(comments of the referees are printed in blue, responses of authors are held in black)

Response letter to Anonymous Referee #2 (Interactive comment on Geosci. Model Dev. Discuss., 6, 645, 2013. C148–C155)

Referee #2: In the paper "A site-specific agricultural water requirement and footprint estimator (SPARE:WATER 1.0) for irrigation agriculture" S. Multsch, Y. A. Al-Rumaikhani, H.-G. Frede , and L. Breuer introduce a newly developed software tool to inform agricultural water management decision making. The motivation comes from the need to assess consumptive water use at farm or regional scale using local data and to provide a means to determine sustainable management strategies. The authors provide a detailed description of the underlying model structure of the software tool. The software itself seems to be useful in practice due to its seemingly ease of use (mind the issues related to collection and preparation of the required input data). The paper also includes an application of the developed software for Saudi Arabia. It is very positive that the software is being made publicly available by the authors, as certainly more tests are required to determine its general applicability. The scientific community and practitioners now have the change to test this model and provide feedback.

Referee #2: General comments
In general the paper is well written and the structure allows to follow the development well. What I did not find was a notion of the spatial grid resolution. This will depend on the input data available, as crop production is not modeled. Hence a smaller scale, local assessment is always dependent on the availability of data at high spatial resolution. This may make investigations at small scale impossible, as often local data are not available.

Comment by authors: The SPARE:WATER model is not restricted to a certain resolution. Thus, it depends on the case study and the spatial resolution of available data. We agree with the referee that applications on small scale might be hampered by missing detailed spatial input data, including spatially explicit yields. Though information from remote sensing might help to solve this problem in the future. Nevertheless, we included the following sentence to strengthen this current limitation:

> *"The SPARE:WATER tool allows the quantification of agricultural water footprints across a range of spatial scales, which is defined by the spatial resolution of required input data."*

Furthermore, we have included a more precise description of the spatial input data we use in our case study for Saudi Arabia:

> *"The analyses of variance from year to year of climatic variables were conducted for testing their suitability to be used outside the observation period. The average annual standard deviations of minimum (0.8-1.5°C) and maximum (0.8-1.9°C) temperature, relative humidity (2.1-8.5%) and wind speed (0.19-0.48 m s-1) indicate very low inter-annual and intra-annual variations (Appendix A, A1). We therefor conclude that the annual variation is low and that average data can be used to simulate water footprints in other time periods as well. The 30 climate stations were finally interpolated (Arc ESRI Kriging tool; settings: ordinary Kriging, spherical semivariogram) to grid maps with a resolution of 0.063°."*

Referee #2: The authors state to have extended/improved the concept of Hoekstra et al. (2011) by at least incorporating irrigation efficiency and different irrigation methods and a new grey water footprint. It is difficult to understand as to why this is an extension of the method. Different irrigation efficiencies and methods can of course be included in the water footprint assessment. The fact that the selected studies that the authors cite have not done this does not mean that it is not feasible.

Comment by authors: We agree with the statement that the cited studies do not confirm the assumption that the incorporation of irrigation efficiency and method is an extension of the current guidelines from Hoekstra et al. (2011). Words such as "extend" or "improved" might have been misleading. We therefore reworded those relevant sections throughout the manuscript, as for example:

> "*For this, the calculation of the blue water footprint has been slightly modified in comparison to Hoekstra et al. (2011), by considering two important characteristics of irrigation agriculture, i.e. the irrigation efficiency and the irrigation method.*"

Referee #2: The new definition of the grey water footprint by the authors leads to having to also evaluate how much water percolates (and hence returns to the same catchment where it has been withdrawn) and how much is needed to dilute the salt. This remark is not alluding to a specific case (the authors looked at conditions in Saudi Arabia only, p. 664), but it is an issue of general applicability of the tool. The authors are asked to take a look at the work by Chapagain and Hoekstra (2011), which alludes to percolation, and reflect on this work in light of their own work beyond the brief remark on p. 667.

Comment by authors: The conclusions have been extended the whole passage about the allocation of percolation water now reads as:

> *"Compared to temperate regions or regions with a shallow ground water table, the water lost in semi-arid and arid agro-ecosystems by insufficient irrigation systems is evaporated to the atmosphere or percolated to deep soil layers, and for this reason, is not available for future water use. This is especially the case for crop production in Saudi Arabia. Under other conditions percolation water may return and be available for crop water uptake. Such conditions have been considered by Chapagain and Hoekstra (2011) in rice productions systems in China where percolation makes up to 1025 m^3 t^{-1} and which has not been added to the water footprint."*

Referee #2: In Multsch et al. no irrigation methods have been tested (e.g. drip irrigation, sprinkler irrigation, etc.), it is only mentioned that the efficiency has been set to resemble surface and sprinkler irrigation (p. 665). It is also not clear as to how those different methods have been implemented (see text on p. 649, line 25). With respect to irrigation efficiency it is advised to be critical about the data provided and included for the calculations. There are a number of publications that debate this issue (e.g. Jensen, 2007; Perry, 2007; Lankford, 2012).

