nature sustainability

ARTICLES

https://doi.org/10.1038/s41893-020-0559-9

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Increasing dependence of lowland populations on mountain water resources

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Mountain areas provide disproportionally high runoff in many parts of the world, but their importance for water resources and food production has not been clarified from the viewpoint of the lowland areas downstream. Here we quantify the extent to which lowland inhabitants potentially depend on runoff contributions from mountain areas (39% of the global land mass). We show that ~1.5 billion people (24% of the world's lowland population) are projected to depend critically on runoff contributions from mountains by the mid-twenty-first century under a 'middle of the road' scenario, compared with ~0.2 billion (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 only a minor role. We further show that one-third of the 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 twenty-first century. Mainly due to population growth and associated food production, global water consumption has increased almost fourfold over the past 100 years[1], and water demand is approaching the total renewable fresh water available today[2]. The importance of water for environmental, economic and social aspects places it at the heart of the United Nations Sustainable Development Goals[3]. Mountain areas, in turn, play an important role in water resources in that they often deliver disproportionally high runoff to the subjacent lowlands that is crucial for irrigation, industry, drinking, domestic use, hydropower and ecosystems[4–7]. In this context of superior runoff contributions, 'mountain areas' and 'mountains' are used here in a broad definition that also includes hills and elevated plateaus[4,5] (Methods).

The contributions of mountain areas to water resources are very important but need to be better understood. In particular, demographic, socio-economic and environmental changes affecting mountain water resources must be viewed in the larger picture of global development planning and policymaking[8]. The large lead times required for implementing adaptation measures, such as reservoirs and water transfer systems, emphasize the urgency of a solid basis for the long-term management of water resources originating in mountain areas[9]. Moreover, a clearer picture of the increasing pressure imposed on mountain areas through rapidly growing water demand in both mountains and lowlands is a key ingredient of sustainable mountain development[10].

The importance of mountain areas in providing fresh water for a substantial portion of the world population has been recognized in principle for a long time[4,11], and a global typology of mountain areas in water resources revealed that almost half of these areas worldwide provide supportive or even essential water resources for the areas downstream[5]. 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 billion people living directly downstream of mountain areas dominated by snow and ice could be negatively affected by climatic and socio-economic changes[14].

Still lacking 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 a comprehensive mapping and quantification of lowland inhabitants who depend 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 common resolution of 30′. This improved resolution is important for water resources management at the level of individual regions, as well as for setting priorities in future research. This is especially the case for regions where detailed models and studies are not available[16], 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 (Shared Socio-economic Pathway (SSP) 2–Representative Concentration Pathway (RCP) 6.0), a 'green road' scenario (sustainability and an accelerated demographic transition; SSP1–RCP4.5) and a 'rocky road' scenario (regional rivalry with high population growth in developing countries; SSP3–RCP6.0). While the extension into the future is crucial for more comprehensive planning of water resources under climate and global change, the look back allows for a quantification of changes in the Anthropocene era[17].

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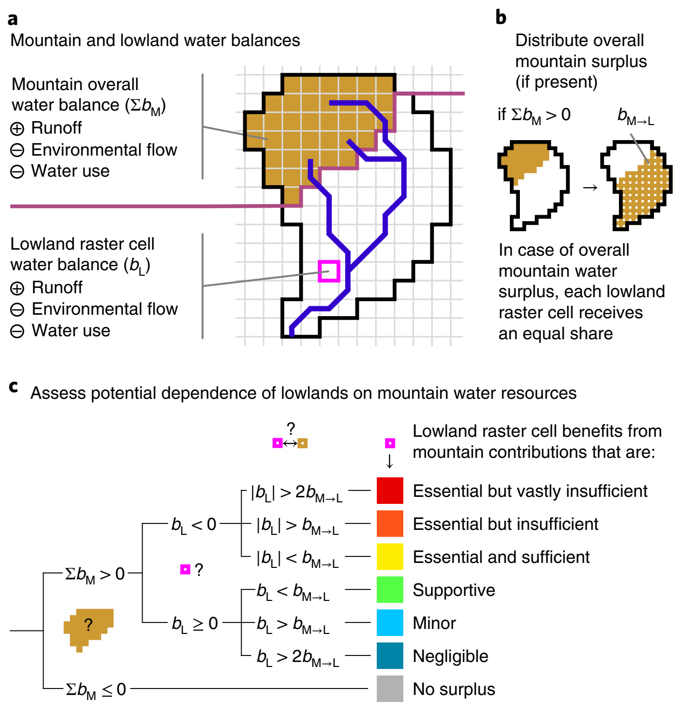

Fig. 1 | Analysis framework. a, For each raster cell in the lowlands (pink square), a water balance is computed, and a similar water balance sum is computed for the mountain area upstream in the same river basin (area in brown). **b**, A mountain water surplus, if present, is then distributed equally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

Dependence of lowland inhabitants on mountain water resources

Our assessment is based on the high-resolution and state-of-the-art global hydrological model PCR-GLOBWB version 2.0, which simulates both runoff and 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 impacts[18]. On the basis of relief roughness and elevation, the global land surface area (excluding Greenland and Antarctica) is then divided into mountain (39% of the total) and lowland (61%) parts (Methods and Extended Data Fig. 1). The mountain part encompasses mountainous areas in the strict sense as well as plateaus and rugged hills of at least medium elevation. This is relevant because all of these areas can have an important role in providing runoff to the lowlands[5]. 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 (EFRs) 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), except for small catchments that are analysed in groups and may share disconnected mountain and lowland areas (Methods). Because we lack 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 connections 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 we discuss alternatives to this choice 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 contributions (Fig. 1c). Lowland areas depending on essential mountain surpluses are further analysed by assessing how large the equally distributed mountain surplus is compared with the lowland deficit. This allows for differentiating lowland regions where mountain surpluses are insufficient or even vastly insufficient for balancing out water deficits, and where 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 the lowland population depends critically on mountain surpluses and where it is located. This issue has been touched on (but not elaborated on in more detail) for the rivers that originate in high-mountain Asia[21]. A similarly differentiated picture can then be painted for the dependence of lowland food production on mountain runoff.

Changes in the global picture from the past to the present to the future

The 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 billion (23% of the total lowland population) in the 1960s to ~1.8 billion (39%) in the 2000s and ~2.5 billion (39%) in the 2040s under the SSP2–RCP6.0 scenario (SSP1–RCP4.5, ~2.3 billion (39%); SSP3–RCP6.0, ~2.7 billion (40%)). In relative terms, the major part of this growth already took place in 1961–2010 (Extended Data Fig. 2a), while the dependence on contributions from mountains becomes increasingly critical, with ~0.2 billion (7%) benefitting from essential but insufficient contributions in the 1960s, ~0.9 billion (19%) in the 2000s and a projected ~1.5 billion (24%) in the 2040s under SSP2–RCP6.0 (SSP1–RCP4.5, ~1.3 billion (22%); SSP3–RCP6.0, ~1.6 billion (24%)). A complete lack of runoff surplus from mountain areas is found in various regions, caused by low runoff (for example, parts of the Rocky Mountains and South Africa), high water consumption (for example, parts of China and India) or both (for example, 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 options[22], 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 or will do so by the mid-twenty-first century (for example, on the Indian Peninsula[24]) (Supplementary Fig. 1 and Supplementary Tables 1 and 2).

These figures, however, paint only 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 systems[20]. In these cases, mountains are elevated humid islands within an arid region and

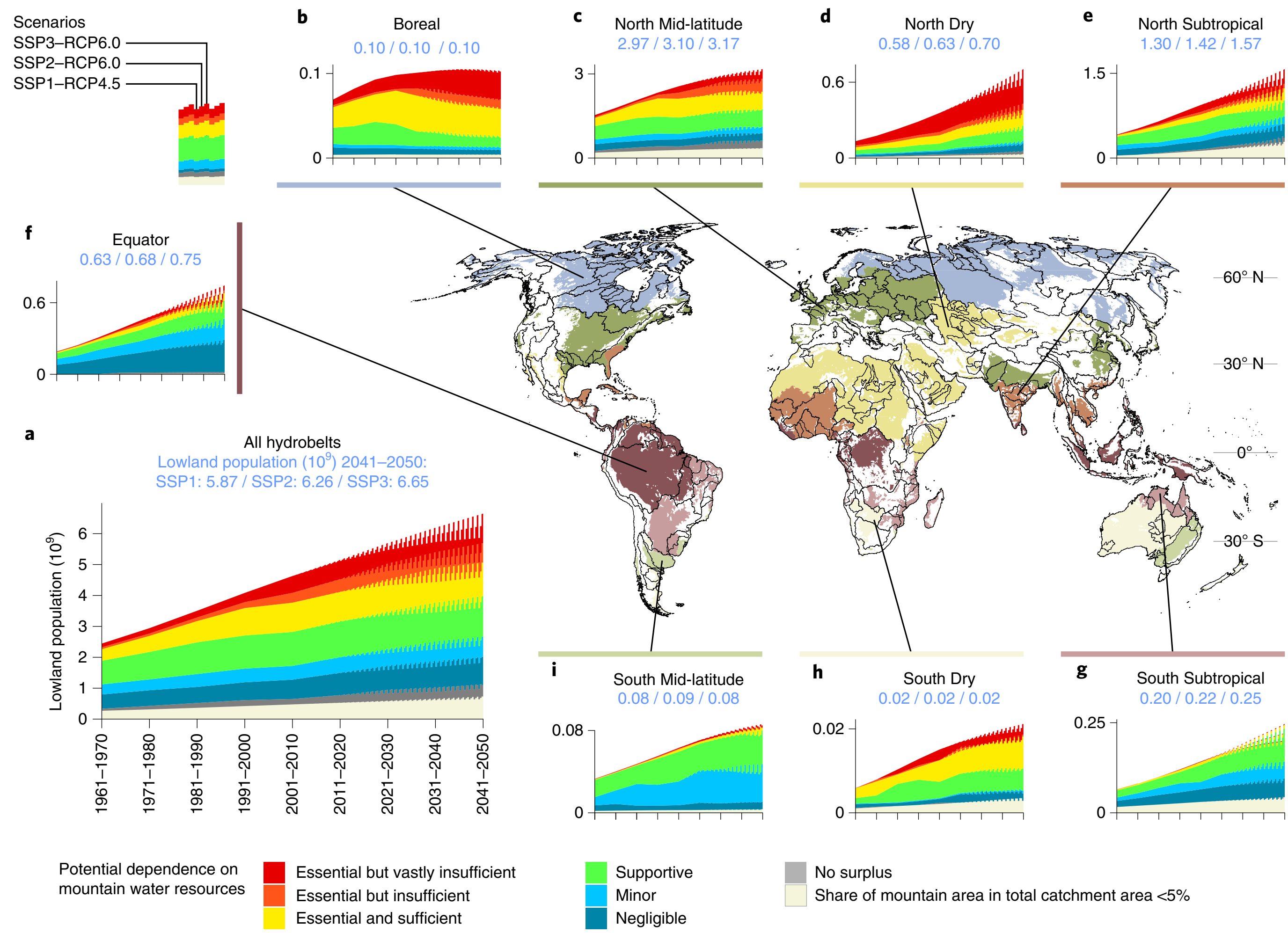

Fig. 2 | Dependence on mountain water resources from 1961 to 2050. a–i, Results are shown as decadal averages for the lowland population in each category, summarized for all hydrobelts (**a**) as well as differentiated by hydrobelt (**b–i**). The hydrobelts are limited by river basin boundaries[25] (Methods). The corresponding fractions of the lowland population are shown in Extended Data Fig. 2.

