Investing in Adaptation:

The Challenge of Responding to Water Scarcity in Irrigated Agriculture

Susanne M. Scheierling and David O. Treguer

Agriculture's Water Economy

Federal Reserve Bank of Kansas City Agricultural Symposium

July 11-12, 2016

Susanne M. Scheierling (sscheierling@worldbank.org) is Senior Irrigation Water Economist in the Water Global Practice, World Bank, Washington, DC. David O. Treguer (dtreguer@worldbank.org) is Natural Resources Economist in the Agriculture Global Practice, World Bank, Washington, DC.

The authors wish to acknowledge research support from Kathia Havens, and financial support from the Water Partnership Program (WPP), a multi-donor trust fund at the World Bank. The findings, interpretations, and conclusions expressed in this article are entirely those of the authors. They do not necessarily represent the views of the International Bank for Reconstruction and Development/World Bank and its affiliated organizations, or those of the Executive Directors of the World Bank or the governments they represent.

Water scarcity is increasingly acknowledged to be a major risk in many parts of the world (World Economic Forum, 2015). Projections indicate that water-related problems may significantly worsen over the next several decades due to rising water demands as a result of demographic, socioeconomic and technological changes, and due to the effects of climate change (World Water Assessment Program, 2012; Jiménez Cisneros *et al*., 2014). Significant advances in water management and more integrated policy making, including increased investments in adaptation measures, will be necessary to reduce the risk of possibly dramatic consequences for economic growth and environmental sustainability.

The need for water-related adaptation measures will probably be most critical in the agricultural sector, especially in irrigated agriculture. This is because of four main issues. First, irrigated agriculture accounts for about 70% of total freshwater withdrawals worldwide (Molden and Oweis, 2007). Especially in semi-arid and arid regions, water use in agriculture tends to be closely linked to the water scarcity situation, and improvements in agricultural water management would have large implications on the overall management of the water resource. Second, water use in agriculture tends to have relatively low net returns as compared to other uses (Young, 2005). Thus, as water becomes scarcer and supply augmentation more expensive, other users tend to turn to agriculture as a potential source of water. Third, at the same time, agriculture is expected to increase production—and concomitantly agricultural water use—to meet the likely demands from a growing population with changing diets (Alexandratos and Bruinsma, 2012). And, fourth, the impacts of climate change will further increase the need for water-related adaptation measures, and add layers of complexity for agriculture (IPCC, 2007; Jiménez Cisneros *et al*., 2014). Freshwater resources will be affected due to altered amounts and frequencies of precipitation events—especially in semi-arid and arid areas that often already

experience water scarcity. Due to more intense precipitation and prolongation of dry periods, rainfed agriculture may need to be converted to irrigation. Crop growth more generally will be affected not only by changes in the precipitation regime but also by changes in temperature, evapotranspiration and soil moisture.

In order to at least partially respond to these challenges, a wide range of water-related adaptation options are being considered and increasingly applied in the agricultural sector (Noble *et al*., 2014). Adaptation investments can occur at different scales from the field- and farm levels to the policy and institutional levels (Porter *et al*., 2014). Given the complexity of the challenges, adaptation measures may aim at different objectives. A distinction can be made between at least three objectives (Scheierling and Treguer, 2016). The two key objectives are maintaining or increasing agricultural production, in some cases linked with an attempt not to worsen water scarcity; and conserving agricultural water in response to pressures for reallocating water to other uses, including for the environment, and/or for coping with water scarcity. A third objective that may be linked to the other two objectives is increasing, or at least maintaining, agricultural net revenues. However, it seems that in many cases the objectives of adaptation investments are not clearly stated, and their broader results not closely assessed. This adds to the constraints facing adaptation measures, limits their effectiveness in implementation, and may even lead to unintended and/or counterproductive outcomes. This article aims to further shed light on these issues.

The remainder of the article is organized as follows. Section I highlights some of the unique characteristics of water that underlie many of the complexities in adequately responding to water scarcity in irrigated agriculture. The links between irrigated agriculture and water scarcity are illustrated in section II, including with data at the global level. This is followed by a

discussion of two broad categories of adaptation measures. Section III examines engineering and technical measures, probably the most common adaptation measures and usually applied on-farm with private investments, often supported with pubic subsidies and/or technical assistance. Section IV focuses on policy and institutional measures. While both categories of measures may pursue any or all of the three key objectives, engineering and technical measures tend to contribute to the first and, in particular, the third objective; and policy and institutional measures have an important role to play in achieving, in particular, the second objective. Section V presents recommendations for going forward.

I. Characteristics of Water Important for Considering Adaptation Measures

Water has unique characteristics that distinguish it from most other resources and commodities, and pose significant challenges for selecting appropriate adaptation measures (and for designing water policy in general). Based on Young (1986; 2015), who provides a full discussion of these characteristics, the section below focuses on the features that may be the most important to keep in mind when considering adaptation measures.

A key physical attribute of water is its mobility. Typically found in its liquid form, water tends to flow, evaporate, and seep as it moves through the hydrologic cycle. This makes it a high-exclusion cost resource, implying that the exclusive property rights which are the basis of a market or exchange economy are relatively difficult and expensive to establish and enforce.

Water supplies, although generally renewable, also tend to be relatively variable and unpredictable in time, space, and quality. Local water availability usually changes systematically throughout the seasons of the year and over longer cyclical swings, with climate change now affecting both short and longer-term supply trends as well as the extremes of the

probability distributions, i.e. floods and droughts. Due to these supply variations, coupled with variations in local demand, water-related problems are typically localized and interventions, such as adaptation measures, often need to be adapted to the local context.

The physical nature of water, combined with supply variability, causes unique interdependencies among water users that become ever more pervasive and complex as water scarcity intensifies. This is because water is rarely completely "consumed" in the course of human consumption or production activities. In the case of irrigated agriculture, for example, it is not unusual to find that half of the water withdrawn from a water source is returned to the hydrologic system in the form of surface runoff or subsurface drainage. (An even larger proportion is typically returned from municipal and industrial withdrawals.) Other, particularly downstream, users are thus greatly affected (positively or negatively) by the quantity, quality and timing of releases or return flows of upstream users.

These interdependencies among water users have several implications, especially for on-farm adaptation measures. They make it difficult to derive water-related insights from what is observed on the field or farm level for the overall effects at the basin level. They lead to externalities (or uncompensated side effects of individual activities) where the full costs of the activities are not incorporated in individual users' decisions, and outcomes for the society are suboptimal. Thus there is a need for public policy to complement individual activities and/or orient them toward more desirable outcomes from a social point of view.

II. Irrigated Agriculture and Water Scarcity: A Global View

Establishing a link between irrigated agriculture and water scarcity is made difficult by a number of factors. Among them are not only the special characteristics of water discussed

above, but also the problem of defining water scarcity as well as the availability of data related to current and projected agricultural water use, especially at the global level.

Central Role of Water Use in Agriculture

As a first step, it is useful to keep in mind the global trends in agricultural water use. Based on data from Shiklomanov and Rodda (2003) and the Food and Agriculture Organization of the United Nations (FAO, 2016a), Figure 1 shows the development in agricultural withdrawals[1], total water withdrawals[2], and consumption[3] since 1900. By far the largest part of total water withdrawals has continually been for the agricultural sector. From 1900 to 1995 its share decreased from 89% to 66%; recently it increased again to 70% (based on the data set from FAO, 2016a). Almost all of total water consumption has been agricultural consumption, with the share slightly decreasing from 97% in 1900 to 93% in 1995. Agricultural consumption as a share of agricultural water withdrawals increased from 63% to 70% over the same period. Overall, both total and agricultural water withdrawals increased dramatically since 1900, but since about 1980 their rates of growth started to decline. A factor that contributed to this outcome was that in most OECD countries total and agricultural water withdrawals have tended to remain stable or decreased (OECD, 2013).

