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LETTER

Key drivers and pressures of global water scarcity hotspots

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Abstract

Global freshwater resources are vital to humanity and Earth's ecosystems, yet about one third of the global population is affected by water scarcity for at least one month per year. In these areas, the overuse of freshwater resources can lead to the threat of depletion, marking them as the global 'water scarcity hotspots'. This study combines outputs from a global hydrological model (PCR-GLOBWB 2) with an extensive literature search to provide a comprehensive intercomparison of the key drivers, pressures, states, impacts and responses (DPSIR) that shape the water gap between water demand and availability at the most important water scarcity hotspots worldwide. Hydroclimatic change, population growth, and water use for the industrial, municipal and agricultural sectors are the most important driving and pressuring forces on the water gap, affecting both water quality and quantity. These drivers and pressures have been showing increasing trends at all hotspots, which is concerning for the future development of the water gap. Additionally, we identify and characterize seven clusters of hotspots based on shared DPSIR patterns, revealing their common mechanisms. Our work highlights the diversity of water scarcity related issues at hotspots, especially the variety of impacts involved and governmental responses in place. The results of our DPSIR analysis provide valuable insights for building causal networks representing water gap dynamics at the hotspots. They form a foundation for conceptual models that illuminate human-water interactions, trade-offs, and synergies at the hotspots, while guiding policymakers in addressing the multifaceted challenge of closing the water gap.

1. Introduction

Global freshwater availability is considered to be one of nine earth-system processes associated with a planetary boundary, meaning that exceeding this boundary (freshwater depletion) will result in unacceptable environmental change, harming human society and ecosystems. Current estimates indicate that global freshwater availability has exceeded its planetary boundary, threatening the stability and resilience of Earth system (Richardson *et al* 2023). Freshwater availability also plays a key role in the Sustainable Development Goals, e.g. (6) clean water and sanitation, (3) good health and well-being (12) responsible consumption and production and (15) life on land (United Nations 2018, Di Baldassarre *et al* 2019), which shows the importance of water for social-ecological systems.

Since the 1950s, human influence on the Earth system has been increasing dramatically, which is known as the Great Acceleration (Steffen *et al* 2015). During this period of rapid global change, population growth and economic development have been increasing the total demand for freshwater resources and thus increasing water withdrawal rates around the world (Wada and Bierkens 2014). From 1960 to 2000 global groundwater abstraction is estimated to have doubled to quintupled from approximately 100 to 200–500 $km^3 yr^{-1}$ (Bierkens and Wada 2019). Also, hydroclimatic variability, deforestation, and water contamination have been decreasing freshwater availability (Haddeland *et al* 2014, Van Vliet *et al* 2021,

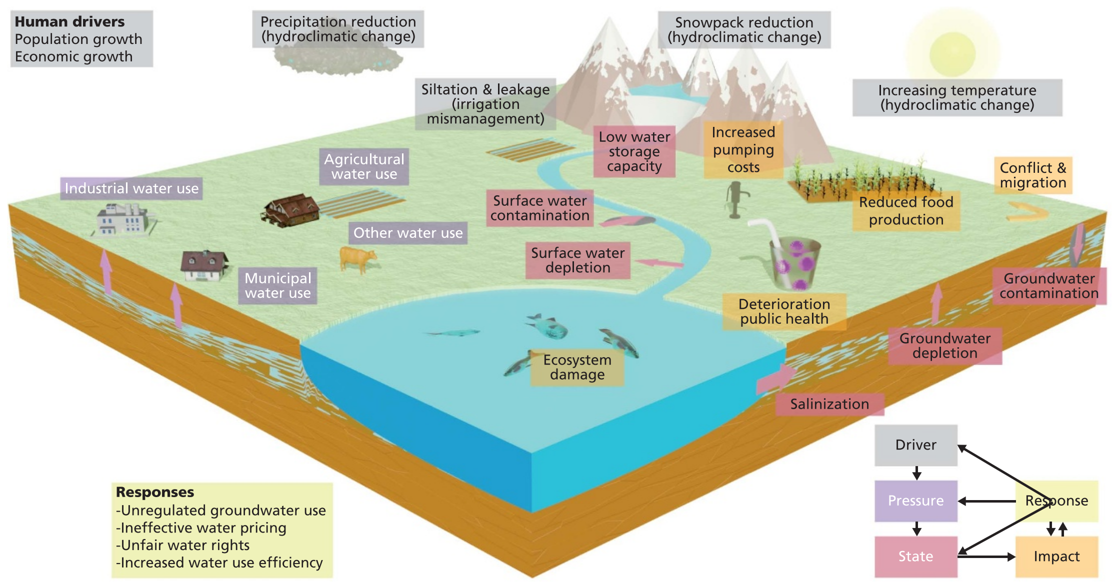


Figure 1. Example of the most important water scarcity drivers, pressures, states, impacts and responses (DPSIR) in the Indus Basin. The colours of the text boxes with system processes correspond to the respective DPSIR component from the legend in the bottom right. Black arrows in the legend indicate how DPSIR components affect each other. Coloured arrows in the figure give spatial direction to corresponding system processes.

Liu *et al* 2022) (figure 1). If a long-term imbalance occurs, where demand exceeds the availability of freshwater resources, a region develops a water gap and risks long-term water scarcity (Straatsma *et al* 2020). In this work the water gap is defined as the yearly accumulated difference between daily water demand and availability and occurs if daily demand is larger than daily availability. In regions with a large and persistent water gap, i.e. chronic shortage, water use is frequently unsustainable. This is by virtue of water being pumped from groundwater systems at rates that surpass the natural recharge or water being abstracted from surface water at quantities exceeding environmentally safe limits, both depleting freshwater resources. The occurrence of such a long-term water gap in a region that leads to depletion, we thus define as water scarcity. Socio-political and institutional factors play an important role in the occurrence or perception of water scarcity, as inefficient water use and mismanagement of water resources may exacerbate the water gap (Mehta 2014). Lastly, water scarcity problems can be intensified locally by production of water-intensive crops or goods for global trade and subsequent pollution (Vörösmarty *et al* 2015, Mekonnen and Hoekstra 2016). Ultimately, the interplay between these different factors determines whether a water gap occurs in a region or if water use is sustainable.

