Mapping incentives for sustainable water use: global potential, local pathways

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Abstract

Competition for freshwater resources is intensifying water scarcity and its impacts on people, economies, and the environment, posing a growing challenge for sustainable development. Meeting these challenges will require incentives to encourage sustainable water use. Prior calls to shift from supply-driven solutions to a soft path of demand management (pricing, markets, behavioral changes) have encountered stubborn obstacles. We undertake a multi-scale assessment of water reallocation and investment in water conservation technologies to understand their potential and limits for addressing different drivers of water scarcity. Our model identifies what drives water scarcity at the subbasin scale, and examines two prominent responses to these drivers. Our analysis distinguishes different types of water scarcity based on the demands for water and their timing, creating nine (9) categories of water competition, which can overlap. Water demand within agriculture contributes to scarcity in 94% of the basins experiencing scarcity, concentrated in central USA, Spain, and India. Urbanization has led to competition between cities and agriculture in 1,596 of 3,057 subbasins (52%). We examine how different institutional mechanisms (incentive-based water reallocation) and technologies (investment in water conservation technologies) can address these different types of water scarcity. This study builds on several local and high-resolution models demonstrating the potential to increase the economic efficiency (and marginal productivity) of water use. The gap between potential and implementation is high, however. Efforts to bridge this gap in priority geographies can link modelling advances with the design of pathways that combine incentives with robust water accounting, caps on water extraction, and enforcement capacity at multiple scales.

Introduction

The World Economic Forum’s global risks survey has identified water scarcity as one of the top five global risks affecting people’s well-being (WEF 2020). Water supply variability, exacerbated by climate change, is already a significant challenge for food growing regions (Hanjra and Qureshi 2010, Connor et al 2012) and cities (Richter et al 2013, Padowski and Gorelick 2014). Water demand globally has increased due to multiple, interrelated factors including urbanization, changing diets, and a growing population. As a result, water abstraction today is nearly six times greater than it was 100 years ago (Wada et al 2014). Historically, water policies and investments have favored supply-side solutions like dams, desalination and groundwater development (McEvoy 2014, Baldassarre et al 2018). However, incentive-based approaches to manage demand—including improved water allocation policies—consistently rank among the lower-cost options to enhance water security (World Bank 2016, O’Donnell et al 2019). This article focuses on the question: which types of incentives and investments can address different types of water scarcity? This requires us to first understand what drives scarcity, and then evaluate appropriate incentives and investments that match the type of water scarcity.
What drives water scarcity?
Water scarcity can be defined as an excess of water demand over available supply (Steduto et al. 2012). Within this definition are several important components. Freshwater supply or availability depends on precipitation over land which divides into either runoff or evapotranspiration (Hoekstra 2019). Water availability fluctuates over space and time, and exacerbations in hydrologic variability due to climate change challenge water management and policy (D’Oдорico and Bhattachan 2012, Hall et al. 2014). There are also different types of water demands and uses. Consumptive use (evaporation or transpiration) can be beneficial (e.g. intended for a cooling plant or irrigation) or non-beneficial (e.g. evaporation from a lake) (Perry 2007). Water consumption can either be recoverable (e.g. return flows from sewage systems) or non-recoverable (e.g. flows to the sea) (Perry 2007). Economic policies and technological changes respectively, influence the demand and supply curves of water. Economic policies (e.g. trade policies, subsidies) drive changes in water use which affect water productivity (Debaere and Kurzendoerfer 2017) and comparative advantage (Debaere 2014).

Studies demonstrate that agriculture is the largest water consumer (Falkenmark and Rockström 2006, Tuninetti et al. 2019) and that globally, the area equipped for irrigation has expanded fivefold over the 20th century (Siebert et al. 2013). Urban water demand is projected to increase by 80% by 2050 and competition between cities and agricultural users could affect hundreds of millions of people (Flörke et al. 2018). Competition between hydropower and agricultural users (Zeng et al. 2017) and industrial water users (Strzepek and Boehlert 2010) also occurs. Water demands for the environment should be considered as well, as environmental flow requirements and management play an important role for freshwater conservation (Poff and Zimmerman 2010). However, over 40% of global irrigation water use occurs at the expense of environmental flow requirements, (Jägermeyr et al. 2017) and groundwater pumping has already resulted in environmental flow limits being reached in a substantial number of watersheds (Graf et al. 2019).

