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Published in:
Nature Sustainability

DOI:
[10.1038/s41893-020-0559-9](https://doi.org/10.1038/s41893-020-0559-9)

Published: 01/11/2020

Document Version
Peer reviewed version

Please cite the original version:
Viviroli, D., Kummu, M., Meybeck, M., Kallio, M., & Wada, Y. (2020). Increasing dependence of lowland populations on mountain water resources. *Nature Sustainability*, 3(11), 917-928. <https://doi.org/10.1038/s41893-020-0559-9>

Increasing dependence of lowland populations on mountain water resources

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Keywords:

global water resources, climate change, global change, highland-lowland-systems,
food security, irrigated areas, water towers, mountain areas

*This is a post-peer-review, pre-copyedit version of an article published in Nature Sustainability.
The final authenticated version is available online at <http://dx.doi.org/10.1038/s41893-020-0559-9>.*

Mountain areas provide disproportionately high runoff in many parts of the world, but their importance for water resources and food production has not been clarified so far from the viewpoint of the lowland areas downstream. Here we quantify for the first time the extent to which lowland inhabitants potentially depend on runoff contributions from mountain areas (39% of land mass). We show that ~1.5 billion people (24% of world's lowland population) are projected to depend critically on runoff contributions from mountains by mid-21st century under a 'middle of the road' scenario, compared to ~0.2 B (7%) in the 1960s. This striking rise is mainly due to increased local water consumption in the lowlands, whereas changes in mountain and lowland runoff play a minor role only. We furthermore show that one third of global lowland area equipped for irrigation is currently located in regions that both depend heavily on runoff contributions from mountains and make unsustainable use of local blue water resources, a figure that is likely to rise to well over 50% in the coming decades. Our findings imply that mountain areas should receive particular attention in water resources management and underscore the protection they deserve in efforts towards sustainable development.

Water is a key resource for the 21st century: Mainly due to population growth and associated food production, global water consumption has increased almost four-fold over the past 100 years¹ and water demand is approaching the total renewable freshwater available today². The importance of water for environmental, economic and social aspects places it at the heart of the UN Sustainable Development Goals (SDGs)³. Mountain areas, in turn, play an important role in water resources in that they often deliver disproportionately high runoff to the subjacent lowlands that is crucial for irrigation, industry, drinking, domestic use, hydropower and ecosystems⁴⁻⁷. In this context of superior runoff contributions, "mountain area" and "mountains" are used here in a broad definition that also includes hills and elevated plateaux^{4,5} (Methods).

The contributions of mountain areas to water resources are very important but need to be understood much better yet. In particular, demographic, socio-economic and environmental changes affecting mountain water resources must be viewed in the larger picture of global development planning and policy making⁸. The large lead times required for implementing adaptation measures, such as reservoirs and water transfer systems, emphasise the urgency of a solid basis for long-term management of water resources originating in mountain areas⁹. Moreover, sharpening the picture of increasing pressure imposed on mountain areas through rapidly growing water demand both in mountains and lowlands is a key ingredient to sustainable mountain development¹⁰.

The importance of mountain areas in providing freshwater for a substantial portion of the world population has been recognised in its principle for a long time^{4,11}, and a global typology of mountain areas in water resources revealed that almost half of these areas world-wide provide supportive or even essential water resources for the areas downstream⁵. In studies focused on individual regions, Asia has received particular attention due to the vast population of well over a billion that live in the river basins originating in High Mountain Asia^{12,13}, and a recent global study estimated that 1.6 B people living directly downstream of mountain areas dominated by snow and ice could be negatively affected by climatic and socio-economic changes¹⁴.

Still lacking to date is a global overview that addresses and differentiates the potential dependence of lowland populations on mountain runoff, is meaningful at the regional scale, and assesses changes over time, including anticipated future changes^{15,16}. In an attempt to fill this gap, we here present the first comprehensive mapping and quantification of lowland inhabitants depending on mountain water resources, and a subsequent analysis of the importance of mountain runoff contributions for food production. We achieve a resolution of 5' (arc minutes, ~9 km at the Equator) and can thus also examine smaller highland-lowland systems that would be clustered in the currently still common resolution of 30'. This improved resolution is also important for water resources management at the level of individual regions, as well as setting priorities in future research. This is especially the case for regions where detailed models and studies are not available¹⁶, although the global picture we are painting here can of course not be fully accurate everywhere (Supplementary Information). In the temporal dimension, we cover the time from 1961 to the present and consider three possible developments for runoff and consumptive water use until 2050. We explore a “middle of the road” scenario (SSP2-RCP6.0 pathway), a “green road” scenario (sustainability, accelerated demographic transition; SSP1-RCP4.5), and a “rocky road” scenario (regional rivalry, high population growth in developing countries; SSP3-RCP6.0). While the extension into the future is crucial for a more comprehensive planning of water resources under climate and global change, the look back allows for a quantification of changes in the Anthropocene era¹⁷.

Dependence of lowland inhabitants on mountain water resources

Our assessment is based on the high-resolution and state-of-the-art Global Hydrological Model (GHM) PCR-GLOBWB 2.0 that simulates both runoff as well as consumptive water use and includes reservoir regulation^{18,19}. The model has already been applied to numerous projects that quantified global water resources and climate change impacts¹⁸. Based on relief roughness and elevation, the global land surface area (not including Greenland and Antarctica) is then divided into a mountain (39% of total) and a lowland (61%) part (Methods; Extended Data Fig. 1). The mountain part encompasses mountainous areas in the strict sense as well as plateaux and rugged hills of at least medium elevation. This is important because all of these areas can have an important role in providing runoff to the lowlands⁵. The extent of this importance largely depends on the combination of climatic conditions found in the mountain and lowland portions of a catchment^{5,20}. Lowlands encompass the remaining land surface area.

We identify the potential dependence of lowland areas on mountain water resources by computing a water balance for each lowland raster cell, with local runoff on the credit side, and local consumptive water use and environmental flow requirements on the debit side. The resulting surplus or deficit of each lowland raster cell is then compared with a similar balance that represents the entire related mountain area (Methods). ‘Related’ here means that this comparison always takes place in a river catchment, and thus follows the hydrological link between mountain and lowland areas (Fig. 1a), with the exception of small catchments that are analysed in groups and may share disconnected mountain and lowland areas (Methods). In lack of comprehensive and accurate data on water transfers within the lowlands, we assume that any mountain area surpluses alleviate the pressure on water resources in the entire lowland part of a basin, rather than only in the lowland areas with direct hydrographic connection to the mountains (Methods). We implement this assumption by distributing any surplus from the mountain area equally throughout the lowland part of the basin (Fig. 1b) and discuss alternatives to this choice further below as well as in the Supplementary Information. With the comparison of mountain and lowland balances, the dependence of each lowland raster cell on mountain runoff is determined, differentiating the potential contribution from mountains into essential, supportive, minor and negligible (Fig. 1c). Lowland areas depending on essential mountain surpluses are further analysed by assessing how large the equally distributed mountain surplus is as compared to the lowland deficit. This allows for differentiating lowland regions where mountain surpluses are insufficient or even vastly insufficient for balancing out water deficits, and sensitivity towards variations and changes in the contribution from mountains is large. On this basis, we can then quantify the number of lowland people potentially depending on mountain runoff. A key benefit of this analysis is that we take into account local climatic conditions and water consumption patterns in the lowlands and thus can assess what portion of lowland population depends critically on mountain surpluses and where it is located.