thus match the original concept of "water towers"[5]. We therefore further analyse our results by hydrobelts—that is, hydrological basins aggregated to regions with similar hydroclimatic characteristics[25] (Methods, Fig. 2b–i and Extended Data Fig. 2b–i). The most notable changes are found in the North Mid-latitude hydrobelt, where the lowland population that depends on essential mountain contributions increases by almost a billion from ~0.4 billion (26% of this hydrobelt's lowland population and 16% of the world total lowland population) to ~1.4 billion (45% and 22%) in the same time (Fig. 2c). Further notable increases are found in the Boreal, North Dry, North Subtropical and Equator hydrobelts (Fig. 2b,d,e,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 high today or is projected to become so in the future (Fig. 3a–c and Box 1). South and East Asia are of particular relevance, especially the Ganges–Brahmaputra–Meghna catchment, which hosts the largest number of lowland people who depend on essential mountain contributions, namely 94 million in 1961–1970, 390 million in 2001–2010 and 570 million in 2041–2050 under SSP2–RCP6.0 (Table 1). It is worth noting that this sixfold increase (+476 million) also represents the major part of population growth in this catchment from 1961 to 2050 (+639 million). Another vast growth of lowland population that depends on mountain contributions is found in the Yangtze River catchment, with a 2.6-fold increase from 114 million (1961–1970) to over 264 million (2001–2010) to 294 million (2041–2050, SSP2–RCP6.0). Substantial growth in the lowland population (an increase of more than 25 million 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 million from 1961–1970 to 2041–2050, SSP2–RCP6.0), followed by China (+249 million), Pakistan (+152 million) and Egypt (+86 million) (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 consumption[26]. 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

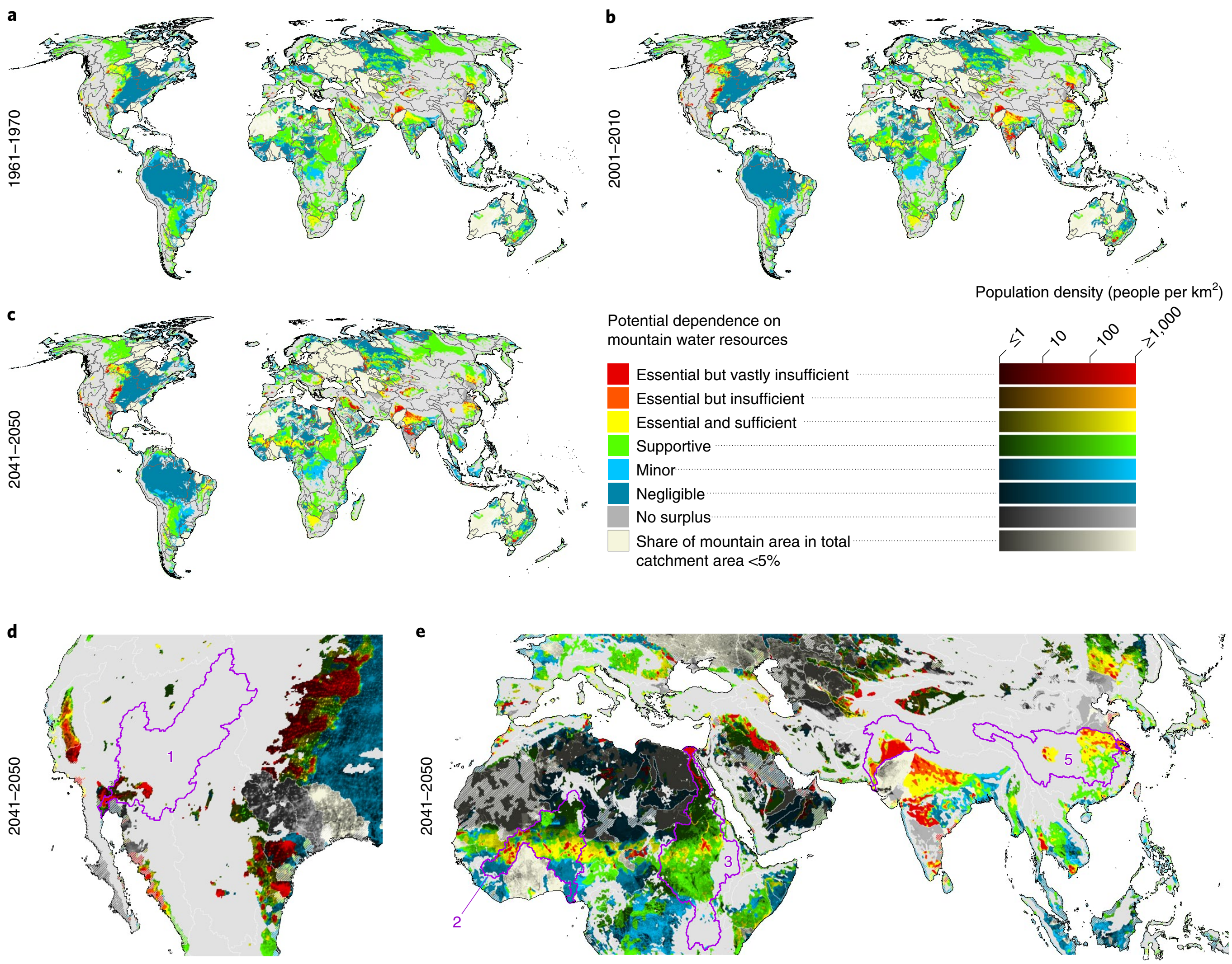

Fig. 3 | Spatial patterns in dependence on mountain water resources from 1961 to 2050. a–c, The maps show the water resources index (*W*) (Methods) for 1961–1970 (**a**), 2001–2010 (**b**) and 2041–2050 (SSP2–RCP6.0) (**c**). Beige denotes areas where mountains occupy less than 5% of the total catchment area, and an assessment of their contributing potential to lowland water resources should only be done carefully (shown in Supplementary Fig. 2). **d**,**e**, Magnifications are shown for selected hot-spot regions in 2041–2050. These panels show population densities as well. The areas equipped for irrigation and food production are shown in Extended Data Fig. 4. The boundaries of catchments with areas of 100,000 km^2 and more are outlined in grey (**a**–**c**) and white (**d**,**e**) for orientation, and small catchments with areas of less than 10,000 km^2 are hatched in white. The locations of the example river basins presented in Box 1 are outlined in purple: (1) Colorado (United States and Mexico), (2) Niger without Benue, (3) Nile, (4) Indus and (5) Yangtze.

relation (Extended Data Fig. 5), although it changes in favour of mountain runoff in some regions (for example, the Himalayas and parts of the Andes) and in favour of lowland runoff in others (for example, the Central and Southern Rocky Mountains, southwest Africa and the 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 in 2041–2050, and comparing that with results from a baseline scenario with runoff and total water consumption unchanged at the 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 the global scale, the per capita lowland water consumption does not exhibit major changes from 1961 to 2050 under all scenarios considered, although there are regions with clear increases (for example, the Boreal and North Mid-latitude hydrobelts) and decreases (for example, the 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 above, we distribute any mountain runoff surpluses equally across the lowlands. In the absence of comprehensive data on water transfers, we thus refrain from making assumptions that may not be correct in the individual cases. We instead assume that water from rivers is generally transferred effectively within a basin,

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

In the **Indus River basin**, the lowland population is projected to increase close to fivefold, from 44 million in the 1960s to 210 million in the 2040s. Even though the 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%) 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. The potential for conflict over the use of mountain runoff and vulnerability to changes are high.

The **Niger River basin** (without the Benue River) shows a marked increase in the essentially dependent lowland population, from only 3% in the 1960s to a projected 41% in the 2040s. Together with a sevenfold increase in the lowland population from 1961 to 2050 and a low but stable lowland per capita water consumption, this puts 71 million 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 the population and is concentrated in the lower parts and the delta area in Egypt, as well as in the south of Sudan. More than half of the lowland population depends on vastly insufficient mountain surpluses (52%–65%). Projected lowland population growth from 1961 to 2050 is more than fourfold and sets off a decrease in the 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 million people (74% of the lowland population) depended on it in the 2000s. Interbasin water transfers to the rivers further north compensate for the 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), which together had a lowland population of 141 million in the 2000s. The lowlands of all three river basins are characterized 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 the 1960s values are expected to roughly double by the 2040s.

In the **Colorado River basin** (United States and Mexico), virtually the entire lowland population (>99%) depends on essential mountain water resources throughout 1961–2050, even though the 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 southwestern California, including Greater Los Angeles. These conditions foster disputes over water use between Mexico and the United States (and even within the United States), and render water users vulnerable to drought events.