Through global modelling studies different regions that experience severe water scarcity have been identified (Wada and Bierkens 2014, Kummu *et al* 2016, Mekonnen and Hoekstra 2016, Liu *et al* 2017, Greve *et al* 2018, Huggins *et al* 2022). In those modelling efforts, the assessment of the causes of water scarcity and intercomparison between the well studied regions is limited, as the models do not capture all relevant processes, especially regarding human-water interactions. Model development focuses mainly on representing the most dominant drivers of water gaps, such as hydroclimatic change and growing water demand. There are, however, limited anthropogenic water data and consistent theories on modelling of human water withdrawal, distribution, and consumption, making the representation of human water demand in global hydrological models (GHMs) less homogeneous (Bierkens 2015, Nazemi and Wheater 2015a, 2015b, Döll *et al* 2016). Moreover, the (indirect) impact of water scarcity on society and ecosystems, as well as the alleviating or aggravating effect of water management policies on water scarcity, are also often disregarded in such GHM studies. Thus, global assessments may result in a simplification of the more complex real world trade-offs and synergies in different human-water systems due to lack of local process knowledge. To assess these in more detail at each water scarcity hotspot, local data and knowledge are required e.g. input of local datasets or local case studies (Boretti and Rosa 2019).

In contrast, regional studies have assessed water scarcity by providing more detailed insights on the existence and development of water scarcity hotspots and localized solutions. These case studies provide local context on climate (change), water resource management and key water security issues (South-Asia: Roth *et al* 2019, Pakistan: Ishaque *et al* 2023, West USA: Perrone and Jasechko 2017, Murray–Darling Basin: Wheeler *et al* 2013) through geospatial data analyses, literature and policy reviews. In low-income regions water scarcity research is, however, more limited (Sun *et al* 2022). To our knowledge there are no studies that give a global perspective on water scarcity issues using local research at water scarcity hotspots, or they are solely focused on the state of water resources (Richey *et al* 2015, Jägermeyr *et al* 2017, Ahmadi *et al* 2020, Van Engelen *et al* 2022).

Despite a multitude of local and global studies on freshwater depletion, a systematic global analysis of the drivers and pressures contributing to the water scarcity at hotspots is lacking, as well as the impact of water scarcity on the socio-environmental system, and subsequent societal response. Such a systematic analysis would make water scarcity narratives comparable between hotspots and would allow for the identification of common mechanisms and assessment of the specificity or commonality of proposed solutions. Therefore, the main objective of this work is to identify the internal and external drivers, pressures, states, impacts and responses (DPSIR) that are related to the development of the current water scarcity hotspots and to find similarities and differences between the hotspots. This allows us to draw parallels between regions that are at different stages of water scarcity development and identify key factors contributing to changes in global water scarcity.

2. Methods

2.1. Hotspot identification

To identify water scarcity hotspots, we first chose a measure of water scarcity. Rather than using a Water Scarcity Index (WSI e.g. Wada *et al* 2011), we chose to calculate the water gap, i.e. the difference between water demand and availability. The advantage of the water gap is that it is an actual layer of water per unit area ($m^3\,m^{-2}$) that allows for comparison between locations and straightforward averaging over larger areas, such as water provinces. This is in contrast to a WSI that represents a ratio, which is often ambiguous in comparison and spatial averaging, e.g. it can result in large values even if both demand and availability are very small. This is, for example, the case when calculating the WSI for extremely arid regions with a low population density (e.g. North Africa). The actual volume of water that is lacking in these regions is relatively low. Thus, the societal challenge to compensate for the water shortage is also relatively low, which is well reflected in the low value of the water gap, unlike the high value of a WSI.

In this work we used the 5 arcmin output of the GHM PCR-GLOBWB 2 (Sutanudjaja *et al* 2018) to estimate the global water gap (table 1). This model is well-suited in estimating water gaps as it simulates water storage for multiple layers (atmosphere, surface—including rivers, lakes and reservoirs, soil, groundwater) and fluxes between them, while it additionally integrates modules that calculate sectoral water demand and water withdrawal from these layers. From the water gap, we identified which regions use more water than naturally available, therefore depleting their resources and risking water scarcity. The difference between water demand (WD) and water abstraction (WA) is used on a daily scale to determine the daily Water Gap (WG), which is then summed to provide the yearly total WG ($m\,yr^{-1}$) from 1980 to 2019:

$$\mathrm{WG_{annual}} = \sum_{t=1}^{\text{days per year}} \max\left(\mathrm{WD_{total}}(t) - \mathrm{WA_{total}}(t), 0\right) + \mathrm{GWA_{nr}}(t) \qquad (1)$$

where $\mathrm{WD_{total}}(t)$ is the total gross water demand from the agricultural, industrial, domestic and livestock sectors including losses and return flows ($m\,d^{-1}$), $\mathrm{WA_{total}}(t)$ is the total abstraction from desalination, renewable surface and groundwater sources ($m\,d^{-1}$), and $\mathrm{GWA_{nr}}(t)$ is non-renewable groundwater extraction ($m\,d^{-1}$) (table 1). The max() operator indicates that the daily WA cannot exceed the daily WD, and that the water gap cannot be a negative value. Non-renewable groundwater extraction occurs in PCR-GLOBWB when the total groundwater withdrawal is larger than the total natural groundwater recharge and riverbed infiltration. Subsequently, the groundwater storage balance in the model becomes negative, and water is withdrawn from non-renewable groundwater resources, meaning that there is a permanent loss of groundwater storage (Sutanudjaja *et al* 2018). Thus, the water gap is increased by non-renewable water use, as withdrawal from non-renewable water resources causes a permanent loss of water resources and is therefore explicitly added to the water gap in equation 1. Abstraction from water sources is, however, not allocated to nearby cells to reduce the water gap. So, apart from the water flowing through the river network, this calculation of the water gap does not account for water transfers over larger distances (approximately >10 km) or virtual water trade. This may lead to an overestimation of the water gap in regions with extensive irrigation networks or that depend on interbasin water transfers to meet local demands.

Table 1. PCR-GLOBWB 2 output variables that are used to calculate the water gap (equation 1). All variables are in m day^{-1} with a spatial resolution of 5 arcmin. The total water abstraction is retrieved from sources in the respective order: desalination, surface water, renewable groundwater, non-renewable groundwater.