There are also differences in how water scarcity is measured, and the assumptions in those definitions affect the analysis. Both blue water and green water are affected by water scarcity. Blue water scarcity (BWS) is defined as the ratio between societal blue water demand and renewable blue water availability (Rosa et al. 2020). Green water scarcity (GWS) is defined as the ratio between irrigation water requirement and total crop water requirement (Rosa et al. 2020). Within the literature, blue water scarcity has received significant attention, in part because it represents competition between water users (Brauman et al. 2016, Rosa et al. 2020). Studies on green water scarcity lag behind (Rockström et al. 2009, Schyns et al. 2015) even though accounting for GWS is critical for agricultural production (Aldaya et al. 2010) and represents opportunities for reduced water use and increased water productivity (Molden et al. 2010, Davis et al. 2017). There are also important differences in measuring water scarcity in terms of livelihoods (Srinivasan et al. 2012), natural-human systems (Jaeger et al. 2013) or biophysical definitions (Brauman et al. 2016)4. Here we focus on a biophysical definition of water scarcity defined by (Brauman et al. 2016) as depletion, i.e. the fraction of available renewable water consumptively used by human activities within a watershed.

Which incentives can address different types of water scarcity?
There are multiple types of incentives for addressing water scarcity. The literature is extensive and inconsistent in its terminology for what counts as an incentive, and whether incentives should be considered strictly ‘demand-side’ given their heavy reliance on supply infrastructure. We examine economic instruments for water management drawing on typologies developed through recent work in the European Union (Rey et al. 2019), environmental conservation organizations (Springer et al. 2021), and irrigation technology for water conservation (Pérez-Blanco et al. 2020). We focus on incentive-based reallocation (which can be coordinated by markets or negotiation) and investment in water conservation technologies (which involves technology adoption and behavior changes). Incentives and investments designed to address competing water uses require an increase in the economic productivity of water (Debaere et al. 2014) i.e. the value of product over volume of water extracted. Specifically, we assess how the policy and technological changes required for water reallocation and water use efficiency can address different types of competition for water.

We map incentives for sustainable water use by addressing two gaps: (1) What types of demand drive water scarcity? and (2) Which incentives and investments can address those drivers in the short term and long term? To answer these questions, we take four steps. First, in this section (above), we reviewed the literature on the drivers of water scarcity and the role of different incentives and investments. Second, in the methods, we construct a basic typology of water scarcity that considers the types of demand driving water scarcity and their timing. Third, we formulate a rules-based logic for matching incentives and investments with different types of water scarcity. Fourth, we map the drivers of water scarcity and potential incentives globally, and illustrate the sub-national heterogeneity in the context of Mexico.

3 See supplementary materials for references for blue and green water.
4 For a more complete list of the trade-offs of different water scarcity metrics, see (Rijsberman 2006).
Our analytical framework links drivers of water scarcity to different incentives and investments. This framework needs to be tailored by water managers for application at different decision-making scales. The initial objective is to understand where, and how, different incentives can respond to water scarcity. Matching the type of scarcity to appropriate incentive-based tools can help identify priorities for policy reform and investment.

**Methods**

Our framework for linking water scarcity with incentives and investments focuses on the interaction of human and natural components of water (Srinivasan et al. 2012, Jaeger et al. 2013). We create this link using three steps:

1. **Map** the drivers of water scarcity by looking at the intersection of (a) types of demand and (b) their timing.
2. **Define** different types of incentives and investments, their strengths and weaknesses, limiting factors, and enabling conditions.
3. **Compare** how certain incentives and investments impact water scarcity (e.g. change in use, increase economic productivity, increased environmental flows, etc.).

**Step one: map the drivers of water scarcity**

We develop a typology of water scarcity built on two axes: (1) types of demand and (2) timing of water scarcity (figure 1 below). The two axes reflect trends in literature that competition (Flörke et al. 2018, Kendy et al. 2018) and timing (Hanasaki et al. 2013, Schewe et al. 2014) are critical attributes for understanding water scarcity. To develop the types of demand axis, we examine three types of demand that can drive water scarcity in the context of limited water supply using WaterGAP3 (Brauman et al. 2016) and City Water Map (McDonald et al. 2016) (described in supplementary material (available online at stacks.iop.org/ERC/3/041002/mmedia)). First, we...
identify basins where competition for water is driven by irrigated agriculture (figure 1: Types 1–3). Second, we identify basins where water scarcity is driven by competition between agriculture and urban users (figure 1: Types 4–6). Finally, we identify competition between urban and industrial users (figure 1: Types 7–9). Future iterations should consider environmental flows (Richter et al 2012) which would highlight additional layers of competition within a basins and aquifers.