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

and that water availability usually does not decrease much with distance from the main rivers[27]. Where mountain surpluses are not distributed with the 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 followed a more targeted strategy and distributed mountain surpluses equally only among the lowland areas that show a deficit, the needs of 83% (~1.5 billion) of the lowland inhabitants facing a deficit could be met in the 2000s, instead of only 52% (~0.9 billion) with equal distribution among the entire lowland area. This number would rise as high as 93% (~1.7 billion) if we started balancing out lowland deficits where they are lowest and proceeded to areas with progressively higher deficits until any mountain surplus was distributed. These strategies, however, imply highly targeted, widespread transfers that would probably require considerable discharge capacity. Furthermore, ~1.1 billion lowland inhabitants not in deficit would lose supportive contributions from the mountain areas. The sensitivity of our results to 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 worldwide, as higher sophistication at local and regional scales is currently beyond reach. If detailed global data for transfers and diversions become available in the future, a refined analysis will 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 where lowland dependence becomes even stronger).

Potential impacts on food production

Roughly three-quarters of global food production (caloric value) originates in lowlands today, and lowlands host about the same share of the global area equipped for irrigation (AEI) (Supplementary Tables 5 and 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 in 2001–2010, 68% (or $1.54\times10^6\,km^2$) was located in regions that depend on essential runoff contributions from the mountains. Half of that ($0.77\times10^6\,km^2$) shows low sustainability of local blue water use (liquid water in rivers, lakes and aquifers[30]), 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 the lowland AEI ($1.28\times10^6\,km^2$) would be located in regions both depending on mountain runoff and making unsustainable use of local blue water resources. This expansion is occurring mainly in regions that already depended on mountain water resources in 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 the 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 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 nonlinear reaction of the cryosphere to climate forcing[36–39], these changes in seasonality

Table 1 | Lowland populations depending on essential mountain runoff contributions from 1961 to 2050

#	River catchment	1961–1970	2001–2010	2041–2050[a]	Major mountain ranges, hills and plateaus[b]	Share of mountain area in total area	Hydrobelt[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 and 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
16	Amu Darya	3.7	12.6	$20.2^{+0.0}_{-0.0}$	Pamirs, Hindu Kush	69%	NDR
17	Han (Korea)–Imjin	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	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	$13.0^{+1.1}_{-1.2}$	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
Remaining catchments		188.8	616.7	$673.6^{+93.0}_{-87.8}$	—	38%	—
Total		**555.6**	**1,809.8**	$\mathbf{2,462.4^{+239.4}_{-82.3}}$	**—**	**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, 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 General Circulation Model (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. Details are shown for all river catchments with a lowland population of 10 million or more in 2041–2050 that potentially depend on essential mountain runoff contributions. The numbers are given in millions of people and encompass all areas that depend on contributions that are essential and sufficient (yellow colour in Figs. 1–3), essential but insufficient (orange) and essential but vastly insufficient (red). The results refer to catchments with a share of mountain area of at least 5% of the total area; the projections are based on the SSP2–RCP6.0 scenario. The results for other hot-spot regions mentioned in the main text but not appearing here are reported in Supplementary Table 2.

Table 2 | Factors that drive changes in dependence on mountain water resources as projected for 2041–2050

	Essential but vastly insufficient	Essential but insufficient	Essential and sufficient	Supportive	Minor	Negligible	No surplus
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**

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

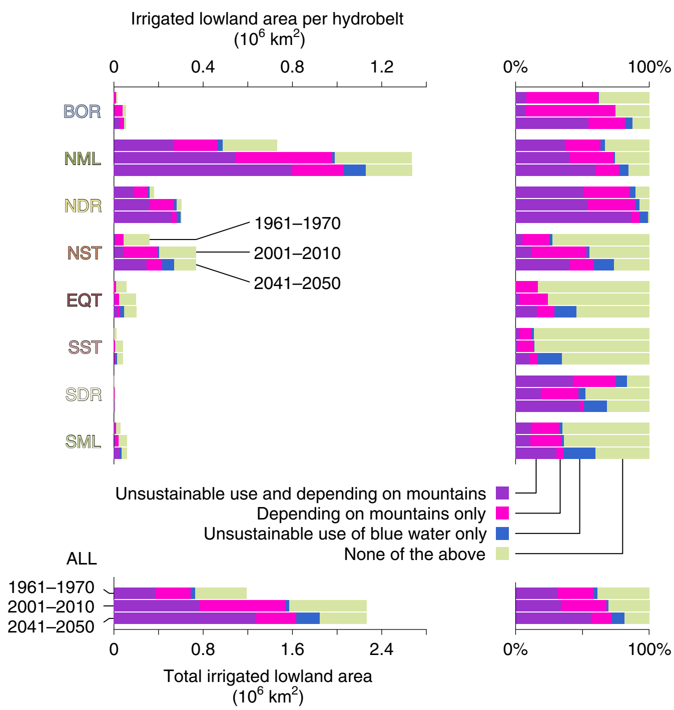

Fig. 4 | Lowland AEI under non-sustainable blue water use and depending on essential mountain runoff contributions in the 1960s, 2000s and 2040s. Results are shown for each hydrobelt (EQT, Equatorial; SST, South Subtropical; SDR, South Dry; SML, South Mid-latitude; for a map of hydrobelts, see Fig. 2) and for the entire land surface area (ALL, without Greenland and Antarctica). The projections are based on the SSP2–RCP6.0 scenario.

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 climate[39], as highlighted by our finding that well over half of lowland areas equipped for irrigation might depend on both mountain water surpluses and unsustainable lowland water resources by the mid-twenty-first 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 sustainability[41]. In addition, large-scale human interventions such as land-use and land-cover changes, the construction of dams and reservoirs, and withdrawals from surface water and groundwater negatively affect the downstream parts of river catchments and may lead to additional imbalances between mountain and lowland areas[42]. All of this underscores the special protection and attention that 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 in both mountain and lowland areas[28]. In summary, our work emphasizes that hydrosolidarity[43] 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 km^2 or more. Smaller catchments are aggregated into groups contributing to the same coastal segment[44], 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′ (~56 km at the Equator) to 5′ (~9 km) resolution using high-resolution hydrographic information[45,46] and a detailed topographic atlas[47].

To establish hydrological connections between large urban areas at the coast and major rivers nearby, the catchments of 48 rivers were extended to contain major delta areas[48]. Depending on the prevailing conditions, the main river catchment is thus extended by areas with high population and high runoff (for example, the Ganges–Brahmaputra–Meghna, Mississippi and Niger River Deltas), high population and low runoff (for example, the Indus, Nile and Yellow River Deltas), low population and high runoff (for example, the Amazon River Delta), and low population and low runoff (for example, the Lena and Mackenzie River Deltas). River systems are analysed jointly if they all contribute to the same delta area and if the 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, such as from the Yangtze River in the northern direction) are not considered. For similar reasons, the hydrological link to irrigated areas situated outside of the supplying catchment is not established (this is relevant in the Nile River catchment, for example). 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 (for example, the upper Niger River, White Nile River, Chari and Logone Rivers, and 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 characterized by 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 concept follows earlier mountain-related studies on global change (for example, refs. [51,52]) and water resources (for example, refs. [5,53]), rooted in the physical and socio-economic linkages between mountain and lowland areas. A related concept is that of highland–lowland interactive systems, as examined in a United Nations University programme initiated in 1978 (refs. [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[56] (Extended Data Fig. 1). Following an earlier typology of global mountain water resources[5], 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 plateaus of medium, high and very high elevation. This inclusiveness is imperative because all of these relief classes can have an important role in providing runoff to lowland areas[5]. 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 more than 200 m above sea level (a.s.l.) if their relief roughness is at least 45‰, (2) all areas more than 500 m a.s.l. if their relief roughness is at least 21‰, (3) all areas more than 1,000 m a.s.l. if their relief roughness is at least 10‰ and (4) all areas more than 1,500 m a.s.l. regardless of their relief roughness. Criterion 3 is an addition to the original typology that was necessary to more realistically depict 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 (for example, alluvial plains) with higher-elevation areas in some exorheic regions such as South Africa. The thresholds for relief roughness were adapted from ref. [5] to reflect the relation between the resolution of the detailed digital terrain model 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 relief roughness of the raster cells along their outlines and then classified them using the above rules. This procedure was applied to all natural and dammed lakes with an area of at least 50 km^2, except for the Caspian Sea, which 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 five by five raster cells. As a result, 39% of the global land surface area (132.7 × 10^6 km^2, 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 the 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 as elastic to some extent[58]. However, an earlier study has shown that the assumptions made here lead to a consistent analysis framework, and that the results are relevant in the context of water resources[5]. For the present study, we have also tested slightly altered definitions of mountain and lowland areas. These experiments did not lead to fundamentally changed patterns compared with the ones presented here, so 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 areas of less than 10,000 km^2 contributing to the same coastal segment. The realism of the 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, for example, refs. [6,59,60]), there are catchments without notable mountain areas (for example, the Dnepr River) as well as catchments without notable lowland areas (for example, 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 the 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 presented in Supplementary Fig. 2. The lowland population of catchments with a share in mountain area smaller than 5% is constantly about 11% of the total lowland population (269 million in 1961–1970 and 689 million 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 by more than a few percentage points in most catchments. Additional context to this point is provided through assessing the overall contribution of mountain areas to the total catchment discharge (Extended Data Fig. 10a) and setting this contribution in relation to the share that mountains have in the 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 $e_L[i,j]$ represents EFRs. For the mountain area of 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 EFRs. 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 $b_{M\to L}[i,j]$ for each lowland i (Fig. 1b).

We then further develop and extend the methods of ref. [5] to compute a value of water resources index W for each i belonging to j as

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

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):

$W \le -2$: Essential but vastly insufficient. 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. The lowland raster cell has a deficit larger in absolute value than the distributed mountain surplus.

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

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

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

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

$W \ge 2$: Negligible. 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 the categories essential and sufficient, essential but insufficient, and essential but vastly insufficient ($W < 0$); mentions of 'essential but insufficient' encompass the categories essential but insufficient and essential but vastly insufficient ($W \le -1$).

The case where mountain areas provide no surplus overall ($\Sigma b_M[j] \le 0$) can be due to low runoff from mountains (a mean decadal runoff less than 30 mm per year (a), which is a threshold for permanent river flow[61]), high consumptive water use in mountain areas (more than 18.6 mm a^{-1}, which is the average value in 2001–2010 for all land surface area excluding Greenland and Antarctica) or both. A distinction among 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 worldwide. The extent of arheic mountain regions (with a mean decadal runoff less than 3 mm a^{-1}, which is a threshold for any type of active flow[61]) is given for additional interpretation in Supplementary Fig. 3.

