Interactive comment on “Marginal cost curves for water footprint reduction in irrigated agriculture: guiding a cost-effective reduction of crop water consumption to a benchmark or permit level” by Abebe D. Chukalla et al.

**Reply to Anonymous Referee #1**
We thank Referee #1 for the comments; below we give the reply to the comments.

**Comment**
The manuscript presents the first attempt to derive MCC for WF reduction. This way the authors add the cost dimension to the water footprint assessment that has not been done before. This is a very timely study and could be interesting for wider audience. The paper needs further revision before it got accepted. The introduction and the discussion section need to further expanded. Please look my detailed comments below:
# The introduction section is very limited. The authors argue that the MCC has not been used in the WF study (Line 474-475) but they fail to carry out a good literature review of the existing literature in the MCC in irrigation water and energy use in irrigated agriculture. **I suggest to include some more literature review on the MCC analyses in general and the application of the MCC in irrigation water in particular.** There are a number of studies that have been carried out to assess the MC of irrigation water eg. **Gonzalez-Alvarez et al. (2006); Samarawickrema and Kulshreshtha (1999).** This way, you will put your study in perspective.

**Reply:** We agree to the reviewer’s comment on the originality and timeliness of introducing MCCs for WF reduction, and to the comment on the literature context being presented limitedly. The following remarks will be incorporated in the revised version of the paper.

MCC for WF reduction is a tool showing measures that are ordered according to their cost effectiveness (WF reduction achieved per cost unit) to achieve an increasing amount of WF reduction. Every measure comes with an additional (i.e. marginal) cost and contributes an incremental (marginal) reduction of the WF in crop production. The MCC has been applied extensively in carbon footprint reduction, its application in the area of water footprint is just starting in the industry sector (Tata-Group, 2013).

Previous studies in other thematic domains add the cost dimension to e.g. the management of irrigation water. Addams et al. (2009) apply the MCCs for increasing water supply to close the gap between water supply and demand in irrigated agriculture, particularly focussing on the reduction of irrigation water withdrawal. Khan et al. (2009) discuss two possible pathways to reduce the environmental footprints of water and energy inputs in food production: improving water productivity and energy use efficiency. This work however does not explicitly specify the measures and their cost effectiveness, which would inform the unit cost of improving water and energy use efficiency. Gonzalez-Alvarez et al. (2006) and Samarawickrema and Kulshreshtha (2009) consider the cost dimension in analyzing the management of scarce water resources: the first study makes implications about how farmers would respond if the marginal cost of irrigation water is changed, and the second study assesses the marginal value of irrigation water in the production of alternative crops in order to allocate the water based on the highest marginal value.

**Comment**

# line 250: you are leaving out the major component of the irrigation curve. This is especially very relevant in those water scarce regions where water is pumped from deep groundwater or from faraway places (Knutson et al., 1977)! I expect this will change the whole analysis of your MCC. This will further brings up what is the water source, how deep is the groundwater, how far is the surface water, what energy is required to pump the water? The question is then if you include the energy required to bring the water to the field, how will your conclusion change? Do you think, the relative cost saving will warrant the relative yield loss?

**Reply:** We agree with the referee's comment that 'the cost of bringing irrigation water from the source to the field is significant, especially in water scarce regions where water is brought from deep groundwater and/or far away'. The cost of bringing irrigation water to a field is affected by different variables, of which the two most important are the volume of irrigation water and the energy cost required to transport a unit volume of irrigation water. The volume of irrigation water required to grow crops varies with the management at field level (irrigation technology and strategy), while the energy cost to bring a unit volume of irrigation water from a particular source can fairly be assumed equal irrespective of the type of management at field level. The total cost to bring irrigation water from the source to the field, the energy cost per unit volume of water multiplied by the total volume of irrigation water, varies with the source of the irrigation water: the cost is high when the source of water is a deep water well and/or far away, and the cost is low or zero if irrigation water flows to a field due to gravitational force or natural pressure, for example from an artesian aquifer or an elevated reservoir.

