Chapter 6
A Global Approach to Estimating the Benefit-Cost Ratio of Water Supply Measures in the Agricultural Sector

A. K. Schürkmann, A. Biewald and S. Rolinski

Abstract This study assesses at the global scale the potential costs and benefits of new infrastructure needed for the additional supply of irrigation water, focusing on rainwater harvesting, desalination and groundwater extraction. The cost and applicability of each measure is assessed and estimated separately. The potential benefit of additional water supply infrastructure is given by the water shadow price, which is generated by the global land and water use model MAgPIE (Model of Agricultural Productivity and its Impact on the Environment). Based on these results the irrigation potential (in Mha) is calculated. We find that groundwater extraction is cost-efficient in the most places and therefore has the highest irrigation potential (152.5 Mha) followed by rainwater harvesting (61.5 Mha) and desalination (0.5 Mha). The results reflect the current practice of supplying irrigation water, and a sensitivity analysis shows that rainwater harvesting has the largest potential to alleviate irrigation water scarcity through decreasing prices. The sensitivity analysis also shows that if the price of desalinated water continues to decline as it has in the past, desalination could become cost efficient especially in arid, coastal regions of the world.

Introduction

World population is projected to reach a number of 9–10 billion by 2050 (Lutz and Samir 2010) while income levels are expected to increase (Rask and Rask 2010). Higher incomes lead to more food consumption in total and an increase in the

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share of animal calories consumed (Kearney 2010; Valin et al. 2014, *Accepted*). To meet this increasing demand for agricultural products, agricultural production must also increase. Although production has grown continuously in the past, increases in crop production have slowed down recently (Foley et al. 2011).

Increasing agricultural production is mainly achieved in one of the following ways: expanding cultivated area, developing and implementing new and more productive crop varieties, and intensifying agriculture on currently cultivated land.

Agricultural intensification reduces the yield gap (Cassmann 1999; Ramankutty et al. 2002), which is defined as the difference between the potential maximum yield of a crop in a certain place and the actual yield (see: Global Yield Atlas 2013). For many crops, global yield gaps are substantial; if 95 % of the crops' harvested areas met their current climatic potential, up to 60 % higher yields could be achieved (Licker et al. 2010). In their study Licker et al. (2010) found that one of the most promising ways to close the yield gap is increasing irrigation. This is because water is frequently the limiting factor regarding plant growth, this is particularly true for the arid regions of the world where yield gaps are high.

Globally, irrigation agriculture accounts for 40 % of the world's food production while occupying only 20 % of cultivated land (Siebert et al. 2007; UN Water World Water Assessment Program 2009). Increasing irrigation and expanding the area under irrigation on currently cultivated but unirrigated land are major methods for increasing future food production. However, in many regions of the world water is scarce or access to water is limited (Rosegrant et al. 2009). Problems of water scarcity in agriculture can be addressed (1) by reducing the demand for irrigation water and (2) by increasing the amount of water available for irrigation.

Demand for irrigation water can be reduced by increasing irrigation efficiency, minimizing irrigation water losses or distributing water in a more productive way (Seckler et al. 2003; Rockström and Barron 2007; Molden et al. 2010). While many studies examine the potential to reduce irrigation water demand, the present study focusses on the expansion of the area under irrigation which requires additional water supply. Measures for increasing irrigation water supply include dam construction, water transfer, desalination of salt and brackish water, rainwater harvesting, groundwater extraction and waste water reuse. Even though implementing any of these measures is subject to difficult political and social constraints and decisions (Woolley et al. 2009), implementation depends largely on the cost and cost efficiency of the specific measure (Hussain et al. 2007).

Implementation of a water supply measure is cost efficient only when the benefits of increased agricultural production outweigh its construction, operation and maintenance costs. Costs and benefits of a measure vary substantially depending on local or regional conditions. To determine where the impact of a water supply measure is highest, it is necessary to compare the cost efficiency (1) for the same measure in different locations and (2) for different measures in the same location.

