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Complex Policy Mixes are Needed to Cope with Agricultural Water Demands Under Climate Change

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Abstract

The divergence between agricultural water use and the annual supply of water resources (water gap) has been increasing for decades. The forecast is that this water gap will continue to widen, compromising the water security of a large share of the global population. On the one hand, the increase in demand is attributed to an ever-growing population that, in addition, is adopting a high-water consumption per capita lifestyle (e.g., meat-rich diet, increased use of biofuels and of irrigated agriculture). On the other hand, climate change is increasing aridification and the spatio-temporal heterogeneity of precipitation worldwide. The water gap is particularly acute in drylands, where development and food security has been based on the massive exploitation of water resources, particularly groundwater. Here we analyze the mechanisms underlying this water gap, which is mainly driven by water use in agriculture, and suggest suitable solutions that can help to close it. Using causal diagrams, we show how population generates different demands that create a water gap that prevailing supply-side solutions cannot close. Indeed, it has been widening over the years because water consumption has grown exponentially. This behaviour is explained by a series of mechanisms that it is necessary to understand to realize the complexity of water scarcity problems. For solving the water gap, we propose and exemplify eight lines of action that can be combined and tailored to each territory. Our analyses corroborate the urgent need to plan an integral management of water resources to avoid widespread scenarios of water scarcity under future climatic conditions.

Keywords Water gap · Drylands · Supply-side solutions · Water management · Causal diagrams · Desertification

1 Introduction

Water security is a key issue in the agenda of many nations and international institutions (UNU-INWEH 2013; Marcal et al. 2021). The achievement of nearly all of the Sustainable Development Goals (SDGs) depends on it (Vörösmarty et al. 2018) and appears explicitly in SDG 6 (Ensure availability and sustainable management of water and sanitation for all).

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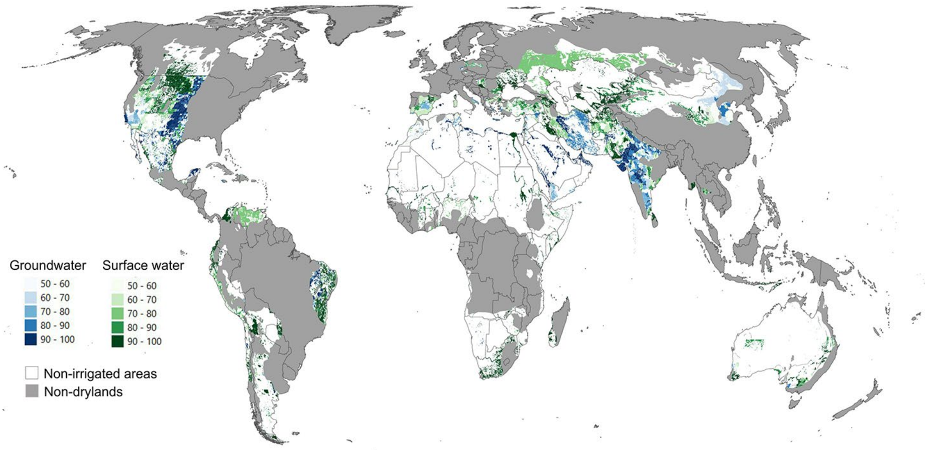

Fig. 1 Irrigation in drylands according to the source of water (%).Source: Own elaboration using data in Siebert et al. 2015

However, development, in its most basic (e.g., SDGs 1, 2 &3) or advanced (e.g., SDGs 8, 9 & 11) aspects, is another global priority. These objectives, together with an ever-growing population and increasing per capita consumption, imply growing pressure on natural resources. Much of this demand ends up being translated -either directly (ensuring freshwater supplies) or indirectly (using water to increase crop yields)-, in an increase in the ratio of total water withdrawal to available renewable water (water gap hereafter). This water gap is also increasing by the decrease in water supply due to climate change, which is altering the distribution of rainfall and increasing both snowmelt and evapotranspiration (Qin et al. 2020; Wang et al. 2022).

Total annual water withdrawal from agriculture, urban areas and industries rose from less than 580 km^3 in 1900 to more than 3,900 km^3 in 2016 (FAO 2018), and it is expected to reach 5,500 to 6,000 km^3 by 2050 (Boretti and Rosa 2019). The fact that 70% (2,800 km^3 out of 4,000 km^3) of freshwater consumption worldwide is used in agriculture (FAO 2021) focuses any attempt to address the water gap on this sector, where it is necessary to provide the most innovative solutions. In addition, urban areas of the world, despite the constant demographic growth that experience, are more dynamic in the implementation of measures to guarantee the water supply (He et al. 2021). The expansion of the global area equipped for irrigation follows the increasing path of the last three centuries. From 5 Mha in 1700 (Cherlet et al. 2018) we have moved on to 338 Mha in 2018 (FAO, 2021), which already exceeds by far the 322 Mha estimated for 2050 a decade ago (Alexandratos and Bruinsma 2012). Approximately 40% of global irrigation occurs in dryland regions (Siebert et al. 2015) (Fig. 1), which extend over almost half of the earth's surface (45%), host one out of every three inhabitants of the planet (UNCCD 2022) and include 90% of the world's water-stressed cropland sub-basins (Vico and Davis 2019). Drylands are of paramount importance for sustaining the global population, as 30% of crops originate here (Safriel et al. 2005), and support 50% of the world's livestock, 44% of croplands (Cherlet et al. 2018), and 30% of forested areas (Guirado et al. 2022),. The increasing uncertainty and ongoing changes in precipitation patterns, which decouples rainfall from crop phenology (Ficklin et al. 2022), in drylands are fostering the conversion of rainfed crops to irrigation in these areas (Rosa et al. 2020). Given their good climatic conditions for agricultural production, some dryland regions (e.g., California, Iran, South Peru, SW Europe) are paradoxically exporters of water through their products (Dalin et al. 2017; Akhavan and Gonçalves 2021).

Despite the many solutions that have been devised to meet the increasing demand for water, the water gap continues to widen globally, and it is expected to be high (40–80%) or extremely high (80%) in virtually all drylands by 2040 (Gassert et al. 2013). The current patterns of agricultural intensification are stretching the productive capacity of land and water systems to the limit, and are "at breaking point" according to FAO (FAO 2021). To contribute to the understanding of the importance and occurrence of the water gap and how to tackle it, we (i) examine how the water gap has traditionally been addressed with water supply-side solutions; (ii) delve into the mechanisms that generate this water gap; and (iii) present concrete solutions, together with policy instruments and economic incentives, to close it. We focus on drylands because the water gap is particularly acute in these areas and because they host most of the 1–2 billion people already affected by severe water stress (Byers et al. 2018), numbers that will increase by millions in the coming decades because of ongoing climate change (Stringer et al. 2021).

2 Supply-side Solutions: Not Enough to Close the Water Gap

The water needs of the agricultural sector have historically spurred the search for new water supply sources, triggering the development of large infrastructures and engineering solutions (Palmer et al. 2015; Shumilova et al. 2018). This is a vicious circle. As water demands are met, new ones are generated in anticipation of new water resources (Molle 2008; Gohari et al. 2013; Wanders and Wada 2015; Di Baldassarre et al. 2018). The construction of dams, reservoirs and major diversion projects, the exploitation of groundwater or the use of cutting-edge irrigation technologies such as saltwater desalination or brackish groundwater desalination, have been unable to close the gap between available water and current and future water needs (Paul et al. 2019).

The supply-side paradigm has reigned since millennia. The damming of rivers and the diversion of their water for irrigation has meant that some of the largest rivers on Earth run dry during all or part of the dry season, when irrigation water is most needed (Postel 2000). These include rivers such as the Ganges in South Asia, the Yellow in China, the Amu Dar'ya and Syr Dar'ya in Central Asia, the Nile in Africa, and the Colorado in the American Southwest (Postel et al. 1996; Diamond 2005). In many cases the supply of water for irrigation never meets the needs, because these never stop growing. This fact is well illustrated by the collapse of the Aral Sea. The water derived from the rivers that flowed into this inland sea to irrigate cotton did not stop growing until its collapse. In 1910 the Aral Sea was the world's fourth largest inland lake with an area of 68,000 km^2. In the following decades the irrigated area grew steadily from 2.5 Mha in 1910 to 7.5 Mha in 1990, and irrigation withdrawals peaked in 1980 at48.3 km^3 (Cai et al. 2003). By 2008, the lack of water supply to the Aral Sea meant that it was reduced to 10% of its initial surface area (Micklin et al. 2014). The case of the Aral Sea is not an exception but a situation that is repeated in other parts of the world (Wurtsbaugh et al. 2017).