Insert Figure 1 here

Table 1 presents data on the ten countries with the largest annual agricultural water withdrawals, based on the latest available data from FAO (2016a; 2016b). These are also the

[1] Data of FAO (2016a) on agricultural water withdrawals include the annual quantities of water withdrawn for irrigation, livestock and aquaculture purposes.
[2] Data of FAO (2016a) on total water withdrawals include the annual quantities of water withdrawn for agricultural, industrial and municipal purposes. In-stream uses, such as recreation, navigation and hydropower are not considered.
[3] Consumption, or evapotranspiration in the case of agriculture, is the amount of water that is actually depleted by the crops, i.e. lost to the atmosphere through evaporation from plant and soil surfaces and through transpiration by the plants, incorporated into plant products, or otherwise removed from the immediate water environment.

countries with the largest total withdrawals. The ten countries are among the countries with the largest areas equipped for irrigation,[4] and belong to the 17 most populous in the world (World Bank Group, 2016). Except for the United States and China, the countries' percentage of total water withdrawals allocated for agriculture is larger than the worldwide average of about 70%. When dividing the amount of agricultural water withdrawals by the area equipped for irrigation, half of the countries are shown to withdraw an irrigation depth of 1 meter or more for their respective area equipped for irrigation. The lowest value of 0.5 for is shown for China, followed by 0.7 meter for the United States.

Insert Table 1 here

When considering all countries with agricultural water withdrawals, a close relationship can be established between agricultural water withdrawals and total water withdrawals as well as area equipped. According to Figures 2a and b, agricultural water withdrawals are highly correlated with total water withdrawals; and an increase of 1 cubic meter in total water withdrawals is associated with an increase of 0.74 cubic meter in agricultural water withdrawals. According to Figures 3a and b, agricultural water withdrawals are also highly correlated with the area equipped for irrigation; and an increase in 1 square meter of area equipped for irrigation is associated with an increase of 0.77 cubic meter in agricultural water withdrawals.

Insert Figures 2a and b, and Figures 3a and b here

Linking Irrigated Agriculture and Water Scarcity

[4] Data of FAO (2016b) on the area equipped for irrigation includes areas equipped for full and partial control irrigation, equipped lowland areas, pastures, and areas equipped for spate irrigation. It does not necessarily represent the area that is actually irrigated. The available data from FAO on the area actually irrigated are too limited for further analysis.

Various definitions of water scarcity have been proposed and different indicators applied (UNEP, 2012). A widely used indicator is based on a comparison between total water withdrawals and total renewable water resources[5] at the national level. A country is considered to experience "scarcity" if total water withdrawals are between 20 and 40 percent of total renewable water resources, and "severe scarcity" if this value exceeds 40 percent. Figure 4 displays this indicator based on the latest available data from FAO (2016a). Countries in the Middle East and North Africa (MENA) are all shown to experience severe water scarcity. In other parts of the world, including most countries in South Asia and Central Asia, water is also considered to be scarce or severely scarce. Some countries' water withdrawals are even higher than their total renewable water resources. Saudi Arabia is the most extreme case, withdrawing almost ten times the amount of renewable resources available, and thus relying mostly on non-renewable groundwater.

Insert Figure 4 here

In order to illustrate the link between water scarcity and irrigated agriculture, we modify the indicator and, instead of total water withdrawals, include only agricultural water withdrawals in comparison with total renewable water resources (Scheierling and Treguer, 2016). Figure 5 shows the data for the modified indicator. The astonishing result is that the classification of countries with "scarcity" and "severe scarcity" is almost the same as in Figure 4, even though only agricultural withdrawals are considered. This shows the central role of irrigated agriculture in such assessments of water scarcity at the national level. The most extreme cases are in MENA: In Saudi Arabia, water withdrawn for irrigated agriculture alone is more than eight times

[5] Total renewable water resources comprise internal renewable water resources (i.e. the long-term average annual flow of rivers and recharge of aquifers generated from endogenous precipitation) and external renewable water resources (such as surface and groundwater inflows from upstream countries).

the amount of total renewable water resources; in Libya it is about 5 times, in Yemen 1.5 times, and in Egypt slightly more than the amount of total renewable water resources.

Insert Figure 5 here

Some caveats apply to both indicators. On the one hand, they may underestimate water scarcity. Since they refer to the national level and apply annual water data, they do not indicate water scarcity situations that may occur at the regional and/or local levels (especially in large countries, such as China) or during the year. They also do not consider water quality issues, or water requirements for the environment. On the other hand, they may overestimate water scarcity since data on withdrawals would include the reuse of return flows that in many cases can be substantial (such as along the Nile in Egypt).

The available data do not allow for an analysis of how changes in agricultural water withdrawals have affected water scarcity over time. However, a look at historical data on area equipped for irrigation can provide some insights (FAO, 2016b). Globally, the area equipped for irrigation increased from 164 to 324 million hectares (ha) over the past 50 years. Figure 6 shows the trends by geographical region (excluding high-income countries) for the period from 1962 to 2012. The biggest growth occurred in South Asia, followed by East Asia and the Pacific. Only the region Europe and Central Asia has seen a reduction in the area equipped for irrigation since the 1990s, mostly due to reductions in the countries of the former Soviet Union.

Insert Figure 6 here

The largest percentage increase in area equipped for irrigation of any country occurred in Saudi Arabia (from 0.3 to 1.6 million ha), followed by Libya (from 0.1 to 0.5 million ha) and Yemen (from 0.2 to 0.7 million ha), and these three countries are now experiencing some of the most severe water scarcity. Large increases, in both percentage and absolute terms, also

occurred in India (from 26 to 67 million ha), a country that is now considered as water scarce, and also in China (from 45 to 68 million ha).

Projected Trends

Agricultural water withdrawals will continue to be a major factor in shaping the water situation worldwide, not least given the expected need for an increase in irrigated area due to rising demand for agricultural products. Projections vary depending on the models employed and the assumptions and scenarios used. For example, projections by FAO indicate that agricultural production in 2050 would have to be 60 percent higher than in 2005/2007, and irrigation water withdrawals would need to increase from 2,761 to 2,926 billion cubic meter per year to meet the likely demand (Alexandratos and Bruinsma, 2012). Considering the historic data of Figure 1, and the rapidly growing other water demands, especially from the municipal and environmental sectors, this projected increase—which is based on rather optimistic assumptions—is quite worrisome.

Projections become even direr, and more uncertain, when the impacts of climate change are taken into account (Elliott *et al*., 2014). The latter projections suggest that by the end of this century renewable water resources may allow a net increase in irrigated agriculture in some regions (such as in the northern/eastern United States and parts of South America and South East Asia) while in other areas the previous expansion would need to be reversed—with a move to rainfed agriculture in some currently irrigated regions (such as the western United States, China, MENA, and Central and South Asia).

III. Investing in Engineering and Technological Adaptation Measures

Probably the most common adaptation investments for responding to water scarcity in irrigated agriculture are engineering and technological measures. They are usually applied on-farm and financed with private investments, often supported with subsidies and/or technical assistance. They include more capital-intensive irrigation technologies, improved seeds, and precision farming to help optimize the use of water and other inputs tailored to local conditions. As water scarcity and/or the variability in supplies increase, large private and public sector investments are being made in many countries for such adaptation measures.

Conversion to More Capital-Intensive Irrigation Technologies as a Popular Measure

A popular and widely adopted measure is the conversion to more capital-intensive irrigation technologies. They increase the "efficiency" of irrigation water use on a field by reducing evaporation and losses from surface runoff or subsurface drainage. The implicit assumption is that a switch to such irrigation technologies will allow to maintain agricultural production with less water withdrawn and applied to a field, and at the same time contribute to the objective of conserving water for reallocation to other uses.