A common way to assess the cost efficiency of an investment is calculating the benefit-cost ratio (BCR). The benefit-cost ratio expresses the monetary benefit of a project or investment relative to its cost. Unfortunately, the cost of many water supply measures is lacking for many parts of the world. Despite their importance, two common methods for supplying freshwater, water transfer and dam construction, will not be assessed in the current study. Data for the cost of water transfer are lacking. While some data are available for the location and size of moderate and large dams globally, there are very few data available for the cost of supplied irrigation water. Furthermore, dams often have substantial and complex, negative social, political and environmental impacts that cannot be included in a global study (WCD 2000). Therefore, in the present study we focus on three methods for increasing agricultural water supply: rainwater harvesting, desalination, and groundwater extraction. To our knowledge there has been no global scale analysis of their cost efficiency so far.

These three measures represent different types of water sources, namely groundwater (groundwater extraction), surface water (rainwater harvesting) and unconventional water (desalination; after Siebert et al. 2010). They represent different parts of the water cycle and different methods for supplying additional water. In this context, different methods mean either spatial or temporal redistribution of water as done by groundwater extraction and rainwater harvesting or the generation of additional freshwater by desalination.

At the small to medium scales, rainwater harvesting is often cost efficient in developing countries and can benefit individual farmers and communities (for case studies on India, see: Panigrahi et al. 2005; Pandey 1991; Goel and Kumar 2004; Sharma et al. 2010; for China see Yuan et al. 2003; Liang and van Dijk 2011; and for Kenya see Ngigi et al. 2005). Furthermore, at the global scale, small scale rainwater harvesting structures can significantly increase yields and therefore improve food security (Wisser et al. 2010).

Although there has been broad interest in the development of new, cheaper technologies for extracting salt from seawater (Karagiannis and Soldatos 2008), using desalinated water for irrigation is not common practice, occurring only in Spain and some parts of the Arabian Peninsula (Al-Rashed and Sherif 2000; Mezher et al. 2011; Zarzo et al. 2013).

Groundwater is commonly extracted throughout most of the world and is often overexploited (e.g. Aeschberg-Hertig and Gleeson 2012; Werner et al. 2012 or ISARM Internationally Shared Aquifer Resources Management a collection of global groundwater related data available on http://www.isarm.org/publications/119). In some places groundwater contributes up to 90 % of irrigation water supply (Al-Rashed and Sherif 2000).

To assess the potential benefit of increased water supply, we use the water shadow price, which is calculated by the global land and water use model MAgPIE (Model of Agricultural Production and its Impact on the Environment; Lotze-Campen et al. 2008).

This study is the first attempt to assess globally the cost efficiency of different irrigation water supply measures. Using spatially explicit cost and benefit data, we determine where investments in different water supply measures may be most cost efficient.

To assess and compare the cost efficiency of the three water supply measures, we developed a conceptual framework that differentiates between the applicability,