In the current study, we are interested to compare the cost effectiveness of measures in reducing the WF of growing crops at field scale, and thus we consider WF of growing a crop and cost of a measure at field scale. The energy cost to bring the water from a source to a field and the water consumption while transporting water between the source and the field level are worth to include, these are however case specific and beyond the scope of the current study. Besides, including these costs would not change the conclucions from the study as we will explain. The overall annual cost per measure increases if we add the cost of energy to bring irrigation water from a source to a field to the annual cost of a measure at field level. The cost increase will depend on the measure (see Fig. 1): the cost increase is highest for furrow irrigation, followed by sprinkler and drip or subsurface drip irrigation; furthermore, the cost increase is more with full irrigation than with deficit irrigation; and finally, the cost increase is most with no-mulching followed by organic and synthetic mulching). One can see that the additional cost related to energy for transporting the water to the field decreases in the direction of decreasing WF. Thus, this does not affect the order of measures ranked based on their cost effectiveness in reducing WF.

We did not include the cost of yield losses because our aim is a cost effectiveness analysis: to see what can be done best at least cost to achieve a certain desired WF reduction.

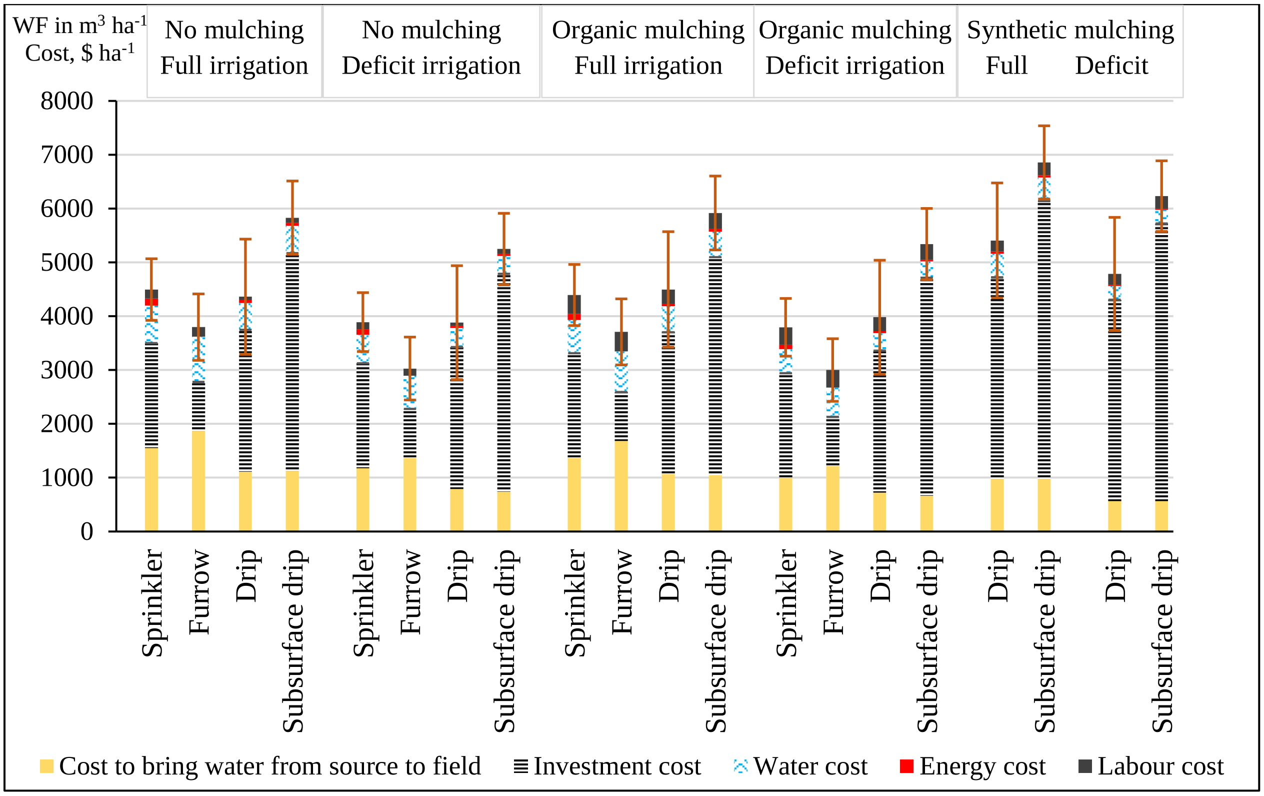

Figure 1: Average WF per area (m$^3$ ha$^{-1}$) for maize production and average annual costs associated with 20 management packages. The whiskers around WF estimates indicate the range of outcomes for the different cases (different environments, soils and hydrologic years). The whiskers around cost estimates indicate uncertainties in the costs. WF estimates are split up in blue and green components; costs are split up in investment, water, energy and labour costs. The energy cost to bring irrigation water from a source to a field is calculated by multiplying the volume of irrigation water by a cost of energy, assumed 0.2 $ per m$^3$.