In pursuit of the objective of water conservation, farmers in both advanced and emerging market economies are often provided financial and technical assistance from the public sector to help them convert to more capital-intensive irrigation technologies. For example, the U.S. Department of Agriculture has long provided such assistance to farmers, including under the Environmental Quality Incentives Program that was first authorized in the 1996 Farm Act (NRCS, 2014). It provides cost-sharing of up to 75% to help farmers install more capital-intensive irrigation equipment, such as sprinklers and pipelines, with the aim to conserve ground and surface water resources. Subsidies of over US$10 billion have been provided under the

program for technology adoption, including for water conservation (Wallander and Hand, 2011). Similarly, Morocco is currently implementing the National Irrigation Water Saving Program, launched under the Government's Green Moroccan Plan in 2008 and supported with planned public investments of US$4.5 billion. It aims to conserve irrigation water by helping to convert about 550,000 ha from surface to drip irrigation by 2020, with subsidies of up to 100% for farmers' on-farm investments (EMWIS, 2014).

Effect on Water Scarcity when Return Flows Are Important

In many contexts, however, on-farm investments in "irrigation efficiency" contribute more to the objective of maintaining or increasing agricultural net revenues (and frequently also to the objective of maintaining or increasing production) than to the objective of conserving water for alternative uses. For the United States, an increasing number of studies show that while such interventions may reduce on-farm water applications, they do not necessarily provide real water savings and thus may not have much effect on addressing water scarcity. In contexts where return flows matter to downstream uses, real water savings (i.e., the provision of a "new supply" of water for reallocations) would require a reduction in water consumption. In many instances, the conversion to more efficient irrigation technologies may have the counterproductive effect of increasing consumption, and thus contribute to a worsening of water scarcity.

Furthermore, there may be situations where the introduction of more efficient irrigation technologies even leads to increases in the amounts of water withdrawn and applied. In energy economics this is known as the rebound effect, or Jevons paradox, whereby efficiency increases in the use of a resource result in more being demanded (Alcott, 2005). In the field of water

management in agriculture, the rebound effect is increasingly being discussed—usually in connection with the risk of increasing water withdrawals and applications (Chambwera, 2014; OECD, 2015a). However, the rebound effect can be observed for consumption as well as, and may be even more prevalent in the case of consumption.

Hartmann and Seastone (1965) were among the early water economists who drew attention to the interdependencies among water users and the resulting externality problems. They pointed out that only part of the water withdrawn from a river is used consumptively, whereas the non-consumptively used part typically returns to the stream as runoff or percolates into the underlying groundwater deposits and becomes available for pumping. Using a simplified river system as an example, they illustrated that any change in these return flows (in magnitude, timing, or quality) may affect downstream users. Huffaker and Whittlesey (1995) and Whittlesey (2003) used similar examples to show that improvements in on-farm irrigation efficiency reduce withdrawals and applications, but that in the presence of significant usable return flows this effect only appears to produce additional water. If the "saved" water is used to increase irrigated acreage, consumption may even increase.

Subsequent studies based on normative models showed that because more efficient irrigation technologies—by converting a larger share of the water applications into consumption—reduce the effective cost of consumption, farmers optimally respond to this cost change by increasing consumption and irrigated acreage, *ceteris paribus*. Furthermore, these changes may decrease or increase the demand for applied water (Huffaker and Whittlesey, 2003). Scheierling et al. (2006a) showed that a subsidy policy may increase consumption even in places where an expansion of irrigated land beyond the original land to which a water right applies is not permitted, such as under Colorado's prior appropriation system. This would occur

when farmers find it profitable to alter the crop mix and/or change the irrigation schedule. Ward and Pulido-Velazquez (2008) analyzed the effect of subsidies by applying an integrated basin-scale programming model to the Upper Rio Grande Basin, and found that—although water applied to irrigated lands may fall—overall consumption increases. Where return flows are an important source of downstream water supplies, water right holders that depend on these flows would be negatively affected. Contor and Taylor (2013) showed more generally that whenever an improved irrigation technology reduces the non-consumed part of applied irrigation water, consumption will increase at any non-zero marginal costs for water.

In a study based on an econometric approach, Wallander and Hand (2011) used farm-level panel data from national samples of irrigators to estimate the impacts of the Environmental Quality Incentives Program on water conservation, in particular changes in water application rates and irrigated acreage. Results suggested that, for the average farm, payments may have reduced water application rates but also may have increased total water use, and led to an expansion in irrigated acreage.

Effect on Water Scarcity when Return Flows Are Not Important

While in river basins where return flows constitute a considerable part of the downstream supplies, a reduction in consumption is the appropriate measure for water conservation, the situation may be different in cases where return flows are less important. An example would be a region irrigated from a deep aquifer, such as the Ogallala that is beneath the Great Plains, where the return flows to the aquifer are minimal and/or very slow. Water conservation may then be appropriately measured by reductions in withdrawals. Studies have shown that the switch to more efficient irrigation technologies in such a situation may be an increase or decrease

in withdrawals, depending on the context, and that empirical analysis is required to determine the effect.

Various approaches to generate empirical estimates have been used for the Ogallala region, not least because of the relatively good availability of water-related data. For example, Peterson and Ding (2005) applied a risk-programming model to corn production on the Kansas High Plains, and found that even under simplifying assumptions the effect of an efficiency change on withdrawals was ambiguous. Their results suggest that a conversion from flood to subsurface drip irrigation would decrease both irrigation application per acre and the volume of groundwater withdrawn. A conversion from flood to center pivot, on the other hand, would increase irrigation applications per acre but decrease the overall volume pumped because fewer acres would be irrigated. The latter conversion would also be cost-effective.

In an econometric evaluation, Pfeiffer and Lin (2014) used panel data from over 20,000 groundwater-irrigated fields in western Kansas for the period from 1996-2005 when farmers converted from flood irrigation or traditional center pivots to more efficient center pivots with drop nozzles—supported by subsidies from state and national sources, including the Environmental Quality Incentives Program. They found that, with the conversion, the amount of groundwater pumped and applied to fields increased. This is because farmers tended to shift toward a crop mix with relatively more corn—a more water-intensive crop than the traditional wheat and sorghum—, and apply more water per acre. They also irrigated a slightly larger proportion of their fields, and were less likely to leave fields fallow or plant rainfed crops.

These considerations, such as the local context and the relative importance of return flows—illustrated above using the example of more efficient irrigation technologies—, are likely to be similarly important in determining the effect on water scarcity in the case of other

engineering and technological measures that are applied on-farm. However, there will also be exceptions. In the case when returns flows are important and the focus is on reducing consumption (while at the same maintaining agricultural production), this would include adaptation measures that directly aim to either decrease evaporation (for example, the application of mulching techniques or conservation tillage) or transpiration (for example, the switch to crop varieties with shorter growing season length).

IV. Investing in Policy and Institutional Adaptation Measures

With growing water scarcity, investments in policy and institutional adaptation measures are becoming increasingly important. They may range from raising awareness and fostering innovations to applying economic instruments for balancing water supplied and demands (Noble *et al*., 2014). While supply side measures, such as investments in water storage infrastructure and alternative sources of water supplies (such as desalinized water or treated wastewater) may continue to play a role, the emphasis is progressively moving to demand-side measures (OECD, 2015a). With engineering and technological adaptation measures applied on-farm often more focused on maintaining or increasing agricultural net revenues and production, policy and institutional measures are essential to contribute to the objective of conserving agricultural water for reallocation to other uses and/or for coping with water scarcity. They also need to promote and ensure the alignment of private adaptation investments with this objective.