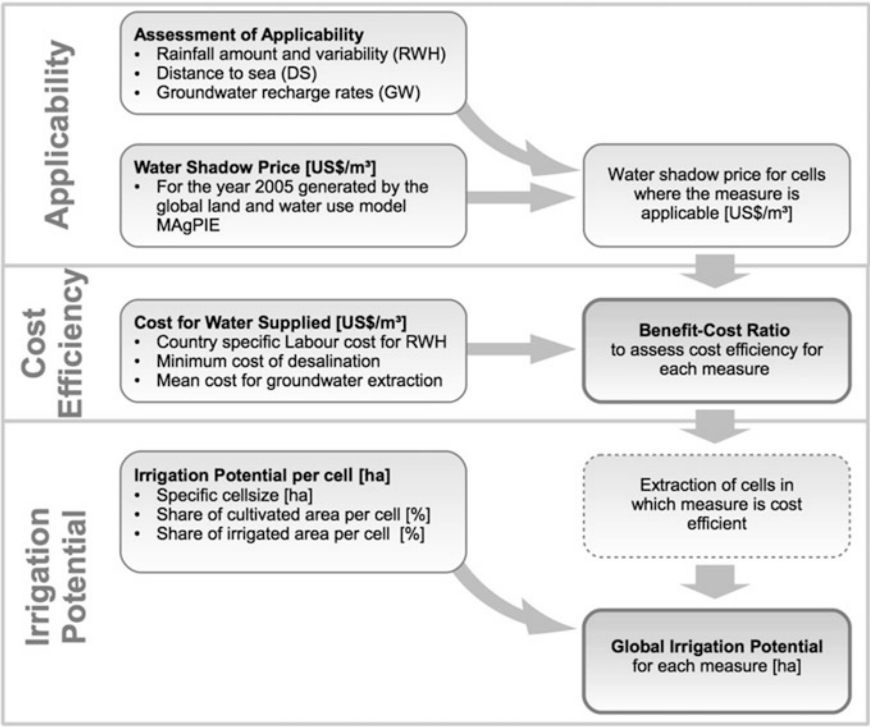

Fig. 6.1 Flowchart of the conceptual framework illustrating the different steps of the analysis. (*RWH* rainwater harvesting, *DS* desalination, *GW* groundwater extraction)

the cost efficiency, and the potential impact of each measure (Fig. 6.1). Applicability refers to the physical feasibility of implementing a measure depending environmental conditions and resource availability.

Where a measure was deemed applicable, the benefit-cost ratio was determined, using the cost and water shadow price data. A sensitivity analysis was conducted to address uncertainties in the collected data. Then the irrigation potential was calculated for each measure based on the amount of land under cultivation and the share of that land that was irrigated. In the final step, the applicability, cost efficiency, and irrigation potential for the three measures were compared.

Methods

The Lund-Potsdam-Jena dynamic global vegetation model with managed Lands (LPJmL) was used to generate vegetation growth, crop yields, and water consumption on a $0.5° \times 0.5°$ grid in daily time steps. This model uses twelve crop functional types and nine functional types for natural vegetation to simulate crop

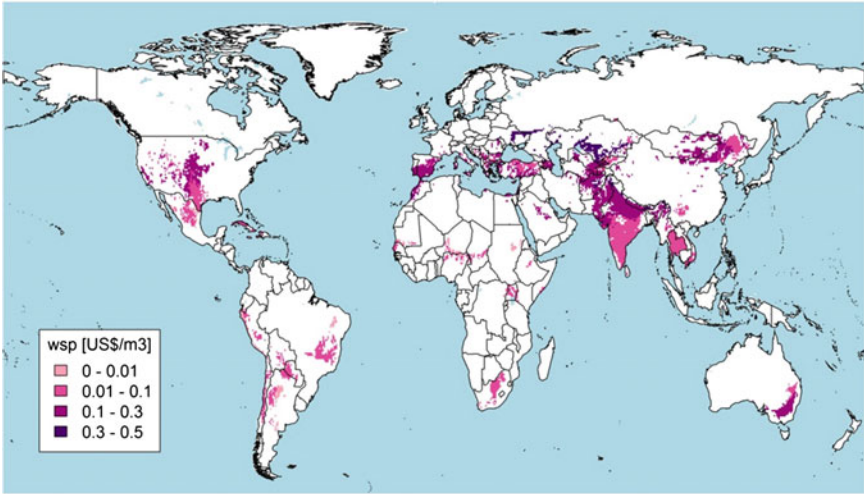

Fig. 6.2 Global map of the water shadow price (WSP) generated by MAgPIE for the year 2005 in US$/m^3. White cells indicate areas with no irrigation agriculture or where irrigation water is not scarce. Cell size is 0.5° × 0.5°

yields and land use based on observed land use patterns and climatic and biogeochemical conditions (Sitch et al. 2003; Bondeau et al. 2007). Results from LPJmL, which include the availability of irrigation water per grid cell, were combined with regional economic information, and used as input data for MAgPIE, a model of agricultural production and its impact on the environment, which calculates the water shadow price.