Symbol	Name	Description
WD_{total}	Total gross water demand	$WD_{irrigation} + WD_{domestic} + WD_{livestock} + WD_{industry}$
$WD_{irrigation}$	Total gross irrigation water demand	Crop water requirement based on crop composition and irrigated area per grid cell
$WD_{domestic}$	Total gross domestic water demand	Number of persons per grid cell with corresponding country-specific per capita water withdrawal
$WD_{livestock}$	Total gross livestock water demand	Number of livestock per grid cell with corresponding drinking water requirement
$WD_{industry}$	Total gross industry water demand	Industrial water demand with country-specific economic development
WA_{total}	Total gross water abstraction	$DWA + SWA + GWA_r + GWA_{nr}$
DWA	Desalinated water abstraction	Total water abstraction from desalination plants
SWA	Surface water abstraction	Total water abstraction from surface water (including reservoirs, rivers and lakes) that does not exceed the environmental flow limit (10% of natural discharge)
GWA_r	Renewable groundwater abstraction	Part of water abstraction from groundwater resources that does not exceed natural recharge and riverbed infiltration rates
GWA_{nr}	Non-renewable groundwater abstraction	Part of water abstraction from groundwater resources that exceeds natural recharge and riverbed infiltration rates
WG	Water gap	$WD_{total} - WA_{total} + WA_{nr}$

As we are interested in finding hotspots where water scarcity has been occurring persistently (multiple years) and on a large scale (larger than the 5 arcmin grid sizes of the WG as calculated from PCR-GLOBWB), we compute the zonal mean water gap over the period of 2010-2019 per water province, which are areas that respect both political and hydrological borders (Straatsma *et al* 2020). We identified hotspots to be water provinces where the *WG* exceeds 0.015 m yr^{-1} ($\sim$0.05 mm d^{-1}), a threshold that separates water provinces with a very small water gap from regions with a significant water gap that would cause a yearly groundwater decline of at least 5 cm. We chose this limit as it provides the largest congruence between the identified hotspots from modelling with well-known water scarcity hotspots from previous global studies (Wada *et al* 2014, Kummu *et al* 2016, Mekonnen and Hoekstra 2016, Liu *et al* 2017, Greve *et al* 2018, Huggins *et al* 2022).

Additionally, we identified hotspots to be large spatial aggregates of (adjacent) water scarce provinces. When a cluster of water scarcity hotspots was found to be comprising multiple major surface or groundwater basins, for example in India or China, we labelled the approximate center of the region or basin as a water scarcity hotspot. To ensure that hotspots are regions where the severity of problems related to the water gap is high, we only labelled regions as water scarcity hotspot if they were also widely supported by literature (more than 7 case studies per hotspot that report water scarcity related issues).

2.2. Literature selection and screening

For the semi-systematic literature review, we used Elsevier's scientific database Scopus (www.scopus.com) to select literature in English that addresses water scarcity in each of the quantitatively selected hotspots. This database provides peer-reviewed literature with a high standard of scientific relevance that is updated daily. Moreover, it contains a relatively high coverage of journals within the social sciences (Mongeon and Paul-Hus 2016), and can thus provide multi-disciplinary insights needed for the DPSIR analysis (section 2.3).

In Scopus specific keywords consisting of '*water scarcity*' and various other terms related to water scarcity were considered within the title, abstract or keywords of an article. Within the search string, we used the AND operator for '*water scarcity*' and for the specific location of the hotspot e.g. *Indus* or *California*. Occasionally, OR operators were added, depending on how many hits were generated when only searching for the AND terms. We did this to limit the results of a search per hotspot to a maximum of 50 case studies. These additional keywords cover conceptual, technical or social terms that are related to water scarcity (supplementary table A). For our analysis we selected studies that were published between 1982 and May 2023.

Content inclusion criteria that were considered relate to the driving forces and pressures on unsustainable use of water resources, the change in their quality and quantity, their social, economic or environmental impact and (in)effective water management. The relevance of a case study was examined before adding it to the semi-systematic literature review. Studies should contain considerable input on the inclusion criteria given above. For example, when studies solely focus on future scenario or optimization modelling, such as improving crop irrigation efficiency and allocation, or the implications of future climate change on a water system, and give limited context on water scarcity issues in the region, they were dismissed. Publications were also excluded when they are inaccessible, duplicated in search results of multiple hotspots, or have a scope outside of the hotspot area.

2.3. DPSIR analysis

For our literature analysis we applied a DPSIR framework to the literature selection for each of the water scarcity hotspots (EEA 1999). Results of a DPSIR analysis give insight on which policy direction to follow for enhancing sustainable management and use of water resources. In this work we evaluate the occurrence of each DPSIR indicator per case study from our semi-systematic literature selection. Subsequently, all DPSIR components were accumulated per hotspot to find the relative importance of each component and enable comparison between the water scarcity hotspots. The relative importance of each DPSIR component provides information on the most dominant and driving factors that are connected to the WG magnitude and trends at each hotspot. A full list of DPSIR indicators and their definitions is given in supplementary table B.

2.4. Data

As an independent validation to the DPSIR analysis, we consulted global gridded datasets that represent the most important drivers, pressures and states involved in the water scarcity hotspots. These datasets are products of *in situ* or remotely sensed variables, or country statistics that are interpolated, disaggregated, extrapolated, classified by algorithms, or dynamically modelled to fill data gaps and result in products with global coverage (supplementary table C). We aggregated the temporal scales of all data sources to yearly timesteps as we are studying long-term trends and slow temporal dynamics. Each gridded product was then clipped according to the defined water scarcity hotspot areas (section 2.1) and either summed or averaged over that region, depending on the variable of the dataset, to result in a timeseries for each variable at each hotspot.

2.5. Hierarchical clustering

To find the similarities and dissimilarities between the hotspots, we clustered the hotspots by applying an agglomerative hierarchical clustering method on the DPSIR results (Murtagh and Contreras 2012). The method finds dissimilarities that are determined by the maximum (Euclidean) distances between the standard deviations of each DPSIR indicator. Initially, we assigned each hotspot to its own cluster, then the algorithm iteratively merged similar hotspots into clusters until all hotspots belong to one cluster. We represented the hierarchical clustering in a dendrogram structure, where the vertical axis represents the dissimilarity of clusters. From this dendrogram a number of clusters was derived, according to where the dissimilarity (height on the vertical axis) was largest.

3. Results

3.1. Water scarcity hotspots

From the model output we have identified 21 hotspots with a large WG between 2010–2019 (figure 2). The zonal mean of the water scarcity hotspots varies from 0.017 (US High Plains) to 0.38 (Indus Basin) m yr^{-1}. Most hotspots are predominantly located in the Northern Hemisphere, particularly at the Mediterranean, Middle East, as well as South and East Asia.