This issue was e.g. touched upon (but not elaborated in more detail) for the rivers that originate in High Mountain Asia²¹. A similarly differentiated picture can then be painted for the dependence of lowland food production on mountain runoff.

Changes in the global picture from past over present to future

Results for the entire globe (excluding Greenland and Antarctica) in a decadal timeline from 1961 to 2050 reveal notable changes (Fig. 2a): The lowland population depending on essential mountain runoff contributions grows from ~0.6 B (23% of total lowland population) in the 1960s to ~1.8 B (39%) in the 2000s and ~2.5 B (39%) in the 2040s under the SSP2-RCP6.0 scenario (SSP1-RCP4.5: ~2.3 B / 39%; SSP3-RCP6.0: ~2.7 B / 40%). In relative terms, the major part of this growth took place in 1961–2010 already (Extended Data Fig. 2a), while dependence on contributions from mountains becomes increasingly critical, with ~0.2 B (7%) of population benefiting from essential but insufficient contributions in the 1960s, ~0.9 B (19%) in the 2000s, and a projected ~1.5 B (24%) in the 2040s under SSP2-RCP6.0 (SSP1-RCP4.5: ~1.3 B / 22%; SSP3-RCP6.0: ~1.6 B / 24%). A complete lack of runoff surplus from mountain areas is found in various regions, caused by low runoff (e.g., parts of the Rocky Mountains and South Africa), high water consumption (e.g., parts of China and India), or both (e.g., parts of the Yellow River catchment) (Extended Data Fig. 3a, c, e). In the lowlands, such a lack is especially grave if a deficit prevails there (Extended Data Fig. 3b, d, f). In this case, the lowlands must be expected to resort to other options²², including dams, desalination, water recycling, use of fossil groundwater and interbasin transfers (such as in California and China)²³. Our analysis suggests that a number of catchments have already moved into this situation in the past decades or will do so until mid-21st century (e.g., on the Indian Peninsula²⁴) (Supplementary Fig. 1, Supplementary Tables 1, 2).

These figures, however, only paint part of the picture since the dependence of lowland inhabitants on mountain runoff strongly depends on the climate zone in focus, and global averages thus tend to underrate this dependence in individual regions. Especially in dryer climate zones, mountains provide important runoff that is distributed downstream via the river systems²⁰. In these cases, mountains are elevated humid islands within an arid region and thus match the original concept of “water towers”⁵. Therefore, we further analyse our results by hydrobelts, i.e. hydrological basins aggregated to regions with similar hydroclimatic characteristics²⁵ (Methods) (Figs. 2b–i, Extended Data Figs. 2b–i). The most notable changes are found in the North mid-latitude hydrobelt, where the lowland population depending on essential mountain contributions increases by almost a billion from ~0.4 B (26% of this hydrobelt’s lowland population; 16% of world total lowland population) to ~1.4 B (45%; 22%) in the same time (Fig. 2c). Further notable increases are found in the North dry, North subtropical, Boreal and Equator hydrobelts (Fig. 2d, e, b, f).

Hot spot regions

The global picture shows a number of ‘hot spot’ regions where the dependence of lowlands on mountain runoff was high already in the past, is today or is projected to become so in the future (Fig. 3a–c, Box 1). South and East Asia are of particular relevance, especially the Ganges-Brahmaputra-Meghna catchment that hosts the largest number of lowland people depending on essential mountain contributions, namely 94 M in 1961–1970, 390 M in 2001–2010 and 570 M in 2041–2050 under SSP2-RCP6.0 (Table 1). It is worth noting that this six-fold increase (+476 M) also represents the major part of population growth in this catchment from 1961 to 2050 (+639 M). Another vast growth of lowland population depending on mountain contributions is found in the Yangtze River catchment, with a 2.6 fold increase from 114 M (1961–1970) over 264 M (2001–2010) to 294 M (2041–2050, SSP2-RCP6.0). Substantial growth in lowland population (increase of more than 25 M from 1961–1970 to 2041–2050) in areas with essential mountain contributions is further found in the Nile and Niger River catchments, and it takes place almost exclusively in these areas in the Amur, Kaveri, Euphrates-Tigris, Godavari, Indus, Pearl, and Volga River basins. At the level of countries, India shows the biggest increase in lowland population depending on essential mountain contributions (+645 M from 1961–1970 to 2041–2050, SSP2-RCP6.0), followed by China (+249 M), Pakistan (+152 M) and Egypt (+86 M) (Supplementary Table 3). In addition, many catchments have a notable lowland population that benefits from supportive runoff from mountain areas (Supplementary Table 4).

Main drivers for change

An important question for water resources management is whether the developments found here are driven by changes in runoff or by changes in water consumption²⁶. Since we are interested in a comparison of lowland and mountain water balance, it is imperative to examine the relation of mountain runoff to lowland runoff over time. However, no fundamental changes in pattern are found in this relation (Extended Data Fig. 5), although it changes in favour of mountain runoff in some regions (e.g., Himalayas, parts of the Andes) and in favour of

lowland runoff in others (e.g., Central and Southern Rocky Mountains, South-West Africa, Atlas Mountains). Moderate changes are also visible in a breakdown to individual hydrobelts (Extended Data Fig. 6b–i), but do not prevail in the global summary (Extended Data Fig. 6a).

We achieve a deeper insight into the drivers by looking at the number of people projected to reside in a specific dependence category 2041–2050, and comparing that to results from a baseline scenario with runoff and total water consumption unchanged at 1961–1970 values. There are then four potentially relevant drivers: mountain runoff, mountain water consumption, lowland runoff, and lowland water consumption. Varying one of these at a time shows that the 2.5-fold increase in lowland water consumption between 1961 and 2050 (SSP2-RCP6.0) is by far the most important factor shifting people towards higher dependency on mountain runoff (Table 2). At global scale, per capita lowland water consumption does not exhibit major changes from 1961 to 2050 under all scenarios considered, although there are regions with clear increase (e.g. Boreal and North mid-latitude hydrobelts) and decrease (e.g., North dry and Equator hydrobelts). Overall, lowland population development is therefore the most important factor in determining the dependence of lowlands on mountain runoff (Extended Data Fig. 8), whereas changes in mountain water consumption, mountain runoff and lowland runoff are of minor importance.

Distribution of mountain surpluses

As noted further above, we distribute any mountain runoff surpluses equally across the lowlands. In absence of comprehensive data on water transfers, we thus refrain from making assumptions that may not be correct in the individual case. Rather, we assume that water from rivers is generally transferred effectively within a basin, and that water availability usually does not decrease much with distance from the main rivers²⁷. Where mountain surpluses are not distributed with help of engineering, they can still effect an indirect alleviation because competition for water resources from the river system is reduced in the entire lowland area of a catchment.

If we would follow a more targeted strategy and distribute mountain surpluses equally only among the lowland areas that show a deficit, the needs of 83% (~1.5 B) of the lowland inhabitants facing a deficit could be met in the 2000s, instead of only 52% (~0.9 B) with equal distribution among the entire lowland area. This number would rise as high as 93% (~1.7 B) if we would start balancing out lowland deficits where they are lowest and proceed to areas with progressively higher deficits until any mountain surplus is distributed. These strategies, however, imply highly targeted, widespread transfers that likely would require considerable discharge capacity. Furthermore, ~1.1 B lowland inhabitants not in deficit would lose supportive contributions from the mountain areas. The sensitivity of our results on these and further strategy choices is discussed in more detail in the Supplementary Information (“Strategies for distributing water balance surpluses”).