MAgPIE is a global, spatially explicit, economic land and water use model with a cost minimization function (Lotze-Campen et al. 2008). It minimizes global production costs for producing crops and livestock and requires that agricultural demands be met. MagPIE simulates time steps of 10 years starting in 1995 and uses the optimal land use pattern from the previous period as a starting point. In each time step, MAgPIE meets growing demand, driven by changes in population and income projections, by increasing agricultural production. Production can be increased by either increasing the area under cultivation or intensifying agriculture on cultivated lands. Intensification of agriculture can, besides others, be achieved through increased irrigation. The available amount of irrigation water is calculated by LPJmL and used as one constraint in MAgPIE.

When all available water in a cell is used for irrigation, the water shadow price (WSP) is calculated and an estimate of how much an additional unit of water would be worth in the model context (Fig. 6.2). The water shadow price is used as a water scarcity indicator and expresses the willingness to pay to increase irrigation water supply by one unit. Currently the water shadow price is computed only for cells where irrigation agriculture is already partially practiced (based on Döll and Siebert 2000).

In this study rainwater harvesting (RWH) is defined as the redirection of surface runoff from a small catchment into a surface reservoir, to store water for watering crops during dry periods (For an overview of rainwater harvesting methods see: Boers and Ben-Asher 1981; Ngigi 2003). We considered RWH to be applicable in places (a) with a minimum of 350 mm rainfall per year, based on the mean annual precipitation for the years 2000–2009 (Sharma and Smakhtin 2006; Abdel-Shafy et al. 2010), and (b) where rainfall is unevenly distributed throughout the year in a way that negatively affects crop growth. To determine which regions had suboptimal rainfall distributions throughout the year, we used LPJmL to calculate the mean ratio of rain fed and irrigated yields as:

$$mr = \frac{1}{15} \sum_{crop=1}^{15} \left(\frac{Y_{rf}}{Y_{ir}} \right)_{crop}$$

This ratio accounted for variable potential yields (in tons of dry matter per hectare [t/ha]) of the 15 main food crops implemented in MAgPIE. The reciprocal is the potential to increase crop yields through irrigation. RWH was deemed applicable for cells with at least 350 mm/year rainfall and where crop yields could be increased by more than 10 % through irrigation.

The cost of a RWH facility was considered to be the sum of construction, operation and maintenance costs over the expected lifespan of the structure. Over the lifespan of the structure, material and maintenance costs were considered to be negligible (Fox and Rockström 2000; Saha et al. 2007). We assumed that labour costs are proportional to the size of the reservoir, with $\sim$3500 h being required to build a 150 m^3 reservoir (Fox and Rockström 2000) and that the reservoir lifespan is 25 years (Goel and Kumar 2004; Sturm et al. 2009). Over the projected lifespan of the reservoir, the total amount of water provided (w_{tot}) is 3750 m^3. The labour investment per unit water (L_w) can be calculated as:

$$L_w = \frac{L_t}{w_{tot}}$$

yielding an estimate of 0.93 h/m^3.

Hourly salaries (S_h) for workers in construction and agriculture were calculated based on data from the International Labour Organization (ILO), converted to US Dollars using historical exchange rates and then adjusted for inflation to the base year of 2005 using the conversion factors provided by Sahr (2012). For countries lacking data, we used the median hourly salary for countries with similar economies, based on the World Bank classifications. Finally a discount rate of 3 % over the lifespan of 20 years was incorporated to account for the increasing value of the initial investment over time.

Multiplication of labour investment per unit water (L_w) with hourly salaries (S_h) for a farm worker (in \$/h) gives the final cost (C_{RWH}) per m^3 water supplied by rainwater harvesting:

$$L_w * S_h = C_{RWH}$$

We considered desalination applicable in areas with direct access to the sea, where water can be extracted and processed without transportation over large distances. Therefore, we limited our analysis to MAgPIE cells with at least one neighboring cell belonging to one of the oceans.

We excluded all large inland water bodies, except the Caspian Sea because it holds saltwater with an average concentration of about one third that of sea water (Dumont 1998) and its water level has risen over the last four decades (Ozyavas and Khan 2012).