3.2. Key DPSIR results

Here, we summarize the two or three most important indicators (largest percentages) per DPSIR category from our semi-structured literature analysis. We identify hydroclimatic change (49% case studies at all hotspots), population growth (31%), and agricultural (77%), municipal (46%) and industrial water use (30%) to be the key global drivers and pressures as indicated in figure 3. The most important affected states of the water resources are groundwater depletion (48%), contamination (33%), and salinization (25%). Subsequent impacts on social-environmental systems are less homogeneous between the hotspots, with damage to ecosystems (24%), conflict and migration (18%), and reduced agricultural production (17%) as main impacts. Responses also vary greatly. While some responses have a positive impact on alleviating water scarcity (i.e. increased storage capacity (25%), water treatment (18%), or water transfers (16%)), others are ineffective in attempting to close the WG or can even worsen water scarcity problems due to, for example, a lack of groundwater regulating policies (13%) or an unfair distribution of water rights (11%). When comparing the most important results of the drivers, pressures and states to the historical trends, we find that they increased over the past decades (supplementary D). The individual DPSIR results can be found in supplementary E and F.

3.3. Intercomparability of hotspots

Hierarchical clustering results in 7 different hotspot clusters depicting similarities in DPSIR components (figure 4). The following subsections will elaborate on similarities occurring in each cluster and provide insights into the WG development. We named the clusters according to their predominant DPSIR commonality. Note that the prevalent DPSIR components may be important within multiple different clusters.

3.3.1. Cluster 1 Water treatment and desalination: Arabian Peninsula

The Arabian Peninsula (Saudi-Arabia, Qatar, UAE and Bahrain) is a cluster on its own. Striking to

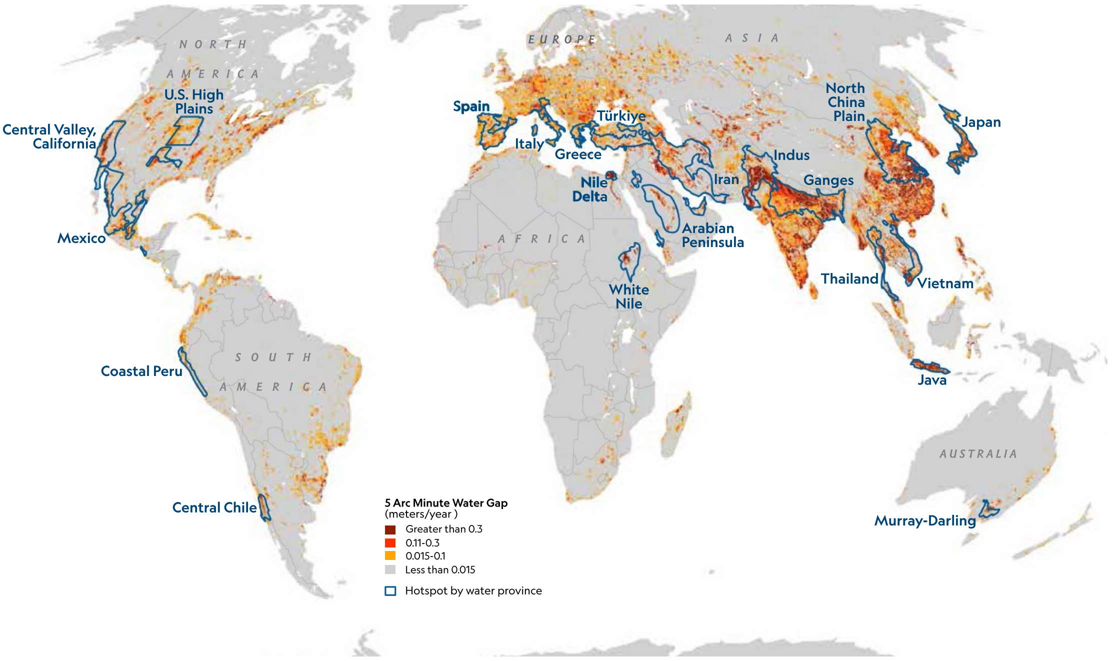


Figure 2. The 21 identified water scarcity hotspots based on the water gap from the time period of 2010–2019 at water province scale. Hotspot boundaries (blue) are determined by water provinces with a water gap exceeding 0.015 m yr^{-1}. Also shown are the underlying water gap values at the 5 arcmin resolution as obtained from PCR-GLOBWB 2.