Globally, although developing countries still have prime locations for building new dams (Gray and Sadoff 2006), the best sites on which to build dams have already been tapped as shown by the S-shaped curve of the evolution of water storage (Di Baldassarre et al. 2018). The reservoir capacity grew at a very good rate during the 1960s compared to demand growth (300% versus 15%, respectively), but in more recent decades the dynamics have reversed, and demand has grown faster (20%) than storage capacity (2%) (Di Baldassarre et al. 2018).

Parallel to the construction of reservoirs, infrastructure has been developed to bring water from wetter to drier areas. Initially, water transfers are donations to save dying economies or regions. However, they quickly become a source of conflict between ceding and receiving regions across the world (Hernández-Mora et al. 2014; Bozorg-Haddad et al. 2020). The justification behind this solution is that only surplus water is transferred. With climate change and economic growth in the ceding regions, there is no longer any surplus water. Despite this, water transfers are still a key supply-side solution in countries like Mexico, Spain, Iran, United States, Australia, and China, to name a few. Worldwide, approximately 14% of global water withdrawal (540 km^3) is provided through inter-basin water transfer projects. Far from being a solution in decline, more than 70 water transfer megaprojects (i.e., those with construction costs ≥ US$1 billion, distances ≥ 190 km and volumes ≥ 0.23 $km^3\ yr^{-1}$) are expected to be built (many of them to supply water to large irrigation projects) worldwide (Shumilova et al. 2018). Projected transfer volumes for planned or proposed projects (1,910 km^3 per year) are an order of magnitude greater than existing projects, with a total transfer distance of more than twice the length of the Earth's equator (Shumilova et al. 2018; Scanlon et al. 2023).

Since water transfers and reservoirs do not suffice to cover the growing demand for water, groundwater has become the most reliable source of water for irrigation in drylands. The development of drilling technology, together with rural electrification and major advances in geological and hydrogeological knowledge (Foster and Chilton 2003), opened the door to the massive use of groundwater. Currently 2 billion people depend on groundwater (Famiglietti 2014) as their primary source of drinking water, and groundwater supplies around half of the world's irrigation surface (Siebert et al. 2010). Globally, it is estimated that one-quarter (585 $km^3\ yr^{-1}$) of the total water withdrawals are drawn from groundwater (Scanlon et al. 2023). As a consequence, immense reservoirs that seemed inexhaustible are experiencing rapid depletion rates (Famiglietti 2014; Bierkens and Wada 2019; Jasechko and Perrone 2021; Scanlon et al. 2023).

Perhaps the most absurd cases are those irrigated lands located in hyper-arid areas (such as the Atacama Desert or the Arabian Peninsula), where natural recharge rates of the groundwater bodies are null. The Arabian aquifer, for example, has been drained in a matter of decades, following an aggressive state policy that pursued the chimera of growing alfalfa and other fodder crops in order to make Saudi Arabia self-sufficient in dairy products (Elhadj 2004; Martínez-Valderrama et al. 2020a). The extraordinary yields of irrigated areas (with just 20% of cultivated land they contribute ~ 40% of global food production (FAO 2018)) have led to their continuous expansion and, therefore, to the search for alternative sources of water to maintain them. In this context, advocates of technological innovations see the reuse of reclaimed water and the desalination of seawater and highly brackish water as the definitive solution to tackle situations of water deficit in dryland areas.

In many dryland regions of the world, including SE Spain (Martínez-Alvarez et al. 2016; Ricart et al. 2020), Middle East and North African countries (Awaad et al. 2020), South Australia (Barron et al. 2015), North China (Lin et al. 2021), and California (Qin and Horvath 2020), desalination is beginning to be considered as a solution to close the current water gap in agriculture (Beltrán and Koo-Oshima 2006; Yermiyahu et al. 2007). Globally, there are 15,906 operational desalination plants producing around 95.4 $hm^3 day^{-1}$ (34,810 hm^3 yr^{-1}) of desalinated water for human use (Jones et al. 2019). Its efficiency has improved dramatically, reaching unsuspected yields and proving to be an essential source of freshwater in the Middle East and North African countries, which use 48% of the world's desalinated water (Jones et al. 2019). Most desalinated water is produced for human consumption (62.3%), and industrial applications (30.2%), whilst only 1.8% of the global desalination capacity being currently used for irrigation purposes (Jones et al. 2019).

Except in the Gulf Cooperation Council countries, where crude oil is cheap and environmental regulations allow the use of obsolete and inefficient thermal desalination, reverse osmosis has become the technology of choice to desalinate water worldwide. It accounts for 69% of the volume of desalinated water produced and its recovery ratio (i.e. the proportion of intake water that is converted into high quality (low salinity) water for sectoral use) almost doubled that of thermal technologies (a ratio of 0.42 vs. 0.22 or 0.25, depending on the type of thermal desalination) (Jones et al. 2019). Reverse osmosis requires subjecting water to extremely high pressures (ranging from 1,700 to 6,900 kPa or 1.8–2.9 kWh m^{-3}) to make seawater to pass through 0.5–2 nm (Zhang et al. 2019) membranes capable of filtering viruses and bacteria. The operation gives rise to two flows: brine, a hyper-saline residue, and desalinated water, whose journey does not end here. Desalinated water is not directly usable by crops, as it presents several phytotoxicity problems (Yermiyahu et al. 2007; Martínez-Alvarez et al. 2016). A further treatment of desalinated water, such as a second filtration to remove boron, adding nutrients, rescheduling irrigations by blending saltwater desalination with other 'bad' quality waters with a higher concentration of ions (Ben-Gal et al. 2009; Martínez and Martín 2014), is often necessary before using it to irrigate crops. Thus, in addition to the energy needed in the filtration process, it is necessary to add >1 kWh m^{-3} consumed by the intake, pre-treatment, post-treatment, and brine discharge stages of the desalination plant (Fritzmann et al. 2007). Over the years, its efficiency has been improved by developing materials and designing water circulation circuits with energy recovery devices (Elimelech and Phillip 2011). The amount of power needed to drive desalination has declined exponentially in the past 40 years (Fritzmann et al. 2007), dropping from more than 15 to 1.82 kwh m^{-3} (Elimelech and Phillip 2011), very close to the thermodynamically feasible minimum (1.06 kWh m^{-3} for the desalination of 35 g/l seawater at 50% recovery (Elimelech and Phillip 2011). The hope of further improving performance lies in the development of fouling-resistant membranes with tailored surface properties.

Although energy needs of desalination have severely decreased, this technology still requires high energy inputs, and thus has a large CO_2 footprint. Most desalination plants run on conventional fossil fuels, generating emissions of 1.3–1.48 kg CO_{2eq} m^{-3} of desalinated water (Martínez-Alvarez et al. 2016), which, if used on a large scale, would result in a considerable increase in the carbon footprint of agriculture (unless renewable energy is used (Ghaffour et al. 2011). Operating costs increase as water is adapted for agricultural uses, distribution infrastructure is added, and the brine generated is neutralized. In SE Spain, the price difference between water that is pumped from aquifers (0.161–0.41 € m^{-3}) or comes from transfers (0.081–0.17 € m^{-3}) and desalinated water (0.661–0.693 € m^{-3}) (Martínez-Alvarez et al. 2016) is so significant that many farmers consider its use unfeasible to become competitive. For this reason, the dense network of desalination plants set up by the Spanish government in 2004 (Downward and Taylor 2007) to supply water to irrigation systems – 21 high-volume desalination plants, with a potential desalinated-water production of 1,063 hm^3 yr^{-1} (Aznar-Sánchez et al. 2017)– was only operating at 17% of its capacity in 2014 (Collado 2014). Only when desalinated water is subsidized, as is the case in Murcia (Spain) (Martínez-Alvarez et al. 2017), it is massively used by farmers. In many Arab countries, much of the oil and gas production is used to generate electricity and produce water in cogeneration power–desalination plants. Saudi Arabia uses a quarter of them and in Kuwait the energy required to meet desalination plant demand is expected to be equivalent the country's current fuel oil production by the year 2035 (Sewilam and Nasr 2015). Although the price of energy in this region is affordable, costs fluctuate between \$1.50 and \$4 m^{-3}, but in some cases are subsidized up to prices of 4 cents m^{-3} (UNDP 2013).