A variety of methods exist for desalinating seawater (El-Ghonemy 2012), and the cost of desalination (C_{DS}) can range from 0.45 to 11.0 US$/m^3 based on the technology, facility size, energy source and salt content of the water (e.g. Karagiannis and Soldatos 2008; Froiui and Oumeddur 2008; Mezher et al. 2011).

Because desalination is a comparatively expensive method for supplying additional freshwater, we chose the minimum reported cost of 0.45 US$/m^3 as a optimistic global estimate. This price of 0.45 US$/m^3 comes from a desalination plant south of Tel Aviv, Israel, which uses reverse osmosis and is connected to the electricity grid. It produces about 330 000 m^3 of water per day and up to 110 million m^3/y mainly to secure the freshwater supply to surrounding towns (Dreizin 2006; Sauvet-Goichon 2007).

Groundwater is the largest unfrozen freshwater resource in the world and accounts for about 40 % of irrigation water worldwide (BGR/UNESCO 2008; Siebert et al. 2010).

Because groundwater overexploitation leads to declining groundwater levels (Aeschberg-Hertig and Gleeson 2012), groundwater extraction is applicable only in places with recharge rates high enough to support irrigation. We assumed that groundwater extraction is applicable only where recharge rates are higher than 20 mm/year for major groundwater basins and areas with complex hydrogeological structures and where recharge rates exceed 100 mm/year for local and shallow aquifers. Although saline water is sometimes used for irrigation (Flowers 2004), it can increase soil salinity and negatively impact plant growth (Shalhevet 1994), so we excluded areas with saline groundwater. We determined where groundwater extraction would meet these criteria for applicability, based on data from the Worldwide Hydrogeological Mapping and Assessment Program (WHYMAP; BGR/UNESCO 2008).

The cost of groundwater extraction (C_{GW}) is proportional to the distance between the groundwater level and the land surface. The cost of groundwater extraction is comparatively low, ranging from 0.01 US$/m^3 to 0.08 US$/m^3 (Water Resources Group 2009). We used the mean value (0.04 US$/m^3) for the cost of groundwater extraction

We used the benefit-cost ratio (BCR) to determine whether an investment in water supply infrastructure was cost efficient. The benefit-cost ratio for each measure (BCR_{RWH}; BCR_{DS}; BCR_{GW}) was calculated as:

$$BCR_{measure} = \frac{WSP}{C_{measure}}$$

where *WSP* was the water shadow price for the year 2005 in US$/m^3, C was the cost for water supplied by one of the three measures, rainwater harvesting (C_{RWH}), desalination (C_{DS}) and groundwater extraction (C_{GW}), also in US$/m^3 for the year 2005.

The BCR is a dimensionless number with values <1 indicating that the costs are higher than benefits, and values >1 indicating that the economic benefits outweigh the costs. Being a dimensionless indicator, the benefit-cost ratio allows for comparison of the economic performance of different projects and investments regardless of their nature and possible incompatibility.

To determine how uncertainties in the costs impacted the BCR, we conducted a sensitivity analysis of the effects of the infrastructure costs for each measure on the BCR with costs ranging from 1–200 % of the calculated price. This sensitivity analysis shows how high subsidies for a measure would have to be to make the investment worthwhile.

The irrigation potential was calculated based on LPJmL data and the absolute size of MAgPIE cells in ha. LPJmL determines the share of cultivated and irrigated area per cell. Using results for 2005, we calculated the potential increase in irrigated area for each cell as the difference between the cultivated and irrigated areas per cell. The potential increase in irrigated area of all cells with BCR >1 were summed to calculate the global irrigation potential for each measure.

