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Review

Climate change impacts on water security in global drylands

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SUMMARY

Water scarcity affects 1–2 billion people globally, most of whom live in drylands. Under projected climate change, millions more people will be living under conditions of severe water stress in the coming decades. This review examines observed and projected climate change impacts on water security across the world's drylands to the year 2100. We find that efficient water management, technology, and infrastructure, and better demand and supply management, can offer more equitable access to water resources. People are already adapting but need to be supported with coherent system-oriented policies and institutions that situate water security at their core, in line with the components of integrated water resources management. Dryland water governance urgently needs to better account for synergies and trade-offs between water security and other dimensions of sustainable development, to support an equitable approach in which no one gets left behind.

INTRODUCTION

Drylands are the hyper-arid, arid, semi-arid, and dry sub-humid parts of the Earth, found on all continents. Grasslands, savannas, and woodlands in these environments are rich in biodiversity[1] and store substantial amounts of the world's terrestrial carbon in their soils and biomass. Drylands possess a varied and rich geological, cultural, and historical heritage[2,3] and are home to approximately 40% of the world's human population[4] (Figure 1; based on data from the Centre for International Earth Science Information Network[5]. Dryland extent is based on Millennium Ecosystem Assessment delineation).[6] Major land uses include agriculture and pastoralism, with the majority of livelihoods directly reliant upon natural resources. A number of megacities, including New Delhi, Beijing, Los Angeles, Cairo, Tehran, and Mexico City, all of which have complex and diversified economies, are also located in these water-limited environments.[7] Life can be very difficult for people living in dryland areas, particularly in developing regions, where around 70% of the world's drylands are found.[8] In many of these areas, people already face stark challenges related to poverty, food insecurity and malnourishment, poor access to healthcare, poor governance, economic hardship, and marginalization.[9] These difficulties are often exacerbated by land degradation, flooding, drought, and climate change. Drylands in hot, tropical areas have already experienced temperature rises that are higher than the global average, and temperatures are projected to increase by 2°C–4°C by 2100 under higher emissions scenarios (Representative Concentration Pathways [RCP] 4.5 and 8.5).[10] Understanding what these changes mean for water security in drylands is therefore vital.

Several different measures are relevant to the assessment of observed and projected future water security in drylands, and because they consider slightly different aspects of the system, they can highlight different trends. Climatological indices measure the physical components of water security, and include the Aridity Index (AI), drought indices such as the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Evapotranspiration Index (SPEI), the Ecohydrological Index (EI), and soil moisture and terrestrial water storage (TWS). There are also measures that indicate biological responses to physical or climatological variables, such as changes to dryland vegetation indicated by the Normalized Difference Vegetation Index (NDVI). Box 1 explains these terms for each of the indices referred to in the main text in relation to observed and projected impacts of climate change on water security.

By definition, precipitation in drylands balances evaporation from the land and vegetation surfaces. As a result, water is a key limiting factor that shapes the drylands, with these systems being highly sensitive to precipitation and PET dynamics.

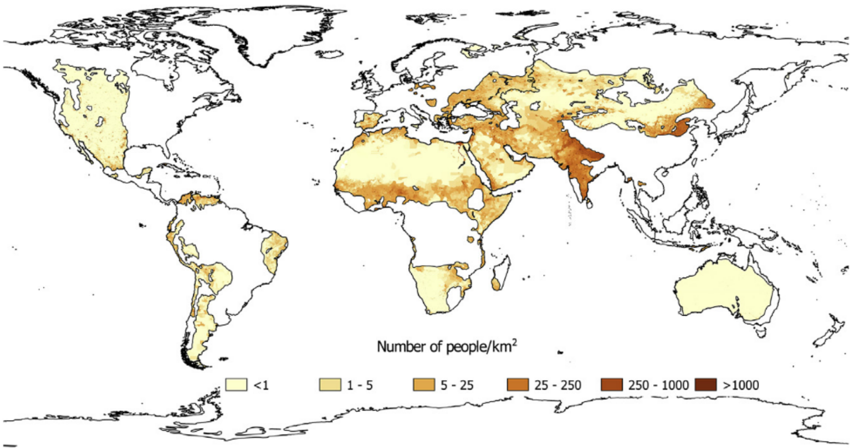

Figure 1. Human population density in drylands
The map shows the population density (number of people/km^2) in drylands, as determined by the AI (see Box 1). High latitude (polar) regions where PET $\leq$400 mm y^{-1} constitute cold drylands. Cold drylands are excluded from this review given their sparse human populations compared with hot (tropical) drylands.

Globally, water scarcity already affects between 1 and 2 billion people, the vast majority of whom live in drylands, where the gap between the demand for and supply of water is the highest in the world. This challenge means that the impacts of climate change, combined with water management decisions, will have profound impacts on drylands and their inhabitants into the future. Projected climate changes indicate that, in a matter of just a few decades, millions more people (approximately half the world's population in total) will be living under conditions of high water stress.[24] This will have impacts not just in dryland areas but also for neighboring countries and beyond, particularly because water and its impacts do not respect national political and administrative boundaries.

The impacts of climate change on water security in drylands go beyond access to clean water and sanitation; they are highly intertwined with many other dimensions of sustainable development, including eradicating hunger and reducing poverty, peace, and security, gender equality, education, and health[25] (Figure 2). For example, water scarcity can negatively affect women more than men because of women's key role in household water provisioning in many developing countries[26] resulting in more time spent by female household members, including children, in fetching water for domestic consumption. Climate change affects the structure and functioning of multiple ecosystem attributes across the world's drylands,[27] with important implications for agriculture and vegetation productivity, as well as the livelihoods they support. Increased water scarcity due to climate change will make attainment of the Sustainable Development Goals (SDGs) more difficult in many drylands, especially in the developing world.[10] Improved knowledge about new emerging hotspots of climate change-driven water insecurity will be critical for measuring progress toward the achievement of the SDGs.[28]