We argue that our assumptions are appropriate for the goal of identifying important patterns and hot-spot areas world-wide, as more sophistication at local and regional scale is currently beyond reach. In case detailed global data for transfers and diversions become available in the future, a refined analysis would be highly desirable. It would then also be possible to assess how mountain surpluses are consumed along their flow paths in the lowlands, and to identify regions where the surpluses become increasingly insufficient with increasing distance from the mountains, and thus lowland dependence becomes even stronger.

Potential impacts on food production

Roughly three quarters of global food production (caloric value) originate in lowlands today, and lowlands host about the same share of global area equipped for irrigation (AEI) (Supplementary Tables 5, 6). Mountain areas, despite their small share in food production, can contribute important runoff to lowland irrigated agriculture^{28,29} (Fig. 4): Of the AEI present in lowlands 2001–2010, 68% (or $1.54 \cdot 10^6$ km²) were located in regions that depend on essential runoff contributions from the mountains. Half of that ($0.77 \cdot 10^6$ km²) show low sustainability of local blue water use (liquid water in rivers, lakes, and aquifers³⁰) in addition, thus amplifying the dependence on contributions from mountain areas.

Under runoff and water consumption conditions projected for 2041–2050 (SSP2-RCP6.0), as much as 56% of lowland AEI ($1.28 \cdot 10^6$ km²) would be located in regions both depending on mountain runoff and making unsustainable use of local blue water resources. This expansion is mainly occurring in regions that did already depend on mountain water resources 2001–2010, while the area making unsustainable use of blue water resources also increases. The North dry hydrobelt, already under critical conditions to a large extent in the 1960s and 2000s, shows a particularly alarming development in this direction, with 86% of lowland AEI projected to be under unsustainable conditions and depending on mountain areas. An important rise in this combination of

critical conditions is also apparent in the North subtropical hydrobelt. Overall, these numbers imply that mountain areas could become even more important to support food production in the future, especially in regions like India, Egypt, and Southern Africa (Extended Data Fig. 9).

Implications for global water resources

Our new findings provide a guide to regions where more profound knowledge is necessary regarding the dependence of lowlands on mountain runoff, and the impacts of population dynamics and climatic changes should be studied in more detail. For facilitating water resources management, it will be imperative to also consider the seasonality of both lowland water consumption and mountain water provisions, especially with a view to changes in the important contribution of snowmelt and, in some regions, also ice melt^{31–35}. Bearing in mind the sensitivity of mountain environments, the amplification of warming with elevation and the non-linear reaction of the cryosphere to climate forcing^{36–39}, these changes in seasonality may also reveal a more distinct impact of climate change and qualify the dominant control of lowland water consumption found in this study, especially in wet-dry climates of the subtropics.

We show that lowland water resources have become increasingly dependent on mountain areas in the past decades and are likely to become even more so in the future: Water scarcity is projected to be more severe, and ongoing groundwater depletion may pose a serious water security risk in intense agricultural regions^{2,12}. This might cause higher vulnerability under an uncertain climate³⁹, as highlighted by our finding that well over half of lowland areas equipped for irrigation might depend both on mountain water surpluses and unsustainable lowland water resources by mid-21st century under a ‘middle of the road’ scenario. At the same time, population and land use pressure are expected to increase further^{39,40}, leading to considerable challenges to environmental sustainability⁴¹. In addition, large-scale human interventions like land use and land cover changes, construction of dams and reservoirs as well as withdrawals from surface water and groundwater negatively affect the downstream parts of river catchments and may lead to additional imbalances between mountain and lowland areas⁴². All of this underscores the special protection and attention mountain areas deserve in efforts towards sustainable development, and suggests that highland-lowland interactions should not be a one-way process in favour of the lowlands, but that compensation mechanisms in the reverse direction should be considered to support sustainable development both in mountain and lowland areas²⁸. In summary, our work emphasises that hydrosolidarity⁴³ between mountain and lowland populations sharing a common river basin is essential, with the goal of an ethically sound orchestration of land, water and ecosystem related activities.

Methods

Catchments. We perform our analyses individually for each river catchment with an area of 10,000 km² or more. Smaller catchments are aggregated to groups contributing to the same coastal segment⁴⁴, and each of these groups is analysed individually as well. All results are then composited for a global map. This scheme follows the framework developed in ref. ⁵ whereas the original catchment boundaries and the coastal segmentation were refined from 30' (arc minutes, ~56 km at the Equator) to 5' (~9 km) resolution using high-resolution hydrographic information^{45,46} and a detailed topographic atlas⁴⁷.

To establish a hydrological connection between large urban areas at the coast and major rivers nearby, the catchments of 48 rivers were extended to contain major delta areas⁴⁸. Depending on the prevailing conditions, the main river catchment is thus extended by areas with high population and high runoff (e.g., Ganges-Brahmaputra-Meghna, Mississippi and Niger River Deltas), high population and low runoff (e.g., Indus, Nile and Yellow River Deltas), low population and high runoff (e.g., Amazon River Delta), as well as low population and low runoff (e.g., Lena and Mackenzie River Deltas). River systems are analysed jointly if they all contribute to the same delta area and, in addition, delta morphology and population distribution make it difficult to attribute the flow of the individual rivers to individual population centres. This is the case for the Ganges, Brahmaputra and Meghna Rivers (Bengal Delta), the Rhine, Meuse and Scheldt Rivers (Rhine Delta) and the Pearl, West, North and East Rivers (Pearl River Delta).

Due to a lack of reliable and comprehensive data, actual water transfers from one basin to another (interbasin transfers, e.g. from Yangtze River in northern direction) are not considered. For similar reasons, the hydrological link to irrigated areas situated outside of the supplying catchment is not established (relevant e.g. in the Nile River catchment). Both factors should be included in future studies with more regional focus, provided that suitable data become available.

We keep river network and thus catchment boundaries constant over time and do not consider the potential segmentation and shortening of rivers in dry regions that could result from reduced runoff (e.g., upper Niger River, White Nile River, Chari and Logone Rivers, Tarim River).

Mountain and lowland areas. We use “mountains” and “mountain areas” as extended geographic terms rather than in a strict geomorphologic sense. They encompass elevated terrain with potentially high relevance in water resources for the subjacent lowlands and refer to areas that are characterised with the symbolic term “water towers”^{4,5}. Mountain areas have their counterpart in lowland areas, which are the areas that depend on mountain water resources, and are affected by environmental and societal change in mountain areas^{49,50}. This follows earlier mountain-related studies on global change (e.g., refs. ^{51,52}) and water resources (e.g., refs. ^{5,53}), rooted in the physical and socioeconomic linkages between mountain and lowland areas. A related concept is that of “highland-lowland interactive systems” as examined in a United Nations University (UNU) programme initiated in 1978^{28,54}.

More specifically, our definition of mountain areas is based on a comprehensive typology of relief roughness and elevation. This typology, originally conceived at a resolution of 30' (see ref. ⁵⁵ for details), was enhanced for our resolution of 5' on the basis of a high-resolution (7.5", arc seconds, ~0.23 km at the Equator) Digital Terrain Model (DTM)⁵⁶ (Extended Data Fig. 1). Following an earlier typology of global mountain water resources⁵, we then chose a rather extensive definition that covers mountain areas of low, middle, high and very high elevation and also includes rugged hills as well as plateaux of medium, high and very high elevation. This is imperative because all of these relief classes can have an important role in providing runoff to lowland areas⁵. A further differentiation of results into relief types (as provided in ref. ⁵) could reveal additional patterns but is beyond the scope of the present study, and not necessary for the overview envisaged here.