Next, we develop the timing axis by categorizing the timing of scarcity as either seasonal, chronic, or anticipated. For seasonal and chronic scarcity we rely on existing categories developed by (Brauman et al 2016). For anticipated scarcity we rely on the WRI’s Water Risk Atlas, Future 2030, Business as usual, Water Stress indicator (Luck et al 2015). Combining the drivers and timing of water scarcity results in a 3 × 3 matrix categorizing 9 types of water scarcity based on the relationship between competition and timing. Each of the 9 types of scarcity identifies what drives water scarcity in a given basin. For example, basins with type 5 water scarcity are characterized by competition between urban and agricultural users, and the timing of scarcity is chronic.

Step two: define different incentives and investments

Incentives for sustainable water use need to be matched to local contexts and designed based on available legal and regulatory frameworks, and the underpinning. However, as a first step in assessing locally relevant metrics we focus on incentives and investments associated with water reallocation (exemplified by transactions) and investments in water conservation technologies (WCTs). We identify basins which can be served by either water reallocation, WCTs, or both. WCTs may apply anywhere there is or could be irrigation, while reallocation applies where it is legal, and there are heterogeneous uses particularly agricultural to urban, hence differences in the marginal productivity of water.

The ability to reallocate water (via transactions, other incentive-based mechanisms, and even some administrative procedures) can create incentives that can increase the marginal productivity of water by forcing water users to consider the opportunity cost of water in alternative uses (Thobani 1997). A classic example includes neighboring farms with differing marginal productivity of water; the ability to reallocate water forces the farm with the lower marginal productivity to consider whether using the water is more profitable than selling it to the neighbor. However, water reallocation depends on regulatory limits to water extraction based on sustainability criteria, well-defined property rights to water, adequate water accounting, and associated governance mechanisms for enforcement, stakeholder inclusion and conflict resolution (Easter et al 1999). For our model, we focus on two considerations: (i) legal permission to reallocate water under specified conditions and (ii) the heterogeneity of water uses, which implies the potential for economic gains from reallocation. Legal permission for water reallocation is interpreted more narrowly than stipulated above, and includes documented formal water allocation reforms and the separation of land ownership and water rights and is assessed at the national level (water laws are set at the sub-national level in some countries). There are 74 countries where water reallocation has been authorized and implemented based on data from prior publications (Endo et al 2018) and the OECD’s Water Resource Allocation report (OECD, 2015). Basins in countries where reallocation is either not yet authorized or documented can only use WCTs.

Water conservation technologies can increase the economic productivity (in terms of yields per unit of water) and typically focus on increasing physical irrigation efficiency. However, WCTs can only lead to a net reduction of water consumption when paired with the following: limits to water extraction, clearly defined and enforced property rights to water, and attention to the water balance and accounting (Perez-Blanco et al 2020, Grafton et al 2018). The heterogeneity of crops produced within a basin offers a proxy for diversity of use, although the marginal productivity of water can vary even within a basin dominated by a single crop due to effects of other factors of production on crop productivity. We use data from the 2010 Spatial Production Allocation Model (SPAM) (Yu et al 2020) and identify variation in the value of crop production within a basin. We consider the basins containing higher variation in the value of crop production as better candidates for incentive-based reallocation than those with lower variation. We assumed that basins with near homogenous values of production have less incentive to reallocate water, although there will be exceptions when there is high variation in other factors of production.

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5 Example: (Richter et al 2017).
6 Example: (Garrick et al 2019).
7 Example: (Strzepek and Boehlert 2010).
8 For a complete review of WCTs see Pérez-Blanco et al 2020.
9 The ratio of water consumption by the crops in a field to the water diverted from a water source (Pfeiffer and Lin 2014).
10 For more information of calculations, refer to supplementary material.
Step three: compare how incentives and investments impact water scarcity

The applicability of incentives involves legal and institutional criteria as well as economic costs and benefits. While transactions costs (Garrick et al 2013) and the paradox of irrigation efficiency (Grafton et al 2018) impede reallocation and WCTs respectively, the short and long-term costs and benefits are an empirical matter, and shaped by historical, cultural, technical and other contextual factors.