The major difference from earlier studies on "water towers"[5] is that here we can explicitly analyse lowland areas, and thus map and quantify the dependence of lowland populations on mountain runoff. This was not feasible with the earlier typology that addressed mountain areas and compared their runoff with bulk estimates for lowland water resources. Apart from that, two further important extensions were made. First, we have implemented realistic estimates of consumptive water use, on the basis of a global model that is calibrated against observed water consumption (see 'Consumptive water use'). Compared with 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. It also ensures that population growth does not automatically lead to increased total consumptive water use, and considers increases in water use efficiency[2] (Extended Data Fig. 8). Second, we here consider minimum EFRs, which leads to improved validity of our results for the sustainable management of water resources.

In our assessment, we do not discern between lowland regions situated at different tributaries of the main river, and we 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, 339×10^3 km^2; remainder of the Niger River, $1{,}759\times10^3$ 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').

Water availability. To estimate water availability, we used the state-of-the-art global hydrological and water resources model PCR-GLOBWB (version 2.0), which 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, as well as the 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' and Supplementary Figs. 4–6). Below, we briefly present the main features of the model as concerns the 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) model[64], using fixed values for the temperature of rain–snow transition (0 °C) and the degree day factor (2.5 mm °C^{-1} d^{-1}). We argue that this is sufficient for the decadal timescale 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 examined by ref. [65] while keeping constant other components of the water balance such as precipitation and evapotranspiration). Given that ice-melt contributions to the total runoff become small to negligible with increasing distance from the glaciers in most regions[66], this limitation of all current global models does not call our findings into question[19]. Subgrid variability is taken into account by separately considering tall and short vegetation, paddy rice, non-paddy crops, rain-fed crops, open water (lakes, reservoirs, floodplains and wetlands), different soil types and the area fraction of saturated soil calculated with the improved Arno scheme[67] as well as the frequency distribution of groundwater depth based on the surface elevations of the HYDRO1k Elevation Derivative Database[68]. For snow, the subgrid variability is represented via elevation-dependent gradients of temperature (0.65 °C per 100 m) over ten elevation zones for each raster cell, again based on HYDRO1k (ref. [19]). The groundwater store is explicitly parameterized on the basis of lithology and topography. Natural groundwater recharge fed by net precipitation, and additional recharge fluxes from irrigation (that is, return flow) fed by the irrigation water supply and from industrial and domestic sectors occur as the net flux from the lowest soil layer to the groundwater layer (that is, deep percolation minus capillary rise). Groundwater recharge interacts with groundwater storage by capillary rise and base flow. Groundwater flow between cells is not considered here due to the very high computational cost; however, the lateral connections of base flow that contributes to the overall river discharge are accounted for.

The 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 required[19] 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 segment[44]. 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 version 2.0. 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 water balance, soil water balance and evapotranspiration. The losses (that is, return flow) during water transport and irrigation application are included in the simulation using daily evaporative and percolation losses per unit crop area, which are based on the surface and soil water balance. For the industrial sector, the model calculates country-specific water use intensities on the basis of 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'). Daily water demand variations are determined using daily air temperature as a proxy[18]. The country per capita domestic water extraction in the year 2000 is multiplied with the estimated water use intensities to account for economic and technological development. The details are provided in ref. [18] for the past and ref. [63] for the projections. For a validation of simulated sectoral water use (where data are available), see ref. [72].

As regards the regionalization 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. The present study therefore uses state-of-the-art water demand projections based on the Water Futures and Solutions 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 using daily evaporative and percolation losses, which are based on the surface and soil water balance. For the industrial and domestic sectors, return flow occurs on the same day (with no retention due to wastewater treatment). For the domestic sector, the return flow occurs only from the areas where the urban and rural populations 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.

The model outputs were processed with the same robust smoothing algorithm and pycnophylactic adjustment that were used for water availability (see 'Water availability').

Historical climate and climate scenarios. The historical forcing dataset for 1961–2010 is based on time series of monthly precipitation, temperature and reference evaporation from the CRU TS 3.2 dataset[73], disaggregated to daily values with ERA40 (ref. [74]) (1961–1978) and ERA-Interim[75] (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 ratios[76]. 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 five CMIP5 GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM and NorESM1-M; see ref. [77]) based on the ISIMIP project (https://www.isimip.org). All analyses were done individually for each GCM first, and the 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 with 30′ values for 2001–2010 derived from the five GCMs we use, and the 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 by the present 5′ runoff. Essentially the same procedure was used for downscaling projected consumptive water use, whereas bias correction was done at the country scale (rather than at the grid scale, as in the case of runoff) because the data required for calculating irrigation water demand are available mostly at that scale only.

EFRs. For estimating the amount of water necessary to sustain freshwater ecosystems, we computed EFRs on the basis of the variable monthly flow method[78]. In this method, each year is first divided into low-flow months (the mean monthly flow (MMF) is less than or equal to 0.4 times the mean annual flow (MAF)), intermediate-flow months ($0.4\times MAF < MMF \leq 0.8\times MAF$) and high-flow months ($MMF > 0.8\times MAF$) individually for each raster grid cell. The EFRs are then computed separately for each of the three flow ranges as specific ratios of the 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 five GCMs (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM and NorESM1-M) in the period 1971–2050 (ref. [77]), specific for each raster cell of a $30'\times 30'$ grid. We then computed the annual ratio by summing up the monthly EFRs and dividing by the total annual flow. We could not include the 1961–1970 decade in these calculations, as the data for some GCMs used start from 1971. The resulting annual ratios vary between 0.29 and 0.40 between raster cells and were multiplied by the actual total annual flow to obtain the EFRs for each period analysed.

Population scenarios. Population figures at 5′ resolution were extracted from the HYDE 3.2 database[79], 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 (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 EFRs (Σe_M, e_L) were recomputed accordingly.

We then assessed the impacts of these drivers on the dependence of lowland areas on mountain water resources in 2041–2050 and computed how many lowland inhabitants are changing categories. 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 in 1961–1970 (Fig. 3a) and applies these patterns to the projected population in 2041–2050.

For visualizing the detailed class changes (Extended Data Fig. 7), we used the circlize (circular visualization) package for R 3.0.0 by Zuguang Gu[80]. It follows from our methods that some changes can be caused only by certain drivers. First, a change from supportive, minor or negligible to essential and sufficient, essential but insufficient, or essential but vastly insufficient requires that the lowland water balance shifts from positive to negative. This can be caused only 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 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 (for example, when only the combined impacts of more than one driver lead to a category change, or when the combined impacts lead to a more extensive change in category than only one driver, or when changes in opposite directions balance each other).

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

Irrigated areas and food production. Spatially explicit data on areas equipped for irrigation at 5′ resolution are from ref. [81]. For the period 1961–1970, the average of the years 1960 and 1970 was used; for the period 2001–2010, the year 2005 was used. For the period 2041–2050, we assumed that the irrigated area is similar to that of the period 2001–2010. The spatially explicit estimates of food production for the year 2000 (5′) are from ref. [82]. It should be noted that the food production data refer to both rain-fed and irrigated agriculture. The interpretation of these data (Extended Data Fig. 4c,d) should therefore be made in connection with the extent of the irrigated areas (Extended Data Fig. 4a,b) and bearing in mind that 40–45% of the world's food originates from irrigated agriculture[83].

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

Data availability

The following datasets were used in this study: hydrographic data from http://hydrosheds.org, elevation data from http://topotools.cr.usgs.gov/gmted_viewer/viewer.htm and https://doi.org/10.5066/F77P8WN0, population data from http://themasites.pbl.nl/tridion/en/themasites/hyde/download, hydroclimatic regions from https://doi.org/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, and irrigated areas from http://mygeohub.org/publications/8. The data from the resulting typology (W) have been deposited in the Dryad Digital Repository[85] (https://doi.org/10.5061/dryad.ns1rn8pnt).

Code availability

The R code for the pycnophylactic adjustment has been deposited in the Zenodo Digital Repository[71] (https://doi.org/10.5281/zenodo.3563243).

Received: 25 June 2019; Accepted: 22 May 2020;
Published online: 06 July 2020

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Acknowledgements

Part of this study was funded by a SNSF Fellowship for advanced researchers to D.V. (grant no. PA00P2_131464). M. Kummu was funded by the Academy of Finland funded projects SCART (grant no. 267463), WASCO (grant no. 305471) and WATVUL (grant no. 317320), the Emil Aaltonen Foundation funded project eat-less-water, the European Research Council under the European Union's Horizon 2020 research and innovation programme (grant agreement no. 819202), and the Academy of Finland SRC project Winland. M. Kallio received funding from Maa- ja vesitekniikan tuki ry. We thank E. Sutanudjaja and N. Wanders for making the PCR-GLOBWB version 2.0 validation data available. For their roles in producing, coordinating and making available the ISIMIP model output, we thank the modelling groups (see Methods) and the ISIMIP coordination team.

Author contributions

D.V. designed the research together with M. Kummu, M.M. and Y.W. M.M. initiated some of the global-scale river basin typologies used in this paper. D.V. performed the main research. M. Kummu contributed analyses regarding EFRs, food production, irrigation and model efficiency and implemented the delta change method. Y.W. performed the global hydrological model runs and contributed data on the sustainability of blue water use. M. Kallio contributed the pycnophylactic adjustment and supplementary sensitivity analyses. D.V. interpreted the results and wrote the paper, with all coauthors providing comments.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41893-020-0559-9.

Supplementary information is available for this paper at https://doi.org/10.1038/s41893-020-0559-9.