Comment by authors: A detailed description on the implementation of irrigation efficiency is given chapter 2.2.3 (equation 9), which has been modified in accordance to comments by the reviewer. The text now reads*:*

> *"IRR_{eff} is defined for each cell of a grid map during model setup by the user. We note that the term irrigation efficiency has been intensively discussed (e.g. Jensen, 2007; Lankford, 2012) and that there is not a common definition available. The problem is to*

define which fraction of water contributes to irrigation efficiency (e.g. consumptive and non-consumptive water use, recovered and non-recovered return flow). Thus, users of SPARE:WATER are requested to carefully think about the irrigation use efficiency used in their respective study."

Referee #2: The model proposed is in a great many of aspects CropWat of FAO with additions. It is not clear why AquaCrop of FAO has not been mentioned nor discussed, as it is intended to cope with some of the aspects that have been implemented by the authors and relates to the spatial scale that is investigated here, other than the references mentioned. SPARE:WATER 1.0 has, at this point, precisely the functionalities required for the shown test case of Saudi Arabia, which is a very peculiar case. AquaCrop has more functionality, in particular it is clear in terms of irrigation practices.

Comment by authors: CropWat provides the basis for SPARE:WATER as it paved the ground for the general water footprint method. To be in line with the water footprint approach we decided to also use the same model (CropWat), rather than changing to another model (e.g. AQUACROP). This is now better emphasized in the manuscript:

"Site specific simulations of crop water, irrigation and leaching requirement are assessed in accordance with FAO irrigation guidelines (Allen et al., 1998; Ayers and Westcot, 1994) and in line with the water footprint manual (Hoekstra, 2011), in which the utilisation of CropWat (Smith, 1992) or EPIC (Williams et al., 1984) is recommended.".

It was a shortcoming of the first version of this paper that AQUACROP was not even mentioned and we therefore included AQUACROP in the comparison of models in the introduction as described above.

Referee #2: In SPARE:WATER 1.0 salt has been included, but fertilizer, pesticides, herbicides and other pollutants have not been considered. In general they will need to be included. Is this feasible? The authors state on p. 664 that "the grey water footprint component need not be considered in Saudi Arabian agriculture". This statement is flawed. If salt needs to be diluted to not degrade soil quality, then for the same reason pollutants also need to be diluted. The authors are asked to reflect on this.

Comment by authors: The full section on p. 664 addresses why we think that the calculation of water for salt dilution is relevant, but water for diluting fertilizers or pesticides is not:

"Under the climatic conditions of Saudi Arabia no return flow of irrigation water to rivers or groundwater exists. Thus, water pollution through fertilizers or pesticides usually considered in estimating the grey water footprint component need not to be considered in Saudi Arabian agriculture. Maintaining soil quality is more important, e.g. through low salt concentrations, and thus should be considered in the estimation of crop water footprints."

Another aspect – which we did not extensively discuss in the current paper – is the kind of grey water that is being calculated in the water footprint framework. Grey water to dilute fertilizers or pesticides is calculated in the way that it is the amount of water needed to dilute the solutes to levels of standard water quality. Hence, it is a *calculated* volume of water that is *theoretically* needed, but which is in *reality* never applied in agriculture. In contrast, grey water to desalinize soil is *part of the agricultural management* and thus is *real water*.

Referee #2: The wording used when it comes to "water footprint related" issues must be revised in several places. Please use the same nomenclature throughout, as otherwise even more confusion arises than there already is (examples: p. 646, line 6: spatial decision support system; p. 646, line 23: withdrawn instead of consumed; p. 663, line 6: the Water Footprint of Nations (WFPN) model: I would think that this is a name that has been created by the authors, i.e. not in the original work cited. Even worse, water footprint assessment is not a model and this should be rectified; p. 666, line 6: WF assessment ;p. 667, line 4: explicit spatial water footprint system).

Comment by authors: We have thoroughly revised the manuscript and specifically corrected those terms listed by the referee. We have modified the description of the data provided by Mekonnen and Hoekstra (2010) and we now use the official abbreviation WaterStat instead of WFPN, see http://www.waterfootprint.org/?page=files/WaterStat-ProductWaterFootprints.

Referee #2: I disagree with the authors' statement that a monthly time step is sufficient for analyses in the agricultural sector (p. 668). But this is scope of future work, which the authors acknowledge in the conclusions/outlook section.