Taking into account the magnitude and importance of these emerging challenges, this review focuses on the impacts of climate change on water security in drylands, considering both environmental and human systems. Water security has been defined in various ways depending on the discipline, method, and scale of analysis that is adopted,[29] but the different definitions agree that water security and water scarcity are multi-faceted. Water scarcity is often perceived as determined by the (non-)availability of water resources, also termed physical water scarcity; however, scarcity can also result from lack of infrastructure (economic water scarcity), poor water quality (clean water scarcity), or insufficient retention of water resources in ecosystems (environmental water scarcity). Most global freshwater resources are transboundary, adding a political water security dimension: potential disruption to the availability, access, and quality of water resources when managed across two or more jurisdictions. These determinants vary in their spatial distribution, where physically water-abundant regions can be water scarce due to high pollution levels, or lack of infrastructure, or uncoordinated transboundary water use (Figure 3, which uses AQUASTAT/Food and Agriculture Organization [FAO] values for 2015,[30] calculations based on Falkenmark et al.,[31] and water quality risk based on Damania et al.[32]). Water security therefore encompasses aspects of availability, accessibility, quality, and stability[28] (Figure 4). Stability refers to the time dimension of water availability, access, and quality. If availability, access, and quality of water resources fluctuate substantially, people cannot be considered water secure. Political water security is a major factor that can affect water stability, and climate change and associated increases in rainfall variability are becoming a key source of instability in water security. While water security can be quantitatively measured[28,33] across physical, economic, and quality dimensions, it also involves contested views, particularly regarding what is implied by stability and political water security. The dynamic and subjective nature of these concepts makes it difficult to create maps showing water stability and political water security. Water security may be linked to food security, to energy security, to physical water scarcity generating conflicts, or even viewed as a potential weapon in conflicts.[34] While physical water scarcity is real in many locations, for instance as a result of dwindling groundwater aquifer supplies or increased salinity, a discourse of scarcity may also be used to justify certain political interests (e.g., building a high dam for hydropower development).[35] Climate change directly affects all four dimensions of water security.

The remainder of this review synthesizes: (1) observed climate changes in drylands to date and their impacts on water security; (2) future changes under different climate change projections, considering what may be anticipated in terms of water security challenges; and (3) the management of water security challenges in drylands. Effective water management under a changing climate needs to target all dimensions of water (in)security in a holistic way. The review concludes by presenting the major features

Box 1. The aridity paradox: Defining and delineating the drylands

Dryland extent describes both the physical boundaries of dry areas (a climatological definition, commonly measured using the AI), and the extent of dryland vegetation (an ecological definition). Climatological and ecological definitions do not always delineate the same geographical areas when projecting future changes to dryland extent.

The AI is the ratio of annual precipitation to potential evapotranspiration (PET). It has a long use history, defining drylands as areas with AI < 0.65.[11] Sub-categories include (1) dry sub-humid (0.5 ≤ AI < 0.65), (2) semi-arid (0.2 ≤ AI < 0.5), (3) arid (0.05 ≤ AI < 0.2), and (4) hyper-arid (AI < 0.05) areas (Figure 1). Cold (polar) drylands (not considered here) are where PET is <400 mm/year.[12] The AI usually projects increasing aridity under climate change, leading to projections of widespread dryland expansion.[13,14] However, while the AI has been decreasing over the last 50 years,[15] dryland vegetation has been increasing globally.[16–19] Hence, correspondence between changes in AI and changes in dryland vegetation over recent decades is limited.[15] The AI overestimates the role of PET compared with rainfall,[15] and neglects CO_2 impacts on evapotranspiration and seasonality in rainfall and evapotranspiration. Increased annual PET due to higher temperatures may have little impact if temperature and actual evapotranspiration are not increasing during the wet season when there is vegetation growth. Given the AI's limitations, indices that incorporate the influence of plant physiology on evapotranspiration, such as precipitation minus actual evapotranspiration, soil moisture, runoff, and land water storage, may be more suitable for future projections. The EI is directly based on observations of land surface ecohydrological properties using Coupled Model Intercomparison Project Phase 5 (CMIP5) models.[15] The EI aims to capture the role of vegetation responses under higher CO_2 levels. Results show that EI decreases in some regions (reflecting increased aridity) and increases in others, better capturing observed dryland changes than the AI.

The PDSI is a standardized index, generally spanning −10 (dry) to +10 (wet). Values lower than −3 represent severe to extreme meteorological drought. The PDSI incorporates prior precipitation, moisture supply, runoff, and evaporation demand at the surface level to estimate relative dryness.[20] It is based on temperature data and a physical water balance model, so can capture global warming effects on drought through changes in PET. However, it does not compare well across regions, and is not amenable to assessing short timescales, making it difficult to correlate with specific water resources.[21] The Standardized Precipitation Index (SPI) characterizes meteorological drought on a range of timescales. The SPI can be calculated for periods of 1–36 months, using monthly input data, so can characterize drought at timescales corresponding with the temporal availability of different water resources (such as soil moisture, groundwater, river discharge, and reservoir storage). The SPI is more comparable across regions than the PDSI because it is calculated in relation to climatological norms for the location and season. However, the SPI does not consider evapotranspiration, so does not capture the effect of increased temperatures associated with climate change on moisture demand and availability.

The SPEI is a drought index, calculated as the difference between precipitation and PET. By incorporating evaporation, it captures the main impact of increased temperatures on water demand. It can be calculated at different timescales (e.g., monthly or weekly). The SPEI is used to measure drought severity in terms of intensity and duration and can identify the onset and end of drought episodes. PET (or potential evaporation) describes the amount of evaporation that would occur if unlimited water were available. It is influenced by surface and air temperatures, radiation and wind, vegetation characteristics (such as ground cover and plant density), and soil type. By definition, annual potential evaporation exceeds annual precipitation in drylands. PET is estimated using various methods, such as the Penman-Monteith equation. The surface water balance, the difference between precipitation and actual evapotranspiration, describes the availability of surface water on land, while soil moisture is the water content stored in a given layer of soil. Global analyses rely on satellite data or model simulations because *in situ* observations are still unavailable for most of the world.