In detail, our definition of mountain areas includes (1) all areas above 200 m a.s.l. if their relief roughness (RR) is at least 45%, (2) all areas above 500 m a.s.l. if RR is at least 21%, (3) all areas above 1,000 m a.s.l. if RR is at least 10%, and (4) all areas above 1,500 m a.s.l. regardless of RR. Criterion (3) is an addition to the original typology that was necessary to depict more realistically high-elevation lowland areas at our improved resolution, most of all in the Kalahari Desert and the Tarim Basin. It should be noted that this additional criterion might mix low-elevation regions (e.g., alluvial plains) with higher-elevation areas in some exorheic regions such as South Africa. The thresholds for RR were adapted from ref. ⁵ to reflect the relation between resolution of the detail DTM and that of the results in our study (7.5" to 5"), which slightly differs from the original relation (30" to

30'). To classify lakes in a way meaningful for our study, we assigned them the average RR of the raster cells along their outline and then classified them using above rules. This procedure was applied to all natural and dammed lakes with an area of at least 50 km², except for the Caspian Sea that was not considered part of the land mass. To achieve a more consistent delineation of mountain areas, single isolated mountain cells within lowland areas were eliminated by retaining the more frequent of the two classes in a moving window of 5×5 raster cells. As a result, 39% of global land surface area (132.7·10⁶ km², omitting Greenland and Antarctica, but including endorheic areas) is classified as mountains, the remaining area as lowlands. This re-creates the extent chosen in an earlier typology of mountains as “water towers”⁵ and roughly compares to the figure of 36% of land area mentioned by ref. ⁵⁷ as belonging to mountain and hilly terrain on the basis of relative relief and roughness.

In reality, there is of course no sharp boundary between mountain and lowland areas as we assume it here, and the criteria for narrowing down such a boundary zone should be regarded “elastic” to some extent⁵⁸. It has however been shown in an earlier study that the assumptions made here lead to a consistent analysis framework, and that the results are relevant in the context of water resources⁵. For the present study, we have also tested slightly altered definitions for mountain and lowland areas. These experiments did not lead to fundamentally changed patterns as compared to the ones presented here, so that our results can be considered robust.

The area-wide mapping we achieve in our analysis entails two limitations. First, it follows from the methods used for delineating catchments (see above) that mountains and lowlands are shared among small catchments with an area of less than 10,000 km² contributing to the same coastal segment. Realism of results may be limited in these areas, but none of the regions we discuss falls within this limitation. Second, in contrast to the upstream-downstream dichotomy that applies to all river catchments (see e.g. refs. ^{6,59,60}), there are catchments without notable mountain areas (e.g., Dnepr River) as well as catchments without notable lowland areas (e.g., the endorheic Salar de Uyuni). A hypothetical lowland area was added to catchments that had not a single raster cell classified as lowland. This hypothetical lowland area was defined as a circular area with a radius of two raster cells, located at the lowest point of the catchment in question. In a similar fashion, a hypothetical mountain area was added at the highest point of catchments that had not a single pixel classified as mountainous. In summary analyses, however, lowland catchments with a share of mountain area of less than 5% were not assessed because the importance of runoff contributions from mountain areas might appear exaggerated. Instead, these catchments were mapped as a separate category, and their full results are found in Supplementary Fig. 2. The lowland population of catchments with a share in mountain area smaller than 5% is constantly about 11% of total lowland population (269 M in 1961–1970, 689 M in 2041–2050 under SSP2). We also tested excluding catchments with a share of mountain area of less than 10%, or not applying such a threshold at all, finding that the overall results did not change more than a few percent in most catchments. Additional context to this point is provided through an assessment of the overall contribution of mountain areas to total catchment discharge (Extended Data Fig. 10a) and setting this contribution in relation to the share that mountains have in total catchment area (Extended Data Fig. 10b). In principle, these two analyses could also have provided a threshold for excluding catchments where mountains have only minor importance in lowland hydrology. However, such a threshold already contains hydrological information. To avoid circular argumentation, we retained the strictly physiographical threshold based on area and thus on relief roughness and elevation.

Dependence of lowland areas on mountain water resources. Our assessment is based on a water balance for each raster cell of the lowland part of a catchment (b_L) and a water balance sum for the mountain part of the same catchment (Σb_M) (Fig. 1a), both computed as water volumes:

$$b_L[i, j] = r_L[i, j] - u_L[i, j] - e_L[i, j] \quad (1a)$$

$$\Sigma b_M[j] = \Sigma r_M[j] - \Sigma u_M[j] - \Sigma e_M[j] \quad (1b)$$

For each lowland raster cell i of catchment j , $r_L[i, j]$ is runoff, $u_L[i, j]$ is consumptive water use, and $e_L[i, j]$ are environmental flow requirements. For the mountain area of catchment j , $\Sigma r_M[j]$ is the sum of runoff, $\Sigma u_M[j]$ is the sum of consumptive water use, and $\Sigma e_M[j]$ is the sum of environmental flow requirements. If the water balance sum for the mountain part of a catchment ($\Sigma b_M[j]$) shows a surplus, this surplus is distributed equally across the lowland area of the catchment, giving $b_{M \rightarrow L}[i, j]$ for each lowland raster cell i (Fig. 1b).

We then further develop and extend the methods of ref. ⁵ to compute a water resources index W for each lowland raster cell i belonging to catchment j as

$$W[i, j] = \begin{cases} b_L[i, j] / b_{M \rightarrow L}[i, j] & \text{if } \Sigma b_M[j] > 0 \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

In essence, W quantifies to what extent a raster cell in the lowlands potentially depends on mountain water surpluses. Its values are classified using the following ranges (Fig. 1c):

$W \leq -2$: Essential, but vastly insufficient (red). The lowland raster cell has a deficit at least two times larger in absolute value than the distributed mountain surplus.

$-2 < W < -1$: Essential, but insufficient (orange). The lowland raster cell has a deficit larger in absolute value than the distributed mountain surplus.

$-1 \leq W < 0$: Essential, and sufficient (yellow). The lowland raster cell has a deficit smaller in absolute value than the distributed mountain surplus.

$W = 0$: No surplus (grey). The entire lowland basin cannot benefit from mountain surpluses.

$0 < W \leq 1$: Supportive (green). The lowland raster cell has a surplus, but the distributed mountain surplus is even larger than that.

$1 < W < 2$: Minor (cyan). The lowland raster cell has a surplus larger than the distributed mountain surplus.

$W \geq 2$: Negligible (navy). The lowland raster cell has a surplus more than two times larger than the distributed mountain surplus.

Mentions of “essential” in the main text include categories “essential, and sufficient”, “essential, but insufficient” and “essential, but vastly insufficient” ($W < 0$), mentions of “essential but insufficient” encompass categories “essential, but insufficient” and “essential, but vastly insufficient” ($W \leq -1$).

The case where mountain areas provide no surplus overall ($\Sigma b_M[j] \leq 0$) can be due to low runoff from mountains (mean decadal runoff less than 30 mm per year (a), which is a threshold for permanent river flow⁶¹), high consumptive water use in mountain areas (more than 18.6 mm a⁻¹, which is the average value 2001–2010 for all land surface area excluding Greenland and Antarctica), or both. A distinction of these cases was not made in the main maps (Fig. 3) for reasons of clarity, but is provided separately in Extended Data Fig. 3. Note that following ref. ⁵, we chose a fixed threshold for high consumptive water use rather than one relative to local runoff, as such a fixed threshold is comparable across different regions world-wide. The extent of arheic mountain regions (mean decadal runoff less than 3 mm a⁻¹, which is as a threshold for any type of active flow⁶¹) is given for additional interpretation in Supplementary Fig. 3.