Measures for Facilitating Reallocations

Arrangements for water allocation (the apportionment of water among users within and between sectors) can be grouped into price-based or quantity-based measures. With increasing

water scarcity, a need arises for arrangements to facilitate transfers of water use (a change in type of use, a change in location, or in point of withdrawal) while also protecting affected interests (Young, 1996).

Price-based measures, in particular price incentives involving higher costs of irrigation water, are increasingly considered to be a potential tool for reducing water applications. They could provide stimuli for farmers to use water more efficiently, and make water available for other uses. An economic measure that is often used to assess the effectiveness of price increases is the price elasticity of the derived demand for irrigation water, indicating the proportional change in water demand for a given change in price. Most studies present price-inelastic demand estimates (Scheierling et al., 2006b), and caution against the use of pricing policy. The common argument is that even for relatively small reductions in irrigation water applications, large price increases would be necessary which, in turn, would cause large negative effects on agricultural net returns.

Yet it can be shown that as long as farmers have a range of adjustment options (such as changes in crop mix, irrigation scheduling and/or irrigation technology), even a price-inelastic demand does not necessarily imply that water applications cannot be substantially reduced as the price starts to rise (Scheierling *et al*., 2004). However, even if water prices would rise significantly, they would not be very effective in reducing consumption. In contexts where return flows are important, volumetric charges would therefore not generate much real water savings. In such situations it would be more appropriate to encourage farmers to switch to crops with lower seasonal consumption or to dryland crops, possibly with subsidies. Theoretically, irrigation water pricing could be an effective policy instrument if volumetric charges were imposed on consumption. However, to the authors' knowledge, this has so far not been

attempted, possibly because the cost of measurement and administration would be even higher than for charges on water applications or withdrawals.

Quantity-based measures, or quotas, can be designed to ensure security of tenure, minimize externalities, and consistent enforcement—and, in principle, to achieve an efficient allocation (Young, 1995). A number of difficulties, including variations in water supply, need to be addressed. An example of a quota system is the prior-appropriation doctrine of "first in time—first in right" in the western United States that assigns entitlements in terms of water withdrawals. An alternative to this concept of "release sharing" is the concept of "capacity sharing" that assigns entitlements in terms of shares of stored water. It has recently been introduced in Australia in response to increased water scarcity.

Exchangeable quotas allow reallocations via water markets. This may involve permanent or temporary transfers, including water-supply option contracts where transfers occur only during contractually-specified drought conditions. Water markets provide price signals which encourages the movement of water from lower- to higher-valued uses, and thus enhance economic efficiency (Young, 1995). As water scarcity increases, more countries are experimenting with water trading (Griffin et al., 2013). A number of challenges need to be overcome, such as addressing externalities and protecting the entitlements of potentially affected third parties; considering non-efficiency goals (such as ensuring access to a certain amount of water per person per day); safeguarding instream benefits (for example, for environmental and/or recreational purposes); and reducing information and transaction costs for market participants (Young, 1986; Griffin et al., 2013).

Water markets have mostly been observed so far in countries with strong legal, institutional and regulatory arrangements. In many emerging market economies, other

reallocation mechanisms dominate (Scheierling, 2011). They may comprise transfers of informal rights (such as farmer-to-farmer transfers), transfers made by legal means (such as when legislation establishes priorities at times of drought), transfers by formal administrative decisions (for example, by national, provincial/state or basin entities), and informal transfers by stealth (for example, when expanding cities encroach on irrigated areas). While in the case of water markets compensation is paid, compensation may be paid in the case of administrative decisions (especially if farmers giving up water supplies are readily identifiable and can bring political pressure to bear on decision-makers), but is usually not paid in the case of transfers by stealth (although later complaints can trigger ex-post measures). Only limited information is available on many of these transfers and their effects—not just on water scarcity but also on efficiency and equity. Much could be done to shed more light on these reallocations, and help improve them.

Measures for Promoting and Aligning Private Adaptation Investments

While many of the adaptation investments will be carried out by the private sector, the private sector alone will often not provide the desirable level of adaptation (for example, due to cost considerations). Private adaptation investments will also focus on protecting and enhancing production systems and possibly supply lines and markets, and may not align with broader social objectives—such as water conservation—without public interventions, including in the form of incentives, coordination, and regulation (Chambwera *et al*., 2014; Noble *et al*., 2014).

This can be further illustrated with the conversion to more capital-intensive irrigation technologies. While farmers using groundwater to grow high-value crops, for example, may find it profitable to switch to drip irrigation, this may not be cost-effective for others. If public

subsidies are to be provided to encourage further conversions in response to water scarcity, the objective(s) of such investments should be clearly stated. Also context-specific assessments should be carried out to avoid unintended and/or counterproductive outcomes with regard to irrigation water use—as well as uncompensated third party effects and related conflicts. In areas where return flows are important, care should be taken that farmers' consumption will (at least) not increase. A necessary, though not sufficient, rule should then be that the irrigated area not increase. In advanced water rights systems, such as Colorado's, legal provisions specify the area to which an agricultural water right may be applied. Remote sensing via satellites can help enforce such rules. In areas without well-specified and enforced water rights, farmers should be informed if, and to what extent, reallocations are planned in connection with the subsidy program to allow them to adjust their practices accordingly.

More generally, care should be taken to ensure that a conversion program and the associated changes do not increase farmers' water-related (and other) risk exposures (OECD, 2015a). A switch to more "efficient" irrigation technologies may provide incentives to farmers to follow a path toward more specialized production involving higher value crops that may be more susceptible to a periodic lack of water, for example.

Improved groundwater management, not only in areas with deep and/or nonrenewable aquifers, will be necessary to make any significant progress with water conservation efforts in irrigated agriculture. In large parts of the world, groundwater irrigation remains largely uncoordinated and unregulated. In many instances groundwater entitlements are linked with land property rights, which does not necessarily encourage water conservation or the consideration of externalities imposed on other aquifer users (OECD, 2015b). If strong legal provisions exist, they often apply to irrigated areas with conjunctive water use and aim to prevent

that groundwater pumping affects stream flows and surface water rights or violates interstate water agreements (such as along the Platte River in eastern Colorado and Nebraska).

V. Going Forward

As water scarcity intensifies in many parts of the world, the need for adaptation investments from both private and public sectors in irrigated agriculture will increase. While engineering and technological adaptation measures are important, urgent progress will have to be made with policy and institutional adaptation measures. This will include raising awareness on the severity of the water situation and its link to agricultural water use, but also on the complexities of designing adaptation measures for water resources as compared to other resources or commodities. It will also require a much greater emphasis on research and development for fostering innovations not only in the traditional area of technologies, but in new policy and institutional arrangements that need to provide the framework for their effective implementation (Dinar, 2016).

Many adaptation measures in irrigated agriculture are currently not well explored—in part due to the lack of data on key water measures (including water withdrawn, applied, and consumed) and how they may change as a result of different interventions. An increasing number of studies are being carried out in advanced economies, such as the United States, but due to the localized nature of many water problems their insights are not readily transferrable to other situations. Since adaptations measures often need to be designed with the local context in mind, many more ex-ante assessments should be carried out to estimate the costs and benefits and the associated risks of different investment options—incorporating, among other issues, hydrological aspects as well as the likely behavior of farmers and other affected parties. Also

more emphasis should be given to ex-post assessments that evaluate the implementation processes as well as the results in line with the underlying objectives. This would help inform decision-makers in both the public and private sectors.