There is another important problem associated to saltwater desalination, and is the volume of brine. It depends on the efficiency of the process, but it is typically much greater than the desalinated water produced. Current global brine production stands at 51.7 thousand hm^3 yr^{-1} (Jones et al. 2019). The impact of this waste affects various aspects of marine ecosystems. Substantial increases in salinity and temperature, and accumulation of metals, hydrocarbons and toxic anti-fouling compounds in receiving waters (Roberts et al. 2010) are some of them.

3 Understanding How the Water Gap is Made: A Key Step to Propose Effective Solutions

Supply-side solutions alone do not seem to solve the water gap. Understanding how this gap arises can help to substantiate approaches based on demand management. For doing so, we present here an analysis of different situations in which the water gap can be aggravated or reduced based on causal diagrams from System Dynamics (Forrester 1961). First, we present the general framework under which the water gap is generated (Fig. 2). Then, based on this causal diagram, we represent mechanisms that help to consolidate or create water gaps. Specifically, we analyze: (A) Demand-side solutions; (B) Increasing water use efficiency; (C) Increment of non-food crops; (D) Surplus and food waste. Note that the variants enrich the original scheme shown in Fig. 2 by including new variables.

Population is the driver of water gap growth through three pathways (Fig. 2). As a consequence of a population expected to reach 9.8 billion in 2050, this will result in a 50% increase in food demand, a 55% increase in water demand, and energy demand will rise by an estimated 61% (Shumilova et al. 2018). Since a large part of this demand will continue to be met by fossil fuels, climate change will become more acute, with the result that the supply of water resources will continue to fall (UNESCO, 2019). The water gap has been addressed so far with water supply measures, which in theory should stabilize the system (Fig. 2), as shown by the negative loop that emerges: more water gap leads to supply-side solutions, which leads to more water availability, that implies less water gap. However, the water gap is only widening, showing an exponential growth of global freshwater over the long-run (from 685 billion m^3 yr^{-1} in 1901 to 3.99 trillion m^3 yr^{-1} in 2014) (Our World in

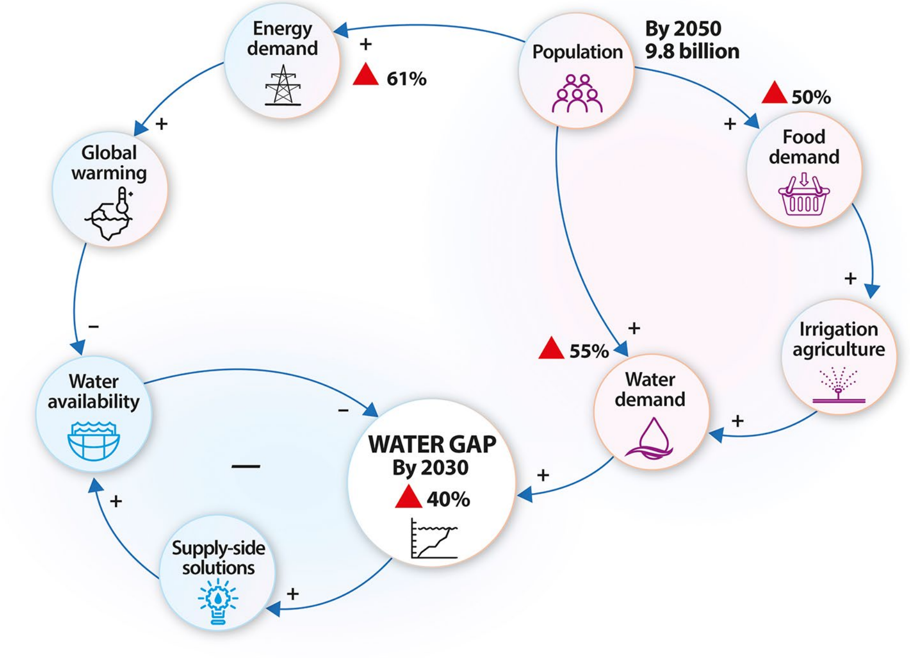

Fig. 2 The creation of the water gap is determined by the interplay between water demand and availability. Theoretically, supply-side solutions (negative feedback) should stabilize the system. The polarity between the independent variables (*x*) and the dependent variables (*y*) can be (i) direct (+) when *x* and *y* move in the same direction, i.e., as *x* increases, *y* increases, or as *x* decreases, *y* decreases; or (ii) negative -or inverse- (-) when *x* and *y* move in the opposite direction, i.e., more *x* less *y* or vice versa. The concatenation of the causal relationships between the variables gives rise to a network of feedback loops. See (Sterman 2000) for details. The sign of the feedback loops illustrates their behaviour: positive feedbacks are self-reinforcing and are behind the explosive or exponential behaviour the system; negative feedback loops are self-correcting and represent the stable performance of the system. An even number of negative arrows or their absence gives rise to a positive feedback loop; an odd number of negative arrows gives rise to a negative feedback loop.Source: Own elaboration

Data 2021). In the following sections we propose several variants of this causal diagram to understand how this behaviour emerges (Fig. 3).

3.1 Demand-side Solutions

One of the most treacherous side-effects of supply-side solutions is that they discourage a better management of demand. This phenomenon is known as the “reservoir effect” (Di Baldassarre et al. 2017), as it is linked to the construction of reservoirs. As green arrows show in Fig. 3A, more water gap means more supply-side solutions, leading to more water availability. This increases water demand, resulting in a larger water gap. The reason of this positive loop is that, once a given demand is met, and capital is invested in transforming land use (e.g., irrigation infrastructure), the feeling is created that it is possible to get more water. This triggers public pressure for action, and the short-term economic losses from not taking action by providing more water cannot compete with the long-term benefit of inter-

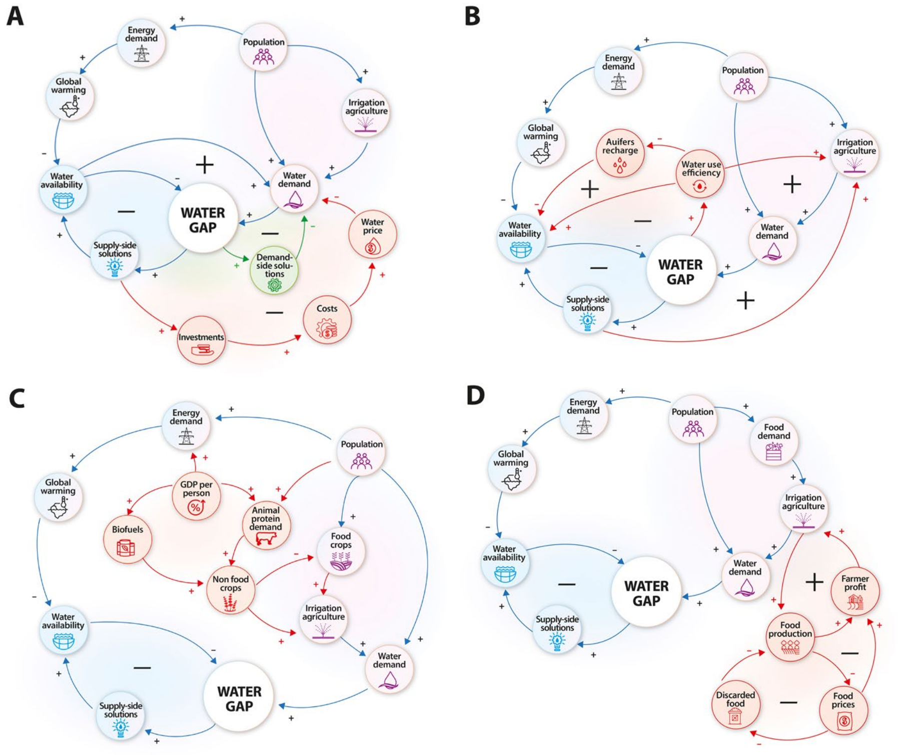

Fig. 3 Mechanisms explaining the anthropogenic increase in the water gap: (A) Increasing water price; (B) Increasing water use efficiency; (C) Increment of non-food crops; (D) Surplus and food waste.Source: Own elaboration

nalizing the environmental impacts of these actions (De Stefano and Lopez-Gunn 2012). Thus, instead of re-adjusting to the amount of water available, socio-economic systems enter into a spiral of unsustainable water demand. The activation and predominance of this loop is behind the “Anthropogenic lands” (Vico and Davis 2019) defined as “croplands where consumptive water demand is greater than long-term average rate of renewable water availability.” They occur both in drylands and in places that are relatively abundant in terms of water resources but can become water-stressed due to unsustainable agricultural water use.