Comment by authors: We agree that monthly values are often not sufficient. SPARE:WATER is generally capable of utilizing data of higher temporal resolution. Often though, such data are not at hand and monthly values are being used. We have slightly modified our statement, it now reads:

> *"So far, many water footprint applications focus on the long term impact of agriculture on water resources and use monthly data to describe seasonal variability, because daily data are often not at hand. However, daily data could become relevant if the impact of weather extremes (droughts, shift of precipitation patterns and intensity) on water resources utilization are of interest.*"

Referee #2: The text has a focus on the agricultural sector. Water Footprint Assessment goes far beyond this. SPARE:WATER does of course not, it is not intended to at present. It is a tool that carries out a methodology. But the authors would be advised to not present water footprint assessment as a means to investigate agriculture only.

Comment by authors: The scope of water footprint assessment has been clarified throughout the manuscript. We also checked for misleading denominations. The scope of the study has been clarified:

> "*In our study, the water footprint is limited to the water consumption by growing crops."*

Referee #2: It is unfortunate that no recommendations are drawn from the results obtained with the decision support system SPARE:WATER to aid in the development of sustainable water management in Saudi Arabia, as this should be the main goal of a DSS. In particular since the authors state that over-exploitation of (fossil) groundwater resources is the norm, rather than the exception in their test case. The focus of the paper is more on the competition with results obtained by others. In a next paper by the authors the usefulness for decision making will hopefully become a focus.

Comment by authors: This paper addresses the presentation of the software tool itself and the underlying concept as well as a case study. We agree that an article with a focus on decision making is needed, for instance by the comparison of alternative production scenarios.

Technical content

Referee #2: The work is certainly relevant. An important research question has been approached. The research methodology is sufficiently (if not overly – I wonder if some of the simple equations could be removed and some in particular CropWat descriptions and equations be moved to an Appendix, so that it does not read like a user manual) described. The authors should reconsider what their work in fact is: a new development or a software development to support decision making based on existing methodologies.

Comment by authors: We also see SPARE:WATER as a tool that facilitates working with an existing methodological framework. Moving equations to an annex though would not really change the layout of the paper nor would it reduce the length of the paper. We therefor prefer to leave the paper structure as is.

Referee #2: Important questions remain: It is stated that different irrigation methods can be modeled. How? Why has pollution not been included? Why is AquaCrop not mentioned, even though it is closely related and widely used software? The application is significant, as the results for Saudi Arabia can certainly be used for decision making.

Comment by authors: The issues listed by the referee in this comment (irrigation methods, pollution, AquaCrop) have been replied to in the former comments. In addition we like to add, that the SPARE:WATER tool will be used by Saudi Arabian authorities for analysing the water footprint of agriculture and to develop water saving strategies.

Writing and Presentation

Referee #2: The writing is it clear, concise and in good English. The development of the argument can be followed. One style correction that should be considered throughout the text: what comes next does not have to be "announced" (next we present...; or ..in Equ (x)...and the equation follows right thereafter).

Comment by authors: The manuscript has been corrected in accordance to the comment.

Referee #2: The title implies that rainfed agriculture cannot be analyzed. Is such an application not intended? That would be unfortunate in light of the importance of rainfed agriculture and the measures that must be taken to make rainfed agriculture more efficient in order to feed a growing world population

Comment by authors: Rainfed agriculture can be analysed. The title was misleading and has been slightly modified. It now reads:

> *"A Site-sPecific Agricultural water Requirement and footprint Estimator (SPARE:WATER 1.0)"*

Referee #2: Specific comments p. 646, line 5: "Most of current water footprint assessments focus on global to continental scale." This is an uninformed statement. Apart from publicly available literature on smaller scale assessments there is a large number of unpublished assessments (for a business, one production site, a sector, an individual, a product). Please consider rewording this statement.

Comment by authors: We agree and modified to:

"By considering site-specific properties when calculating the crop water footprint, this methodology can be used to support decision making in the agricultural sector on local to regional scale."

Referee #2: Also, the list of publications given on p. 647, line 11 onwards is disturbing, as it is used to show that "...all these applications focused on large scales with an emphasis on nations". This gives the impression that nothing else has ever achieved using the water footprint assessment methodology.

Referee #2: p. 647: a large body of literature exists in which the CropWat model...and then three sources are listed. Three is not a large number. And this statement holds true, then the model presented by the authors is also "just CropWat with a twist". Please consider the scientific publication of Hoekstra and Mekonnen (2012).