Adaptation investments related to irrigation water will increasingly have to take into account, and be integrated within, the wider policy framework, including in the agricultural and energy sectors. For example, subsidies that encourage crops with high water consumption may distort incentives for addressing water scarcity. Similarly, subsidies for cheap electricity or for solar-driven pumps may exacerbate groundwater exploitation.

As ever larger shares of total renewable water resources are being withdrawn and consumed for agricultural and other purposes, and the level of interdependencies among users increases, even relatively minor shortfalls in water supplies may create unexpected economic, social and/or environmental crises that currently applied adaptation measures will not be able to address. The planning for such events has to attract increasing attention.

References

Alcott, B. 2005. “Jevon’s Paradox”. *Ecological Economics*, 54, 9-21.

Alexandratos, N., and J. Bruinsma. 2012. *World Agriculture Towards 2030/2050*. The 2012 Revision, ESA Working Paper No. 12-03, Rome: Food and Agriculture Organization of the United Nations.

Chambwera, M., G. Heal, C. Dubeux, S. Hallegatte, L. Leclerc, A. Markandya, B.A. McCarl, R. Mechler, and J.E. Neumann. 2014: “Economics of Adaptation.” In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White. Cambridge University Press, Cambridge, and New York, 945-77.

Contor, B.A., and R.G. Taylor. 2013. “Why Improving Irrigation Efficiency Increases Total Volume of Consumptive Use.” *Irrigation and Drainage*. DOI: 10.1002/ird.1717.

Dinar, A. 2016. “Dealing with Water Scarcity: Need for Economy-Wide Considerations and Institutions.” *Choices*. Quarter 3.

Elliott, J., D. Deryng, C. Mueller, K. Frieler, M. Konzmann, D. Gerten, M. Glotter, M. Floerke, Y. Wada, N. Best, S. Eisner, B.M. Fekete, C. Folberth, I. Foster, S.N. Gosling, I. Haddeland, N. Khabarov, F. Ludwig, Y. Masaki, S. Olin, C. Rosenzweig, A. Ruane, Y. Satoh, E. Schmid, T. Stacke, Q. Tang, and D. Wisser. 2014. "Constraints and Potentials of Future Irrigation Water Availability on Agricultural Production under Climate Change." *Proceedings of the National Academy of Sciences (PNAS)* 111(9), 3239-44.

EMWIS. 2014. The Green Morocco Plan: An Innovative Strategy of Agricultural Development. Euro-Mediterranean Information System on Know-How in the Water Sector (EMWIS). Website accessed on June 1, 2016. [http://www.emwis.org/thematicdirs/news/2014/12/green-morocco-plan-innovative-strategy-agricultural-development]

FAO. 2016a. *AQUASTAT Main Database*. Food and Agriculture Organization of the United Nations (FAO). Website accessed on June 1, 2016. [http://www.fao.org/nr/water/aquastat/data/query/index.html?lang=en]

FAO. 2016b. *FAOStat*. Food and Agriculture Organization of the United Nations (FAO). Website accessed on June 1, 2016. [http://faostat3.fao.org/home/E]

Griffin, R., D.E. Peck, and K. Maestu. 2013. "Introduction: Myths, Principles and Issues in Water Trading." In *Water Trading and Global Water Scarcity: International Experiences*, eds. J. Maestu. RFF Press, New York, 1-14.

Hartmann, L.M., and D. Seastone. 1965. “Efficiency Criteria for Market Transfers of Water.” *Water Resources Research* 1(2), 165-71.

Huffaker, R., and N. Whittlesey. 2003. “A Theoretical Analysis of Economic Incentive Policies Encouraging Agricultural Water Conservation.” *Water Resources Development* 19 (1): 37-55.

IPCC. 2007. *Climate Change 2007: Synthesis Report*. Contribution of Working Groups I, II, and III to Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Eds. R.K. Pachauri and A. Reisinger. IPCC, Geneva.

Jiménez Cisneros, B.E., T. Oki, N.W. Arnell, G. Benito, J.G. Cogley, P. Döll, T. Jiang, and S.S. Mwakalila. 2014. “Freshwater Resources.” In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on climate Change*, eds. C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. Macracken, P.R. Mastrandrea, and L.L. White. Cambridge University Press, Cambridge and New York, 229-69.

Molden, D., and T.Y. Oweis. 2007. “Pathways for increasing agricultural water productivity.” In *Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture*, ed. D. Molden, 279-310. London: Earthscan and International Water Management Institute.

NRCS. 2014. *Farm Bill 2014: Environmental Quality Incentives Program Fact Sheet*. U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS), Washington, DC. Website accessed on June 1, 2016. [http://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/programs/financial/eqip/?cid=stelprdb1242633]

Noble I.R., S. Huq, Y.a. Anokhin, J. Carmin, D. Goudou, F.P. Lansigan, B. Osman-Elasha, and A. Villamizar. 2014. "Adaptation Needs and Options." In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. Macracken, P.R. Mastrandrea, and L.L. White. Cambridge University Press, Cambridge and New York, 833-68.

OECD. 2013. *Environment at a Glance 2013: OECD Indicators*. Organization for Economic Co-operation and Development (OECD) Publishing, Paris.

OECD. 2015a. *Policy Approaches to Droughts and Floods in Agriculture.* Joint Working Party on Agriculture and the Environment. Trade and Agriculture Directorate and Environment Directorate. Organization for Economic Co-operation and Development (OECD) COM/TAD/CA/EMV/EPOC(2014)43/Final.

OECD. 2015b. *Drying Wells, Rising Stakes: Towards Sustainable Agricultural Goundwater Use.* OECD Studies on Water. Organization for Economic Co-operation and Development (OECD) Publishing, Paris.

Peterson, J.M., and Y. Ding. 2005. "Economic Adjustments to Groundwater Depletion in the High Plains: Do Water-Saving Irrigation Systems Save Water?" *American Journal of Agricultural Economics* 87(1): 147-159.

Pfeiffer, L., and C.-Y. C. Lin. 2014. "Does Efficient Irrigation Technology Lead to Reduced Groundwater Extraction? Empirical Evidence." *Journal of Environmental and Economic Management*, 27(2): 189-208.

Porter, J.R., L. Xie, A.J. Challinor, K. Chochrane, S.M. Howden, M.M Iqbal, D.B. Lobell, and M.I. Travasso. 2014. "Food Security and Food Production Systems." In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on climate Change*, eds. C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. Macracken, P.R. Mastrandrea, and L.L. White. Cambridge University Press, Cambridge and New York, 485-533.

Roy, J. "The Rebound Effect: Some Empirical Evidence from India." *Energy Policy* 28(6-7), 433-38.

Scheierling, S.M., R. Young, and G.E. Cardon. 2004. "Determining the Price Responsiveness of Demands for Irrigation Water Deliveries vs. Consumptive Use." *Journal of Agricultural and Resource Economics* 29(2): 328-345.

Scheierling, S.M., R.A. Young, and G.E. Cardon. 2006a. "Public Subsidies for Water-Conserving Irrigation Investments: Hydrologic, Agronomic and Economic Assessment." *Water Resources Research* 42 (3), W03428, doi: 10.1029/2004WR003809.

Scheierling, S.M., J.B. Loomis, and R.A. Young. 2006b. "Irrigation Water Demand: A Meta-Analysis of Price Elasticities." *Water Resources Research*, 42, W01411, doi: 10/1029/2005WR004009.

Scheierling, S.M. 2011. *Assessing the Direct Economic Effects of Reallocating Irrigation Water to Alternative Uses: Concepts and an Application*. Policy Research Working Paper 5797. Water Anchor. World Bank, Washington, DC.

Scheierling, S.M., and D.O. Treguer. 2016. "Enhancing Water Productivity in Irrigated Agriculture in the Face of Water Scarcity." *Choices*. Quarter 3.