The major difference to earlier studies on “water towers”⁵ is that here we can explicitly analyse lowland areas, and thus map and quantify the dependence of its population on mountain runoff. This was not feasible with the earlier typology that addressed mountain areas and compared their runoff to bulk estimates for lowland water resources. Apart from that, two further important extensions were made: First, we have implemented realistic estimates for consumptive water use, based on a global model that is calibrated against observed water consumption (see Consumptive water use, below). As compared to figures estimated from an assumed minimum per capita need and population counts (as also used in ref. ⁵), this leads to lower estimates of consumptive water use in Africa, and higher estimates in Asia. In addition, it ensures that population growth does not automatically lead to increased total consumptive water use, and considers increases in water use efficiency² (Extended Data Fig. 8). Second, we here consider minimum environmental flow requirements, which leads to improved validity of our results for sustainable management of water resources.

In our assessment, we do not discern between lowland regions situated at different tributaries of the main river, and thus neglect possible hydrographic links to individual mountain areas within the same catchment. The only exception is the Benue River, which we separated from the Niger River and analysed as an individual catchment because the paths of the two rivers follow climatically very distinct routes^{5,62}. Here, a joint analysis would strongly confound the impact of the two rivers’ mountain areas on the lowlands. After separation, the two river

catchments are still of major size (Benue River: $339 \cdot 10^3 \text{ km}^2$; remainder of Niger River: $1,759 \cdot 10^3 \text{ km}^2$). Further refinements in this direction should be made in future studies at the level of individual catchments.

The values of W evolve over time, reflecting changes in runoff and consumptive water use in both lowland and mountain areas (see also Drivers of changes, below).

Water availability. To estimate water availability we used the state-of-the-art global hydrological and water resources model PCR-GLOBWB (version 2.0) that integrates human activities including water use and reservoir regulation into hydrology at a daily temporal resolution. The detailed description of the basic hydrologic model structure and associated calculation, and water use calculation, is found in ref. ⁶³. Insights into model performance relevant to our study are given in the Supplementary Information (“Evaluation of simulated water availability”, Supplementary Figs. 4, 5, 6). Below, we briefly present the main features of the model as concerns hydrologic calculations. The model’s representation of consumptive water use is introduced further below.

PCR-GLOBWB simulates for each raster cell and for each time step (daily) the water storage in two vertically stacked soil layers and an underlying groundwater layer, as well as the water exchange between the layers (infiltration, percolation, and capillary rise) and between the top layer and the atmosphere (rainfall, evapotranspiration and snow melt). The model also calculates canopy interception and snow storage. Snow accumulation and melt are temperature driven and modelled according to the snow module of the Hydrologiska Byråns Vattenbalansavdelning (HBV) model⁶⁴, using fixed values for the temperature of rain-snow transition (0°C) and the degree day factor ($2.5 \text{ mm } ^\circ\text{C}^{-1} \text{ day}^{-1}$). We argue that this is sufficient for the decadal time scale we are considering, including the projections. Ice accumulation and melt are modelled via the HBV degree day method (using the same factor as for snow), and we do not capture the rise and subsequent decline of glacier melt runoff over the decades in a changing climate (as e.g. examined by ref. ⁶⁵ while keeping constant other components of the water balance such as precipitation and evapotranspiration). Given that ice melt contributions to total runoff become small to negligible with increasing distance from the glaciers in most regions⁶⁶, this limitation of all current global models does not call into question our findings¹⁹. Sub-grid variability is taken into account by considering separately tall and short vegetation, paddy rice, nonpaddy crops, rainfed crop, open water (lakes, reservoirs, floodplains and wetlands), different soil types, and the area fraction of saturated soil calculated with the improved Arno scheme⁶⁷ as well as the frequency distribution of groundwater depth based on the surface elevations of the HYDRO1k Elevation Derivative Database⁶⁸. For snow, subgrid variability is represented via elevation dependent gradients of temperature (0.65°C per 100 m) over 10 elevation zones for each raster cell, again based on HYDRO1k¹⁹. The groundwater store is explicitly parameterized based on lithology and topography. Natural groundwater recharge fed by net precipitation, and additional recharge fluxes from irrigation, i.e. return flow, fed by irrigation water supply and from industrial and domestic sectors occurs as the net flux from the lowest soil layer to the groundwater layer, i.e. deep percolation minus capillary rise. Groundwater recharge interacts with groundwater storage by capillary rise and baseflow. Groundwater flow between cells is not considered here due to very high computational cost, however lateral connections of base flow that contributes to overall river discharge are accounted for.

Model outputs were processed with a robust smoothing algorithm (ref. ⁶⁹ using a smoothness parameter of 2.0, a maximum of 100 iterations and a tolerance of 10^{-3}) to remove artefacts. This was necessary because parts of the model input data are currently available at $30'$ resolution only, and the downscaling required¹⁹ occasionally leads to sharp boundaries in the outputs. Pycnophylactic (in this context meaning ‘volume preserving’) adjustment^{70,71} was applied after smoothing to ensure that the water availability sum remains unchanged in the mountain part and in the lowland part of each coastal segment⁴⁴. Isolated clusters of less than 25 raster cells were not adjusted separately but merged with their nearest neighbours to avoid overfitting.

Consumptive water use. Water demands were calculated with the same model as water availability, namely PCR-GLOBWB 2. For *irrigation*, this model implements a daily scheme that separately parameterizes paddy and non-paddy crops and dynamically links with hydrological fluxes considering the feedback between the application of irrigation water and the corresponding changes in surface and soil water balance, and evapotranspiration. The losses (i.e., return flow) during water transport and irrigation application are included in the simulation based on daily evaporative and percolation losses per unit crop area based on the surface and soil water balance. For the *industrial sector*, the model calculates country-specific water use intensities based on economic development and technological improvement. *Domestic* water demand is estimated by multiplying the number of persons in a raster cell with the country-specific per capita domestic water extraction (FAO AQUASTAT; see Data availability, below). Daily water demand variations are determined using daily air

temperature as a proxy¹⁸. The country per capita domestic water extraction in 2000 is multiplied with the estimated water use intensities to account for economic and technological development. Details are provided in ref. ¹⁸ for the past and ref. ⁶³ for projections. For a validation of simulated sectoral water use (where data are available) see ref. ⁷².

As regards regionalisation of consumptive water use for the SSP scenarios, it has to be mentioned that the original IPCC SSP scenarios do not include information on specific water demands. Therefore, the present study uses state-of-the-art water demand projections based on the Water Futures and Solutions (WFaS) initiative and reported in ref. ². For these projections, regional sectoral water demand scenarios were constructed that are consistent with the SSP scenario storylines.

After water is withdrawn for the irrigation, industrial and domestic sectors, return flow occurs to the river system. For the irrigation sector, return flow (losses) during water transport and irrigation application are simulated based on daily evaporative and percolation losses based on the surface and soil water balance. For the industrial and domestic sectors, return flow occurs on the same day (no retention due to wastewater treatment). For the domestic sector, the return flow occurs only from the areas where urban and rural population have access to water, whereas for the industry sector, the return flow occurs from all areas where water is withdrawn. For both sectors, the amount of return flow is determined by recycling ratios developed per country. The country-specific water recycling is calculated according to the method developed in ref. ¹⁸. For completeness, we note that consumptive water use is equal to water withdrawal minus return flow.