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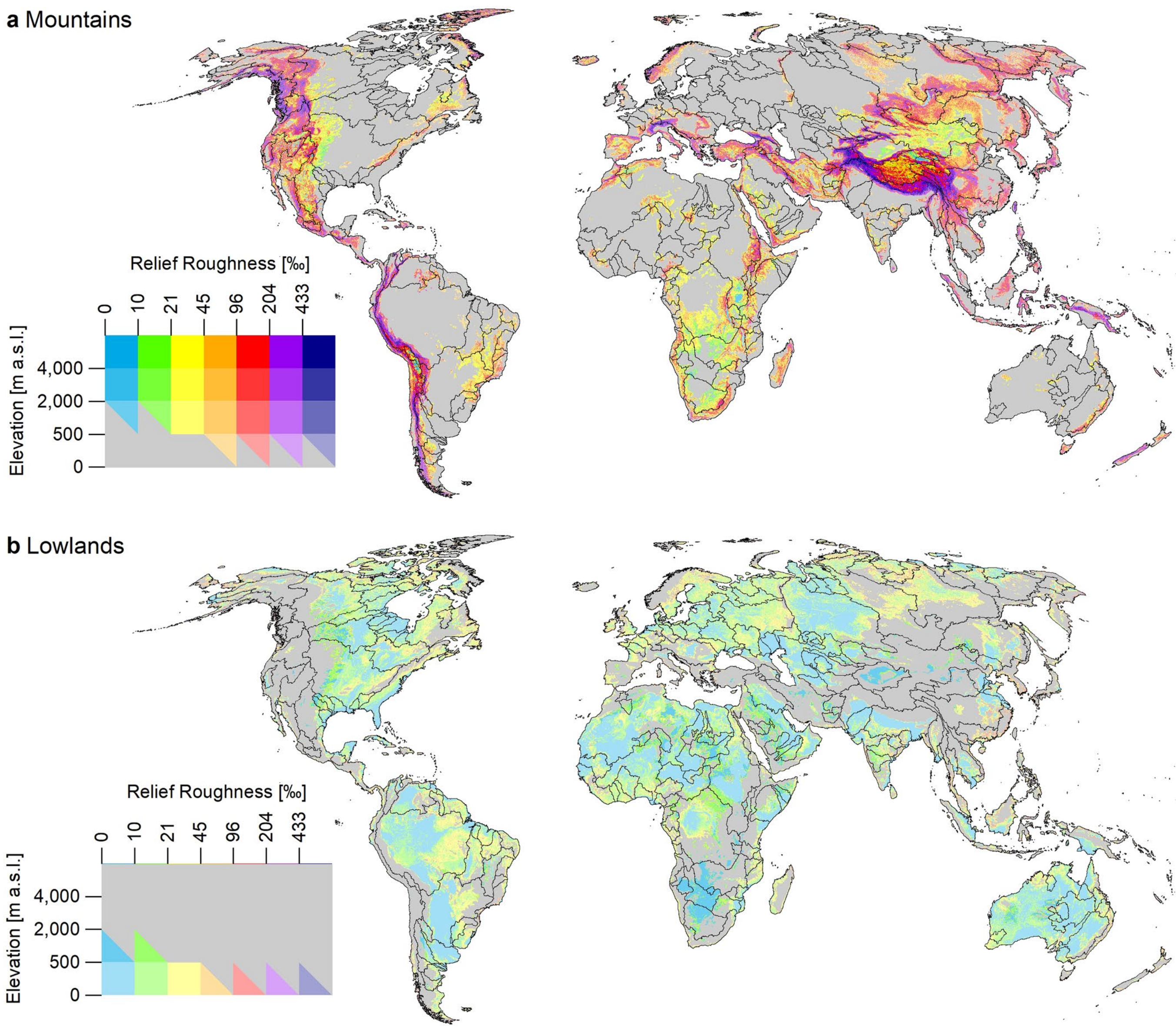
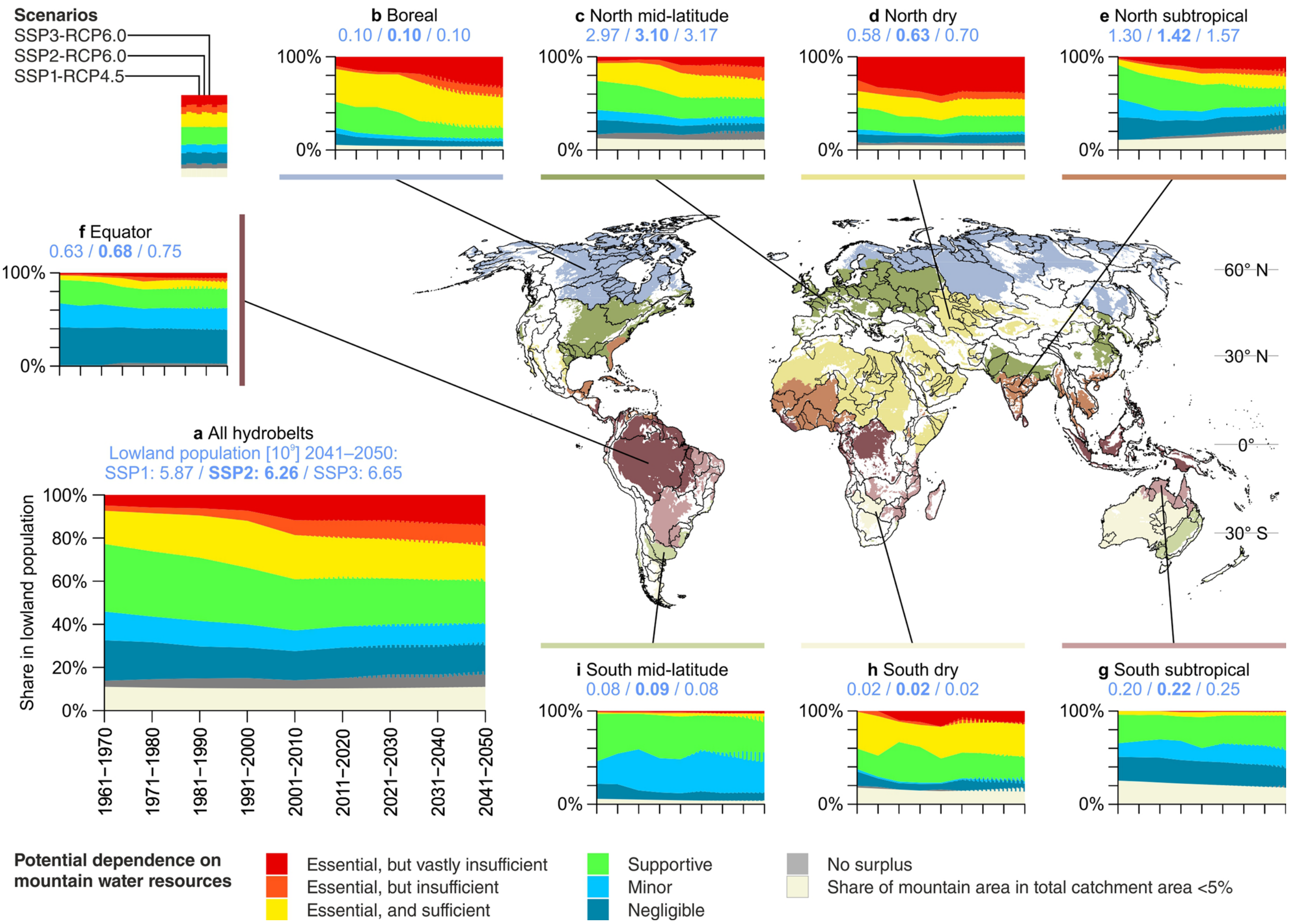
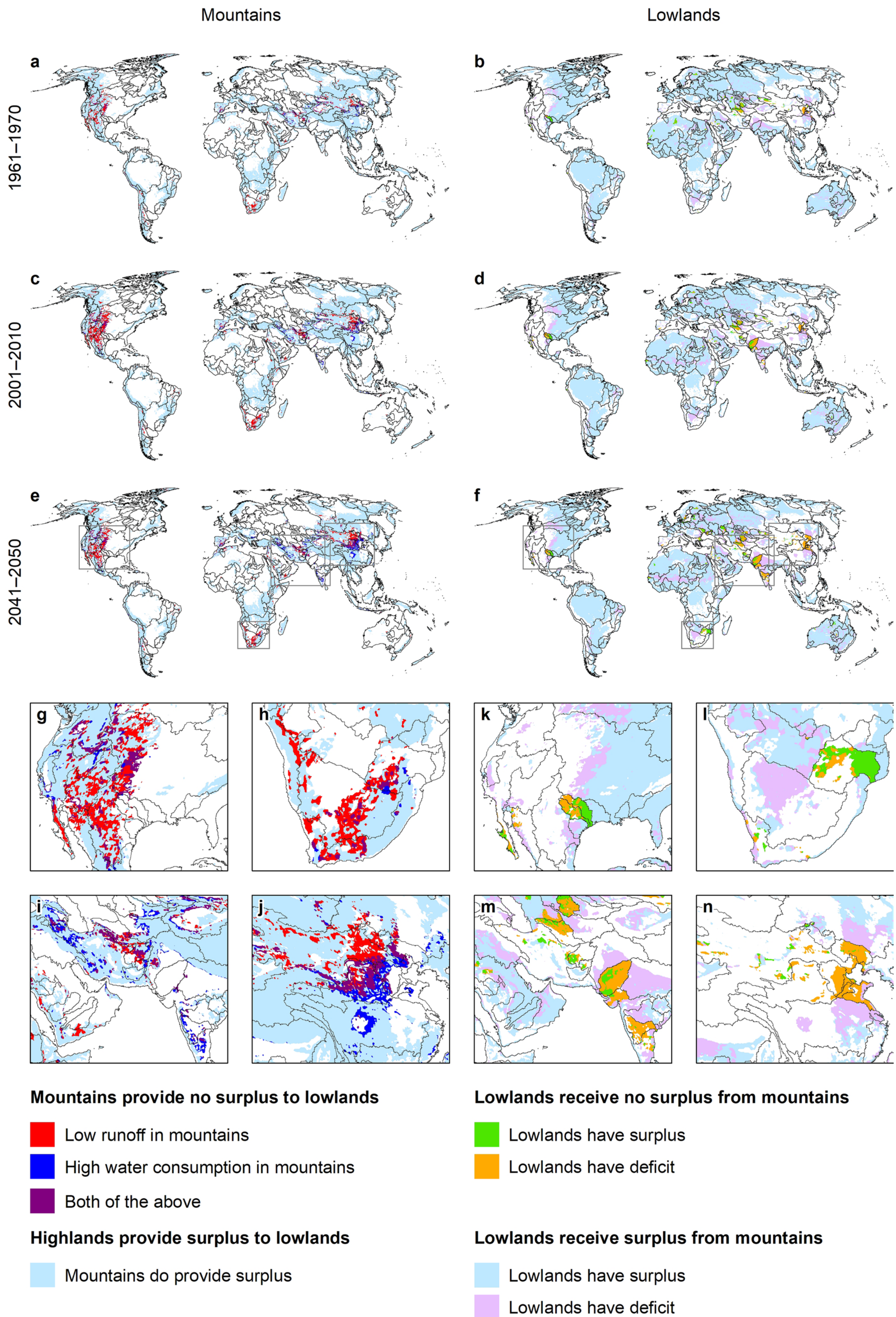