Results and Discussion

Overall, we found that GW was applicable in more places than either RWH or DS (green cells in Fig. 6.3), mainly because of the abundance of groundwater globally. However, in many places in which GW was applicable, water is not the predominant factor limiting crop growth (for comparison see Fig. 6.2). Thus, considering only water-limited localities, RWH is applicable in more areas than either GW or DS (351.6 Mha, 225.6 Mha, 31.6 Mha, respectively; blue cells in Fig. 6.3). Despite relatively widespread applicability of RWH and GW, the costs associated with implementing these measures make them economically inefficient in many areas. For example, we found RWH to be cost-efficient only in India and a small part of Ukraine (Fig. 6.3 top). Our results are supported by several case studies from India, in which RWH was cost-efficient (Pandey 1991; Sharma et al. 2010) with BCRs of 1.17 (Panigrahi et al. 2005) and 1.33 (Goel and Kumar 2005). However, in several places our results do not reflect the results of case studies from other parts of the world. For example, we underestimated the BCR of RWH in rural Beijing, which varies between 1.96 and 6.2 (Liang and van Dijk 2011).

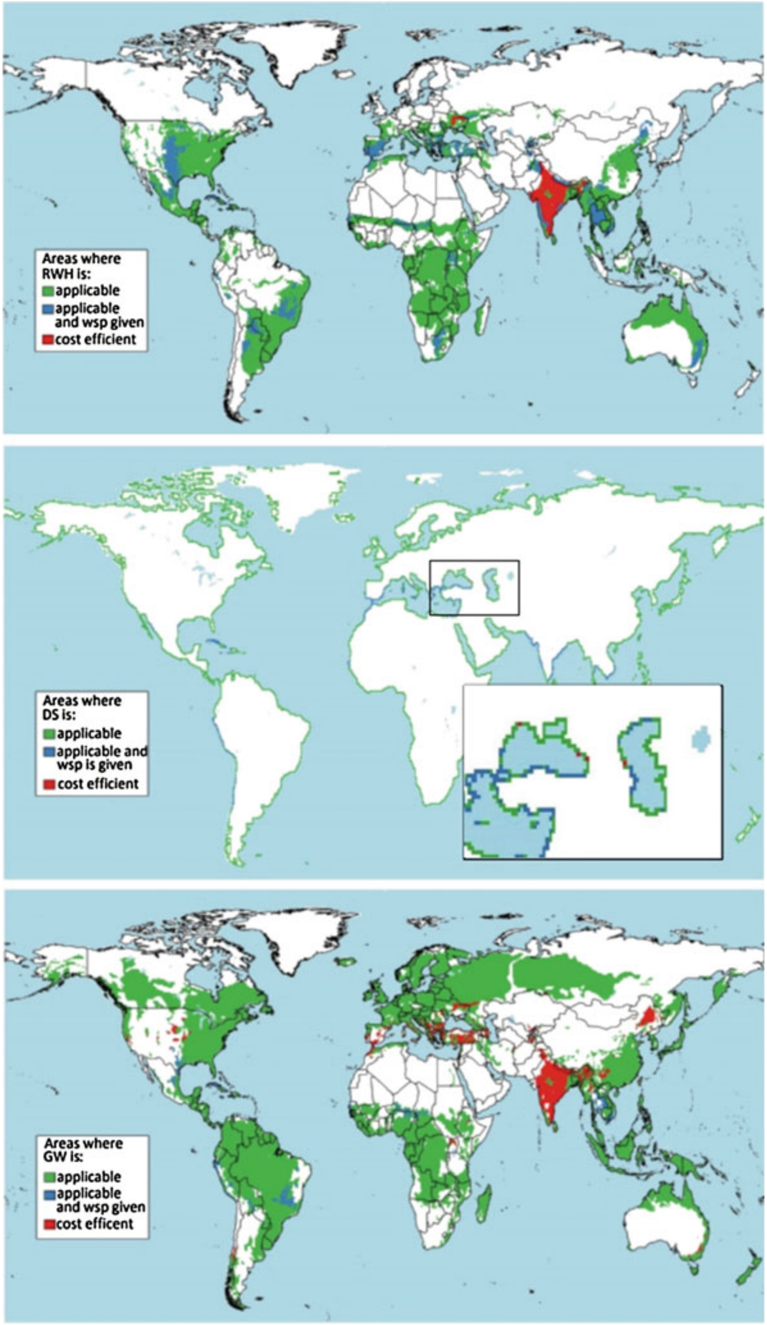

Fig. 6.3 Areas where measure is applicable (*green*), areas where a measure is applicable and a water shadow price is given (*blue*), and areas where a measure is cost-efficient (*red*)