Model outputs were processed with the same robust smoothing algorithm and pycnophylactic adjustment that was used for water availability (see above).

Historical climate and climate scenarios. The historical forcing data set for 1961–2010 is based on time series of monthly precipitation, temperature, and reference evaporation from the CRU TS 3.2 data set⁷³, disaggregated to daily values with ERA40⁷⁴ (1961–1978) and ERA-Interim⁷⁵ (1979–2010) (for further details see ref. ¹⁹). Wind-induced undercatch (particularly relevant in mountain areas) and wetting losses in precipitation have been adjusted using gridded mean monthly catch ratios⁷⁶. For projections in the time after 2010, we used the RCP4.5 (with SSP1) and RCP6.0 (with SSP2 and SSP3) scenarios with an ensemble of 5 CMIP5 GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M; see ref. ⁷⁷) based on the ISIMIP project (<https://www.isimip.org>). All analyses were done individually for each GCM first, and median and range were then computed from these results.

Downscaling. While downscaling was not necessary for the historical period, future water availability under different scenarios had to be downscaled from 30' to 5' to achieve a consistent resolution of past, present and future data. We used a delta change method in which we first aggregated our high resolution runoff values (at 5') for 2001–2010 to the lower resolution of 30'. These 30' runoff data were then compared to 30' values for 2001–2010 derived from the five GCMs we use, and grid specific differences between these two datasets were computed. These differences were then used to bias-correct the future 30' GCM data. Finally, the bias-corrected future data were compared with the aggregated 2001–2010 runoff, and differences (deltas) were derived. To achieve future runoff at 5', these deltas were multiplied with present 5' runoff. Essentially the same procedure was used for downscaling projected consumptive water use, whereas bias correction was done at country scale (rather than at grid scale as in the case of runoff) because the data required for calculating irrigation water demand are available mostly at that scale only.

Environmental flow requirements. For estimating the amount of water necessary to sustain freshwater ecosystems, we computed environmental flow requirements (EFRs) based on the Variable Monthly Flow (VMF) method⁷⁸. In this method, each year is first divided into low-flow months (mean monthly flow $MMF \leq 0.4 \cdot \text{mean annual flow MAF}$), intermediate-flow months ($0.4 \cdot \text{MAF} < MMF \leq 0.8 \cdot \text{MAF}$) and high-flow months ($MMF > 0.8 \cdot \text{MAF}$) individually for each raster grid cell. EFRs are then computed separately for each of the three flow ranges as specific ratios of MMF (low-flow: 0.6; intermediate-flow: 0.45; high-flow: 0.3).

In our analysis, we use a spatially explicit, long term average ratio of EFRs to total annual flow for the entire study period 1961–2050 to avoid introducing additional variables. For this, we first computed EFRs from average monthly flow over 5 GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M) in the period of 1971–2050 (ref. ⁷⁷), specific for each raster cell of a 30'×30' grid. We then computed the annual ratio by summing up the monthly EFRs and dividing by total annual flow. We could not

include the 1961–1970 decade into these calculations, as data for some GCMs used start from 1971 only. The resulting annual ratios vary between 0.29 and 0.40 between raster cells and were multiplied with the actual total annual flow to obtain EFRs for each time period analysed.

Population scenarios. Population figures at 5' resolution were extracted from the HYDE 3.2 database⁷⁹, using the SSP1, SSP2 and SSP3 pathways for projected population from 2016 onwards. We focus on the “middle of the road” pathway SSP2 and add SSP1 and SSP3 in selected results to explore the spread caused by the different pathways (Extended Data Fig. 8).

Drivers of changes. Changes in the potential dependence of lowlands on mountain water resources (water resources index W , Equation 2) were analysed with a view to dominant driving factors. As a basis, we identified four potentially relevant drivers: changes in mountain runoff (Σr_M), changes in lowland runoff (r_L), changes in mountain consumptive water use (Σu_M), and changes in lowland consumptive water use (u_L). The impact of each driver was analysed separately, keeping all other inputs constant at the level of 1961–1970. Where runoff was changed for a driver analysis, the corresponding minimum environmental flow requirements (Σe_M , e_L) were re-computed accordingly.

We then assessed the impacts of these drivers on the dependence of lowland areas on mountain water resources 2041–2050 and computed how many lowland inhabitants are changing category. As a baseline for the comparison, we assumed that runoff and total consumptive water use remain constant at the level of 1961–1970. The baseline result is thus based on the spatial patterns 1961–1970 (Fig. 3a), and applies these patterns on projected population 2041–2050.

For visualising the detailed class changes (Extended Data Fig. 7), we used the “circlize” (Circular Visualization) package for R by Zuguang Gu⁸⁰. It follows from our methods that some changes can only be caused by certain drivers: First, a change from “supportive” (green), “minor” (cyan) or “negligible” (navy) to “essential, and sufficient” (yellow), “essential, but insufficient” (orange) or “essential, but vastly insufficient” (red) requires that the lowland water balance shifts from positive to negative. This can only be caused by changes in lowland runoff (r_L), lowland consumptive water use (u_L), or both. The same is true for a change in the reverse direction, where the lowland balance shifts from negative to positive. Second, any change to “no surplus” (grey) requires that the mountain water balance shifts from positive to negative, which is possible only through changes in mountain runoff (Σr_M), mountain consumptive water use (Σu_M), or both. This is again valid for changes in the reverse direction, where the mountain balance shifts from negative to positive.

It should be noted that we assess how many people move from one category to another, and do not consider here how big the change in W actually is. In principle, this means that small changes in W may still cause a shift in category if its value is close to a category boundary. We argue that this simplification is justifiable to obtain a clear presentation of the results, and is not a major limitation since we are mainly interested in a comparison between various scenarios.

It should further be noted that the category changes given for the individual drivers do not sum up to the overall category changes. This is because the population in a lowland raster cell may be affected by changes in more than one driver, and summing up the corresponding results is not always meaningful, e.g. when only the combined impact of more than one driver leads to a category change, or the combined impact leads to a more extensive change in category than only one driver, or when changes in opposite direction balance each other.

Hydrobelts. Hydrobelts represent an aggregation of natural hydrological basins based on similarities of their characteristic hydroclimatic features²⁵. These features include annual runoff and average annual air temperature. The aggregation results in eight hydroclimatically homogeneous and near-contiguous regions, and these are used in the present study to report the regional scale results. Hydrobelts were designed specifically for high resolution analyses, and as they follow the boundaries of hydrological basins, the contrast between individual regions is more marked as compared to hydroclimatic zones, both as concerns the present state as well as the evolution over time (see ref. ²⁵ for details). The original delineation at 30' resolution was refined to 5' with help of similarly refined coastal segments, and considers important delta areas (see Catchments, above).

Irrigated areas and food production. Spatially explicit data on areas equipped for irrigation at 5' resolution are from ref. ⁸¹. For period 1961–1970, the average of years 1960 and 1970 was used, for period 2001–2010 the year 2005 was used. For period 2041–2050, we assumed that irrigated area is similar to period 2001–2010. Spatially explicit estimates of food production for year 2000 (5') are from ref. ⁸². It should be noted that the food

production data refer to both rainfed and irrigated agriculture. Interpretation of these data (Extended Data Fig. 4c, d) should therefore be made in connection with the extent of irrigated areas (Extended Data Fig. 4a, b) and bearing in mind that 40–45% of the world's food originates from irrigated agriculture⁸³.