For example, water consumption usually increases with water conservation technologies unless combined with limits on water extraction and clearly defined and enforced entitlements to water, underpinned by water accounting (Pérez-Blanco et al 2020). Although WCT projects may involve public investments (Grafton et al 2018; Richter et al 2017), decentralized and private investment by farmers and agribusiness hinge on risk perceptions, access to finance and economic decisions. Valuing water (Garrick et al 2017) and water pricing (Davidson et al 2019; Hellegers and Perry, 2006) will shape the incentives for both water reallocation and investing in WCTs. In practice reallocation and WCTs are interrelated and can be synergistic (e.g. legal permission to reallocation water can create incentives for private investments in WCTs) or counterproductive (when legal permission to reallocate water or public investments in WCTs ignore social and environmental externalities), meaning these results should be interpreted with caution and then downscaled with high resolution data on costs, benefits and behavioral responses. Figure 2 represents an indicative assessment of benefits (private and public) (Pannell, 2008) different incentives can provide. Different drivers of scarcity require different types of incentives.
Results

Our spatially explicit model demonstrates how geographic patterns of water scarcity reflect the types of demand and their timing. On the global scale, our model highlights a total of 1,275 basins that are categorized by one or more of the nine scarcity types. A single basin can have multiple types (median = 2, mean = 2.3). Hotspots of multiple types are prominent in the central California, northern India, north eastern China, and central Mexico (see figure 3).

Water demand for irrigated agriculture remains the most significant driver of water scarcity in our model, echoing recent literature (Davis et al 2017, Perry et al 2017). The scarcity type with the highest count (n = 1,119) was type 4: urban and agricultural competition in seasonal scarce basins, adding to the evidence that competition between agriculture and urban users is a significant challenge (Flörke et al 2018, Garrick et al 2019).

In terms of the timing of scarcity axis, basins categorized as seasonal scarcity (types 1, 4 and 7) had the highest number of basins (n = 1,763) followed by future scarcity (n = 995), and then by chronic scarcity (n = 299). That chronic basins featured considerably less than future and seasonal is a reflection of the WaterGAP3 model, which has demonstrated similar results in previous work (Brauman et al 2016). Along the types of demand axis, urban and agriculture (types 4, 5 and 6) were the most prevalent (n = 1,596), followed by demand within agriculture (n = 1,271), followed by demand between industry and urban users (n = 190).

The graphic below (figure 4) shows areas characterized by each type of water scarcity in our matrix.

We find that globally, 601 basins are potentially suited for water reallocation, 464 are potentially suited for WCT incentives, and 424 meet the criteria for either water reallocation or WCTs, although technically WCTs are feasible and potentially applicable anywhere there is irrigated agriculture. The map below (figure 5) shows the geographic extent of the three portfolios.

The global analysis shows the spatial variation which can be seen across countries and also within them. For example, Mexico (figure 4) illustrates the different types of demands that drive scarcity in the short and long term. Northern Mexico is dominated by seasonal scarcity and competition among agricultural uses and users, and between agriculture and urban users. This includes the Rio Bravo/Grande agricultural valleys as well as major cities like Monterrey, Ciudad Juarez, and Tijuana. Central Mexico is categorized as a mix of several scarcity types including competition between urban and agricultural users in chronic and anticipated scarcity regimes. We find that the ten most-populated cities in Mexico (home to approximately 30 million people) are located within watersheds experiencing one or more types of water scarcity.
Discussion

Water scarcity has human and hydrological components. Bridging these elements helps identify potential pathways for evaluating impacts and responses to water scarcity via incentive-based tools. We find that 73% of the water-scarce sub-basins in our model are located within national boundaries where documented legal water reallocation has occurred. This suggests there is additional potential for strengthening institutions supporting water reallocation, which may in turn drive investment in WCTs and enable reallocation between sectors. Different drivers of scarcity will require different incentives. Integrating multiple incentives can include synergies with existing green and grey infrastructure projects that facilitate the movement of water.

One contribution of this article is to demonstrate that (a) different types of water scarcity are present and emerging, and (b) linking types of water scarcity to specific incentives and investments that may help address water scarcity. We also propose that our three-step approach (map, define, compare) needs to be tailored to local contexts.