Shiklomanov, I. A., and J.C. Rodda (eds.). 2003. World Water Resources at the Beginning of the 21th Century. International Hydrology Series. Cambridge University Press, Cambridge.

UNEP. 2012. *Measuring Water Use in a Green Economy.* A Report of the Working Group on Water Efficiency to the International Resource Panel. United Nations Environment Programme (UNEP). Nairobi, Kenya.

Wallander, S. and M.S. Hand. 2011. "Measuring the Impact of the Environmental Quality Incentives Program (EQIP) on Irrigation Efficiency and Water Conservation." Selected Paper prepared for presentation at the Agricultureal and Applied Economics Association's 2011 AAEA & NAREA Joint Annual Meeting, Pittsburg, PA, July 24-26.

Ward, F.A., and M. Pulido-Velasquez. 2008. "Water Conservation in Irrigation Can Increase Water Use." *Proceedings of the National Academy of Sciences (PNAS)* 105 (47): 18215-18220.

Whittlesey, N.K. 2003. "Improving Irrigation Efficiency through Technology Adoption: When Will It Conserve Water?" In *Water Resources Perspectives: Evaluation, Management and Policy*, eds. A.A. Alsharhan and W.W. Woods. Elsevier, New York, 53-62.

World Bank Group. 2016. *World Development Indicators 2016*. Washington, DC: International Bank for Reconstruction and Development/World Bank.

World Economic Forum. 2015. *Global Risk 2015*. 10th edition. Geneva, Switzerland.

World Water Assessment Program. 2012. *The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk*. Paris: UNESCO.

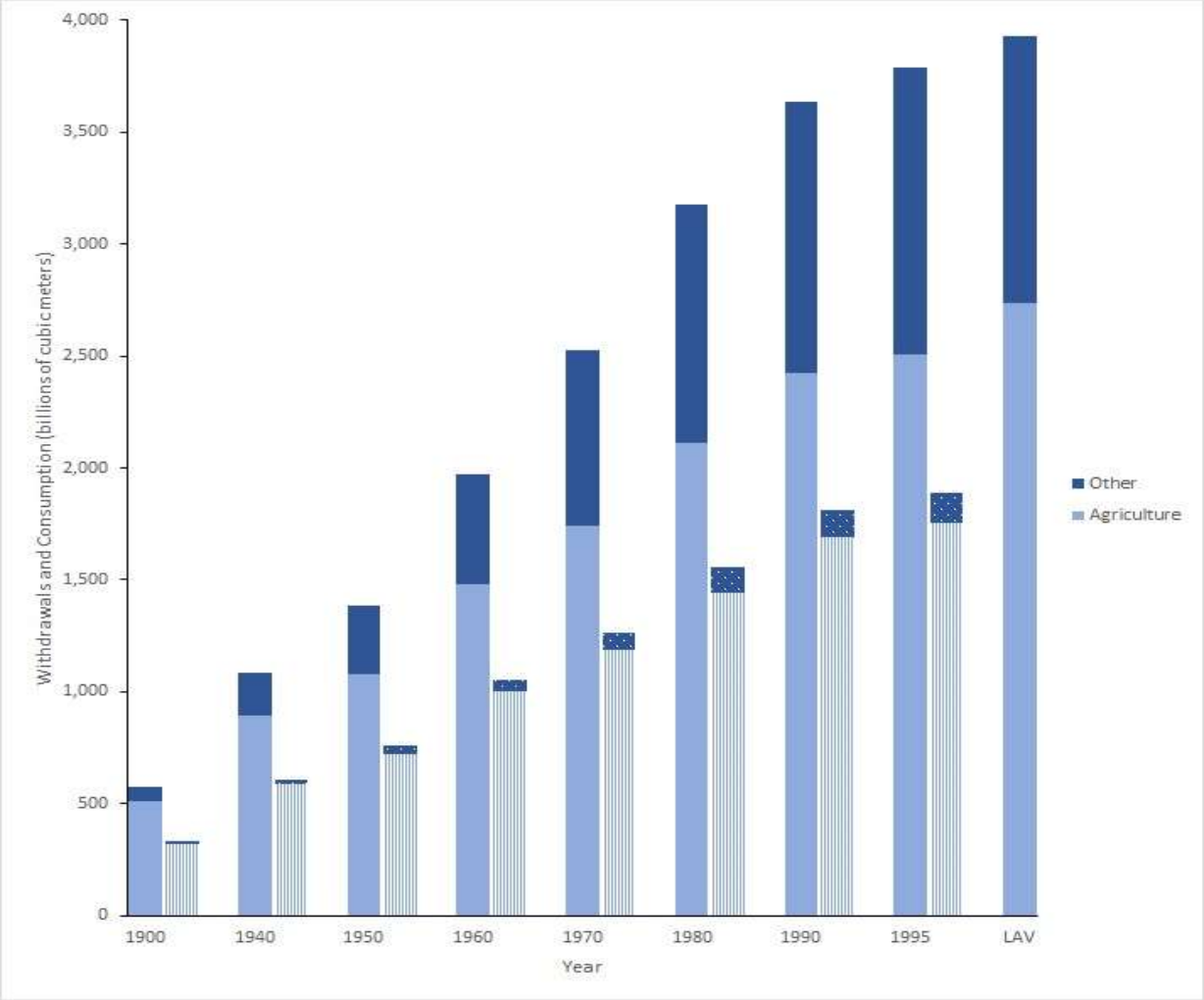
Young, R.A. 1986. “Why Are There So Few Transactions Among Water Users?” American Journal of Agricultural Economics 68(5):1143-51.

Young, R.A. 1996. “Water Economics.” In *Water Resources Handbook*, ed. L. Mays. McGraw-Hill, New York, 3.1-3.57.

Young, R.A. 2005. *Determining the Economic Value of Water: Concepts and Methods*. Washington, DC: Resources for the Future.

Figure 1

Global Trends in Agricultural and Total Water Withdrawals and Consumption



Notes: Solid colors show withdrawals, and patterned colors consumption. LAV=latest available value.

Source: Authors' calculations based on Shiklomanov and Rodda (2003), and FAO, 2016a.

Table 1

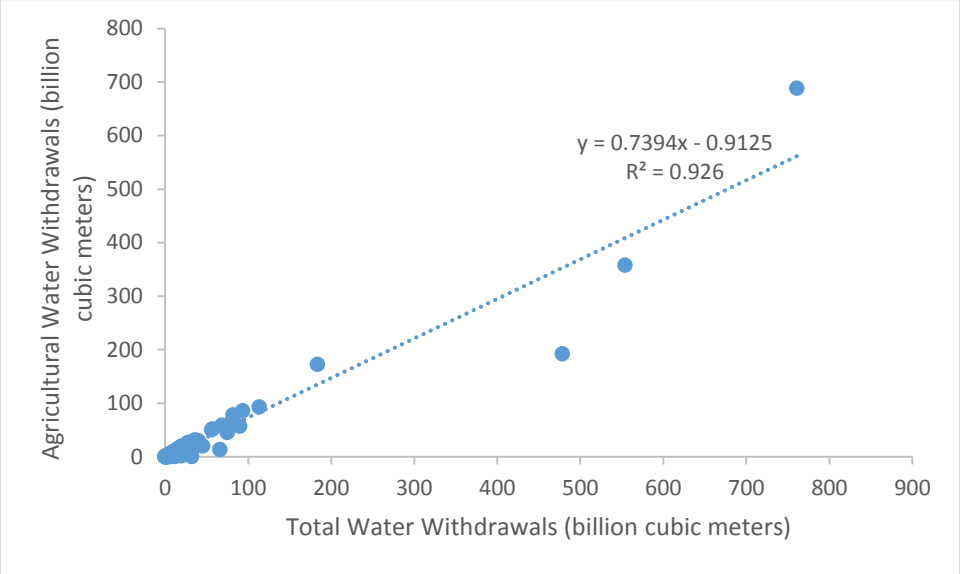
Countries with the Largest Agricultural Water Withdrawals