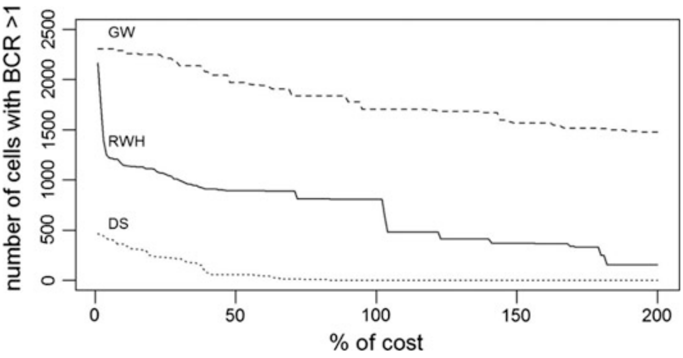

Fig. 6.4 Sensitivity of the benefit-cost ratio of rainwater harvesting (RWH), desalination (DS) and groundwater extraction (GW) to varying cost of supplied water

In other parts of China and in Kenya, RWH has been shown to be economically viable (Yuan et al. 2003; Ngigi et al. 2005).

GW, on the other hand, is cost-efficient in many more places than RWH (e.g. most of India and its neighboring countries, parts of Turkey, Ukraine, the midwest USA, and northeastern China). In total, GW was cost-efficient in more places than either RWH or DS (152.5 Mha, 61.5 Mha, 0.5 Mha respectively). Our results reflect current practices globally, as 40 % of irrigation water globally comes from GW (Siebert et al. 2010). However, groundwater is over-exploited in many places globally, especially in India, limiting the applicability and cost-efficiency of GW as a means for supplying irrigation water (Aeschberg-Hertig and Gleeson 2012; Glendenning et al. 2012; Varghese et al. 2012). The applicability and cost-efficiency of GW in supplying irrigation water strongly depends on the sustainability of its use.

By definition, DS was applicable only in coastal regions, and was cost-efficient practically nowhere. This economic inefficiency of desalination was due largely to its relatively high cost compared to the other measures. These results are consistent with current practices (Al-Rashed and Sherif 2000). Only in Spain is desalinated water used for irrigation, and that is because it is heavily subsidized by the Spanish government (Mezher et al. 2011). Nonetheless, DS has become more cost-efficient over time. The average price of desalinated water in 2000 was only about 10 % of the price in the 1960s (Reddy and Ghafour 2007). The price of DS can be expected to decline as new technologies are developed (for example, see Shaffer et al. 2012).

To explore the effects of cost on the cost-efficiency of these measures, we conducted a sensitivity analysis by manipulating the price for implementation while holding constant the WSP (Fig. 6.4). This analysis showed that a decrease of approximately 60 % in the cost of DS could have dramatic increases in the areas where DS is cost-efficient. However, because DS is limited to coastal regions, the role of DS in supplying irrigation water will undoubtedly remain limited compared to GW and RWH.

Varying the cost of GW from 1–200 % had relatively little effect on the cost-efficiency of GW in supplying irrigation water. Because the current cost of GW is so low (0.04 US$/m^3), even with doubling the cost to 0.08 US$/m^3, it is still well below the WSP in most places (Fig. 6.2). Similarly, the already low cost of GW cannot be reduced much more such that reducing the cost has little effect on increasing the area where it is cost-efficient.

Compared to GW, varying the cost of RWH had a stronger impact on cost-efficiency, due to the wide range in labor costs among countries, which vary from 0.04 US$/m^3 to over 30 US$/m^3. Reducing the high labor costs by over 95 % results in a large increase in the cost-efficiency of RWH. This seems reasonable because we have most likely over-estimated the labor cost associated with constructing a RWH facility for three main reasons. First, farm work is highly seasonal, which means that in many places, farmers have periods in the year in which their time is not fully occupied with any kind of work. During these times of the year, constructing a RWH facility would not come at a cost. Second, farm work, especially in remote locations, can be informal so that actual cost of farm labor is not accurately reported. By its nature, informal labor is cheaper than formal employment, such that reported salaries are probably higher than unreported salaries. Third, the assumption that a RWH facility is filled only once per year may not be true in places with multiple rainy periods throughout the year. In these places, more water is provided throughout the year (the facility can be filled multiple times) at the same labor cost as a facility that is only filled once.