TWS is the sum of continental water stored in vegetation, rivers, lakes and reservoirs, wetlands, soil, and groundwater. It is critical in the global water and energy budget, influencing water resource availability and water flux interactions among Earth system components.[22] While groundwater is an important component of the dryland ecohydrological system, its role in TWS remains poorly quantified.[23] The NDVI is based on global satellite data that characterize vegetation growth by assessing absorption and reflection of photosynthetically active radiation over a given time period, relative to the regional norm. The NDVI describes the relative density of vegetation and is used as an indicator of agricultural drought.

of such a multidimensional approach through the concept of integrated water resources management (IWRM) for drylands.

OBSERVED CLIMATE CHANGES AND THEIR IMPACTS ON WATER SECURITY

Observed changes in temperature, rainfall, and evaporation over recent decades have already affected dryland extent and water security in many areas of the world.[10] In some drylands, rising temperatures have augmented aridity where increases in PET outpace those of precipitation,[36,37] and temperature and aridity increases are exacerbated by the sparse vegetation cover and lower soil moisture of dryland ecosystems.[13] However, this is not a global trend as many drylands are experiencing increases in vegetation cover and rainfall.

Both the amount of rainfall and its seasonality have changed in many dryland areas, associated with natural decadal variability and anthropogenic warming,[36] affecting both availability and stability dimensions of water security. Annual rainfall has increased in some locations (e.g., the West African Sahel, the Karoo in South Africa, Gobi Desert in China, and central/west Australia) and decreased in others (e.g., east Australia, and parts of East Asia), often with fewer, more intense rainfall events and increased unpredictability.[14] Such changes have had major

Goal	Links to water security in drylands	Goal	Links to water security in drylands
1 NO POVERTY	Water security is vital in drylands to support vast populations dependent on agricultural and natural resource based incomes	10 REDUCED INEQUALITIES	Inequalities in access to water crosscut multiple aspects of intersectionality
2 ZERO HUNGER	Rainfed/irrigated food production requires water security to support adequate yields, food security and good nutrition	11 SUSTAINABLE CITIES AND COMMUNITIES	Drought and floods in urban areas can affect large numbers of people given rapid urbanisation trends in many drylands
3 GOOD HEALTH AND WELL-BEING	Water-borne diseases and can be reduced with improved access to clean, safe water	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Water footprint analysis can provide insights into water use and allocation at different points in the production and consumption process
4 QUALITY EDUCATION	Child morbidity due to water-borne diseases can be reduced with improved knowledge and education; reduced time spent collecting water increases time for formal education	13 CLIMATE ACTION	Adaptation is a key response to water scarcity under climate change in drylands
5 GENDER EQUALITY	Lack of water security has differentiated impacts on women and men / girls and boys	14 LIFE BELOW WATER	Wastewater flows and eutrophication can affect coastal biodiversity
6 CLEAN WATER AND SANITATION	Core element with links to all other SDGs	15 LIFE ON LAND	Irrigation, secondary salinization, ecosystem characteristics
7 AFFORDABLE AND CLEAN ENERGY	Water security supports hydro-energy generation and plays a key role in energy security	16 PEACE, JUSTICE AND STRONG INSTITUTIONS	Water can be at the centre of conflicts and competition, as well as being a focus for cooperation
8 DECENT WORK AND ECONOMIC GROWTH	Water sector jobs and jobs in other sectors rely on water (energy, agriculture etc) and link to youth migration, while earning a decent living can enable people to pay for clean water	17 PARTNERSHIPS FOR THE GOALS	Transboundary water governance, technology and knowledge exchange, alongside stakeholder participation can help achieve water security
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Industry creates challenges linked to water pollution, water distribution/sewage but can also help by providing flood defences, dams, precision irrigation systems		

Figure 2. Interlinkages between water security and attainment of the SDGs in drylands

All SDGs show links to water, underscoring the importance of water security for both environmental and human systems.

impacts on water security in desert and semi-arid areas. For those people who directly depend on the natural resource base for their livelihoods, such variability and change present a huge challenge.

Changes in surface water availability (the difference between precipitation and actual evapotranspiration) over drylands have been demonstrated globally over the period 1982 to 2011, with significant decreasing trends occurring in south-western North America and west Asia and significant increasing trends in northern Australia and central and southern Africa.[14] Over the same period, a weak decrease in soil moisture has occurred in drylands globally, although, in some regions, including parts of central western Australia, southern North America, southern South America, west Asia, and the Mongolian Plateau, reductions in soil moisture have been significant.[14] A strong increasing trend in mean NDVI over the past three decades has occurred, consistent with the widely reported greening over Africa, Australia, and South Asia. Greening is associated with precipitation increase in most regions, with the exception of some irrigated regions in the western United States, Arab regions, and north-eastern parts of China, where precipitation has decreased but NDVI increased.[14]

TWS in drylands has also declined globally over the period 2002 to 2017, with stronger trends found in hyper-arid and arid regions.[38] Model experiments suggest that the observed reductions in TWS are due to anthropogenic warming over south-western North America and the Middle East, while water withdrawals have contributed more to the recent declines in TWS over North China.[38]

When measured using the AI, dryland area has increased by ~4% from 1948 to 2004,[12,39,40] with the semi-arid zone expanding at the greatest rate (~7%).[13] However, as described in Box 1, the AI approach is widely critiqued and contested. The rapid rate of warming in drylands and the observed increase in climatological extent of dryland climates, as measured by the AI, has led to assertions that changing aridity would result in a global trend of declining dryland vegetation productivity, and the expansion of drylands.[36,41] However, interactions with land use and variable changes in rainfall and carbon fertilization mean that dryland ecosystems have shown mixed trends of decreases and increases in vegetation and biodiversity in different locations,[10,42,43] both of which can create long-term failure to meet demands for and supply of ecosystem goods and services.[7] Drought and warming-associated tree