The predominance of supply-side solutions is explained by their low cost to users. Although these solutions involve the construction of large and expensive infrastructures, little or none of the investments required are reflected in the price of water (Molle 2008). This is a model for offering resources practically free of charge or at a very low cost which, logically, is in high demand. The price paid by the user usually covers only the costs of water management and distribution. If investment costs were included, demand would be very close to zero. This possibility is reflected in Fig. 3A through the inclusion of red arrows in the sketch that creates a negative loop which tends to stabilize the system described in Fig. 2 (Sterman 2000). Indeed, as investment increases to supply more resources, costs and prices rise and demand shrinks. Therefore, the system harbours latent stabilizing loops (there are other economic tools with the same stabilizing effect) that could decrease water demand. These hidden possibilities must be activated to curb the positive loop that dominates current water policies.

One of the problems created by this blind trust in supply solutions is that it generates an enormous dependence on external resources. It is then that mainly arid areas become sinks of financial and water resources (Mainguet and Da Silva 1998), increasing their vulnerability with respect to the donor areas (Ibáñez et al. 2022). The latter, in turn, are changing their donor status due to climate change and, in addition, often follow a development that mirrors that of the recipient areas (Larraz and San-Martin 2021).

In oases, where the shortage of water is chronic and evident, the reservoir effect is well observed. Complex social mechanisms for water sharing have been developed over centuries in these areas (Nagieb et al. 2004), but these rules have been diluted by the arrival of wells and pumps that increase water availability. The management and maintenance of traditional khettaras or foggaras –underground galleries with gentle slope, which drains water from the upstream aquifer to the drier land downstream– of North Africa is neglected in the face of the use of wells that reach the deepest parts of the aquifers (De Haas 2000; Remini et al. 2011). For example, in Oued-Mird (Morocco), on the edge of the Sahara, the state's plan to settle the nomadic population resulted in an accelerated transition to irrigated agriculture (Martínez-Valderrama et al. 2011). In NW China the "oasification", i.e., the natural or artificial expanding of oases, is increasing the irrigated area to ensure food security for the increasing human population (Xue et al. 2019). This uncontrollable demand can result in the extensive lands being abandoned due to water shortage. Ultimately, this approach increases vulnerability and economic damage when water shortages, driven by the depletion of aquifers that cannot recharged naturally, occur (Di Baldassarre et al. 2018).

3.2 Increasing Water Use Efficiency

It is often argued, specially in drylands, that water is used in a very efficient way, meaning that each drop of water is converted into agricultural product. However, technical improvements do not directly translate into resource savings because producers and consumers adapt their behaviour to such improvements, often resulting in a rebound effect (Paul et al. 2019). Moreover, from an ecohydrological point of view, dryland irrigation systems appear to use water much less efficiently than non-dryland irrigated areas, as in drylands irrigation consumption accounts for 79% of the total water footprint (WF) (blue), but contributes only half (50%) of the world's irrigated land crop production (Davis et al. 2017). Although water savings after technical improvements (necessary and desirable) are congruent from the farm plot point of view, they are not so evident if we broaden the scale of analysis.

It is every farmer's dream to have all the water taken at source for irrigation used by the plants. This has been achieved thanks to technical improvements in the distribution network and application systems. In the case of drip irrigation, efficiency can be 100%. In theory, this change increases the availability of water resources, since it is not necessary to divert as much water for irrigation as in the original situation. This is the negative, or stabilizing, loop shown in Fig. 3B resulting from considering Water use efficiency in the scheme. The balance, however, is often reversed because the increase in efficiency leads to an increase in water use (Lambin and Meyfroidt 2011; Perry 2017; Grafton et al. 2018). This widely described effect, reflected with a new positive loop in Fig. 3B, is known as the

Jevons Paradox (Jevons 1866): “as technological improvement increases the efficiency with which a resource is used, an increase in the consumption of that resource is more likely than a decrease”. An explanation for this phenomenon is that irrigators’ water use rights do not change with these saving measures. The “saved” water is used to generate new profits, either by expanding the area under irrigation (Molle and Tanouti 2017; Birkenholtz 2017) or switching to more water-intensive crops (Molle and Tanouti 2017; Grafton et al. 2018). It even may occur with the same crop when there is a strong marginal yield response from additional irrigation (Grafton et al. 2018).

Another side effect of the implementation of more efficient irrigation schemes is the reduction of inputs to aquifers (Rodríguez-Rodríguez et al. 2011; Molle and Tanouti 2017; Rinaudo and Donoso 2019). Much of the water lost in water transport returns to aquifers. This leads to the formation of a new positive loop in the system, since the more efficient the irrigation, the lower the water availability and thus the greater the water gap.

There is a third way in which the use of supply-side solutions widen the water gap instead of closing it (Di Baldassarre et al. 2018). The mere expectation of new water resources gives wings to farmers who see the possibility of further increasing their water demands, transforming rainfed crops into irrigated crops, leading to higher yields and profitability. A third positive loop (Fig. 3B), in which the mere announcement of new resources (reservoirs, water transfers) spurs the growth of irrigated land (generating new needs), is thus created.

3.3 Increment of Non-food Crops

The increase in water use by agriculture is also explained by the increase in demand for non-food crops requiring a large amount of water for its production. Globally, 35% of crop production (350 Mha) is allocated to animal feed (Foley et al. 2011). On the other hand, the renewed quest for energy independence by many countries and the widespread concern for the reduction of greenhouse gas emissions have fostered the use of alternative energy sources such as biofuels (Gerbens-Leenes et al. 2012). In 2007, feedstock production for biofuel generation required ≈ 25 Mha, and an additional annual growth of 1.5–3.9 Mha was required to meet 2011 policy mandates of petroleum substitution by biofuels (Lambin and Meyfroidt 2011). It is estimated that by 2030, when it is expected that biomass will have the largest share of all renewables (World Energy Council 2007), water use related to biofuel production will increase tenfold compared to that used in 2010 (Gerbens-Leenes et al. 2012). Based on non-food crop harvests (Alexandratos and Bruinsma 2012; Mottet et al. 2017) and the water used in its production (Hoekstra and Mekonnen 2010), we estimated feed and biofuels crop water consumption respectively, at 2,128 km^3 and 130 km^3 in 2012.

The cultivation of non-food crops in the scheme shown in Fig. 1 does not create new loops, but it does increase the pressure on the water gap through several routes (Fig. 3C). Global warming fosters the use of biofuels, while the increase in per capita income –by 2000, GDP per capita was more than 50 times greater than three millennia before (Maddison 2007; Ibáñez et al. 2015)– has boosted meat consumption from 23 kg/per capita/y in the 1960’s to 43 kg/per capita/y in 2013 (FAO 2019). As more agricultural surface is devoted to non-food crops, there is less room for growing food crops. This horizontal competition ultimately leads to an increase in irrigated land and a higher water demand. Changing consumption patterns towards diets with less animal protein and more pulses (producing one kg of beef requires 15,415 m^3 of water compared to 4,055 m^3 for pulses (Mekonnen and

Hoekstra 2012), or the use of renewable energy sources such as the sun, wind or geothermal energy would, at least partially, deactivate these water gap growth paths.

