initiative of a few idealistic individuals but should be actively encouraged and supported.

Finally, sufficient funding should also be granted for long-term monitoring networks to at least reverse the tendency of shrinking observation networks. As noted before, advancement in research is tied to long, reliable and readily accessible records that provide the basis for verifying or even improving models and process descriptions.

6 Conclusions

There is currently not enough knowledge to move much beyond rather broad statements on future changes in the timing and amounts of mountain runoff, and therefore, more detailed regional studies are needed to provide water management with more reliable scenario projections. A number of research areas are relevant in this context, of which precipitation downscaling may currently have the highest prospects for improving the reliability of climate change projections in mountain areas. This is in line with the need for establishing a more integrated approach to mountain water resources research, e.g. by linking more closely hydrological and climatological research or by considering the impacts of land use changes. It should however be borne in mind that beyond these changes in water provision, population dynamics and economic development will significantly increase water demand in some regions (e.g. Lins and Stakhiv, 1998; Koutsoyiannis et al., 2009), such as the Middle East (Bou-Zeid and El-Fadel, 2002) or the densely populated catchments that originate in the Hindu Kush-Karakoram-Himalaya (WWAP, 2009). In view of these challenges and uncertainties, it is imperative to support adaptation processes in water resources management institutions by disseminating research results actively through practice-relevant conduits and, more than that, to establish continuity in knowledge exchange between managers and researchers through, for example, regular workshops and continuing education. These adaptation processes would also benefit greatly from an ongoing effort to get water on the political agenda.

Although some of our findings are certainly universal to water resources management under climate change, many of the problems mentioned are amplified in mountain regions. Most of all, feedback mechanisms in the climate system result in mountains being particularly vulnerable to changes in hydrology if storage in snow or ice or both is important. In addition, mountains feature high climate variability due to strong altitudinal gradients and exposure to solar radiation, frequently complicated when they represent transitional environments in terms of climate (such as the Pyrenees or the European Alps between Atlantic and Mediterranean conditions). In many mountain areas, observation networks are inadequate for capturing the heterogeneity and variability in important processes and thus strongly hinder our understanding of high-altitude regions. Overall, challenges for climate and hydrological modelling in mountain areas are clearly enhanced, which renders integrated water resources management difficult both in the mountains as well as in the lowlands, especially when several political units (states or nations) are involved

In view of the present and future challenges in managing water resources that originate in mountain areas and the related uncertainties, there is strong need for promoting research and exchange of knowledge with practitioners. Although climate change is already a strong focus of present research strategies in developed countries, the common concerns of water resources and mountain areas are in need of more specific support at national and international level. Well-targeted programmes at international level should act to coordinate individual national actions, which would allow a certain comparability of results, facilitate the implementation and anchoring of know-how at the national level and, ideally, even foster new national initiatives. Good examples of this are the first call for the 7th EU Framework Programme (FP) which contained the subject "Climate change impacts on vulnerable mountain regions" or the recent call of the 6th EU FP-funded CIRCLE (Climate Impact Research Coordination for a Larger Europe) on "Climate change impacts and response options in mountainous areas". To support implementation and practice-oriented research, national and international river commissions should also take on a more active role in promoting specific research on mountain regions in view of their importance in water resources.

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Table 1. Regions studied as a basis for the present article.

	Mountain massif(s) or region	Country(ies) in focus	River basin(s) in focus	Special issue contribution
ALC	Alps (Central)	Switzerland	–	–
ALE	Alps (East)	Austria	–	Koboltschnig and Schöner, 2010
ANT	Tropical Andes	Bolivia, Ecuador and Peru	–	Buytaert et al., 2010
DRM	Drakensberg Mountains	South Africa	–	Lorentz et al., 2010
EM	East Mediterranean	Israel	Jordan River	Litaor et al., 2010
HIK	Karakoram Himalaya	Pakistan	Indus River	Archer et al., 2010
UCJ	Upper Changjiang River/Tibetan Plateau	China	Changjiang (Yangtze) River	Huang et al., 2010
TSH	Tien Shan	Kyrgyzstan	Syr Darya River	–
PNW	Pacific Northwest	United States	Columbia River	Hamlet et al., 2010
PYR	Pyrenees	Spain	Ebro River	López-Moreno et al., 2010