As a first step, we chose to illustrate the framework for mapping incentives for sustainable water use at the global scale to understand the global potential. However, as mentioned, local variability can drastically shape the applicability, feasibility, costs, and benefits of incentives. There is a many to many relationship between drivers of water scarcity and applicable incentives, i.e. many options for addressing a given driver. Therefore, as a next step, it is critical to move from the global potential, which overestimates the potential applicability of incentives and investments, to local pathways that consider costs, benefits, and technical and political feasibility (Werners et al 2021). Realizing the local pathways can be informed by (1) downscaling our matrix of types of demand and

Figure 4. The 9 water scarcity types in our analysis. The interaction between competition of users and timing of scarcity provides a more nuanced picture of global water scarcity.
timing of water scarcity, (2) quantifying benefits and costs of specific priority incentives, and (3) focusing on governance, public/policy priorities, and feasibility. All three steps require local high-resolution data and sustained engagement with local stakeholders. Recent research in decision scaling for sustainable water management may offer frameworks for operationalizing potential incentives based on local factors (Brown et al 2012, Poff et al 2016). Additionally, it will be critical to closely evaluate and measure the unintended consequences to the environment (e.g. return flows).

**Downscaling**

Our results illustrate how water scarcity manifests as a result of the dynamics between competing uses and the timing of scarcity. However, an important next step is to test our analytical approach by downscaling to priority geographies. For example, our global model identifies priority geographies including Mexico, India, and California, which suggest their water scarcity types are conducive to incentive-based mechanisms for addressing water scarcity. However, the current resolution of global datasets is not sufficient for prioritizing areas within those geographies for intervention. Downscaling aligns with recent trends in the literature for matching decisions to the scale of the challenge (Brown et al 2012) as well as accounting for the spatial dynamics at appropriate scales (Dobson et al 2020). This will include the need to account for infrastructure and institutional arrangements.

**Moving from qualifying to quantifying**

There is extensive literature on the costs of different kinds of incentive-based programs for water allocation, and include specific costs like transaction costs and monitoring costs (Garrick et al 2013, Marshall 2013). Likewise, many local factors influence these costs which are highly associated with institutional capacity (Grafton et al 2011). As a first step, we were interested in qualifying different benefits associated with specific incentives. As a next step, we need to quantify specific benefits of priority incentives. One approach is by linking the Total Economic Value (TEV) framework to a private and public net benefits framework for choosing policy mechanisms (Pannell 2008). In addition to benefits, it is important to quantify specific costs associated with the transactions of different incentives. This includes special attention to transactions costs (Garrick et al 2013, Erfani et al 2014) as well as gains from trade (Zekri and Easter 2005, Brooks and Harris 2008), and the cost-effectiveness of reallocation, WCTs and different hybrids. There is also opportunity to expand on the types of public and private values to include new legal rights (e.g. for rivers) (O’Donnell and Talbot-Jones 2018) as well as indigenous water justice (Robison et al 2017).
Figure 6. (a) Zooming into Mexico highlights different types of water scarcity based on the interaction between competition of users and timing of scarcity. (b) Linking the type of water scarcity to a portfolio of incentives designed to respond to the specific type of scarcity in a basin.
Focusing on governance and feasibility
Future work will focus on understanding institutional arrangements as a critical step in assessing feasibility. At present our analytical framework is designed to answer the question: where, and how, can different incentives respond to freshwater scarcity? However, missing in this assessment is the feasibility of specific priority incentives. Institutional capacity is critical for achieving sustainable water use (Garrick et al 2017) and especially with incentives like water markets (Casado-Perez 2015). Efforts to combine institutional analysis (Ostrom 2011) and market design (Teytelboym 2019) will play an important role in closing the gap between the theory and practice of incentive-based solutions for water scarcity.

Conclusion
Water scarcity already impacts billions of people and over half of the world’s rivers and their aquatic habitats (Vörösmarty et al 2010, Mekonnen and Hoekstra 2016). Changes in population and climate indicate that the imbalances between the supply and demand of water will be exacerbated in the future (Flörke et al 2018). The inability to close the supply-demand gap has serious consequences for economic and environmental outcomes and jeopardizes our chances of meeting SDG 6.4. Policy-enabled incentives via water reallocation and technology-induced incentives via investment water conservation technologies have been presented as scalable solutions to mend the imbalances of supply and demand for water. However, decades of international experience demonstrate that their success is elusive. As a first step in quantifying the potential of incentives, we developed an analytical framework to demonstrate how certain incentives can match different water scarcity types and meet specific objectives. At the global scale, the results indicate that over twelve hundred unique basins present enabling conditions for at least one incentive for responding to water scarcity. We propose that defining the scarcity type, quantifying the impacts on water scarcity, and calculating the costs and benefits (both public and private) of priority incentives can help water managers examine the tradeoffs of different incentives. Basing decisions on these metrics can help close the gap between the theory and practice of incentive-based mechanisms for water reallocation. Doing so can maximize the chances for incentives to succeed in their local contexts, thus providing a set of cost-effective solutions for achieving SDG 6.4.

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