Sustainability of blue water use. We used the BIWSI (blue water sustainability index) index from ref. ⁸⁴ that expresses the fraction of consumptive blue water use met from non-sustainable water resources, i.e. from non-renewable groundwater abstraction and surface water over-abstraction. The index is dimensionless and ranges between 0 and 1, whereas we assumed a threshold of 0.2 to define non-sustainable use of blue water. Projected data for BIWSI are available for SSP2-RCP6.0 only, and in consequence it was not possible to examine alternative pathways.

Data availability. The following data sets were used in this study: hydrographic data from <http://hydrosheds.org>; elevation data from http://topotools.cr.usgs.gov/gmted_viewer and <https://doi.org/10.5066/F77P8WN0>; population data from <http://themasites.pbl.nl/tridion/en/themasites/hyde/download>; hydroclimatic regions from <http://doi.pangaea.de/10.1594/PANGAEA.806957>; water extraction data from <http://www.fao.org/nr/water/aquastat/main> and <http://geodata.grid.unep.ch>; lake delineations from <http://www.worldwildlife.org/pages/global-lakes-and-wetlands-database>; delta area delineations from <http://www.globaldeltarisk.net/data.html>; food production data from <http://www.earthstat.org>; irrigated areas from <http://mygeohub.org/publications/8>.

Data from the resulting typology (water resources index **W**) have been deposited in the Dryad Digital Repository⁸⁵ (<https://doi.org/10.5061/dryad.ns1rn8pnt>).

Code availability. The R code for Pycnophylactic adjustment has been deposited in the Zenodo Digital Repository⁷¹ (<https://doi.org/10.5281/zenodo.3563243>).

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Acknowledgements

Part of this study was funded by a SNSF Fellowship for advanced researchers to DV (grant no. PA00P2_131464). MK was funded by Academy of Finland funded projects SCART (grant no. 267463) and WASCO (grant no. 305471) and WATVUL (grant no. 317320), Emil Aaltonen Foundation funded project ‘eat-less-water’, European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No. 819202), and Academy of Finland SRC project ‘Winland’. Marko Kallio received funding from Maa- ja vesiteknikan tuki ry. We are very grateful to Edwin Sutanudjaja and Niko Wanders for kindly making PCR-GLOBWB 2 validation data available. For their roles in producing, coordinating, and making available the ISI-MIP model output, we acknowledge the modelling groups (see Methods) and the ISI-MIP coordination team.

Author Contributions

DV designed the research together with MKu, MM and YW; MM initiated some of the global scale river basin typologies used in this paper; DV performed the main research; MKu contributed analyses regarding environmental flow requirements, food production, irrigation and model efficiency and implemented delta change method; YW performed global hydrological model runs and contributed data on sustainability of blue

water use; MKa contributed pycnophylactic adjustment and supplementary sensitivity analyses; DV interpreted the results and wrote the paper with all co-authors providing comments.

Additional information

Extended data and supplementary information are available in the online version of the paper.

Competing Interests

We declare no competing interests.

Boxes

Box 1. Potential dependence of lowlands on mountain water resources in selected river basins.

In the **Indus River basin**, lowland population is projected to increase close to fivefold from 44 M in the 1960s to 210 M in the 2040s. Even though per-capita lowland water consumption decreases by almost two thirds, nearly all lowland inhabitants (92–95%) depend on mountain runoff throughout 1961–2050, a large majority (76–84%) even on insufficient or vastly insufficient mountain runoff. In addition, the immense irrigation system makes unsustainable use of local blue water resources and depends critically on mountain surpluses. Conflict potential over use of mountain runoff and vulnerability to changes are high.

The **Niger River basin** (without Benue River) shows a marked increase in essentially dependent lowland population, from only 3% in the 1960s to a projected 41% in the 2040s. Together with a sevenfold increase in lowland population 1961–2050 and low but stable lowland per-capita water consumption, this puts 71 M lowland inhabitants in dependency on mountain water resources by the 2040s.

In the lowlands of the **Nile River basin**, dependency on essential contributions from the two mountainous source areas is constantly high at 77–83% of population and concentrates on the lower parts and the delta area in Egypt, as well as on the South of Sudan. More than half of lowland population depends on vastly insufficient mountain surpluses (52%–65%). Projected lowland population growth 1961–2050 is more than fourfold and sets off a decrease in lowland per-capita water consumption of roughly 60%. Efforts to make more extensive use of water upstream in the Ethiopian Highlands (Blue Nile River) bear considerable conflict potential.

The **Yangtze River basin**'s mountain runoff is under high pressure of use, not only in the basin's lowlands where 264 M people (74% of lowland population) depend on it in the 2000s: Interbasin water transfers to the rivers further north compensate for absence of mountain surpluses in the **Yellow River basin** (projected to cease in the 2020s) and the **Hai He River basin** (missing from the 1960s onwards) that together had a lowland population of 141 M in the 2000s. The lowlands of all three river basins are characterised by high population density and extensive irrigated agriculture, and lowland per-capita water consumption is projected to rise strongly, especially in the Yellow and Hai He River basins where 1960s values are expected to roughly double by the 2040s.

In the **Colorado River basin** (US and Mexico), virtually the entire lowland population (>99%) depends on essential mountain water resources throughout 1961–2050, even though lowland per-capita water consumption halves over this time. This critical dependence extends to irrigated agriculture that made unsustainable use of local blue water already in the 1960s, and is exacerbated by interbasin transfers to south-western California including Greater Los Angeles. These conditions foster disputes over water use between Mexico and the US, and even within the US, and render water users vulnerable to drought events.

All projections refer to the SSP2–RCP6.0 scenario.

Tables

Table 1. Lowland population depending on essential mountain runoff contributions 1961–2050. Details are shown for all river catchments with a lowland population of 10 M or more in 2041–2050 that potentially depend on essential mountain runoff contributions. The numbers are given in Million people and encompass all areas depending on contributions that are essential and sufficient (yellow), essential but insufficient (orange) and essential but vastly insufficient (red). Results refer to catchments with a share of mountain area in total area of at least 5%, projections are based on the SSP2-RCP6.0 scenario. Results for further hot spot regions mentioned in the main text but not appearing here are reported in Supplementary Table 2.