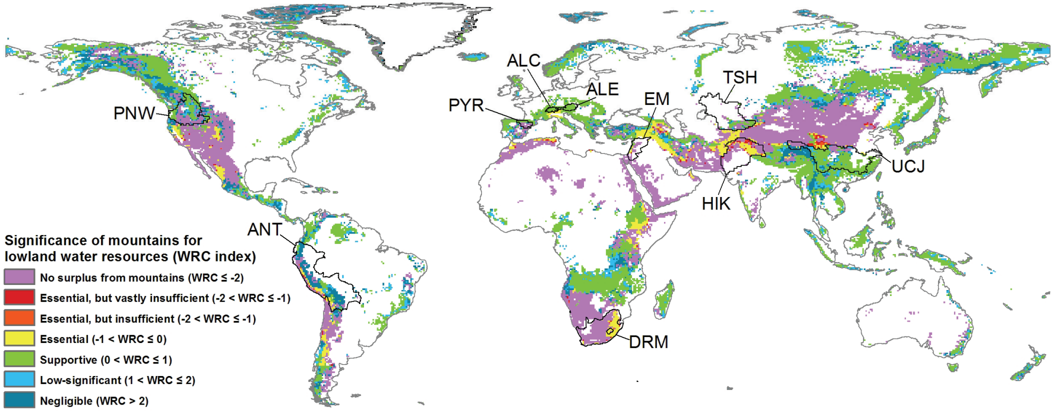

Fig. 1. Location of our case-study regions on a world map at a resolution of 0.5° × 0.5° showing the significance of mountain regions for lowland water resources (following Viviroli et al., 2007).

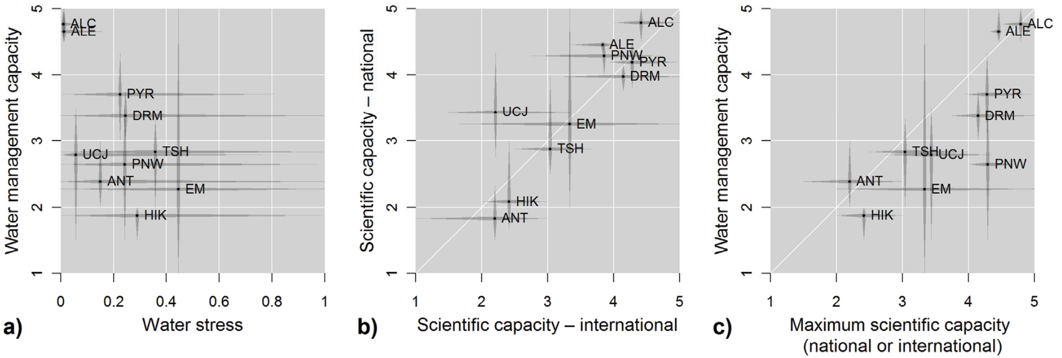

Fig. 2. Characterisation of the regions studied with regard to **(a)** water stress and water management capacity to adapt to climate change; **(b)** national and international scientific capacity regarding climate change and water resources issues; **(c)** water management capacity to adapt to climate change and maximum scientific capacity (regardless whether of national or international origin) regarding climate change and water resources issues. The grey bars indicate the range of values.

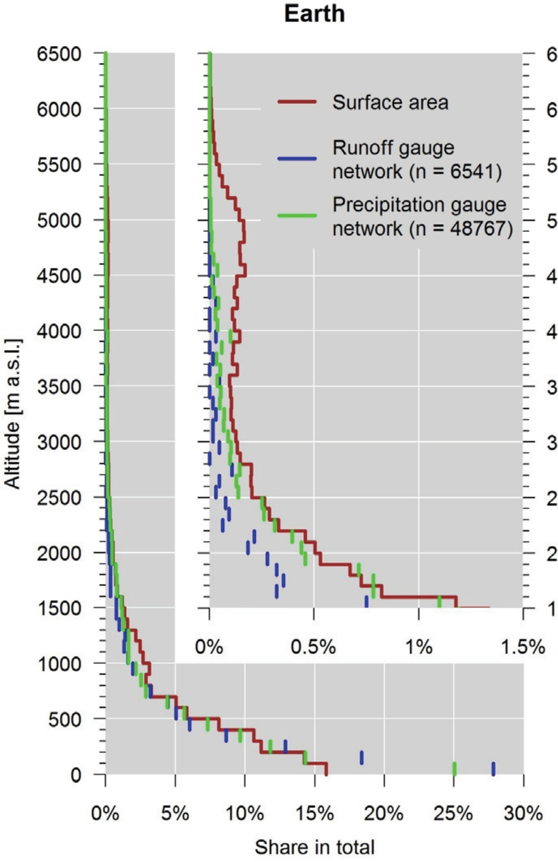

Fig. 3. Altitudinal distribution of global runoff stations represented in GRDC archive and global precipitation station network represented in GPCC archive compared to global hypsography of the land surface area (without Greenland and Antarctica).