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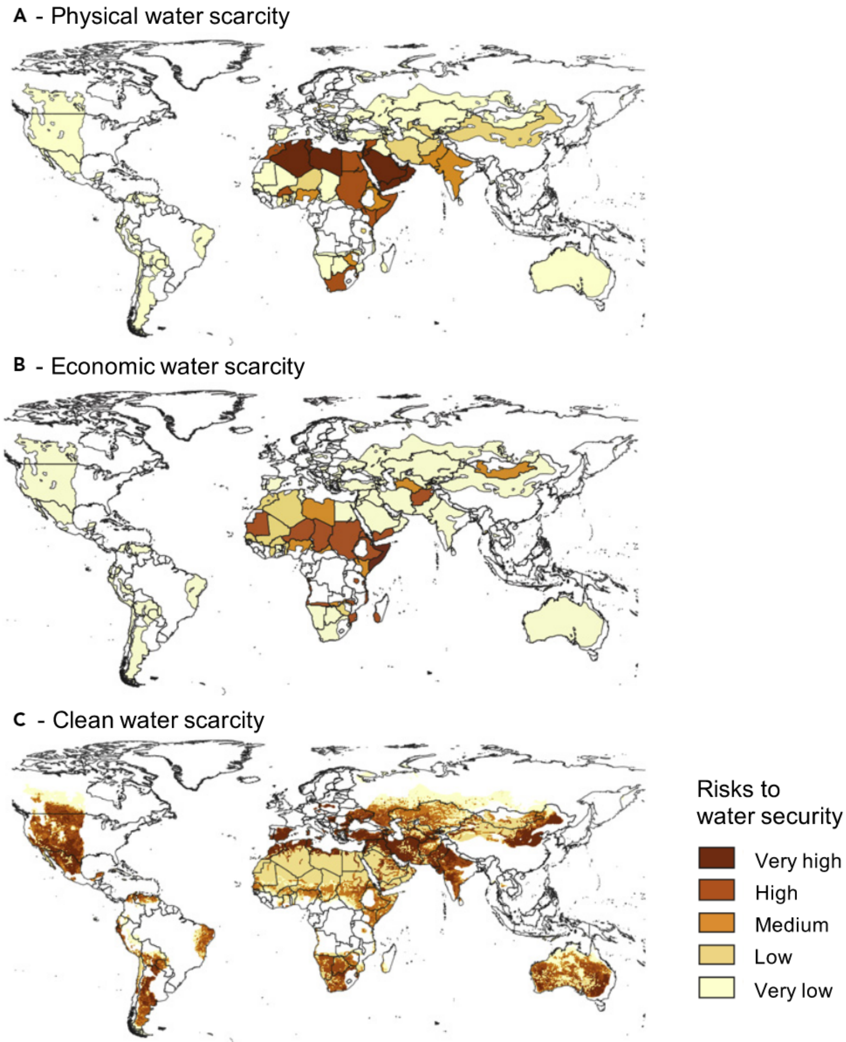

Figure 3. Dimensions of water scarcity in global dryland regions

Different measures highlight the spatial diversity of different dimensions of water scarcity: (A) physical water scarcity (internal renewable water resources per capita); (B) economic water scarcity (total population with access to safe drinking water); and (C) clean water scarcity (water quality risk). Measures are shown for the world's dryland areas, based on the same Millennium Ecosystem Assessment delineation as Figure 1. All variables are normalized to values between 0 and 1 with equal interval classification for comparability.

cover decline and tree mortality have been recorded in localized areas in North Africa's drylands[44,45]; parts of the arid diagonal in South America[46]; patches in North America's Mojave, Chihuahuan, and Sonoran deserts[43,47]; and parts of the Middle East and southwest Asia,[43,48] with desert succulent species appearing susceptible to both heat- and drought-induced mortality.[49,50] Hot droughts in particular may also reduce the resilience of the system, making plants vulnerable to secondary agents of mortality like disturbance or disease[51] and altering vegetation recovery after disturbances (e.g., fire).[52]

Desertification or vegetation browning has been observed in the western United States, eastern Brazil, Iraq, Syria, Jordan, Kazakhstan, Uzbekistan, Mongolia, and parts of Australia,[43] with desertification generally driven by interactions between climate change, land use, and land management. Ecosystems experiencing reduced water availability are more sensitive to unsustainable land management practices like sustained heavy grazing and heavy biomass utilisation.[43] In other regions, widespread dryland greening has been observed,[53,54] with trends driven by large-scale increases in woody cover and a limited increase in herbaceous production at desert-grassland interfaces.[45,55,56] Shrub encroachment and increases in woody vegetation have been recorded widely in North and Central American drylands,[57] the West African Sahel,[58,59] southern African shrublands,[60,61] central Asia,[62] and most tropical savannas,[63] with changes driven by seasonal combinations of changing temperature and rainfall, CO_2 fertilization, and changes in land management (e.g., decreases in large browsers, increased sustained heavy grazing, and fire suppression).[42,57,64] Increases in woody plants are sometimes accompanied by decreases in palatable grass species[65] and significantly reduced grass biomass.[66] These changes have important implications for livestock productivity and livelihoods, especially where herds cannot utilize increasing shrub and tree layers. Research in grasslands and savannas in North and South America identified that for every 1% increase in tree cover, a 0.6–1.6 reduction of reproductive cows per km^2 occured.[67]

Changes in climate and ecosystems both directly and indirectly alter the ecosystem water balance, affecting the availability dimension of water security. Extreme droughts, which are expected to become more frequent,[68] directly alter local hydrology and cause reduced plant productivity and increased tree mortality[69,70] and reduce delivery of water-derived ecosystem services,[71,72] including, e.g., nutrient cycling, hydropower, and flood control. However, simultaneously, woody plant encroachment, invasion, and afforestation alter the ecosystem water balance through increased precipitation interception[73] and increased evapotranspiration.[74–76] Increased woody cover, in combination with extreme droughts, will further reduce soil water availability[77] but can also increase carbon storage in vegetation and soils. Droughts also have considerable impacts on water quality,[78] changes in which can be associated with increased salinity due to lower dilution, enhanced algal production, as well as changes in turbidity levels.[78] While these observed changes demonstrate a range of impacts on different ecosystem components, changes to water regimes also have substantial impacts on people.