**Comment**

# Pareto optimal state that an allocation is optimal if an action makes someone better off and putting no one worse off. Its weakness is that it doesn't clearly tell which of the Pareto optimal outcomes is best. Besides, **it doesn't require equitable** use of the water. If that is the case, won't you think it is against one of the pillar of water management "Equitable share" suggested by Hoekstra (2013)Please clearly define the concept clearly and comment on its usefulness to the current study. You might think of using other term.

**Reply:**

Cost-effective WF reduction means to reduce WF at least cost. In the scatter plot showing cost and WF reduction for different management packages, the Pareto optimal set consists of management packages whereby moving from one to another management package will reduce either cost or WF but increase the other, thus implying a trade-off between the two variables. In the uncommon case of the existence of one “best” solution (no trade-off), the Pareto set would consist of one point. Commonly in multi-objective optimization the Pareto optimal involves trade-offs between the different objectives. “Best solutions” may be identified using the MCC when policy goals are specified e.g. requiring a target WF reduction to be achieved, or a budget to be best spent in reducing WFs.

**Comment**

# Even in irrigated fields, the contribution of the rainwater (green water) is very significant. To measure the contribution of irrigation to the water use efficiency (water productivity), Bos (1980) suggest the following equations (Howell, 2001):

WUEi = (Yi – Yr)/ I

WUEet = (Yi – Yr)/ (ETi – ETr)

where WUEi and WUEet are the contribution of irrigation water to the water use efficiency (WUE) in terms of applied irrigation and actual evapotranspiration, respectively. Yi and Yr, the crop yield under irrigated and rain-fed condition, respectively; ETi and ETr, the actual evapotranspiration from irrigated crops and rain-fed crops, respectively.

You can define your WF as inverse of the above equations and test it if provides a better insight. At least provide a good argument for choosing to use the WF as in Eqn (3).

**Reply:**

In assessing the performance of agricultural management in irrigated crop production, a wide variety of indicators may be used, each stressing a different aspect of what is considered good performance. This may include considering the yield gain per unit of irrigation water applied or per unit of additional ET as a result of irrigation (the two indicators suggested by the reviewer). The introduction of the water footprint, as a policy-relevant indicator, can be found in the first paragraph of the introduction (lines 38-56). The goal of the indicator is to relate human consumption of commodities to appropriation of ET. The choice to subsequently use WF in equation (3) is simply because the goal of the paper is to analyse reductions in water footprints in relation to the costs to achieve these reductions. Lines 176-182 explain that the WF analysed includes both green and blue components. Replacing WF by WUEi, WUEet or yet another performance indicator would yield marginal cost curves that would also be useful, serving different goals. A remark in this direction will be added in the conclusion section.

**Comment**

# The manuscript could benefit by further discussion of the result, the limitations and recommendations for future improvement or further development and application of the MCC in the WF assessment.

**Reply:**

This paper aims to introduce the methodological development of MCC for WF reduction. In addition we give insights in the interpretation of the MCC by giving a synthetic example. We are not claiming the reported specific values for costs and WF to be valid for any case study; we applied the method for a few specific crops, locations and soils only. Data on costs are taken from various literature sources and averaged over three countries. The average cost of water for the case of the three countries (UK, Spain and Italy) is 0.09 US$ per $m^3$. The cost of water in UK and Spain is lower than the average while the cost of water in Italy is higher than the average cost.

**Minor comments: (all minor comments are incorporated)**
# Line 59 McCraw and Motes missing year
# line 68: add "to" to read “... relation to WF reduction...”
# line 69; add "the" to read "... the need to enhance ..."
#line 303: please insert “used is” for “not is used”
#line 461: please delete “the” from “. . . to meet a given the local WF permit.”

References:

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