3.4 Surplus and Food Waste

One of the paradigms that best captures the intensive production system is the treadmill of production (Gould et al. 2004; Sanderson and Hughes 2019). To be competitive, large distributors and supermarkets create a low- price war that forces farmers to produce at the lowest possible cost. As a result, large-scale production is imposed, which requires huge technological investments and a high level of indebtedness. Mass production saturates the market and causes prices to fall again, forcing even more production to cover the high level of indebtedness. As farmers with less financial muscle are driven out of the business, large corporations monopolize a business that now only admits capital-intensive actors. This situation is represented in Fig. 3D through positive feedback that shows irrigation agriculture as a high-profit business attracting capital from different investors (Clapp 2019). This volatile loop has two others associated with it that can control the situation if they gain prominence in the system. The massive production of cheap food leads producers to release part of the harvest or to store it to contain the fall in prices. In effect, three negative arrows are chained together resulting in a negative loop (more food production leads to falling prices due to market saturation, which leads to food destruction or storage, which implies less food production). This practice, which is subsidized in the European Union (Martínez-Valderrama et al. 2020b), prevents the loop from fulfilling its stabilizing role. For example, it has led to the discarding of 114 kt of food apt for consumption in Spain in 2019 (FEGA 2019), equivalent to 78.56 hm^3 of water. In addition, due to the application of cosmetic standards, 51,500 kt yr^{-1} are discarded in the European Union alone (Porter et al. 2018).

The other negative loop captures the profit impact of lower prices, which drives out some producers and may contain the expansion of irrigation. What often happens, however, is that the high investment required for this highly technical industrial agriculture drives out small producers, who are unable to take on high levels of debt. The increase in irrigated area confirms that the positive loop is prevailing, and the other two negative loops play only a secondary role.

4 Do we Really Need More Water? Looking for Inconsistencies in Our Lifestyle

Complex solutions are required to close the water gap, which will also differ from one place to another. In developing regions, where around 70% of the world's drylands are found (Stringer et al. 2017), populations are strongly dependent on natural resource availability. Water scarcity results in severe problems such as food insecurity and malnutrition, poor access to health care, and marginalization (Stringer et al. 2021). Thus, here, where the gap between water demand and supply is the highest in the world, priority must be given to water-related infrastructure development to close the water gap. These supply-side solutions (left side of Fig. 4) are also part of the cocktail of solutions of well-developed economies, and makes no sense to dismantle infrastructures that have already been created when they fulfill their role. However, it is necessary to include in this mix of solutions those that help to

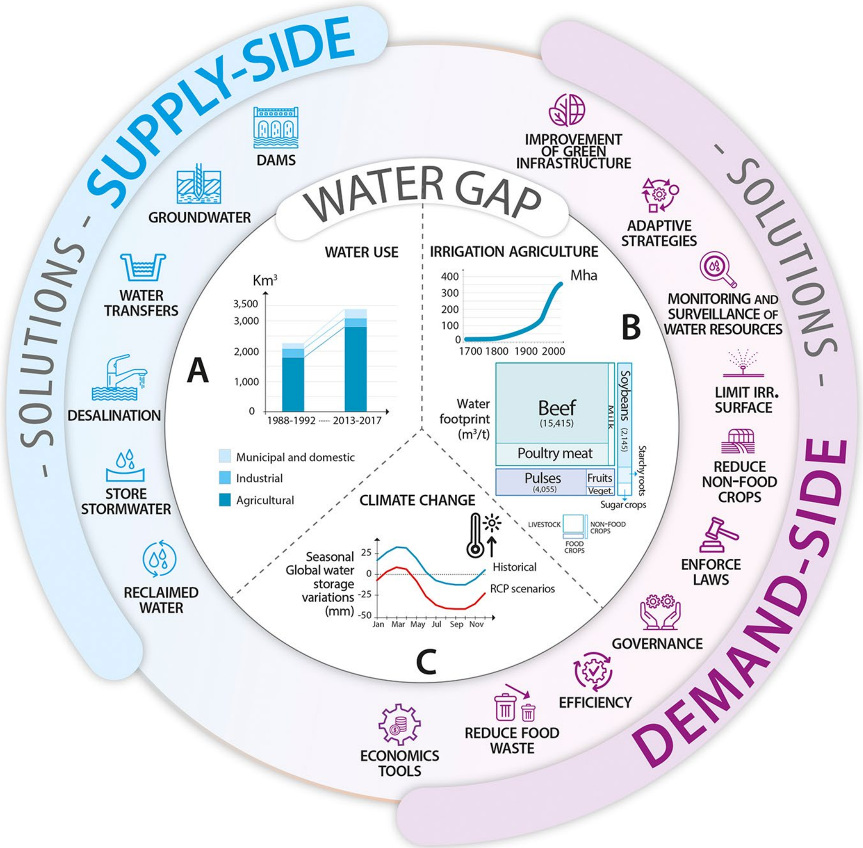

Fig. 4 A complex mix of solutions, both from the supply (left) and demand (right) side need to be implemented to address a water gap that is widening. In the inner circle the reasons for this increase are shown: (A) Water consumption has increased from 2,250 km^3 yr^{-1} in 1988/92 to 3,360 km^3 yr^{-1} in 2013/17; only in the industrial sector has it decreased slightly (from 295 to 280 km^3 yr^{-1}) (FAO, 2021); (B) Especially relevant is the consumption of water by irrigated agriculture (from 1,778 to 2,785 km^3 yr^{-1} in the above period), where global area equipped for irrigation has followed an exponential trend (Alexandratos and Bruinsma 2012; Cherlet et al. 2018; FAO, 2021). This is linked to lifestyle changes that imply an increase in the consumption of animal protein. As can be seen, most of the water footprint is due to meat production (Mekonnen and Hoekstra 2012); (C) The medium-high Representative Concentration Pathway (RCP6.0) scenario warns us of a lower availability of total global water storage relative to the historical climate (Pokhrel et al. 2021).Source: Own elaboration

manage water demand (right side of Fig. 4). It is a matter of combining different approaches to close a water gap that is constantly growing.

Below we propose eight lines of action to close the water gap. Without claiming to be exhaustive -and excluding the "traditional" supply-side solutions, we emphasize that closing the water gap requires actions at many levels (local vs. global; rural vs. urban; structural vs. non-structural) and that one type of solution alone is not sufficient to address the problem.

It is important to note that the solutions proposed here could simultaneously address other environmental problems. Water-smart agriculture, narrowing the water gap, will also be effective in dealing with climate change (Kravcik et al. 2007). For example, maintaining green covers enhances the role of agriculture as a carbon sink (Lal 2019), and mulching and incorporating pruning residues into the soil (Kader et al. 2019) and reducing/eliminating tillage help regulate the water cycle. The linkages between global water cycle changes, associated impacts and mitigation policies are not well integrated and it is essential to develop a framework that would allow scientists and policymakers to "close the loop" between these elements and to include water in international climate change negotiations (Douville et al. 2022).

4.1 Prevention: Education, and Monitoring

Prevention is mandatory when dealing with water resource degradation. This approach is preferable and more cost-effective than allowing water resources to degrade and then attempting to restore them. Salinization of groundwater bodies due to marine intrusion or groundwater depletion in territories where recharge is low or non-existent implies costly technological solutions with the consequent environmental impacts. Prevention actions are in line with the Land Degradation Neutrality (LDN) concept, which has been set up as the main tool to combat desertification by the United Nations Convention to combat Desertification (UNCCD 2015) and is included in SDG 15.3. LDN refers to a state of zero net land degradation, where "the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems" (UNCCD 2016).

The aim of LDN is to intervene as soon as possible due to the irreversibility of the water degradation on a human scale. Prevention strategies include indicators and early warning systems that make it possible to anticipate threatening dynamics. For example, assessing the water balance of the territory in terms of the renewal of water resources and its demand (Martínez-Valderrama et al. 2011) helps to avoid oversizing the economic sector. The use of quantitative and qualitative indicators reporting on the evolution of water resources (e.g., piezometric levels, nitrate content) is necessary to complete the set of indicators currently proposed for LDN monitoring (trends in land cover, trends in land productivity, soil organic carbon). Satellite observations, such as the Gravity Recovery and Climate Experiment (GRACE) mission (Tapley et al. 2004), provide new insights into the global nature of groundwater depletion (Famiglietti 2014) and benefit water management (Zaitchik et al. 2008).

Research and education are key elements for improving the management of water resources in the context of climate change, particularly in drylands (Torabi Farsani et al. 2017). In drylands, governments and individual water users must notice the value of the ecological service of water resources, beyond their economic yield (Zhou et al. 2016). The need to reduce water consumption by agriculture or improve irrigation systems have led to an important effort in basic and applied research in areas with scarce water resources (Martínez Fernández 2006). In addition, the transmission of knowledge about efficient water use and circular water economy must constitute an important part of the teaching on environmental and territorial aspects of the basic educational levels (Akiyama and Li 2013). Incorporating sustainability concepts into the scholar curricula is an obligation in drylands if we want to achieve SDGs 4, 6 and 13 (Morote et al. 2022). It is also important that public administrations put in place systems to monitor water management, which implies the implementation of water consumption meters for urban and agricultural use and the establishment of indicators for the continuous evaluation of water expenditure (Bertule et al. 2017; Jensen and Khalis 2020).