The irrigation potential according to cost-efficiency is highest for GW (152.5 Mha; 10.1 % of global cultivated area) followed by RWH (61.5 Mha; 4.1 % of global cultivated area). RWH is applicable in the most places with an irrigation potential of 351.6 Mha while GW is only applicable in 225.6 Mha. For DS the numbers are up to orders of magnitudes smaller for applicability and cost-efficiency with 31.6 Mha and 0.5 Mha, respectively (Fig. 6.5). In places where RWH was found to be cost-efficient, the same was true for GW and due to the low cost for GW it was always the economically more viable option. However, taking into account the overestimation of applicability of GW and the underestimation of the cost-efficiency of rainwater harvesting we discussed before, this figure may change. Another aspect is the current implementation of these two measures, even though RWH has been practiced for centuries in some places, it was entirely unknown in other water scarce regions until recently (Boers and Ben-Asher 1981). This adds to the potential of RWH, as extracting groundwater has been for many years common practice in most parts of the world, which threatened groundwater resources in many places (Aeschbach-Hertig and Gleeson 2012).

A drawback of this study is that the water shadow price and therefore the benefit-cost ratio are only calculated for cells that are at least partially equipped for irrigation. Because of this areas with possibly high irrigation potential and the highest yield gaps, especially in Africa and Asia (Wisser et al. 2010; Rosegrant et al. 2002), are not included in this study.

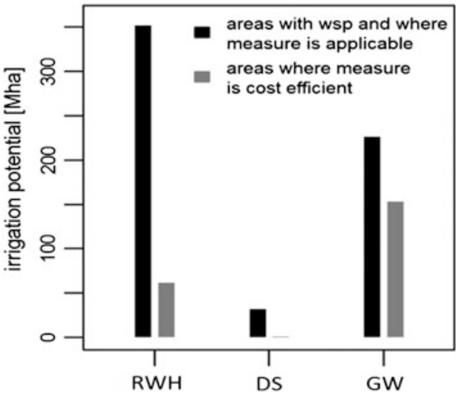

Fig. 6.5 Irrigation potential in Mha for each measure based on applicability and water shadow price (*black*) and cost-efficiency (*grey*) for rainwater harvesting (RWH), desalination (DS) and groundwater extraction (GW)

Conclusion

This study was a first attempt to assess and compare the cost efficiency of different irrigation water supply measures on a global level. Following the steps laid out in the conceptual framework, the current practice of irrigation water supply and its related cost efficiency was reflected in this global study. It could be shown that additional irrigation water can be supplied in a cost efficient way in many regions. Even when only focusing on places where irrigation is already partially practiced, the irrigation potential for the different measures is high for RWH and GW and may contribute substantially to closing the yield gap in many regions.

While RWH is widely applicable, it is cost-efficient for only 4.1 % of the global cultivated land area. With a more accurate assessment of the cost for water supplied by RWH this number is expected to increase. GW has a medium potential to increase irrigation water supply and is economically efficient for 10.1 % of the global cultivated land area. However, incorporating over-exploitation of groundwater, into future analyses will reduce applicability of GW and the area where we found it to be cost efficient. DS only plays a minor role as an irrigation water supply measure due to its high price and its spatial limitation. However, if prices continue to decline, DS may become more important for agriculture in coastal regions and where other freshwater sources are not available.

Future research should focus on better cost assessment (especially for RWH), include data on groundwater over-exploitation, and incorporate the option of expanding irrigation into regions where irrigation is not yet practiced. Calculation of the water shadow price for regions where irrigation is not yet practiced is particularly important for Africa, where yield gaps are high, and the impact of irrigation is expected to be highest (Wisser et al. 2010).

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