Droughts have had the greatest adverse impact on human populations out of any natural hazard during the 20th

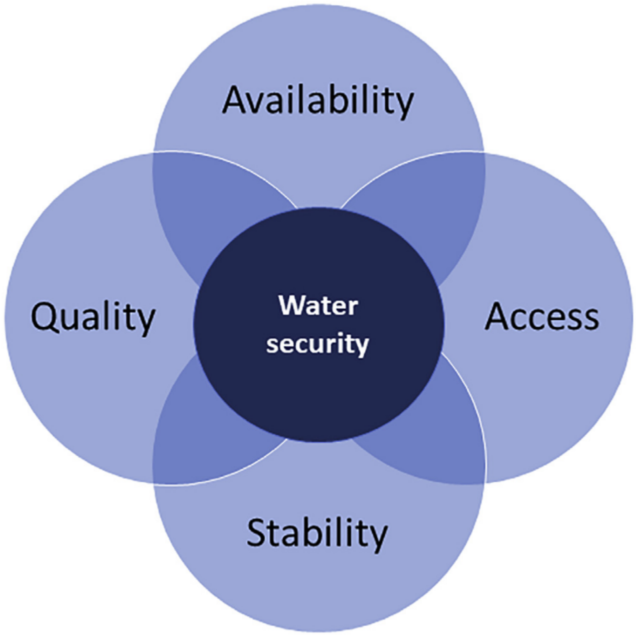

Figure 4. Conceptualization of water security

century,[79] and, in the period 2000–2019, represented 11% of extreme climate events in Africa, but 80% of affected people (270 million).[80] The Dry Corridor in Central America (Honduras, El Salvador, Guatemala, and Nicaragua) has been hit by the worst droughts in decades in the past 10 years, and >1.3 million subsistence farmers and workers, most of whom are considered to be disadvantaged Indigenous people, have lost their livelihoods, experienced severe food insecurity (Integrated Phase Classification 3 or above) and have adapted their migration patterns.[81] In the drylands of El Salvador and Honduras, high levels of out-migration have left many women single-handedly managing farms and tending to families.[81] The severe droughts in this case were followed by fires, heavy rains, flooding, landslides, and serious outbreaks of climate-sensitive vector-borne diseases, including dengue, chikungunya, and Zika.[81] Similar disease impacts, including malaria, diarrhea, and cholera, have been experienced following increased dryland irrigation to produce food (for example, in southern Africa).[82]

Climate extremes, including droughts, have exacerbated seasonal dryland food shortages, affected livelihoods and human resilience, and have been major contributors to food insecurity and malnutrition. This provides a useful example of how instability in water security spills over into instability of food security. Food security challenges affected around 166 million people in 26 countries in Africa and Central America, who required urgent humanitarian assistance to safeguard their lives between 2015 and 2019, the majority of whom were located in drylands.[83–85] Links between droughts and malnutrition are nevertheless complex.[86] Recent studies in Ethiopia, Senegal, and India indicate that drought exposure can contribute to malnutrition, with malnutrition occurring not only during the drought itself but also for several years after the event.[87–89] Children affected by under-nutrition during their first 1,000 days of life can experience lifelong impacts,[90,91] leading to stunted growth, which is linked with impaired cognitive ability and reduced educational and future work performance.[92] Associated costs of stunting in terms of lost economic growth can be on the order of 10% of gross domestic product per year in Africa.[93] On top of this, a lack of access to water and sanitation services causes almost 1,000 deaths among children under 5 years old every day, and increases the risk of numerous diseases through intake of unsafe water.

A lack of water security is not just problematic for human health and wellbeing in rural areas but also in urban dryland areas. Box 2 provides insights into the importance of appropriate water management in relation to various dimensions of water security challenges linked to observed climate changes in Tehran, one of the world's dryland megacities.

PROJECTED CLIMATE CHANGES AND IMPACTS ON WATER SECURITY TO 2100

The accelerated warming that has been observed over drylands in recent decades is expected to continue in the future, with deserts expected to warm at a faster rate than many other terrestrial areas.[10,103] Surface warming over drylands is projected to reach ~6.5°C under the high-emissions scenario (RCP8.5) and ~3.5°C under low-moderate emissions (RCP4.5) by the end of this century, relative to the historical period (1961–1990).[13,36] Associated with increased temperatures, PET is projected to increase in all regions globally, under all RCPs,[10] resulting in drier conditions and lower soil moisture in some locations, even where precipitation is unchanged.

Projected changes in precipitation are more uncertain than temperature projections, because rainfall is naturally highly variable, and the fine temporal and spatial scale of the associated physical processes pose challenges to modeling. Improvements in simulating variability of precipitation, long-term trends, and extremes have occurred in recent years; however, as resolution has increased, parametrization of physical processes has improved.[104] Nevertheless, the large variability in regional precipitation results in widely varying projected changes in annual precipitation over global drylands. For example, projections suggest that annual precipitation could increase by more than 40% over central Asia and the Sahara and Sahel, but decrease by approximately 20% over southern Africa and north-eastern South America.[36]

In general, annual precipitation is projected to increase over most of Eurasia, tropical Africa, and extratropical North America, but to decrease in the subtropical regions, including areas near the Mediterranean Sea, south-western North America, southern Africa, and most of Australia and South America.[37,105–107] The picture overall, though, is mixed. Wet regions are generally expected to become wetter and dry regions drier with the intensification of the hydrological cycle under climate change. Drying trends may be most significant in semi-arid and arid regions,[108–110] but recent research using the EI has shown how variable the impacts are on drylands, highlighting no overall anticipated dryland expansion.[15]

The frequency, severity, and duration of drought conditions are expected to substantially worsen in many regions of the world.[111] In a 1.5°C warmer world, historical 50-year droughts (based on the

Box 2. Water security challenges linked to observed climate changes in Tehran

Urbanization is one of many global megatrends, as people move to both existing and emerging cities around the world. Urbanization is taking place against the backdrop of overall population growth, particularly in sub-Saharan Africa and other tropical and Mediterranean drylands.[94,95] Many large cities around the world, not just in the drylands, are already experiencing prolonged droughts,[96] with water shortages seen recently in Rome (Italy), Chennai (India), Cape Town (South Africa), Tehran (Iran), and Sao Paulo (Brazil).