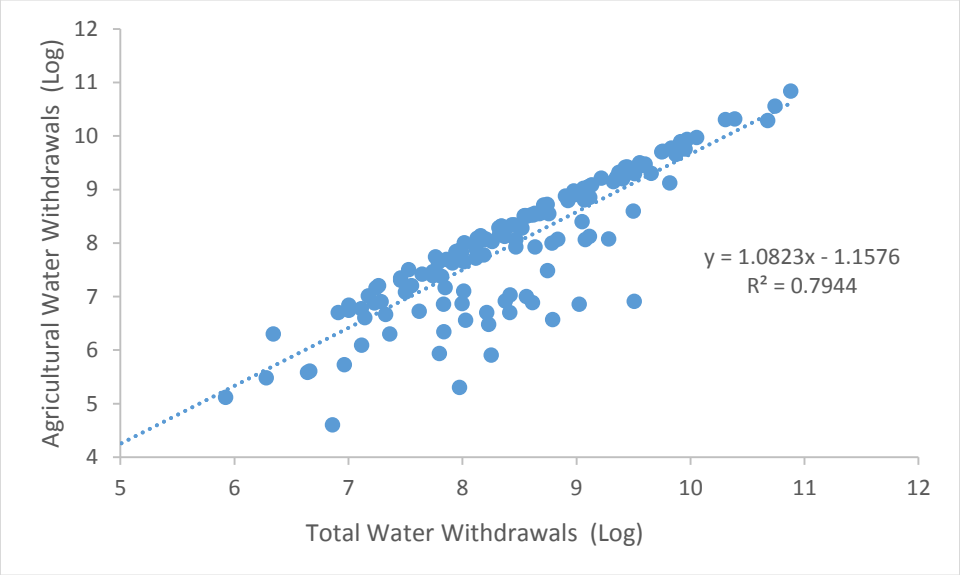
Country	Agricultural Water Withdrawals (billion cubic meters)	Total Water Withdrawals (billion cubic meters)	Agricultural Water Withdrawals as Percent of Total Water Withdrawals	Area Equipped for Irrigation (million hectares)	Area Equipped for Irrigation as Percent of Agricultural Area	Agricultural Water Withdrawals per Area Equipped for Irrigation (m)
India	688	761	90%	67	37%	1.0
China	358	554	65%	69	13%	0.5
United States	175	486	40%	26	6%	0.7
Pakistan	172	184	94%	20	75%	0.9
Indonesia	93	113	82%	7	12%	1.3
Iran	86	93	92%	10	19%	0.9
Vietnam	78	82	95%	5	42%	1.6
Philippines	67	82	82%	2	13%	3.4
Egypt	67	78	86%	4	100%	1.5
Mexico	62	80	77%	7	6%	0.9

Sources: FAO, 2016a; FAO, 2016b.

Figures 2a and b

Agricultural Water Withdrawals and Total Water Withdrawals, by Country

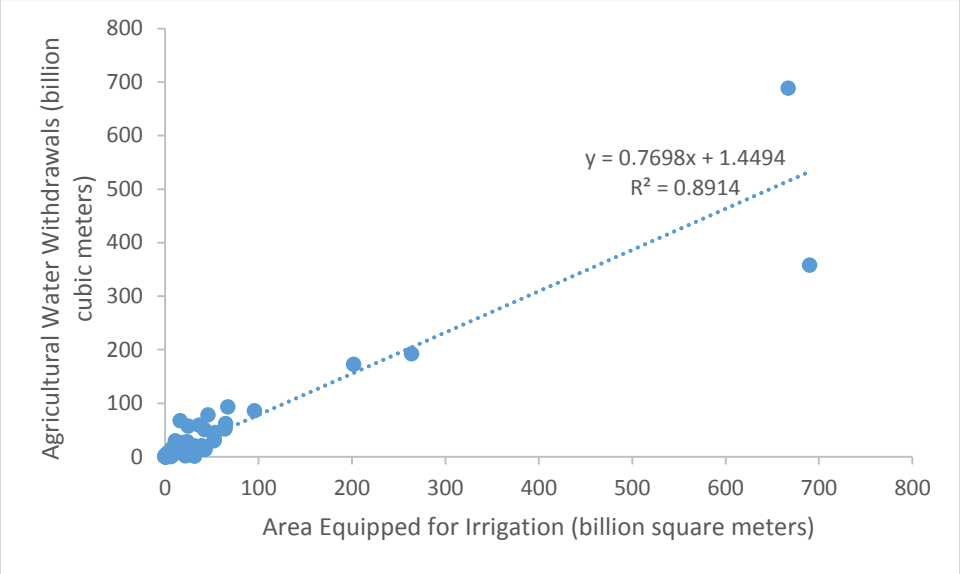


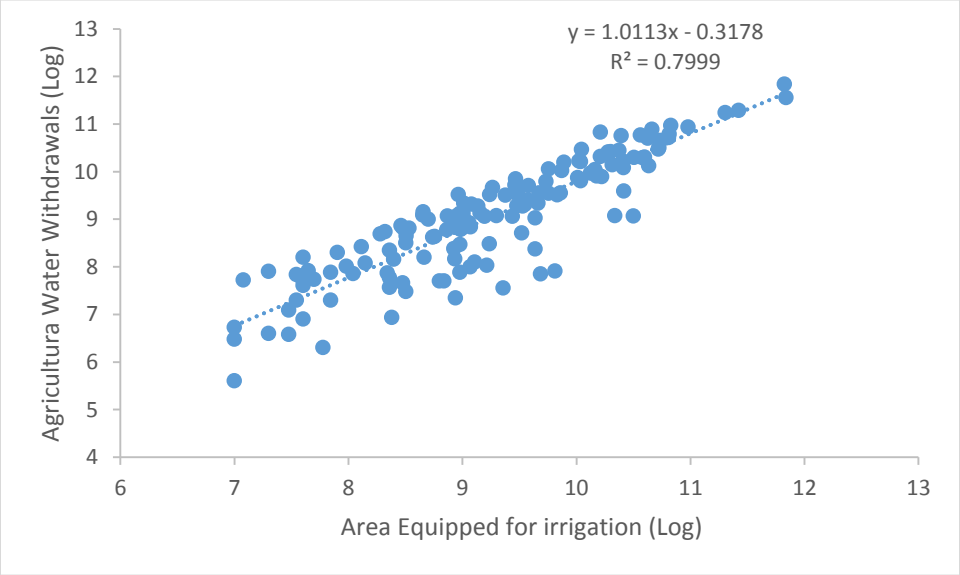


Source: Authors' calculations based on FAO, 2016a.