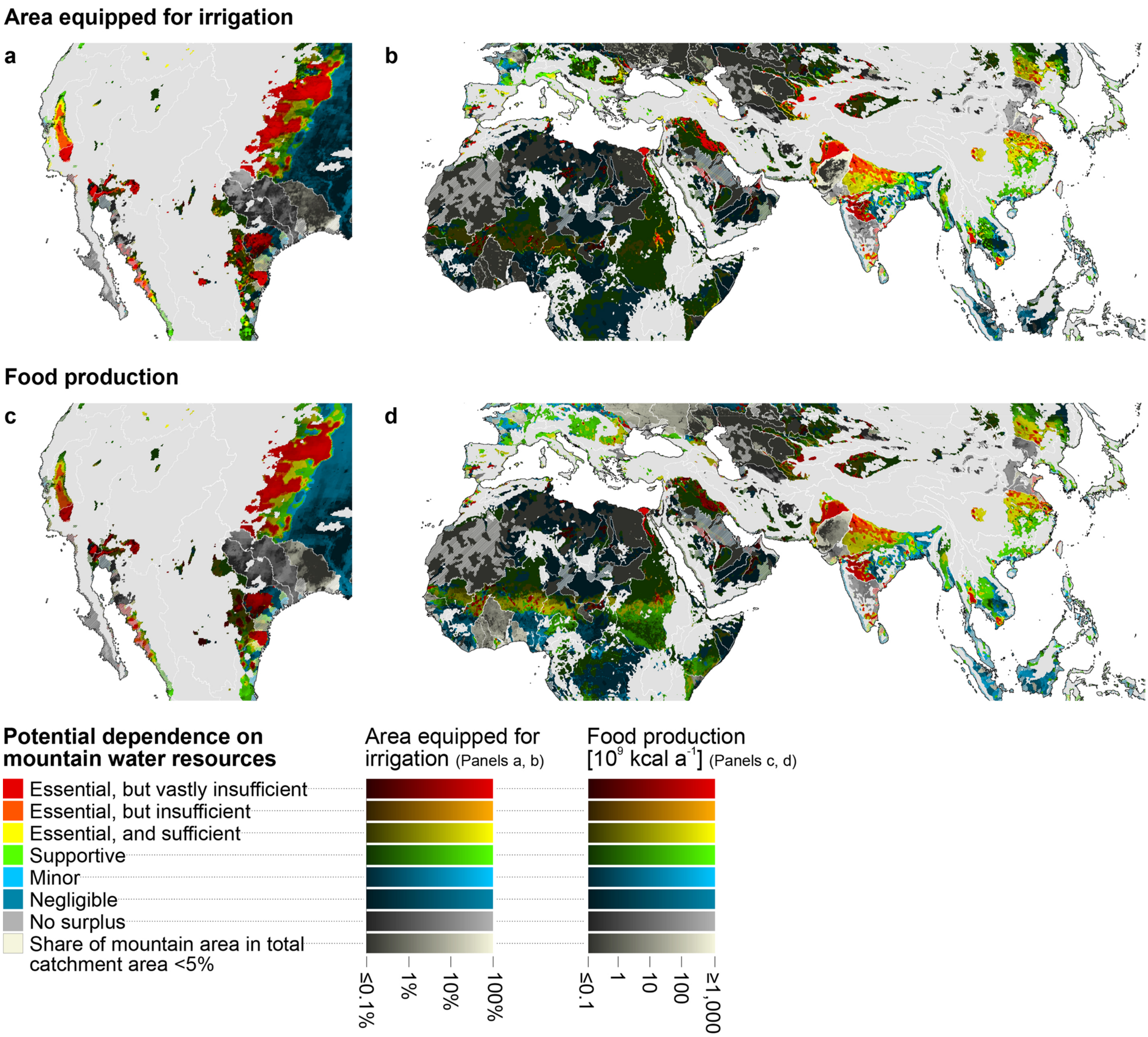
Extended Data Fig. 1 | Relief roughness and elevation classes used for distinguishing mountain and lowland areas. The maps show the global mountain (**a**) and lowland (**b**) areas as defined in the Methods section, both excluding Greenland and Antarctica. Large lakes (>50 km²) are drawn here using their actual relief roughness (which is zero) rather than the assumed average roughness used for distinguishing mountain and lowland areas (Methods). The boundaries of catchments with an area of 100,000 km² and more are drawn for orientation.



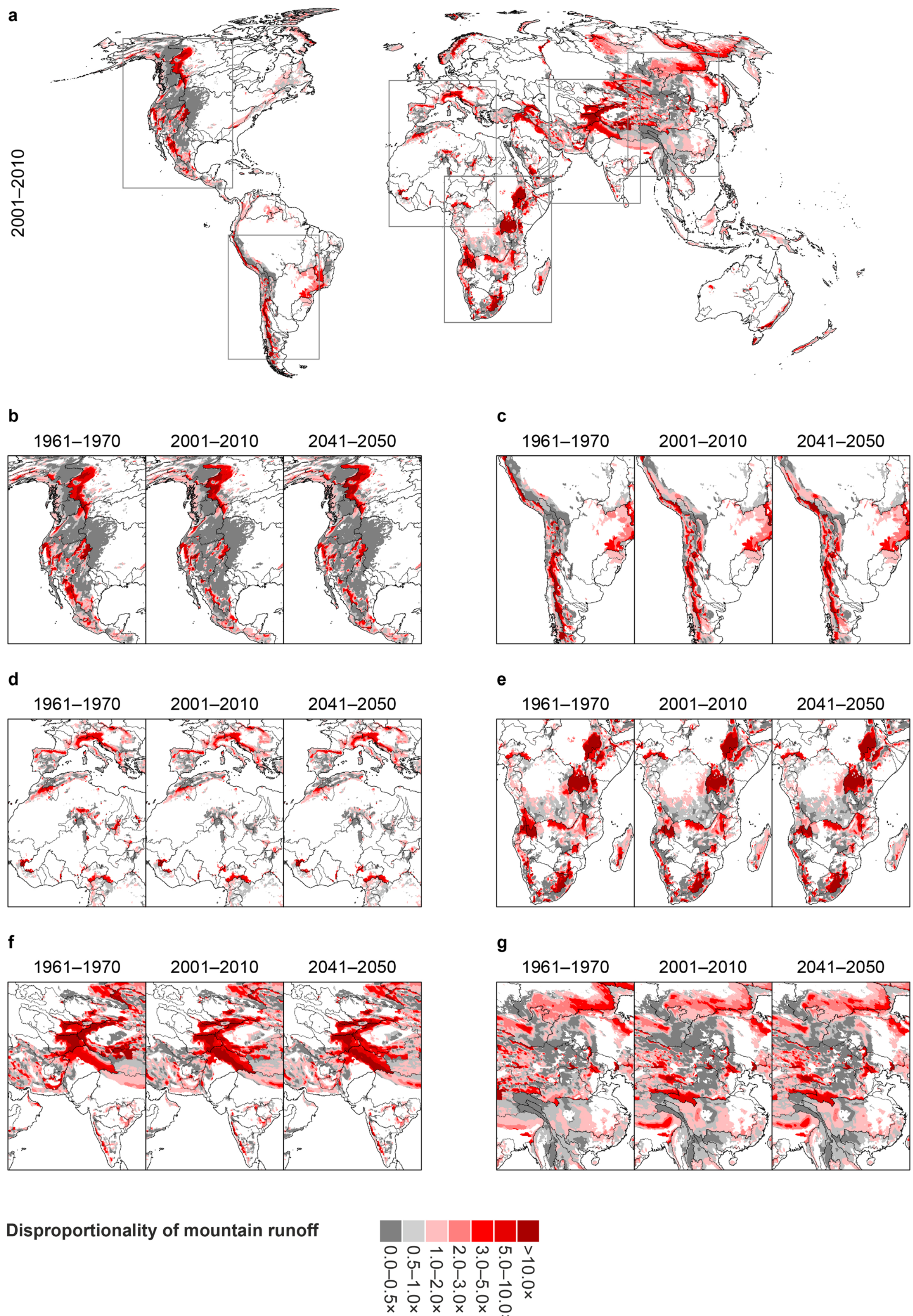
Extended Data Fig. 2 | Share of lowland population depending on mountain water resources 1961–2050. Results are shown as fractions of the respective population totals (decadal averages), summarised for all hydrobelts (**a**) as well as differentiated by hydrobelt (**b**–**i**). For absolute values see Fig. 2 in main text.