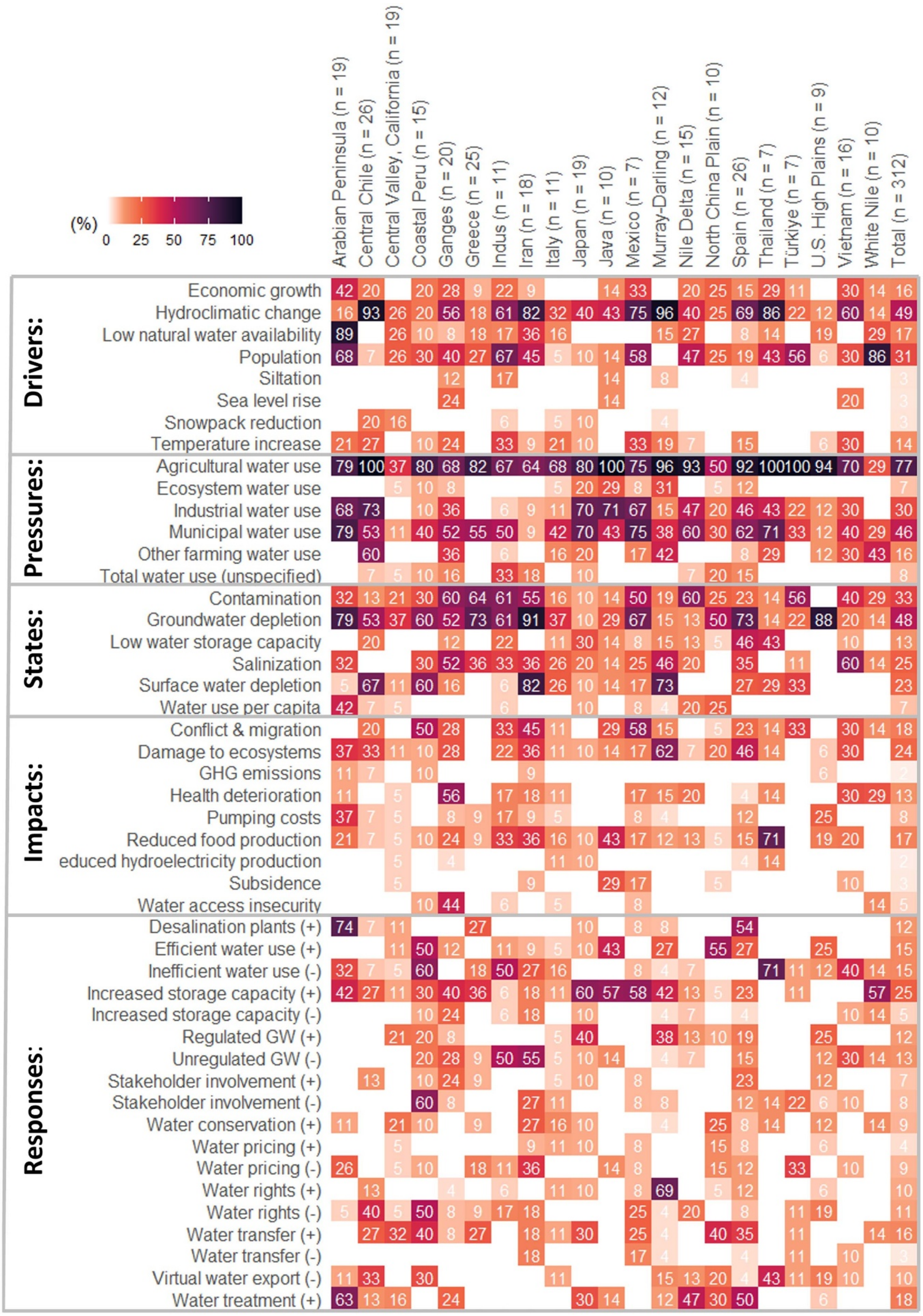
this region is that, unlike any other hotspot, a pattern stands out: low natural water availability (mentioned in 89% of case studies at cluster) in combination with high per capita water consumption (42%) leading to both groundwater depletion (79%) and large scale usage of unconventional water resources (desalination 74% and water treatment 63%). With increased economic growth (42%) since the discovery of oil and natural gas, urbanization (79%) and population growth (68%) have been rising rapidly (supplementary D), raising living standards and thus the per capita water consumption. Simultaneously, governmental subsidization, high leakage rates in water distribution networks, and public unawareness of the value of water have not been encouraging water conservation in the region. Furthermore, the peninsula's high dependency on unconventional water resources is exceptional, as costs are very high due to high energy demands of these techniques. The discovery of large oil and gas reservoirs has, however, allowed the region to invest and innovate in these unconventional water resources. Still, in 2010–2012 it has been estimated that the percentage of unconventional water resources used was only 22% of the total water usage, which is much lower than the percentage of water used from unsustainable groundwater resources (78%) (Al-Zubari *et al* 2017).

3.3.2. Cluster 2 Hydroclimatic change: Central Chile, Spain, Murray–Darling, Japan

For cluster 2, hydroclimatic change is reported as a very important driver of water scarcity (values ranging from 40%–96% in the cluster case studies). Chile has seen consecutive droughts over the past 10 years (Fuentes and Fuster 2021), in Spain the total annual rainfall is declining (Ibáñez and Caiola 2013), and the Murray–Darling basin in Australia had the Millennium Drought (1997-2009) (Wheeler *et al* 2013). At the same time, these hotspots have effective acts and agreements that support sustainable use of water resources (water treatment 12%–50%, water rights 10%–69%, increased storage capacity 23%–60%). An example of this is the monopolization of water rights by the Australian government in the Murray–Darling basin when the basin's environmental flow limit was continuously exceeded (Wheeler *et al* 2013). Subsequently, the government effectively implemented a water market, where farmers can trade their water rights based on water availability and needs. Another similarity between these hotspots is that population growth is not a major driver of the water scarcity (population growth 0%–19%), unlike most other hotspots.

3.3.3. Cluster 3 Agricultural water use: North China Plain, Central Valley California, US High Plains, White Nile Sudan, Nile Delta, Italy, Greece, Türkiye

The third cluster is the largest by number of hotspots, containing eight hotspots. The single commonality between these hotspots is their dominant pressure: agricultural water use (29%–100%). The average value of agricultural water use for this cluster (69%) is, however, not larger than the average of all hotspots (77%), meaning that agricultural water use is not a very strong commonality relative to hotspots outside of this cluster.