#	River catchment	1961–1970	2001–2010	2041–2050 ^a	Major mountain range(s), hills and plateau(x) ^b	Share of mountain area in total area	Hydrobelf ^c
1	Ganges-Brahmaputra-Meghna	94.1	390.4	570.4 ^{+20.1} _{-26.3}	Himalayas, Mishmi Hills, Meghalaya Hills, Chin Hills	44%	NML
2	Chang Jiang (Yangtze)	113.5	263.8	294.0 ^{+16.1} _{-4.5}	Yunnan-Guizhou Plateau, Tibetan Plateau, Bayan Har Mountains, Shaluli Mountains	69%	NML
3	Indus	40.9	115.1	200.4 ^{+3.3} _{-0.9}	Himalayas, Hindu Kush, Sulaiman Range, Karakoram Range	69%	NML
4	Nile	32.7	85.6	139.1 ^{+1.7} _{-0.3}	Ethiopian Highlands ^d , Albertine Rift Mountains ^e , Nuba Mountains	33%	NDR
5	Niger ^f	0.7	16.7	70.9 ^{+7.7} _{-21.0}	Guinea Highlands, Fouta Djallon, Aïr massif	8%	NST
6	Godavari	5.6	42.5	68.2 ^{+4.2} _{-3.8}	Eastern Ghats, Western Ghats	22%	NST
7	Shatt Al-Arab (Tigris, Euphrates)	8.7	30.1	63.9 ^{+2.8} _{-5.0}	Zagros Mountains, Taurus Mountains	41%	NDR
8	Amur	19.8	45.0	48.9 ^{+0.7} _{-1.0}	Yablonovy Range, Greater Khingan Range, Lesser Khingan Range, Sikhote-Alin	60%	BOR
9	Volga	13.1	38.3	43.0 ^{+0.7} _{-1.7}	Ural Mountains	5%	NML
10	Zhujiang (Pearl)-Xi Jiang (West)-Bei Jiang (North)-Dong Jiang (East)	1.9	3.0	37.7 ^{+15.4} _{-2.0}	Yunnan-Guizhou Plateau, Nanling Mountains	73%	NST
11	Kaveri	4.0	22.4	34.9 ^{+0.1} _{-1.4}	Western Ghats, Eastern Ghats	52%	NST
12	Tapti ^g	1.2	11.1	25.5 ^{+0.3} _{-7.5}	Satpura Range, Western Ghats	28%	NST
13	Chao Phraya	5.2	18.4	22.2 ^{+0.9} _{-1.0}	Phi Pan Nam Range, Shan Plateau, Luang Prabang, Range, Phetchabun Mountains	50%	NST
14	Mekong	1.5	12.2	21.9 ^{+4.1} _{-0.7}	Annamese Cordillera, Luang Prabang Range, Shan Plateau, Tanggula Mountains	54%	NST
15	Ob	9.6	17.9	20.5 ^{+0.3} _{-0.7}	Altai Mountains, Kuznetsky Alatau Mountains, Ural Mountains	16%	BOR

[continued on next page]

16	Amu Darya	3.7	12.6	20.2 ^{+0.0} _{-0.0}	Pamirs, Hindu Kush	69%	NDR
17	Han [Korea]-Imjin	0.0	17.1	19.4 ^{+0.1} _{-0.1}	T'aebaek Mountains, Sobaek Mountains	73%	NML
18	Narmada	0.4	9.5	18.3 ^{+3.2} _{-2.3}	Satpura Range, Vindhya Range	33%	NST
19	Danube	4.5	11.2	18.0 ^{+1.1} _{-1.0}	Carpathian Mountains, European Alps, Dinaric Alps, Balkan Mountains	52%	NML
20	Hong (Red)	0.0	10.4	14.6 ^{+5.2} _{-0.5}	Yunnan-Guizhou Plateau, Ailao Mountains, Hoang Lien Son Range, Song Ma Range	87%	NST
21	St. Lawrence	0.0	0.0	13.0 ^{+1.1} _{-1.2}	Superior Upland, Adirondack Mountains, Laurentian Mountains, Appalachian Mountains	9%	NML
22	Syr Darya	4.9	10.0	12.9 ^{+0.1} _{-0.0}	Tien Shan, Alai Range	52%	NDR
23	Mahanadi	0.8	9.8	10.9 ^{+4.1} _{-4.8}	Eastern Ghats, Chota Nagpur Plateau, Satpura Range	31%	NST
<i>Remaining catchments</i>		<i>188.8</i>	<i>616.7</i>	<i>673.6^{+93.0}_{-87.8}</i>	-	<i>38%</i>	-
Total		555.6	1,809.8	2,462.4^{+239.4}_{-82.3}	-	39%	-

^a ensemble median for SSP2-RCP6.0, with differences to the ensemble minimum and maximum added in subscript and superscript, respectively

^b following ref. ⁸⁶ and area labels of major physiographic features provided by Natural Earth (version 3.0.0, available at <http://www.naturalearthdata.com>)

^c BOR: Boreal; NML: North mid-latitude; NDR: North dry; NST: North subtropical (ref. ²⁵)

^d for the Blue Nile River

^e for the White Nile River

^f without the Benue River, which was separated from the Niger River because the paths of the two rivers follow climatically very different routes (Methods).

^g For the Tapti River, one GCM ensemble member sees the entire lowland population receiving no more surplus from the mountains. This ensemble member was not used for computing the bounds shown here.

Table 2. Factors that drive changes in dependence on mountain water resources 2041–2050. As a baseline, it was assumed that runoff and total consumptive water use remain unchanged at 1961–1970 level. The impact of projected changes in mountain runoff, mountain water consumption, lowland runoff and lowland water consumption are then given below (all referring to SSP2-RCP6.0), noting the number of people (in millions) added or taken from each particular class of water resources index *W* by these changes (details in Extended Data Fig. 7).

	<i>Essential, but vastly insufficient (red)</i>	<i>Essential, but insufficient (orange)</i>	<i>Essential, and sufficient (yellow)</i>	<i>Supportive (green)</i>	<i>Minor (cyan)</i>	<i>Negligible (navy)</i>	<i>No surplus (gray)</i>
No changes in runoff and consumptive water use	345	210	968	1,857	874	1,181	133
Projected changes in mountain runoff	-51	+25	+27	-105	-40	+141	+4
Projected changes in mountain water consumption	-6	-21	-103	-138	-6	+111	+164
Projected changes in lowland runoff	+18	+18	+253	-130	-34	-126	0
Projected changes in lowland water consumption	+550	+378	+174	-474	-306	-323	0
All projected changes combined	+527	+395	+18	-618	-312	-328	+318

Figures

Figure 1. Analysis framework. For each raster cell in the lowlands, a water balance is computed, and a similar water balance sum is computed for the mountain area upstream in the same river basin (a). A mountain water surplus, if present, is then distributed equally among all lowland raster cells (b). Finally, the potential dependence of the lowlands on mountain water resources is assessed by comparing lowland water balance to distributed mountain surplus (c) (Methods).

Figure 2. Dependence on mountain water resources 1961–2050. Results are shown as decadal averages for lowland population in each category, summarised for all hydrobelts (a) as well as differentiated by hydrobelt (b–i); hydrobelts are limited by river basin boundaries²⁵ (Methods). Corresponding fractions of lowland population are shown in Extended Data Fig. 2.

Figure 3. Spatial patterns in dependence on mountain water resources 1961–2050. The maps show water resources index W (Methods) for 1961–1970 (a), 2001–2010 (b), and 2041–2050 (SSP2-RCP6.0) (c). Beige denotes areas where mountains as per the definition used here occupy less than 5% of total catchment area, and an assessment of their contributing potential to lowland water resources should only be done carefully (shown in Supplementary Fig. 2). At the bottom, magnifications are shown for selected hot spot regions in 2041–2050 (d, e). These reveal population density in addition. Area equipped for irrigation and food production are shown in Extended Data Fig. 4. The boundaries of catchments with an area of 100,000 km² and more are drawn for orientation, and small catchments with an area of less than 10,000 km² are hatched in white. In addition, the locations of the example river basins presented in Box 1 are shown: 1) Colorado (US/MEX), 2) Niger without Benue, 3) Nile, 4) Indus, 5) Yangtze.

Figure 4. Lowland area equipped for irrigation (AEI) under non-sustainable blue water use and depending on essential mountain runoff contributions in the 1960s, 2000s and 2040s. Results are shown for hydrobelts (BOR: Boreal, NML: North mid-latitude, NDR: North dry, NST: North subtropical, EQT: Equatorial, SST: South subtropical, SDR: South dry; SML: South mid-latitude; for a map of hydrobelts see Fig. 2) and for the entire land surface area (ALL; without Greenland and Antarctica). Projections are based on the SSP2-RCP6.0 scenario.