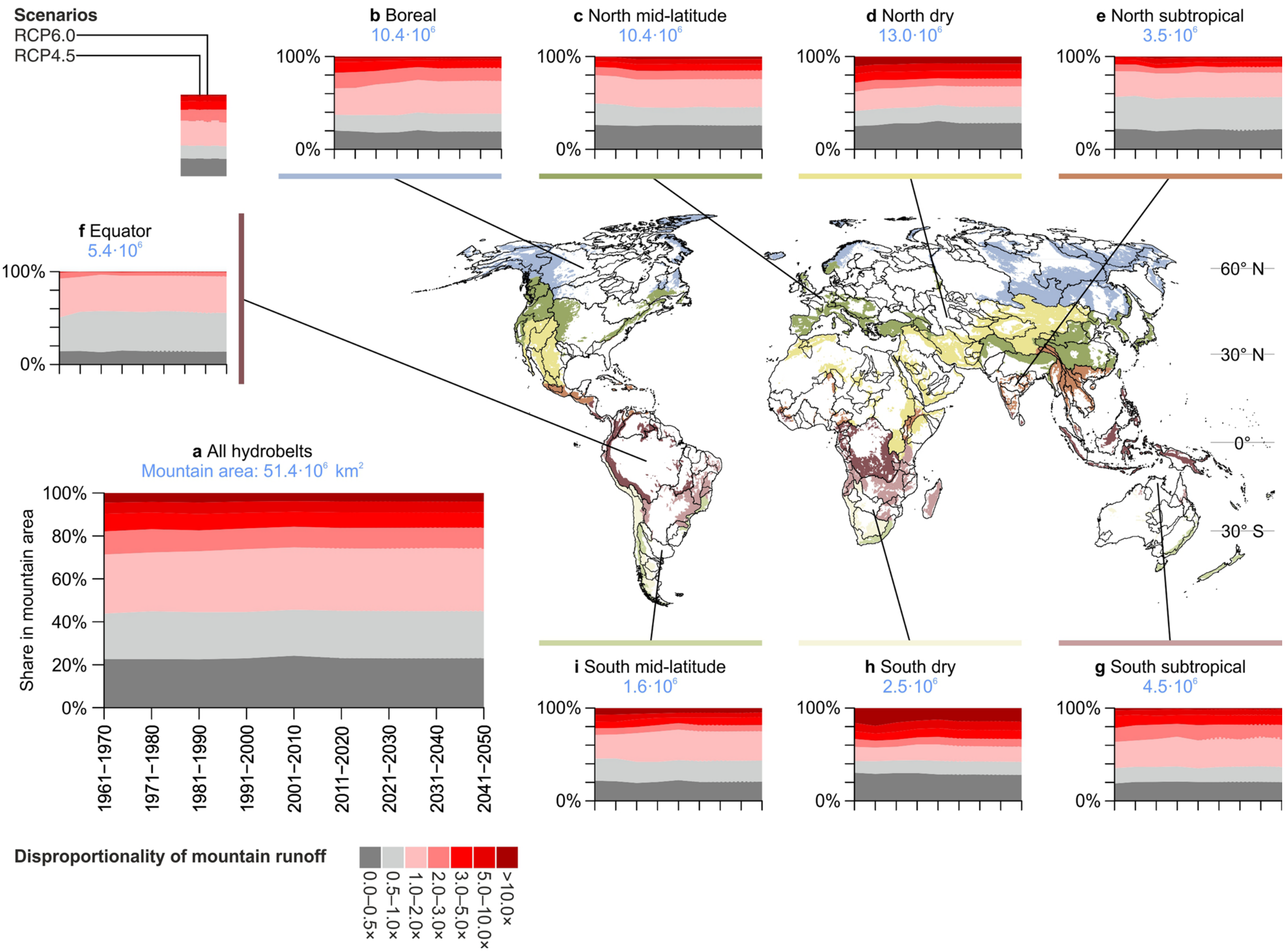
Extended Data Fig. 3 | Causes of missing surplus from mountain areas as well as water balance of lowlands receiving no surplus from mountain areas 1961–2050. Global results are shown for the time periods 1961–1970 (**a**, **b**), 2001–2010 (**c**, **d**) and 2041–2050 (**e**, **f**), magnifications for selected regions for 2041–2050 only (**g**–**j** and **k**–**n**). The boundaries of catchments with an area of 100,000 km² and more are drawn for orientation, and projections refer to the SSP2-RCP6.0 scenario.



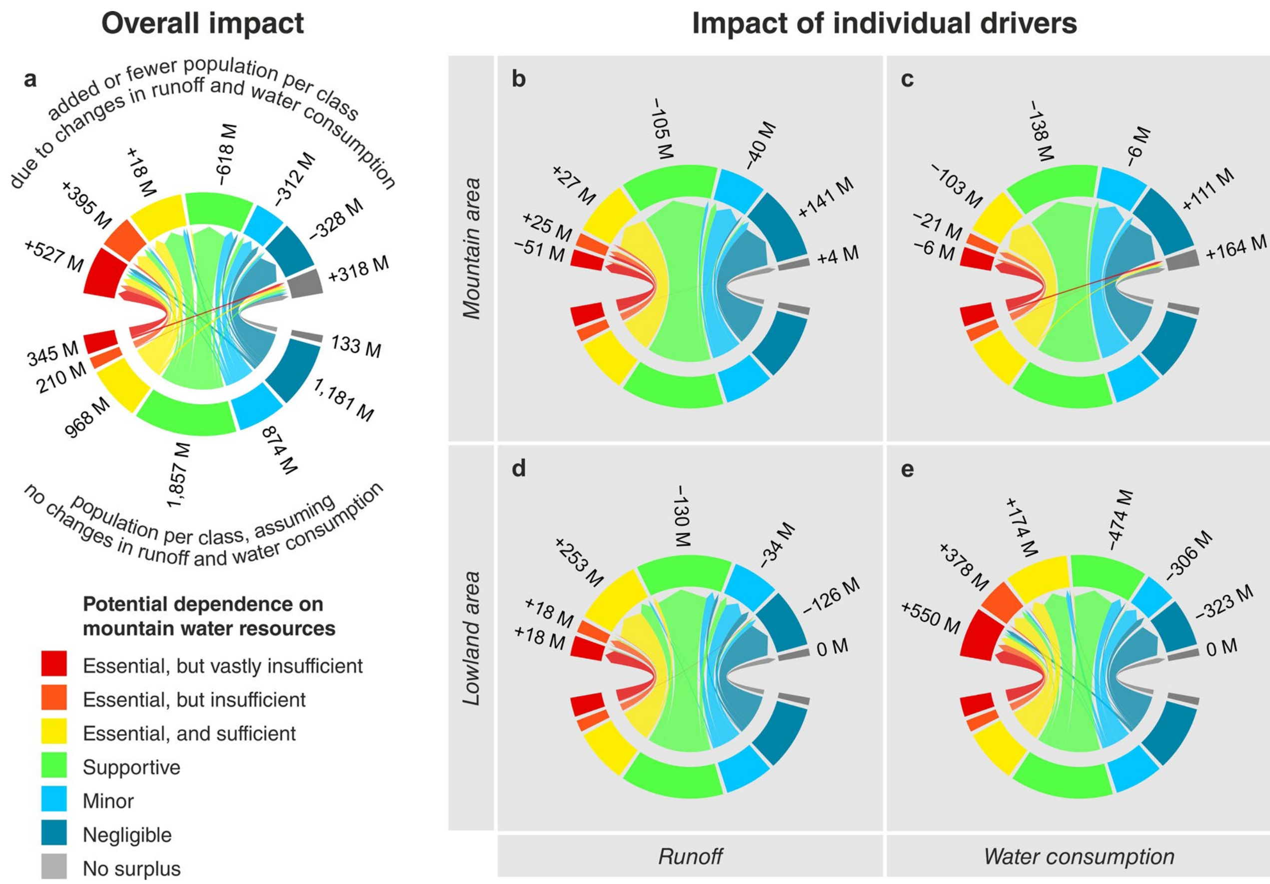
Extended Data Fig. 4 | Hot spot lowland regions potentially depending on mountain water resources 2041–2050, showing current lowland area equipped for irrigation (a, b) and lowland food production (c, d). Beige denotes areas where mountains as per the definition used here occupy less than 5% of total catchment area, and an assessment from the viewpoint of lowlands should only be done carefully (shown in Supplementary Fig. 2). 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. Results are from the SSP2-RCP6.0 scenario. See also Fig. 3 in main text.



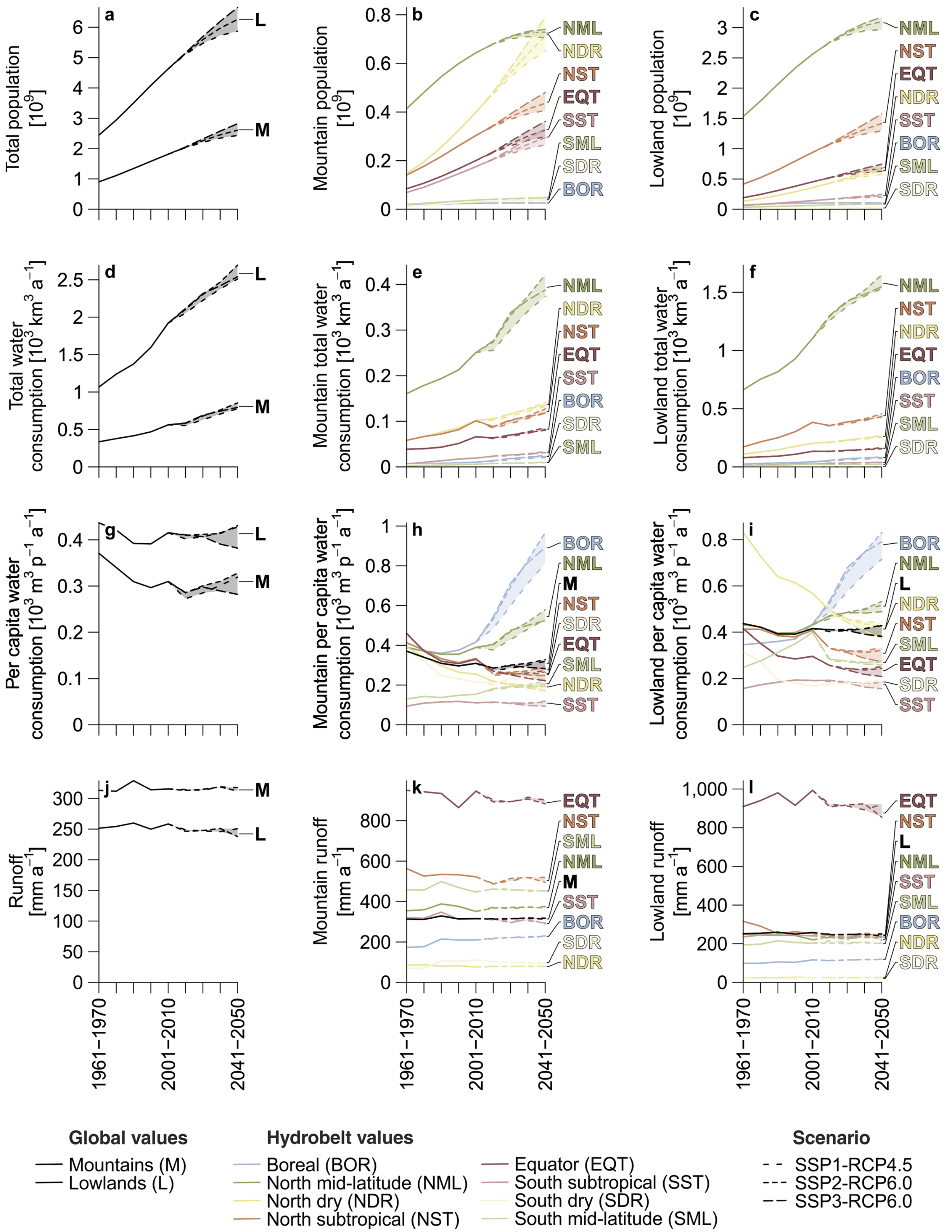
Extended Data Fig. 5 | Spatial patterns of disproportionality of mountain runoff 1961–2050. Global results are shown for 2001–2010 (**a**), whereas magnifications of selected regions are shown for 1961–1970, 2001–2010 and 2041–2050 (**b**–**g**). The boundaries of catchments with an area of 100,000 km² and more are drawn for orientation, and projections refer to the SSP2-RCP6.0 scenario. See also Extended Data Fig. 6 and Supplementary Information.