Figures 3a and b

Agricultural Water Withdrawals and Area Equipped for Irrigation, by Country

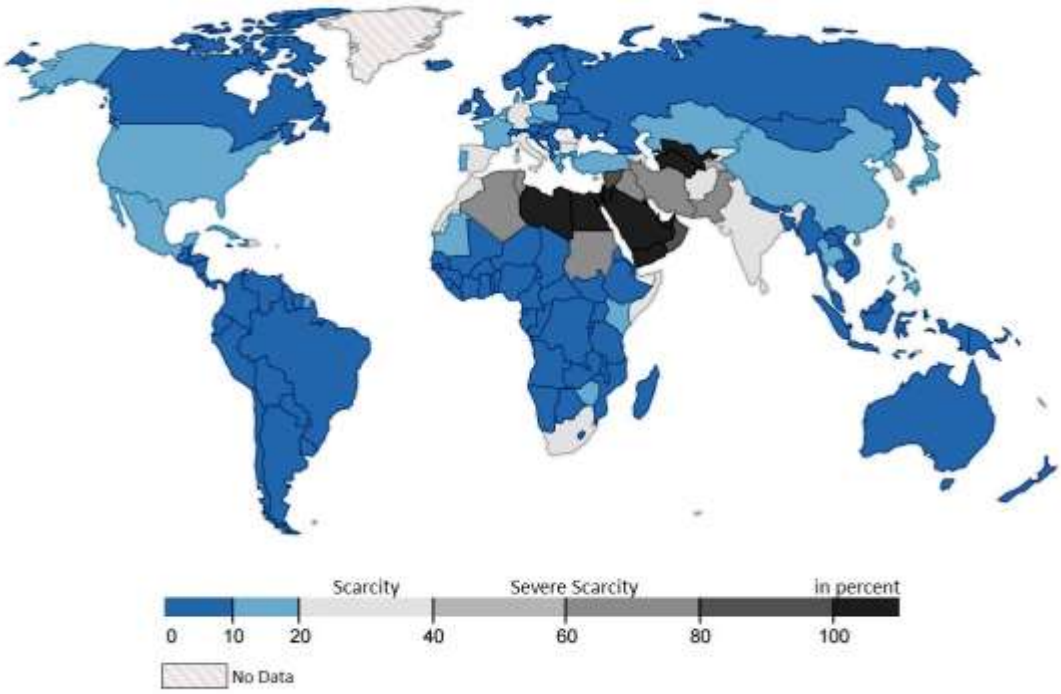




Source: Authors' calculations based on FAO, 2016a; FAO, 2016b.

Figure 4

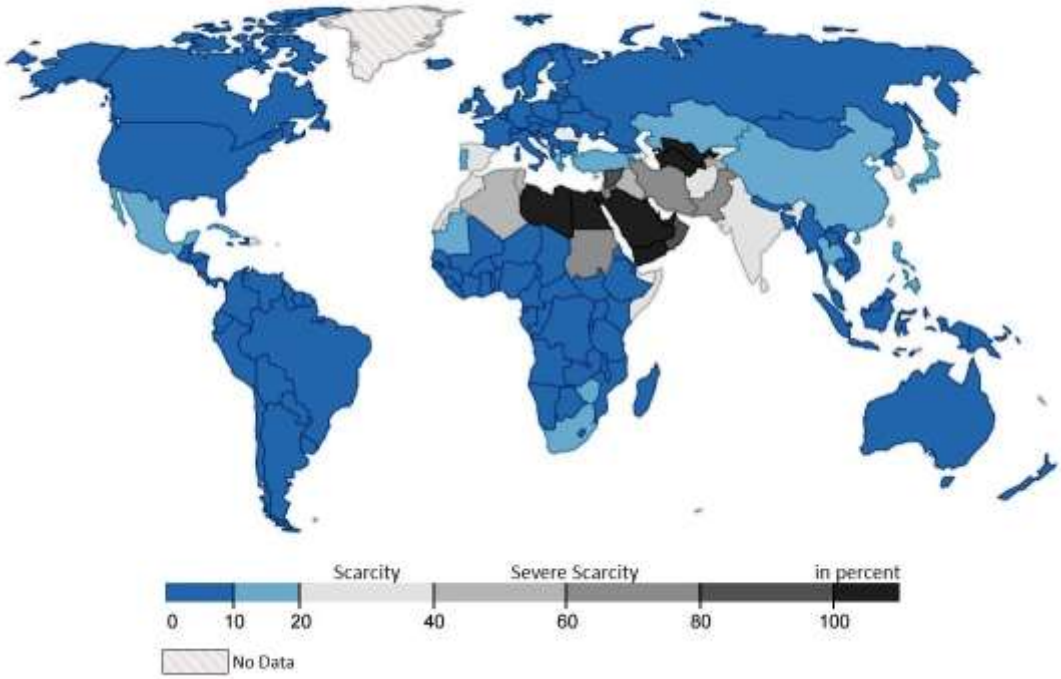
Total Water Withdrawals as Percent of Total Renewable Water Resources



Source: Authors' calculations based on FAO, 2016a.

Figure 5

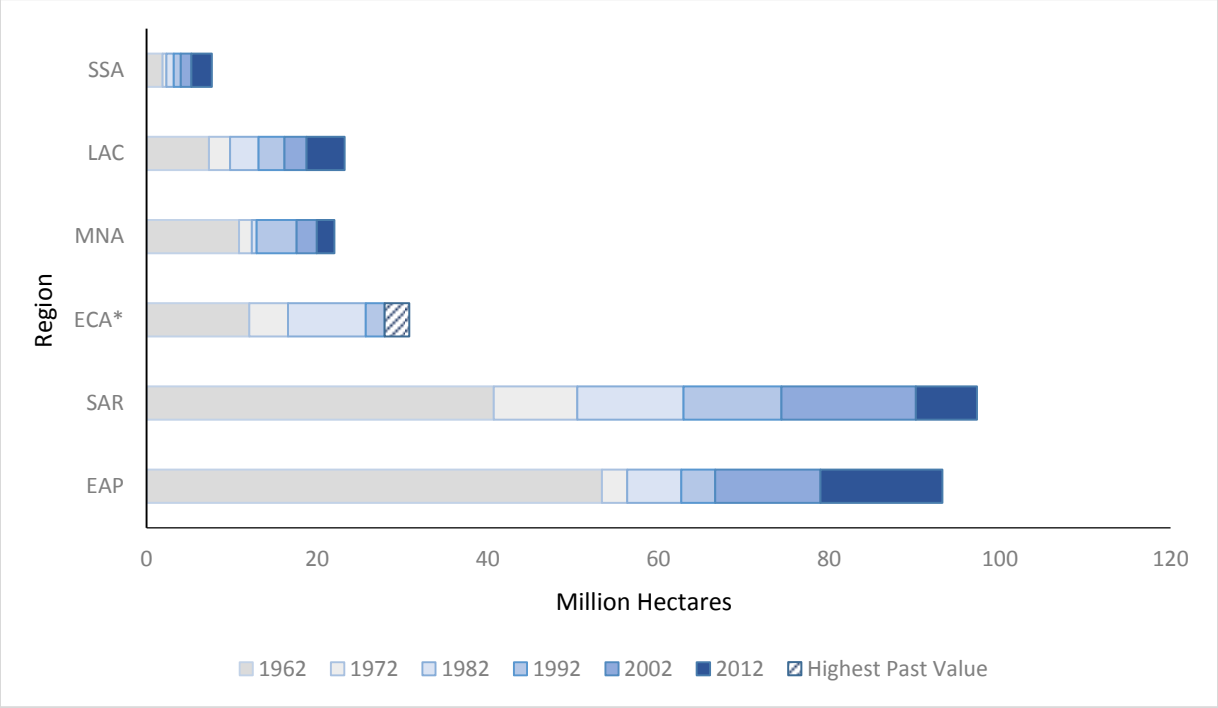
Agricultural Water Withdrawals as Percent of Total Renewable Water Resources



Source: Authors' calculations based on FAO, 2016a.

Figure 6

Trends in Area Equipped for Irrigation, 1962-2012, by Region



Notes: SSA=Sub-Saharan Africa, LAC=Latin America and the Carribean Region, MNA=Middle East and North Africa, ECA=Europe and Central Asia, SAR=South Asia Region, EAP=East Asia and Pacific. ECA* includes data for USSR/Russian Federation.

Source: Authors, based on FAO, 2016b.