		Arabian Peninsula (n = 19)	Central Chile (n = 26)	Central Valley, California (n = 19)	Coastal Peru (n = 15)	Ganges (n = 20)	Greece (n = 25)	Indus (n = 11)	Iran (n = 18)	Italy (n = 11)	Japan (n = 19)	Java (n = 10)	Mexico (n = 7)	Murray-Darling (n = 12)	Nile Delta (n = 15)	North China Plain (n = 10)	Spain (n = 26)	Thailand (n = 7)	Türkiye (n = 7)	U.S. High Plains (n = 9)	Vietnam (n = 16)	White Nile (n = 10)	Total (n = 312)
Drivers:	Economic growth	42	20		20	28	9	22	9			14	33		20	25	15	29	11		30	14	16
	Hydroclimatic change	16	93	26	20	56	18	61	82	32	40	43	75	96	40	25	69	86	22	12	60	14	49
	Low natural water availability	89		26	10	8	18	17	36	16				15	27		8	14		19		29	17
	Population	68	7	26	30	40	27	67	45	5	10	14	58		47	25	19	43	56	6	30	86	31
	Siltation					12		17				14		8			4						3
	Sea level rise					24						14									20		3
	Snowpack reduction		20	16				6		5	10			4									3
	Temperature increase	21	27		10	24		33	9	21	10		33	19	7		15			6	30		14
Pressures:	Agricultural water use	79	100	37	80	68	82	67	64	68	80	100	75	96	93	50	92	100	100	94	70	29	77
	Ecosystem water use			5	10	8				5	20	29	8	31		5	12						7
	Industrial water use	68	73		10	36		6	9	11	70	71	67	15	47	20	46	43	22	12	30		30
	Municipal water use	79	53	11	40	52	55	50	9	42	70	43	75	38	60	30	62	71	33	12	40	29	46
	Other farming water use		60			36		6		16	20		17	42			8	29		12	30	43	16
	Total water use (unspecified)		7	5	10	16		33	18		10				7	20	15						8
States:	Contamination	32	13	21	30	60	64	61	55	16	10	14	50	19	60	25	23	14	56		40	29	33
	Groundwater depletion	79	53	37	60	52	73	61	91	37	10	29	67	15	13	50	73	14	22	88	20	14	48
	Low water storage capacity		20			12		22		11	30	14	8	15	13	5	46	43			10		13
	Salinization	32			30	52	36	33	36	26	20	14	25	46	20		35		11		60	14	25
	Surface water depletion	5	67	11	60	16		6	82	26	10	14	17	73			27	29	33				23
	Water use per capita	42	7	5				6			10		8	4	20	25							7
Impacts:	Conflict & migration		20		50	28		33	45	11		29	58	15		5	23	14	33		30	14	18
	Damage to ecosystems	37	33	11	10	28		22	36	11	10	14	17	62	7	20	46	14		6	30		24
	GHG emissions	11	7		10				9											6			2
	Health deterioration	11		5		56		17	18	11			17	15	20		4	14			30	29	13
	Pumping costs	37	7	5		8	9	17	9	5			8	4			12			25			8
	Reduced food production	21	7	5	10	24	9	33	36	16	10	43	17	12	13	5	15	71		19	20		17
	educed hydroelectricity production			5		4				11	10						4	14					2
	Subsidence			5					9			29	17			5					10		3
	Water access insecurity				10	44		6		5			8									14	5
Responses:	Desalination plants (+)	74	7	11			27				10		8	8			54						12
	Efficient water use (+)			11	50	12		11	9	5	10	43		27		55	27			25			15
	Inefficient water use (-)	32	7	5	60		18	50	27	16			8	4	7			71	11	12	40	14	15
	Increased storage capacity (+)	42	27	11	30	40	36	6	18	11	60	57	58	42	13	5	23		11			57	25
	Increased storage capacity (-)				10	24		6	18		10			4	7		4				10	14	5
	Regulated GW (+)			21	20	8				5	40			38	13	10	19			25			12
	Unregulated GW (-)				20	28	9	50	55	5	10	14		4	7		15			12	30	14	13
	Stakeholder involvement (+)		13		10	24	9			5	10		8				23			12			7
	Stakeholder involvement (-)				60	8			27	11			8	8			12	14	22	6	10		8
	Water conservation (+)	11		21	10		9		27	16	10			4		25	8	14		12		14	9
	Water pricing (+)			5					9	11	10		8			15	8			6			4
	Water pricing (-)	26		5	10		18	11	36			14	8			15	12		33		10		9
	Water rights (+)		13			4		6		11	10		8	69		5	12			6			10
	Water rights (-)	5	40	5	50	8	9	17	18				25	4	20		8		11	19			11
	Water transfer (+)		27	32	40	8	27		18	11	30		25	4		40	35		11			14	16
	Water transfer (-)								18				17	4			4		11		10		3
	Virtual water export (-)	11	33		30					11				15	13	20	4	43	11	19	10		10
	Water treatment (+)	63	13	16		24					30	14		12	47	30	50			6			18

Figure 3. Results from DPSIR analysis per DPSIR category, indicator and hotspot, including averaged results over all hotspot case studies. The values refer to the percentage of the total (n) case studies per hotspot that address the respective indicator.

3.3.4. Cluster 4 Population growth: Indus, Ganges

The Indus and Ganges river basins have many common mechanisms (DPSIR results) driven by a rapid population growth over the last decade (reported in 40%–67% of case studies). Most pronounced are the similarities in impacts from water scarcity on society and the ecosystem (reduced food production 24%–33%, conflict and migration

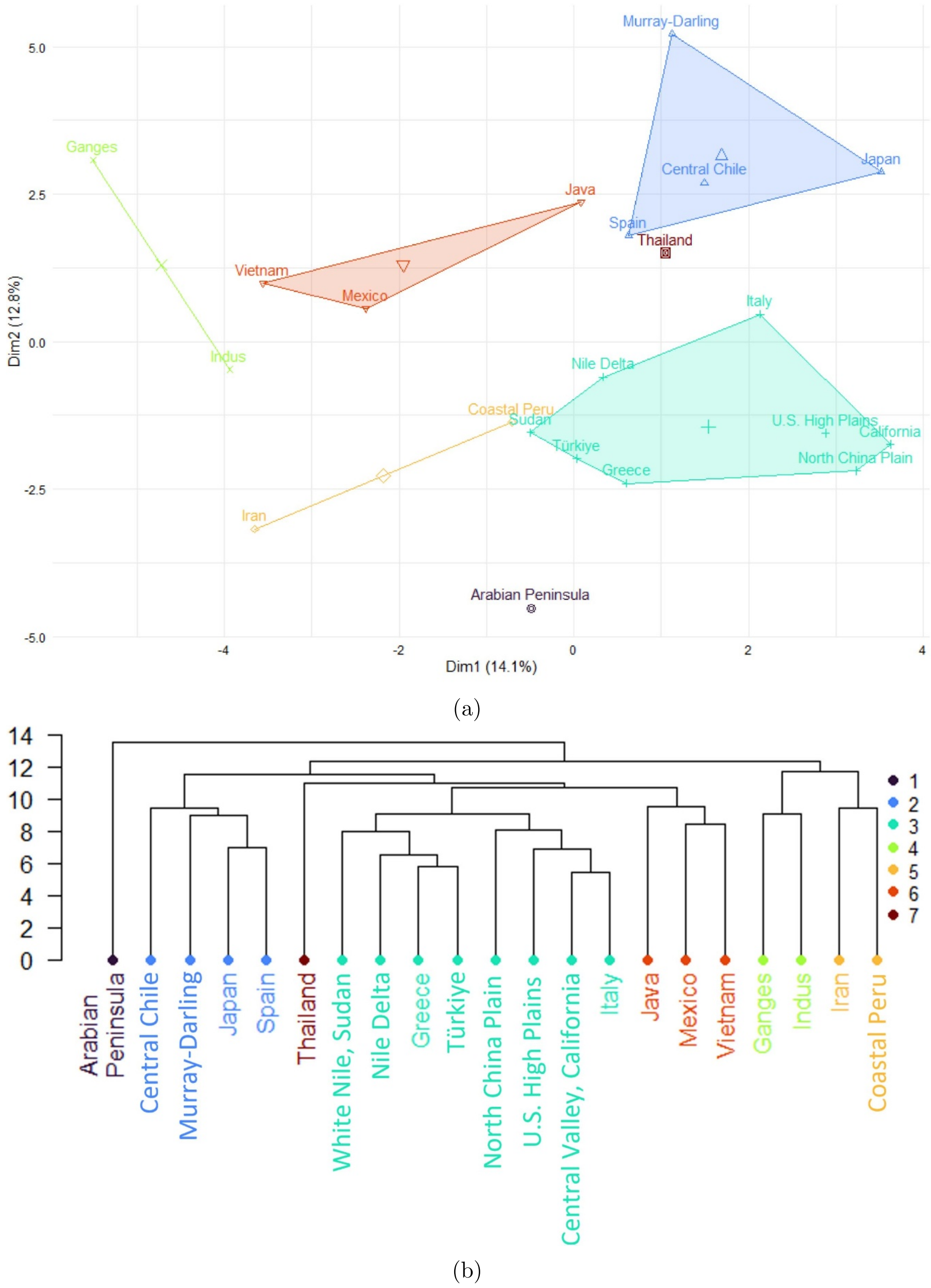


Figure 4. Hierarchical clustering of water scarcity hotspots using the complete linkage method with (a) a representation of the clustering on the two most significant (principal component) dimensions and (b) a dendrogram of the clustering iterations with the distance (dissimilarity) between nodes on the y axis.