Iran is currently facing high water stress in terms of reduced water availability during the current prolonged drought, resulting from a combination of climate variability and change, alongside water mismanagement.[97,98] This has led to water insecurity in Iran's capital, Tehran, a megacity home to around 9 million people. Treated water use per capita in Tehran is two to three times greater than the international average, while leakage rates are high due to the use of old, poorly maintained pipes.[99] The situation highlights economic water security challenges in the city, related to insufficient investment in water infrastructure. Water quality is also strongly affected, with knock-on impacts on access to clean water. Pollution linked to poor soil nutrient management, inadequate wastewater treatment, and sewage is widespread. Around 60% of water withdrawal in Tehran relies on groundwater extraction from wells, springs, and qanats (gently sloping interconnected tunnels in hillsides that use gravity to deliver groundwater to lower-altitude areas).[100] However, after this water is used, it tends to exit the city as wastewater, while investment in reuse, revision of water allocation, and assessments of water supply chains are limited.[97,99] Tehran as a major urban center is not the only part of the country facing water challenges. Even northern and north-western areas that are historically less prone to water insecurity have seen substantial rainfall decreases. Given that the agricultural sector uses 92% of the country's renewable water per year (an amount substantially greater than in other countries),[101] it is clear that these challenges will only be exacerbated by further climate change and that significant adaptation efforts are needed to enable a water-secure future.[102]

SPEI) could double across 58% of global landmasses, an area that increases to 67% under 2°C of warming.[112] Multi-year drought events of magnitudes exceeding historical baselines will increase by 2050 in Australia, Brazil, Spain, Portugal, and the United States.[113] Declines in TWS are projected to continue, with future changes driven primarily by climate forcing rather than land and water management activities.[22]

The magnitude of drought stress in different regions differs depending on the metric used (see Box 1).[114] Projections based on the PDSI suggest drought stress will increase by more than 70% globally, while a substantially lower estimate of 37% is found when precipitation minus evapotranspiration is used.[115] However, the two metrics agree on increasing drought stress in regions with more robust decreases in precipitation, such as southern North America, north-eastern South America, and southern Europe,[115] all of which contain substantial dryland areas. An increase in drought hazards in the later quarter of the 21st century compared with the period 1971–2000 in Mediterranean, southern and eastern Africa, and southern Australia's dryland areas is indicated from the literature.[116] Nevertheless, Coupled Model Intercomparison Project (CMIP) 5 models for all types of droughts exhibit substantial differences, so confidence remains low in relation to drought projections.[117]

Modeling studies based on the AI suggest that the extent of hyper-arid, arid, semi-arid, and dry-subhumid drylands could expand globally by 7% by 2100 relative to 1981–2010 under a 4°C above preindustrial warming scenario.[104] In a 4°C warmer world, 11.2% of global land area is projected to shift toward drier types and 4.24% to wetter,[104] with the majority of newly expanded dryland areas occurring in developing countries.[13] Expansion of arid regions is likely in southwest North America, the northern fringe of Africa, parts of southern Africa, and Australia.[13,104] In contrast, India, northern China, eastern equatorial Africa, and most regions south of the Sahara are projected to have shrinking drylands.[106,118–120] The global picture nevertheless remains mixed under the EI.[15]

Vegetation models that incorporate CO_2 demonstrate a similar paradox, where, with warming, widespread greening with patches of browning are likely.[54,121,122] These models project notable increases in leaf area index (LAI) and woody cover for arid grasslands, desert margins, and tropical savannas[122] to the extent that losses of savannas of magnitudes of between 5% (in Australia) and 55% (South America) are expected to occur through conversion to closed-canopy systems. Browning and aridification have been projected for parts of the Catinga in South America, northern Morocco, and parts of the Namib desert.[54] Projections that incorporate CO_2 most closely reflect the changes in drylands that have been observed in recent decades.

Where areas are likely to experience increased aridification, the warming and drying can reduce soil organic carbon storage.[13] Soil degradation and reduced soil moisture also substantially limit gross primary productivity and affect the rate of photosynthesis, which absorbs CO_2 and stores carbon. In combination with land degradation, which also contributes to greenhouse gas emissions, this is a positive feedback cycle, with the warming and drying reinforcing each other, and dryland soils storing less carbon and emitting more CO_2 into the atmosphere, exacerbating global warming. Nevertheless, dryland areas in which greening is occurring can experience an increase in soil carbon[123] and reduced freshwater availability as the new vegetation uses water that would previously have run off.[124]

Projections show that the number of people residing in drylands exposed to water stress, drought intensity, and habitat degradation will reach ~974 million, ~1,267 million, and ~1,285 million people, respectively, by 2050, at 1.5°C, 2°C, and 3°C of global warming under the Shared Socio-economic Pathway 2 (SSP2; business as usual) scenario.[24] At the same time, projected climate change impacts are far exceeded by the hydrological effects of past and present water extraction in many semi-arid continental river systems.[125] This suggests there are important opportunities that could emerge from improved water governance in drylands into the future.[126]

Limited access to water, land, and livestock; low agriculture productivity; and increases in food prices and household food insecurity are among many factors leading to migration and displacement: "survival migration."[85] However, the literature remains inconclusive on the direct attribution of migration to water insecurity and how this may develop under future climate change scenarios, given myriad contextual factors linked to socio-economic, institutional, cultural, and political aspects.[25] Projections tend to focus on modeling exposure to risk, rather than quantifying how many people will actually migrate as a response to that exposure.[127,128] Food and water insecurity, combined with poverty, may potentially increase the likelihood and intensity of armed conflict in some dryland contexts,[129] although agricultural output and violent conflict tend to be only weakly and inconsistently connected.[130] For example, in the Sahel, droughts and water insecurity have only played a minor role compared with politics and governance in explaining the conflicts that have emerged in the last few decades.[131,132]

Ensuring effective and sustainable access to water and sanitation systems is a challenge, particularly because weather extremes such as floods, storms, heatwaves, and droughts are becoming more common in drylands under climate change. Displaced populations, including those in conflict regions, often have limited access to safe drinking water and/or sanitation and are at increased risk of infectious disease outbreaks such as measles or cholera, which frequently cannot be prevented, treated, or controlled, due to lack of access to health and/or preventive services such as micronutrient supplementation and immunization.[83] It is anticipated that, without intervention, these aspects will worsen into the future. In addition, while water insecurity and physical human health links are well established, there is little understanding of the relationship between water and mental health,[133] including in drylands, where economic impacts of droughts have been associated with increases in suicide, particularly among farmers in India[134] and Australia.[135]