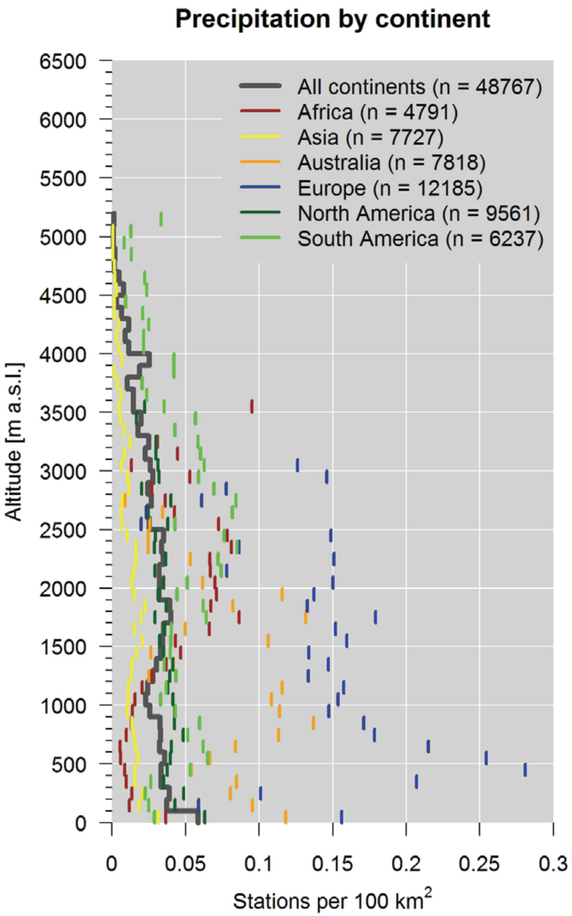

Fig. 4. Density of precipitation stations represented in GPCC archive per continent and altitudinal range.

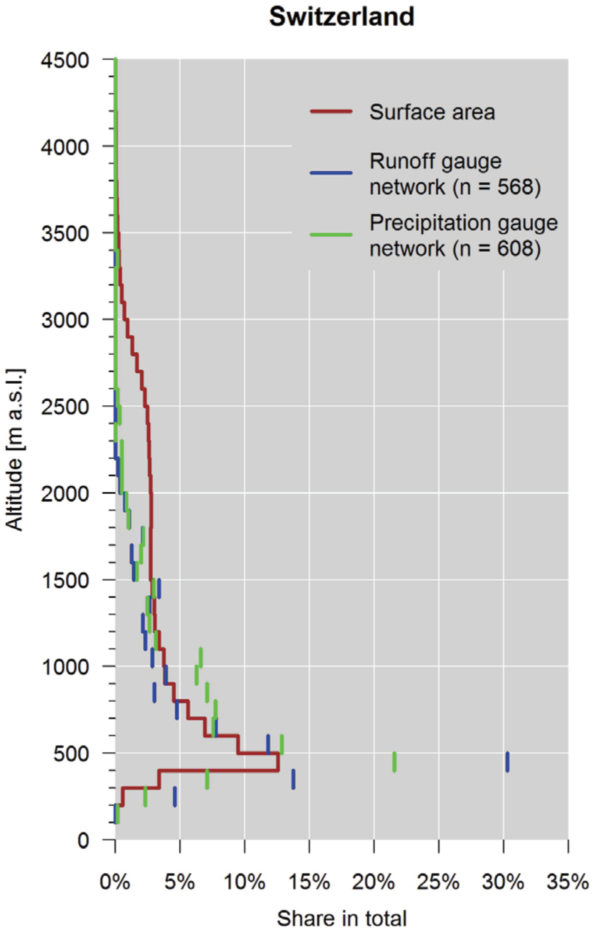

Fig. 5. Altitudinal distribution of runoff and precipitation gauge network in Switzerland compared to hypsography.