4.2 Adaptive Strategies and Livelihood Diversification

The endurance of dryland societies can be explained by their strategies for adapting to a hazardous environment. The scarcity of water, combined with the randomness, both spatial and temporal, of rainfall, make opportunistic behavior, capable of taking advantage of good times and creating reserves to cope with uncertain periods of scarcity, the most appropriate one. However, it is precisely that attitude that leads to taking advantage of the creation of new markets and technological innovations (i.e., pumping and drilling), which threaten water resources in drylands.

In northwest China, oases expanded driven by the profitability of cash crops in detriment of food crops. The change in land use was triggered in the early 1980s, when farmers were given more autonomy in land use (Zhang et al. 2014). In addition, farmers in the least developed regions have few choices for increasing their income besides expanding their agricultural scale (Zhou et al. 2016). As postulated by Puigdefabregas (1995), resource use in arid zones should imitate the predator-prey cycle, i.e., adapt the size of the economic sector to the availability of resources. Otherwise, degradation processes are initiated that, if persistent, lead to desertification. Such adaptability has been typical of water management in arid or hyper-arid areas for centuries (De Haas 2000). For example, in Iran, qanats, a combination of tunnels, wells and irrigation ditches that carry water from a high mountain region to low-lying land, have operated successfully for thousands of years (Salih 2006), and in Negev desert Bedouins modified cropped patchwork farming in wadis from 2500 km^2 in rainy years, to 600 km^2 in dry years (Portnov and Safriel 2004).

However, the quest for short-term profit has led to the expansion of irrigated agriculture that threatens the integrity of oases along the Keriya River in the Taklamakan Desert (Yang 2001), or the Timimoun oasis in the Algerian Sahara (Remini et al. 2011), and has driven countries like Iran close to the collapse of its groundwater resources (Noori et al. 2021). The sedentarisation of nomads north of the Sahara -driven by political reasons- is another example of traditional land-use abandonment. New farmers have overexploited in years the alluvial aquifers that have sustained livestock for centuries (Martínez-Valderrama et al. 2011).

It is necessary to restore the adaptive strategies that have worked for millennia, creating favorable conditions - political and economic - for their implementation. Rather than implementing agriculture suited to more humid ecosystems (Mainguet and Da Silva 1998), it seems more logical to focus on food crops adapted to drylands (Nabhan et al. 2020). It is not only the type of crops that is important, but also their diversification, which allow coping with rainfall variability (Blanco et al. 2017) and promotes multiple ecosystem services (e.g. water regulation) (Giovanni et al. 2022). The choice of livestock species and breeds more adapted to the drylands' water and pasture availability works in this line of action. For example, cattle are being replaced by sheep, goats, and camels in Kenya, which are more tolerant to unreliable water availability and changing vegetation (Volpato and King 2019). This is a much more appropriate strategy than using Friesian cattle in the Arabian Desert (Alqaisi and Ndambi 2010), which generates unaffordable water needs. Alongside this, restoring livestock mobility (Liao et al. 2020; Manzano et al. 2021) to take advantage of pastures that grow as the rains come and relieving pressure on the grazed land is another initiative that requires collateral changes (e.g. promote coexistence with croplands) (IIED and SOS Sahel UK 2010).

Livelihood diversification is a major adaptation strategy and form of risk management (Smith et al. 2020) by reducing dependence on highly variable natural resources (Reynolds et al. 2007). Diversification increases the resilience of rural households against desertification and extreme weather events by diversifying their income and consumption (Mirzabaev et al. 2019). The exploitation of groundwater resources in drylands often leads to ephemeral wealth that benefits only part of the inhabitants of the area, but jeopardizes the legacy of future generations. Capitalizing on these gains in a more diverse and less water-dependent economy reduces the vulnerability of the socio-ecosystem to adverse shocks (e.g., droughts, market crashes, increased production costs). Successful governance of the transition between water-dependent to more complex diversified economies is critical to reducing the water gap (Mukherji 2006; Petit et al. 2017).

4.3 Improvement and Maintenance of Green Infrastructure

Green infrastructure is the network of natural or seminatural features -wetlands, healthy soils and forest ecosystems, as well as snowpack and its contributions to runoff- that supply clean drinking water, regulates flooding, controls erosion, and "stores" water for hydropower and irrigation (Palmer et al. 2015). These include conservation agriculture practices that improve the water-holding capacity of the soil by (i) increasing organic matter and soil organic carbon (Mirzabaev et al. 2019; Stringer et al. 2021); and (ii) reducing surface runoff and enhancing infiltration through different farming techniques such as contour stone bund, pitting, and terracing (Rockström and Falkenmark 2015). Also soil moisture can be increased by alleviating evaporation and enhancing infiltration (Stroosnijder et al. 2012; Jägermeyr et al. 2016). Agroforestry, mulching and no-till farming can improve water retention in soils and reduce evaporation by decreasing exposure to sunlight due to shading (Chukalla et al. 2015).

There is another group of micro-catchment techniques (Stroosnijder et al. 2012) aimed to collect runoff from a relatively small catchment area, within the farm boundary. The runoff water is usually guided into infiltration enhancement structures, i.e., planting pits, and used to grow plants. For example, zaïs (dug pits with manure that concentrate runoff in the plants) in Burkina Faso and Niger have increased agricultural yields (Kaboré and Reij 2004) and vegetation cover (Reij et al. 2009). Finally, at a larger scale, managing aquifer recharge (Dillon et al. 2019) is a promising solution to reduce flood risks and store surplus water for irrigation (He et al. 2021).

4.4 Supply with Local Water Sources

In drylands, the satisfaction of demands must, in principle, be adapted to existing resources, which are usually scarce (Chitsaz and Hosseini-Moghari 2017; Paneque et al. 2018). In some territories, if more resources are needed for controlled urban or agricultural supply, solutions that have less impact on the natural environment must be sought (e.g., reuse of treated wastewater and use of stormwater) and avoid, in any case, those that could assume conflicts between territories (transfers) (Morote et al. 2019). In this context, desalination is costly in economic and ecological terms, but is necessary in some coastal areas without access to other water resources (Swyngedouw and Williams 2016). Another strategy to increase water available to crops is the adoption of rainwater harvesting techniques to capture and store rainwater for supplemental irrigation (Wisser et al. 2010; Piemontese et al. 2020). What is essential is that the water resource supply system is based on the use of multiple sources (surface, underground, reuse, storm water, desalination), so that the failure of one of them (e.g., due to the development of an intense drought) can be replaced by water resources from the others. The principles of the water circular economy must prevail in the planning of resources in drylands.

The reuse of treated urban wastewater is a key water resource for medium or large population centres that produce effluents constantly. Water purification technology allows reaching quality levels of treated water with the possibility of reuse for urban and agricultural uses. In some cities in the southeast of the Iberian Peninsula (e.g., Alicante), a binary water distribution system has been implemented for the distribution of treated waste water for the irrigation of parks and gardens, which avoids the use of drinkable water for this purpose (Rico Amorós et al. 2016). Another resource that adds to the circular economy of water in drylands is rainwater, which can be captured in tanks installed in urban areas. These include both the use of novel and sustainable drainage technologies in lager cities (Arahuetes and Olcina Cantos 2019) and traditional stormwater harvesting systems used for centuries for water supply in rural areas, such as “aljibes” in Mediterranean Spain (Gomes et al. 2014).

4.5 Lifestyle and Geopolitics

The complex world we have created makes it possible to reorganize and distribute goods much more efficiently than in the past. Global trade allows food-scarce regions to rely on excess in production existing elsewhere. This “trade revolution” has reduced local food deficits by increasing global interdependencies in the food system without really increasing the carrying capacity of the planet (D’Odorico et al. 2018). Nowadays, about 85% of countries rely on food imports to meet domestic demand (D’Odorico et al. 2014). The decoupling of production and consumption centers is evidenced by the consumption-based land use inventory (Yu et al. 2013), i.e., the proportion of domestic land used within the territory of a country compared to land used outside a country’s territory. The World average share is 73–27% but in some island countries the balance shifts to a stunning 8–92%, as in the case of Japan, or a 20–80% for the UK. In Europe, the foreign land is, on average, above 50%. This implies that what happens in a given territory has decision-makers (including consumers) all over the world. Hence, understanding the water gap mechanisms is only part of comprehending the problem. In other words, it is cumbersome to know where to act. Problems may occur in one place, and solutions must be applied in another place thousands of kilometers away.