CHALLENGES AND OPPORTUNITIES FOR WATER SECURITY IN DRYLANDS

Proactive strategies are needed to plan for global change issues, including planning for a water-secure future.[136] Drylands offer a long history of adaptation to water constraints and may offer useful insights and lessons for other locations that will experience water scarcity. Water conservation and redistribution efforts in drylands have attempted to improve the location, timing, and quality of water to support water security, either by re-allocating the water itself, e.g., through investments in water infrastructure, or by relocating the human and animal populations that depend on it. For example, in Somalia, Ethiopia, and other parts of East Africa, herders have traditionally moved with their livestock to graze different areas depending on water and pasture availability. While this movement still happens today, these kinds of traditional practices are becoming more difficult due to a range of factors, including sedentarization, conflict, rural to urban migration, and the breakdown of traditional institutions and property rights.[137] Similar challenges emerge from Botswana's Kalahari, where decades of policies supporting sedentarization have led to increased borehole drilling and widespread pasture degradation.[138,139] Geopolitics also affect mobility. In dryland central Asia, pastoralists used to cover extensive distances with their herds, but, with the dissolution of the Union of Soviet Socialist Republics (USSR), movement across what then became international borders became more difficult.[140] These kinds of challenges most starkly and disproportionately affected societal groups who directly depend upon the natural resource base for their livelihoods.

Alleviating economic water scarcity by increasing access to water through installation of large-scale irrigation systems can deliver short-term benefits for agricultural productivity in dry areas. However, in the context of climate change, increasing demand and inefficient management of water and associated infrastructure can result in complex outcomes over the longer term. For example, irrigation systems once operating in the Aral Sea region have resulted in large-scale landscape degradation and downstream water shortages, threatening livelihoods and human health, as levels of inflows into the Aral Sea from the Amu Darya and Syr Darya rivers decreased, and infrastructure became outdated and inefficient.[141] Irrigation has also been shown to affect local climate conditions. While cooling effects have been observed, and are especially pronounced for parts of South Asia,[142,143] there is also the potential for irrigation to increase heat stress, despite a cooler surface.[143]

The Global Water Partnership (GWP) recognizes the interlinked nature of the various dimensions of water security and strongly supports the integration of water concerns across sectors through approaches such as IWRM. IWRM is defined as "a process which promotes the coordinated development and management of water, land, and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems and the environment".[144] In drylands and other areas where water is a key limiting factor, such coherent approaches can be vital in managing water, energy, and food (WEF) security, as these challenges often compete for resources and funding.[145] Considering WEF as a nexus provides a framework to analyze these components as an integrated system involving multiple research disciplines,[136] and can be used to support decision making and the assessment of adaptation options.[145,146]

Often, policies lack sufficient evaluation of trade-offs: temporally and spatially, as well as across different sectors and societal groups.[9,146] This is particularly apparent with large-scale engineering megaprojects seeking to increase water access, which reconfigure desert landscapes (e.g., the Great Manmade River in Libya, the South-to-North Water Transfer Scheme in China, the Central Arizona Project in the United States, and the Greater Anatolia Project in Turkey).[147] Efforts to solve problems originating in other sectors have important impacts on water security across the landscape too. For example, large-scale initiatives to support dryland greening through afforestation programs (e.g., in northwest China)[148] aimed to reduce land degradation and restore watershed ecosystem services, support climate change mitigation and adaptation, as well as address poverty challenges. However, these endeavors, particularly in drylands, can lead to trade-offs where increases in above-ground carbon gain[149] can decrease biodiversity and water availability.[150] In arid drylands where afforestation of previously non-forested ecosystems is likely, the potential increase in above-ground carbon is balanced against increased water interception and evapotranspiration and a decrease in runoff and groundwater recharge, which can result in local and regional water shortages.[75,151,152]

Interactions between climate change and land use change have resulted in extensive dryland regions experiencing significant woody plant encroachment and alien plant invasion.[63,64,153] Increased native woody cover also causes higher evapotranspiration and more water to be removed from the soil, especially from deeper horizons.[154] These processes significantly reduce water resources and further exacerbate drought effects, even though carbon storage may be increased.[73] A key adaptation that has been used to improve water security in this context is large-scale selective woody plant clearing in dryland water catchments and riparian zones. The Working For Water program in South Africa is clearing invasive shrubs to improve water supplies and enhance other ecosystem services (e.g., increase grazer forage availability), while providing employment to local communities.[155] Current estimates indicate that targeted clearing of encroaching shrubs and alien invasives has restored ecosystem services valued at US$8 billion, with the largest benefits coming from increased water resources, timber products, woody fuels, and improved grazing.[156] However, studies valuing encroaching bushes and the ecosystem services they provide generally remain limited.[65]

Along with large-scale infrastructure and landscape adaptations, a wealth of small-scale water harvesting and soil and water conservation measures are used in drylands in the pursuit of water security,[157] including crop diversification, switching to more drought-resistant crops and varieties, and adopting conservation agriculture practices that improve the water-holding capacity of the soil by increasing organic matter and soil organic carbon.[10] In some areas, locally important methods are based on traditional knowledge; however, many of these methods are becoming less widespread. For example, traditional irrigation in Iran over the past 2,500 years has used qanats, but, as Western solutions have proliferated, only around half of the estimated 72,000 qanats remain in use.[158] Another example comes from the pastoral Borana in southern Ethiopia, where the tula well system dates back five centuries and has played a critical role in the sustainable management of pastures, in shaping cultural identity, and the organization of water management.[159] Wells are dug down to deep water aquifers where water is brought to the surface manually. Human labor is regularly demanded for maintenance of the wells, and the capacity to organize workers for re-excavation and repair is crucial for the sustainability of this pastoral system.[159] More recently, hired labor has started to replace clan-based labor, and payments for well rehabilitation have changed from cattle to cash. In addition, plastic buckets are replacing leather buckets, and mechanization also replaces human labor. It is uncertain how these transformations will affect the sustainability of the Borana water management system.[160]