28%–33%, health 17%–56%). A potential cause could be the lack of water regulation policies (28%–50%), leading to unregulated private wells from farmers, and subsequent groundwater depletion (52%–61%). Additionally, the lack of regulation leads to inefficiencies in the water system (0%–50%) and siltation (12%–17%), which has additional consequences for food production and migration when yields become less profitable due to water scarcity.

3.3.5. Cluster 5 Surface and groundwater depletion: Coastal Peru, Iran

Coastal Peru and Iran are both typified as hotspots that have very similar results in their states component. In both hotspots groundwater (60%–91%) and surface water depletion (60%–82%) combined with salinization (30%–36%) and contamination (30%–55%) of water resources are well documented. Peru and Iran are the only hotspots where both surface and groundwater depletion are reported in over 60% of the case studies. Similar to cluster 4, depletion and contamination could be caused by a lack of governmental water resource management and subsequent unauthorized water extraction (irrigation mismanagement 27%–60%, water rights 18%–50%, stakeholder non-involvement 27%–60%, unregulated groundwater 20%–55%). For Peru and Iran conflict and rural-urban migration (45%–50%) are also prevalent due to water scarcity and inequality of water supply.

3.3.6. Cluster 6 Land subsidence: Mexico, Java, Vietnam

Mexico, Java and Vietnam show similarities in above average values of industrial (30%–71%), municipal (40%–75%) and agricultural (70%–100%) water use. While these values can also be found in other clusters, Mexico, Java and Vietnam have one common impact that is unique compared to other hotspots. This cluster is severely impacted by subsidence according to the case studies (10%–27%). This is likely due to groundwater overexploitation (20%–67%), leading to high rates of land subsidence.

3.3.7. Cluster 7 Virtual water trade: Thailand

What signifies Thailand as a water scarcity hotspot in its own cluster is its important water system pressure: virtual water trade (43%). Thailand is one of the largest rice exporters in the world, exporting about one third of their total rice production (Silalertruksa *et al* 2017). Moreover, a limited amount of responses are documented in the case studies, indicating that the extent of policies implemented in Thailand to reduce water scarcity remains limited.

4. Discussion

The global water scarcity hotspots found in this study align with well-known water scarcity regions estimated by previous work, even though methods for identifying them vary per study (Wada and Bierkens 2014, Kummu *et al* 2016, Mekonnen and Hoekstra 2016, Liu *et al* 2017, Greve *et al* 2018, Huggins *et al* 2022). Regions that are not identified as water scarcity hotspot in this study (figure 2), but are often regarded as such in previous work, are mostly found in arid zones with relatively low populations and water demands (e.g. North Africa). These regions are not considered as a water scarcity hotspot in this study as their water demand is too low to result in a significant WG compared to highly populated regions, yet they could still yield a large WSI. Such a relatively small WG implies that the societal challenge to solve water scarcity issues is also relatively more manageable. Therefore, the WG metric proves to be a more accurate representation of regions where populations are coping more severely with water scarcity compared to a WSI, where regions with low demands are also considered as a hotspot (Mekonnen and Hoekstra 2016, Liu *et al* 2017, Greve *et al* 2018).

Still, some regions with a large WG in figure 2 are not identified as hotspots due to lack of published case studies on water scarcity (e.g. South Korea or the Rhine catchment). This indicates that water scarcity problems are not perceived as severe in these regions or there is limited research done on water scarcity here (Sun *et al* 2022).

Our results stress the importance of considering local (case study) knowledge into global assessments, as GHMs, in our case PCR-GLOBWB 2, rely on globally available data that come with uncertainties. For the simulation of the WG external allocation and return flows are, for example, not considered in this study. Consequently, the WG is overestimated in regions where demand is met by allocation from sources outside the local grid squares before non-renewable groundwater use occurs (Padowski and Jawitz 2012, Sun *et al* 2021). This is the case for basins with extensive irrigation networks, such as the Indus, or in the context of inter-basin water transfers. The latter, however, does not necessarily translate into a reduced water gap, as water transfer projects may result in inequality of water distribution to users and the environment (Purvis and Dinar 2020, Sun *et al* 2021). Nonetheless, the general patterns and hotspots remain accurate, as confirmed by other studies.

Another reason that hotspots are not found in literature, but do appear in the model, is that local mitigation measures might have resulted in a decreased WG. While global models aim to include as much local information as possible, it is nowadays still difficult to include all relevant human-water interactions. For example, irrigation by small-holder farmers is often not accurately represented in GHMs, nor are small reservoirs and ponds that are used for local water supply. The use of treated wastewater can also be a reliable source of water, further reducing the WG and local impacts (Jones *et al* 2021). Over time more of these missing processes will be included in GHMs, especially with the push to higher resolution global modeling efforts (Bierkens 2015, Döll *et al* 2016). Until then, this study shows that combining qualitative and quantitative data is a valid alternative to identify local processes associated with human-water interactions.

When comparing the DPSIR results to global assessments of individual DPSIR indicators, it is foremost evident that global assessments on the impacts and responses of the WG are severely lacking. This is likely because impacts and responses are hard to quantify. Global research on the relative importance of water scarcity drivers, pressures and subsequent changes in the state of the water system are, on the other hand, more common, therefore we will focus on comparisons with those.

Our literature study showed that for 14 hotspots water scarcity was found to be predominantly driven by population growth. This is a similar result as that of Kummu *et al* (2016), who found population growth to be important for 9 of these regions. Moreover, at 20 hotspots from the DPSIR analysis the pressure on the water system is high due to high water consumption rates (agricultural, domestic and industrial water use). Of these 20 hotspots 17 are in agreement with the locations of extremely high consumption rates as estimated by Wada and Bierkens (2014) and Huang *et al* (2021). The 20 hotspots where a WG is found to be related to water quality issues, are largely in agreement (19 out of 20) with the water quality hotspots found by Van Vliet *et al* (2021) and Jones *et al* (2022). For salinization, however, the agreement is slightly lower with 6 out of 13 hotspots that are also identified by Jones *et al* (2022).