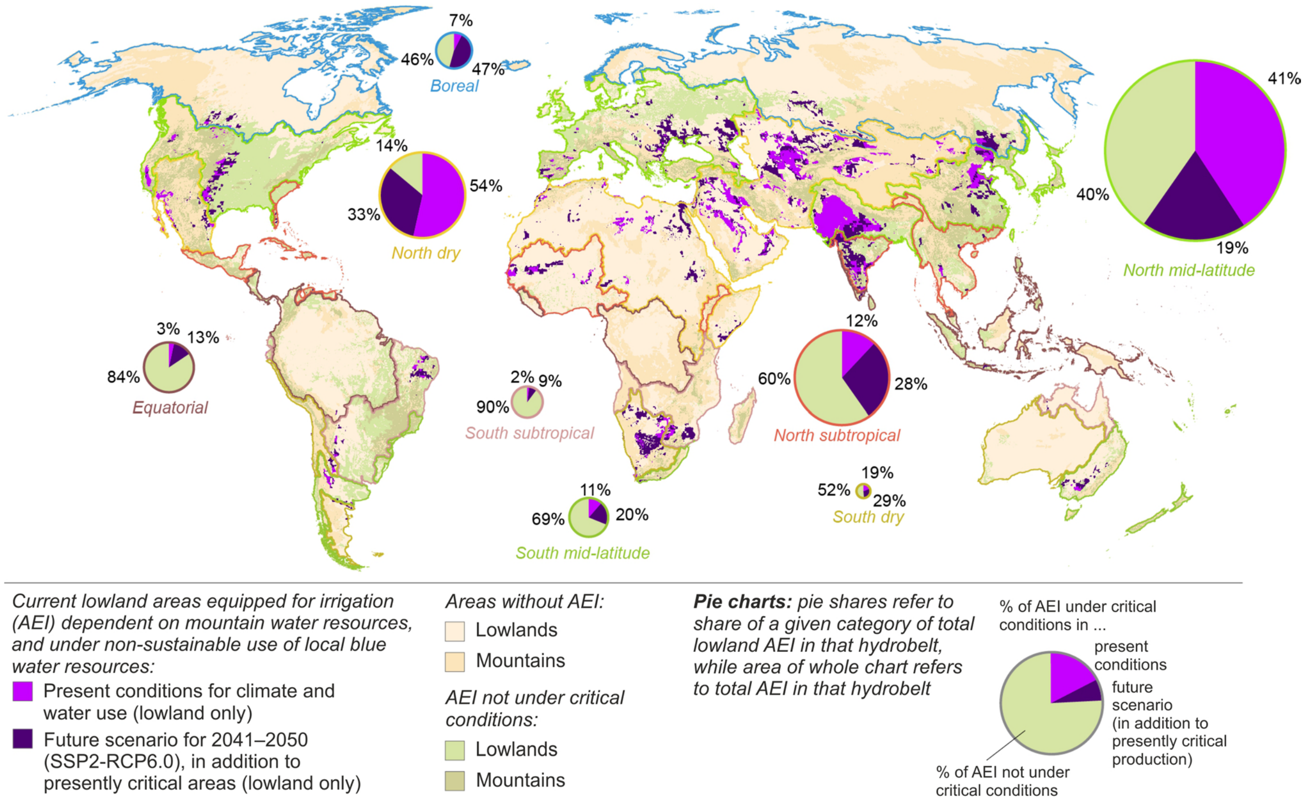
Extended Data Fig. 6. | Temporal evolution of disproportionality of mountain runoff 1961–2050. Results are shown as decadal averages, summarised for all hydrobelts (**a**) as well as differentiated by hydrobelt (**b**–**i**). Projections refer to the SSP2-RCP6.0 scenario. See also Extended Data Fig. 5 and Supplementary Information.



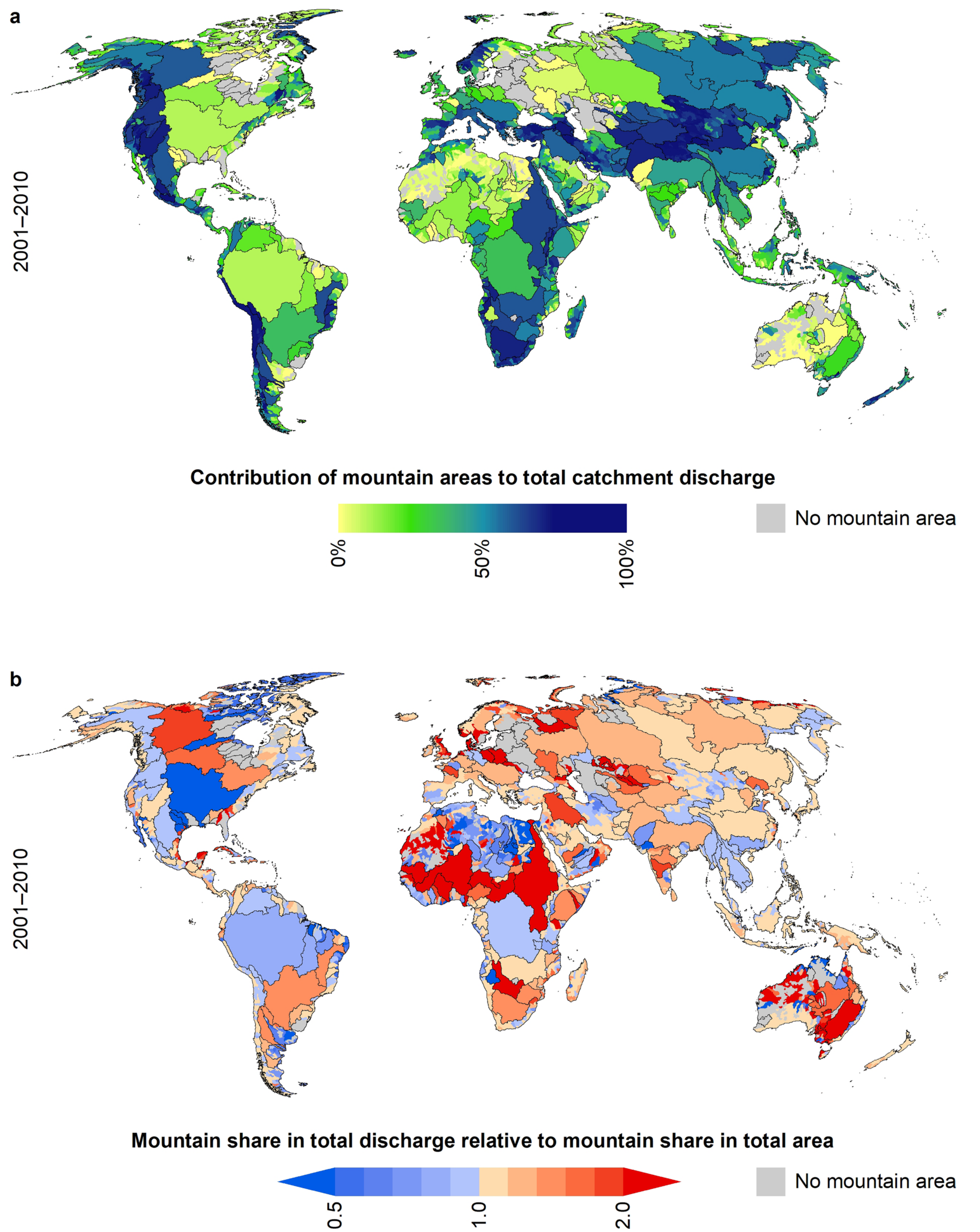
Extended Data Fig. 7 | Detailed breakdown of drivers causing changes in dependence on mountain water resources as projected for 2041–2050. As a baseline, the bottom part of each circular plot represents the number of lowland inhabitants per category 2041–2050, assuming that runoff and total water consumption remain unchanged at 1961–1970 level. The corresponding population numbers are noted under the sectors in Panel **a** (for example, 968 M lowland inhabitants potentially depend on essential and sufficient contributions form mountain areas). The top part of the circular plot in Panel **a** shows results for 2041–2050 under changed conditions as projected with the SSP2-RCP6.0 scenario, and as shown in the main text. Panels **b** to **e** then each show results for changes in only one driver, namely mountain runoff (**b**), mountain water consumption (**c**), lowland runoff (**d**), and lowland water consumption (**e**), all referring to SSP2-RCP6.0. The changes in population per category are noted above each sector for all panels, giving the numbers reported in Table 2 of the main text.



Extended Data Fig. 8 | Population, total water consumption, per-capita water consumption and runoff 1961–2050. Results are shown individually at decadal scale for mountain and lowland areas (**a**, **d**, **g**, **j**) as well as differentiated by hydrobelt for mountain (**b**, **e**, **h**, **k**) and lowland (**c**, **f**, **i**, **l**) areas.



Extended Data Fig. 9 | Lowland area equipped for irrigation (AEI) under non-sustainable blue water use and dependent on essential mountain runoff contributions in the 2000s and 2040s. For 2041–2050, the SSP2-RCP6.0 scenario was used, and it was assumed that location and extent of AEI are identical to year 2005. All numbers are rounded off to the nearest integer.



Extended Data Fig. 10 | Contribution of mountains to total catchment discharge (a) and ratio of mountain share in total catchment discharge to mountain share in total catchment area (b) 2001–2010. In (**a**), a figure of 100% means that all discharge in a basin originates in its mountain area, and 0% that all discharge originates in its lowland area. In (**b**), a value of 1 means that mountains contribute as much to total catchment discharge as they do to total catchment area. Values above 1 denote disproportionally high discharge contributions from mountains, values below 1 disproportionally low discharge contributions from mountains. For both computations, results are shown for the time period 2001–2010 only since changes over the timeframe 1961–2050 are small. The boundaries of catchments with an area of 100,000 km² and more are drawn for orientation.