While traditional efforts to improve water security can deliver useful local benefits, they are often difficult to scale up and out to other locations. Development status matters when it comes to upscaling. In parallel with measures for increasing the supply of available water through reuse of wastewater and sea water desalination, which will become increasingly necessary when faced with growing water scarcity,[161] an essential adaptation is to increase water use efficiency in irrigated agriculture through wider application of well-established technologies such as drip and sprinkler irrigation.[162] In many rainfed areas in drylands of sub-Saharan Africa and central Asia, agricultural economic water scarcity is a major concern. Although successful adaptation to climate change in these areas may require expansion of irrigation, lack of investment in irrigation infrastructure, and, in some instances, limited institutional capacities to effectively manage expanded irrigation, hinders climate change adaptation opportunities.[163] In more advanced dryland economies (e.g., Middle Eastern countries, such as Israel and Saudi Arabia; Australia; United States), deployment of technologies such as desalinization plants and precision irrigation systems is facilitated by the institutional setups, economic incentives (subsidies and/or credit systems), political will, and greater levels of state investment than is feasible in low-income economies. Water processed at many desalination plants, e.g., in the Persian Gulf, is largely for industrial use, although opportunities exist for improved agricultural use.[101] Nevertheless, use of these technologies can increase inequalities both within and between nations, and could lead to increased tensions. The reuse of marginal-quality waters can also increase soil salinity and lead to negative impacts on agricultural productivity and human health,[164] so proper management of water quality and more effective wastewater treatment becomes critical. A major problem from the water quality dimension of water security is that, not only in practice but also in hydro-economic modeling and planning, differentiated economic valuation of different quality waters is still absent from decision processes.

Overall, governance design and implementation deficiencies need urgent attention to better manage water-related challenges in drylands. Water governance benchmarking to monitor progress is essential, with research from Egypt, Jordan, Morocco, Oman, Turkey, and Yemen providing useful insights.[165] Climate-sensitive political leadership is also paramount, especially where transboundary water resources are concerned and political water security challenges are present.[166] Ensuring dryland water security into the future requires governance structures and processes that recognize interlinkages and that support coherent policies that take into account climate change impacts[167] and the nexus between sectors.[168] Such approaches need to carefully balance the short and long term, as well as engage the necessary stakeholders at different levels to enable an equitable approach.[169]

CONCLUSION

The challenges associated with reaching and maintaining water security in the world's drylands are set to become even more difficult, given the plethora of observed climate impacts in drylands to date, and climate projections for the future. Profound ecosystem changes are already being observed and experienced in drylands, alongside impacts on human systems that limit the access of vast numbers of people to sufficient clean and safe water supplies, including those living in rapidly expanding dryland cities. While current adaptation strategies are varied and offer a useful starting point, including those grounded in traditional knowledge and practice, the changes to dryland areas anticipated to 2100 exceed those that have been experienced previously, suggesting new approaches are needed.

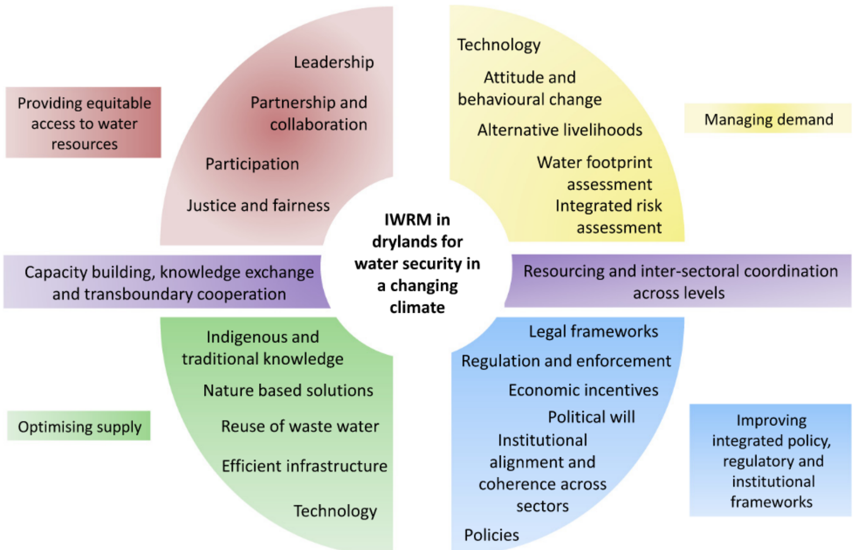

Figure 5. Components of an enabling environment for water security in drylands under climate change, drawing on relevant IWRM

IWRM sets out a useful framework that is applicable to many environments but is urgently required in drylands. Figure 5 establishes the core components of an integrated approach to water resource management in drylands under a changing climate, emphasizing the need to manage demand, optimize supply, and provide equitable access to water resources, as well as establish improved and integrated policy, regulatory, and institutional frameworks, to tackle all the dimensions of water security.

Ostensibly, achieving water security is less of an environmental challenge (availability dimension) and more of a governance issue (access, quality, and stability dimensions), requiring political will, capacity, resourcing, and leadership in the development of a truly integrated and coherent approach to deliver water-related decisions that also align with the needs of other sectors in drylands. Impacts of a lack of water security on food, health, energy, livelihoods, migration, and conflict demonstrate the crucial role of water as a connector. Technological fixes alone will be insufficient and could exacerbate inequalities. Stakeholder engagement is becoming increasingly important, particularly in complex contexts where dryland rivers flow through multiple national boundaries, highlighting the importance of IWRM in shaping more equitable water resource allocation in a transboundary context, as well as in multi-sector SDG contexts.

Adaptations that enhance water security in drylands offer the potential to inform solutions that can be shared with other (dryland and non-dryland) locations, such that climate change impacts in areas that will only just be starting to experience increased water security challenges in the future can benefit. Drylands represent useful climate analogues in this sense but require increased research activity to improve decision making on water management and water security. Improved knowledge is needed to better understand integrated risks and to assess costs, benefits, and trade-offs associated with different water-linked adaptations, across different societal groups and time frames, as well as across different aspects of the environmental system. Such efforts offer considerable scope to accelerate progress toward multiple SDGs, both in the lead up to 2030 and beyond.

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The authors declare no competing interests.

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