Such underestimations may also occur for other indicators in the DPSIR analysis, due to underrepresentation of case studies in regions where research funding is lacking (Mongeon and Paul-Hus 2016), such as Sudan, Thailand or Java, where only seven case studies have been found. Moreover, the global interaction of unsustainable virtual water trade is underrepresented in case studies, as in many regions, such as Indus, Mexico and the USA, the water gap is increased due to production for the global market (Rosa *et al* 2019), while the results of response 'Virtual water trade (−)' are low (figure 3). Therefore, case studies may not cover all aspects of water gap issues at play. Still, local case studies will provide more detailed context on WG issues than GHMs.

The DPSIR results are in agreement with trends shown in global gridded datasets (supplementary table D). Especially the most important drivers and pressures found in this study show a high agreement with upward trends observed in the data e.g. population growth, agricultural, municipal and industrial water use. Hotspots that have had the largest change over time for particular indicators, do not necessarily have the largest DPSIR value for the corresponding indicator. For example, at the North China Plain the observed increase in industrial water use was largest from 1960–2019 (supplementary table D), while the literature reported on this as a major driver for only 20% of the case studies. Other than data source limitations, reason for this could be that the drivers and pressures responsible for the WG at the hotspots are not perceived as important, despite large changes over time observed from the data. When data indicates a large change over time for particular indicators, while these indicators are not mentioned in case studies, this could be a signal that these indicators will become important in the future if current trends persist.

The hierarchical clustering method gives insights on how the WG developed and affected hotspots, thereby revealing common narratives. Therefore, similar solutions may be implemented at hotspot clusters that have a large commonality. For example, cluster 2 (hydroclimatic change) contains hotspots with relatively high incomes and moderate population growth rates. Consequently, measures to close the WG at these hotspots should prioritize reducing the per capita water use by, for example, continuing to promote water conservation through water pricing and water rights system improvements. In contrast, for clusters where population growth is large, such as cluster 4, solutions should instead prioritize making more water available, e.g. wastewater treatment to increase water quality. Regardless, the hierarchical clustering method does not allow for identifying causality of the water gap per cluster. It draws parallels between the hotspots based on the entirety of the DPSIR results using an unsupervised machine learning algorithm. This means that the interpretation of the clusters has to be done with caution, as any causal relationship between drivers, pressures and the water gap should be further substantiated.

Water scarcity is a complex environmental problem that requires an interdisciplinary approach to capture all involved mechanisms. The DPSIR framework is one of a few frameworks that allows for such an interdisciplinary investigation, and is therefore a powerful tool for evaluating complex environmental issues (Tscherning *et al* 2012, Binder *et al* 2013, Zare *et al* 2019). A drawback of the DPSIR framework is, however, that changing system dynamics are not considered (Gari *et al* 2015). The DPSIR framework suggests unidirectional causal relationships in context of a complex social-environmental system. This gives an apparent simplicity of the more complex reality in which feedback and synergistic effects occur. To acquire changes over time and identify positive or negative feedback mechanisms affecting the WG, a more dynamic framework, such as causal inference modelling, is needed. The DPSIR components can be quantified and integrated in such causal inference models describing cause-effect relations of the WG in social-environmental systems (Gari *et al* 2015). As such, the DPSIR results serve as an important basis of causal networks for socio-hydrological models representing human-water interactions at each hotspot, allowing for future estimations in water gap changes. Thereby, such models will provide a better understanding of trade-offs and synergies in different human-water systems around the world and important information for policy makers on where and how to address the multi-faceted problem of water scarcity.

5. Conclusion

Freshwater availability is of fundamental importance for sustaining life on Earth. This study highlights the critical issue of the global water gap that emerges when WD is larger than availability in regions, leading to non-renewable water withdrawal and resource depletion. We applied the DPSIR framework to over 300 case studies in 21 different water scarcity hotspots to examine the local causes of the water gap, the subsequent impacts on the water system, society and the environment, and the actions or lack of actions taken that are positively or negatively affecting the water gap. Through this approach we combine global model estimates of the water gap with more detailed local information.

At the 21 water scarcity hotspots our findings emphasize the dominance of hydroclimatic change (reported in 49% of all case studies) and population growth (31%) as drivers of the water gap. Agricultural (77%), municipal (46%) and industrial (30%) water use emerge as significant pressures. This leads to groundwater depletion (48%), contamination (33%), and salinization (25%). Global trends based on modelled and reported data show that these major drivers as well as pressures have been increasing over the last decades, decreasing water quality and quantity at the hotspots. The most important impacts on the socio-environmental system are damage to ecosystems (24%), conflict and migration (18%), and reduced agricultural production (17%). While certain interventions, including increased storage capacity (25%), water treatment (18%), and water transfer (16%) exhibit positive contributions, many regions continue to face issues due to, for example, unregulated groundwater use (13%) and inappropriate water rights appropriation (11%).

By differentiating shared patterns from the DPSIR results, we have successfully classified them into seven clusters. This categorization facilitates the formulation and prioritization of solutions to alleviate the multifaceted impacts associated with the water gap. This study reveals the complexity and diversity of water scarcity problems, in particular regarding the variety of impacts on society and the environment as well as the varied governmental responses in place. Global modelling efforts are not (yet) able to capture these complex feedback behaviours, making the combination of local qualitative and quantitative data a powerful tool for identifying current and future trajectories of socio-ecological issues. The DPSIR results have a large potential to provide valuable input to conceptual models representing these complex human-water interactions at hotspots, equipping policy makers with more detailed information on the versatility of the water gap and potential strategies to address this critical global challenge.

Data availability statement

The model output of PCR-GLOBWB for the global water gap are openly available on https://worldwatermap.nationalgeographic.org/ and https://doi.org/10.24416/UU01-0Q6SU6. The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.10591425.

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Authors' contributions

Myrthe Leijnse: Conceptualization, Investigation, Data Curation, Formal analysis, Writing—Original Draft **Marc F P Bierkens:** Conceptualization, Writing—Review & Editing, Supervision **Kim H M Gommans:** Investigation **Daisy Lin:** Investigation **Alex Tait:** Writing—Review & Editing **Niko Wanders:** Conceptualization, Writing—Review & Editing, Supervision.

Conflict of interest

All authors declare that they have no conflict of interest.

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