These problems have to do with what we eat. Meat is considered to have a huge WF but it is necessary to distinguish which meat we are talking about, since the WF of beef (15,415 m^3 t^{-1}) is much larger than the WFs from sheep (10,400 m^3 t^{-1}), pork (6,000 m^3 t^{-1}), goat (5,500 m^3 t^{-1}), and chicken (4,325 m^3 t^{-1}) (Mekonnen and Hoekstra 2012). The above figures refer to intensive systems based on feed supply (high WF; Fig. 3C), which is what actually increases WF (mostly in terms of blue water). However, livestock in extensive systems consume mostly grass and forage mainly produced in rain-fed farming systems (low WF) (Ibidhi and Ben Salem 2020). It is necessary to improve livestock water consumption calculations (Boulay et al. 2021) according to, among other things, the type of production system (e.g., feed-based vs. pastoral systems).On the contrary, vegan diets are apparently more sustainable but do not ensure that the water footprint decreases (Frankowska et al. 2019). For example, Tuninetti et al. (2022) show that if all countries adopted the EAT–Lancet diet (i.e., a diet that primarily consists of vegetables, fruits, whole grains, legumes, nuts and unsatu-

PREVENTION

Education. Oasis Unit in Northwestern Arid China. Under an education program, that was established in line with the Japanese government's initiative to promote sustainability education in higher education institutions (Akiyama et al., 2013).

Monitoring. GRACE satellite mission is used for monitoring groundwater changes at the regional-scale (Frappart et al., 2018).

ADAPTIVE STRATEGIES

Development and promotion of herbal, medicinal and aromatic plant (instead of other water consuming crops) to create business opportunities for Tunisians, mainly the poor rural population (Neffati et al., 2018).

Diversification in drylands by increasing labor productivity in the nonfarm sector could be a key driver for structural economic transformation in Uganda and Nigeria (Djido et al., 2016).

GREEN INFRASTRUCTURE

Rainwater harvesting to capture and storage of runoff for for agriculture and livelihoods. It includes traditional zai, earthen bunds and ridges (Nyamadzawo et al., 2013), fanya juus infiltration pits (Nyagumbo et al., 2019), contour Stone bunds (Garrity et al., 2010) and semi-permeable stone bunds (often referred to by the French term "digue filtrante") (Taye et al., 2015).

LOCAL WATER SOURCES

Controlled treated waste-water (TWW) is used (almost 91%) for agriculture in Jordan. TWW covers 25% of the irrigation needs, which is estimated to be 700 Mm3 and around 60% of the annual water budget (Ait-Mouheb et al., 2018).

Exchange. The farmers provide groundwater for urban use in Benidorm during the summer months, when demand increases due to the arrival of tourists. For its part, the city provides reclaimed water free of charge to the Irrigation Communities, during the rest of the year, for the irrigation of fruit trees. (Ricart et al, 2019).

LIFESTYLE

Ecolabelling of sustainable products. The extra virgin olive oil based on the "Olivares Vivos" (Living olive groves) certification scheme bears the hallmark of the recovery of biodiversity and cultural heritage (Rey et al, 2019), and is committed to traditional olive groves as opposed to hedgerow olive groves, predators of water (Martínez-Valderrama et al., 2021).

ECONOMIC TOOLS

Market for Ecosystem Service in Fox Canyon (California) groundwater market. It is an example of how to ensure that the cap on groundwater pumping can include water for nature (Matsumoto et al, 2019).

Cost benefit analysis in Central Tunisia to assess the social and private profitability conclude the need for incentives to encourage the use of cactus in alley cropping to supplement livestock food and watering (Daly-Hassen et al, 2019).

GOVERNANCE

Water governance and conflict management in Lake Chad Basin is assessed using a Qualitative Document Analysis approach and a set of subjective integration scoring criteria. This is an empirical example to ascertain the interdependencies at the adaptation-water-peace nexus. It is also assessed whether and how integration is planned, setting out ways forward for mutually beneficial integration actions (Okpara et al., 2018).

LAND PLANNING

Provide more economic opportunities. Farmers in less developed regions have few options for increasing their income other than expanding their agricultural scale. (Zhou et al., 2016)

Dryland restoration must be carefully planned so as not to worsen the hydrological balance of the area (Mátyás & Sun 2014). Many of the forests we see are the legacy of past climatic conditions and restoration of vegetation cover must take into account the future climate (Guirado et al., 2022).

Fig. 5 Examples of the implementation for the eight lines of action proposed in this review. Source: Own elaboration

rated oils and limits to nearly zero the consumption of processed and unprocessed red meat, added sugar, refined grains and starchy vegetables (Willett et al. 2019)), the water footprint would fall by 12% at a global level but increase for nearly 40% of the world's population. Analysis of the water impact of diets worldwide (Harris et al. 2020) therefore has a key role to play in the design of solutions that narrow the water gap.

Environmental and socio-economic interactions between distant places are not novel, as trade, the spread of invasive species or technology transfer are occurring since millennia. However, they are occurring more rapidly than ever before and taking place in entirely new contexts. This growing socio-economic and environmental interactions over distances is called telecoupling (Liu et al. 2013), and is based on the flows and feedback through which dynamic, social-natural systems are reciprocally connected (Munroe et al. 2019). Water use reflects this recent paradigm well. The human impact on the water cycle is more internationally connected than ever through flows of people, commodities, finance, technology, and information that enable emerging impacts on the water cycle through virtual water flows (Hoekstra and Mekonnen 2012; Dalin et al. 2017; Gleeson et al. 2020).

Water grabbing, linked to land grabbing, i.e., land acquisition in developing countries leaded by agribusiness corporations (Dell'Angelo et al. 2018) is another form of decoupling. It has been suggested that is the need for water, rather than for land itself, is the fundamental driver of the ongoing global "land rush", i.e., the drastic expansion of large-scale land acquisitions (Allan et al. 2012; Franco et al. 2013). Globally, Rulli et al. (2013) found that about 310 $km^3 \cdot yr^{-1}$ of green water (i.e., rainwater) and up to 140 $km^3 \cdot yr^{-1}$ of blue water (i.e., irrigation water) are appropriated globally for crop and livestock production in 47 Mha of grabbed land. This transnational appropriation further increases water insecurity in developing countries, where the local population is becoming increasingly dependent on food aid and international food subsidies, as is the case of Sudan or Ethiopia (Jackson et al. 2015).

4.6 Economic Tools for Water Policy

In mature water economies, where it is not possible to further expand water supply based on traditional structural solutions, water policy is oriented to supply-side measures. This include economic instruments, such as water pricing, trading, and voluntary agreements, focused on the efficient reallocation of existing water resources (Gleick 2000) and with the purpose of adapting individual decisions to collectively agreed goals (Lago et al. 2015a). Pricing mechanisms include incentives, usually introduced via tariffs, and disincentives, like charges or fees, and taxes or subsidies. Ideally, water prices should reflect financial (i.e., service delivering water infrastructure), environmental (i.e., those arising from harm induced to ecosystems and ecosystem services), and resource (i.e., social welfare losses from not using the water for the most socially beneficial purpose) costs (Mysiak and Gómez 2015). Pricing can only work if the demand for water or water services is elastic, i.e., when the quantity demanded of a good or service responds to a change of its price. Apart from this theoretical requirement, practical applications need to overcome information asymmetries, pre-existing permits or water rights that adhere to different legal doctrines, and the hostile reception of water cost increases. According to Lago et al. (2015b), tariffs encourage technological improvements or behavioral changes that lead to a reduction in water consumption, while taxes or charges penalize some water uses or practices. In contrast, subsidies lead to a reduction in the price of more water-friendly products or the adoption of environmentally friendly production methods, resulting in competitive advantage with comparable producers.

Water markets refer to a whole range of institutions that facilitate voluntary exchanges of water between users (Montilla-López et al. 2016). They may take different forms depending on their defining variables, including key aspects, such as their legal status (formal and informal), the rights being traded (permanent rights, temporary rights or "spot markets", and options on temporary rights), or the parties involved (sellers and buyers). Water banks, a particular case of water markets in which intermediaries are involved, are established in California (Howitt 1994), Australia (Wheeler et al. 2014), and northern Chile (Hearne and Donoso 2014) as a water redistribution mechanism. The implementation of water markets requires an infrastructure to move water through and a clear definition of water rights. Some potentially adverse aspects are greater overexploitation of groundwater and a decline in economic activity in water-origin areas (Hanak 2003).

Water compensation mechanisms between cities and croplands in areas with scarce water resources can critically contribute to solve local water gaps (Molle and Berkoff 2009; Qadir and Sato 2016). In some territories, urban areas transfer purified water with advanced treatments suitable for agricultural use and at affordable prices (Xiaowei et al. 2018). And the agricultural activity derives quality flows from surface sources for the supply of a city. Thus, water compensation mechanisms are established between the city and the countryside. The city must assume the higher cost of the infrastructures necessary to activate this water circuit (Rico Amorós et al. 2014). This mechanism can also incorporate water from desalination based on the existing water demand for agricultural use in an area (Tahiri et al. 2020).

4.7 Water Governance

Water governance refers to the mechanisms through which rules that guide the water actions and plans are established and enforced (Katusiime and Schütt 2020). It encompass a range of political, social, economic and administrative systems to develop and manage water resources, and the delivery of water-based services in society (Rogers and Hall 2003). In developed countries, mechanisms for water governance have been activated and are supported by regulations. Governance generally involves planning at the level of the planning area and the participation of stakeholders (irrigators, urban consumers, administrations involved, social partners) (Valdés-Pineda et al. 2014; Woodhouse and Muller 2017). These ideas have been reinforced by the LDN, which appeals to existing spatial planning to achieve its objectives. For effective governance to develop, it is necessary to identify the water stakeholders in a planning area and understanding their interests to reconcile the water planning solutions needed at any given time (Uche et al. 2015; Mohammadinezhad and Ahmadvand 2020; Ricart and Rico-Amorós 2022). Such mechanisms are lacking in less developed countries, where water becomes an object of domination and generates situations of conflict over its control (Nasr and Bachta 2018). Water governance in drylands must incorporate circular economy processes to harness scarce local resources (Casiano Flores et al. 2018; Morseletto et al. 2022; Salminen et al. 2022), enforce water laws (De Stefano and Lopez-Gunn 2012), regulate irrigated areas (which are expanding rapidly as a refuge from climate change), and produce more egalitarian wealth distribution models.

Spatial planning is an operational way to implement water governance in a territory, as it directly affects water consumption (Pijnappels 2009; Morote Seguido et al. 2019). The development of extensive territorial models with urban typologies based on single-family housing supposes a high cost of land and also entails a greater cost of water (Gielen 2016), compared to compact city models where network losses are better controlled and the efficiency of the water distribution network is greater (Saurí et al. 2011; Rico-Amoros et al. 2013). In this way, the water savings that are promoted in the urban area can be transferred to nearby agricultural areas with an affordable economic cost.

It has become clear that top-down solutions fail because they ignore the local context and its particularities and try to impose the same recipe for all territories. However, what happens on a piece of land is ultimately dictated by the aggregate over large areas of individual decisions taken by farmers (Vico and Davis 2019), who often look at short-term profitability and do not consider the long-term benefits of protecting blue and green water resources. The globalization in which we are immersed requires considering the implications of global phenomena. The transboundary nature of water encourages its indiscriminate use. Monitoring and proposing solutions at an international level could avoid falling into the Tragedy of the Commons (Bierkens and Wada 2019), i.e., use it before your neighbor does, and avoid major territorial conflicts (Schillinger et al. 2020). We must also be aware of the impact of the consolidation of urban societies (Satterthwaite 2011), which has fostered telecoupling. Thus, what happens in a territory is linked to remote criteria, and decisions are forged by a set of factors (such as fashion for certain foods or habits) which outcome is unpredictable. The global energy crisis, spurred by conflicts such as the ongoing war in Ukraine, is one of these unforeseen situations that may lead to an increase in demand for biofuels (reducing water availability for other uses). The need to solve the food-energy-water trilemma (D'Odorico et al. 2018) becomes even more important in the current global context.

We must also be cautious about the conclusions drawn from global approaches because local realities often clash with optimistic aggregated assessments. Thus, for example, global trade can reduce water use (Dalin et al. 2012; Rosa et al. 2020) found that up to 35% of currently rain-fed croplands, irrigation could be expanded as an adaptation strategy to climate change without negative environmental externalities on freshwater resources. Davis et al. (2017) found that by reallocating crops to the most suitable locations for growing, the consumptive use of rainwater and irrigation is reduced by 14% and 12%, respectively. These calculations, however, do not consider national security. They also assume that food travels freely from one place to another, which is not always possible (as the current war in Ukraine illustrates), and when it does it increases the carbon footprint of agriculture.

4.8 Land Planning

Land planning is the vehicle for translating land-use policies into the territory, that is, the preferences of society. That is why the LDN considers it as the basic tool (Cowie et al. 2018) to achieve a good governance and sectoral coordination. Land planning should encompass many of the things said above. Thus, limiting the irrigated area in drylands seems an essential action, mostly when water reserves are depleted to produce food so cheap that often it is not even harvested. In any case, the sizing of irrigation should be done according to the local availability of water, coordinating hydrological and agricultural plans. Similarly, reforestation plans must consider their impact on the regional water balance. For all this, it is necessary for the countries to equip themselves with legal spatial planning instruments that have sustainability and adaptation to climate change as the guiding principle of actions and that their compliance be monitored (Liang et al. 2021).

The relationship between land use planning and water resources is most evident in the management of groundwater in drylands. Given their characteristics –transboundary, transsectoral (environment vs. agriculture), difficult to quantify, and with a low or even null replenishment rate– it is necessary to regulate their exploitation. The transition from food crops to cash crops is a generalized trend in places where there are not many more development opportunities, such as in NW China (Zhou et al. 2016). Due to the lack of smart land management strategies, the rapid expansion of cultivated oases usually results in water imbalances and land degradation in drylands (Lü et al. 2020). Land use planning should help to propose and encourage other land uses that ensure the viability of water resources. We cannot assume a smooth transition to rainfed agriculture when water resources are depleted, since many of the soils in these regions are not suitable for agriculture. Nor can the future depend on the arrival of external water resources. This is the case in the Ogallala aquifer (USA), where this transition has been studied and highlights the importance of taking into account local biophysical constraints when planning future land use trajectories (Deines et al. 2020).

5 Conclusion

The water needs of a global population that has now reached 8 billion people continue to increase after decades of implementing a series of highly technical solutions that have tried to bring water to where it is needed. This policy makes sense until people have water security that meets basic standards (as pursued by SDG 6), but it starts to run out of steam when demand soars to use water for all kinds of businesses, lucrative for (decreasing) part of the population. Then, providing water ceases to make economic and social sense since the entire socio-economic framework of the territory is at risk for the benefit of a few. At this point, it is necessary to manage water demand.

We present evidence and arguments to illustrate the impossibility of solving the water gap with single-oriented solutions, and argue that the water gap must be addressed through a sophisticated mix of policies, sufficiently flexible to accommodate the enormous causality of the ongoing water crisis. For this, it is necessary to understand how this water gap is generated. If we figure out those mechanisms, we will have a better chance of designing effective measures. As we have seen, in many cases the exorbitant use of water is a symptom, and the problem has to do with energy, demographic, and educational policies, and wasteful lifestyles that ignore the water limits of the planet. Despite the symptoms of exhaustion of water resources are becoming more apparent, and the growing geopolitical tension due to the dispute over water resources worldwide, it is challenging to move from the supply-side to the demand-side paradigm.

We have presented possible lines of action and some practical examples to narrow the water gap, but each territory must study what happens there and implement measures that considers both local interests and global scenarios. At the same time, the population must understand that water resources are not infinite, and must be used efficiently from both a technical and socioeconomic point of view, and that we must preserve part of water resources to keep healthy ecosystems that can continue providing the multiple services needed for our well-being and development.

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Declarations

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