Referee #2: In the text reference is made to Mekonnen and Hoekstra (2010), which is a data source. It is stated that Mekonnen and Hoekstra (2010) use CropWat (p. 647). After visiting this publication I found the following description given therein: "The green, blue and grey water footprints of crop production were estimated following the calculation framework of Hoekstra et al. (2009). The computations of crop evapotranspiration and yield, required for the estimation of the green and blue water footprint in crop production, have been done following the method and assumptions provided by Allen et al. (1998) for the case of crop growth under non-optimal conditions. The grid based dynamic water balance model used in this study computes a daily soil water balance and calculates crop water requirements, actual crop water use (both green and blue) and actual yields. The model is applied at a global scale using a resolution of 5 by 5 arc minute (Mekonnen and Hoekstra, 2010).We estimated the water footprint of 146 primary crops (as listed in Appendix I) and more than two hundred derived products. The grid based water balance model was used to estimate the crop water use for 126 primary crops; for the other 20 crops, which are grown in only few countries, the CROPWAT 8.0 model was used." (cited from Mekonnen and Hoekstra, 2010) Hence it seems that the statement made by Multsch et al. regarding CropWat is only partially true.

Comment by authors: We reworded and rearranged the sections on p 647 of the introduction that the referee is referring to in his/her comments. It now reads:

"Using this approach, several WFs have been estimated. These studies offer insight into the WF of sectors, products or nations. A global perspective is given by Hoekstra and Mekonnen (2012) who estimate the water footprint of humanity to be 9,087 km³ yr-1, whereby agriculture contributes the largest fraction of 92%. Further publications focus on nations (Chapagain et al., 2006; Hoekstra and Chapagain, 2007; Hoekstra and Hung, 2002, Chapagain and Hoekstra 2008) or commodities produced worldwide (Chapagain et al., 2006; Gerbens-Leenes et al., 2009). Others investigate the water footprint of a business (Ercin et al., 2011) or give deeper insight into the water footprint of single food products (Ercin et al., 2012). Mekonnen and Hoekstra (2010a, 2010b) have assessed world-wide water footprints of a large number of crops and secondary agricultural products. The basis for all these water footprint analyses have been the FAO evapotranspiration guidelines by Allen et al. (1998) or the CropWat model (Smith, 1992), which is based upon the same guidelines. None of the listed works considered irrigation practices in particular."

Referee #2: It is suggested to restructure part 2 of the paper. Consider renaming section 2 in "Method and Data", erase the section "Equations" and then move the third level subsections one level up.

Comment by authors: We have restructured the sections accordingly.

Referee #2: One caveat that came up when reading p. 653, which stands in sharp contrast to the level of detail the authors are aiming for with their work. It is stated that " the model accounts for the runoff losses (RO) as a constant ratio of 20% of precipitation (P). Why precisely 20% and not another percentage?

Comment by authors: The constant fraction of 20% is in accordance with the default settings of the FAO CropWat model and the general water footprint accounting scheme of Hoeckstra and colleagues. We agree that this is only a very rough and simplified approach. We included the following sentences in section 2.4:

> *"The fixed runoff loss of 20% is in agreement with the general water footprint accounting scheme. If higher temporal resolution data are available and a daily accounting of the water footprint is aimed for, more sophisticated approaches are needed to more precisely estimate runoff losses, which are not included in the current version of SPARE:WATER 1.0."*

Referee #2: Section 2.2.4 Site specific leaching requirement: How does this relate to the leaching and runoff fractions in section 3.3.3 of the water footprint assessment manual (Hoekstra et al., 2011)?

Comment by authors: The leaching fraction in our work is defined in accordance with Ayers and Westcot (1976) and is calculated following Al-Zeid et al. (1998). The definition is included in the manuscript as follows:

> *"The leaching fraction (LF) represents the water volume that is lost beyond the root zone in relation to the amount of water irrigated and is estimated in two slightly different ways, depending on the method used for irrigation"*

This is not to be mixed with the leaching-runoff fraction (α) defined by Hoekstra et al. (2011) which describes the *"fraction of applied chemicals reaching freshwater bodies"*.

Referee #2: I would suggest to rename section 3 into "Application to crop production in Saudi Arabia". Proof of concept sounds like a mathematical proof after a derivation.

Comment by authors: Has been changed accordingly.

Referee #2: p. 647, line 8: what is a unit water?

Comment by authors: Modified, text now reads:

> *"… where WF is given in water volume that is consumed and/or polluted per unit biomass (yield) or area."*

Referee #2: p. 648, line 23: the definition of grey wf is not correct. Please refer to the water footprint assessment manual.

Comment by authors: Has been corrected, it now reads:

"In accordance with Hoekstra et al. (2011), the grey WF in these studies refers to the fresh water needed to dilute concentrations of pollutants to meet water quality standards."

Referee #2: Typos:
p. 648, line 6: remove "to" after "regarding"
p. 653, line3: crop coefficient, not coefficients
p. 656, line 5: input parameters, not parameter
p. 657, line 5: a text file, not a text files
p. 669, line 11: crop ET and Kc, not et and kc
p. 669, line 20: use lower case letters, the same on p. 670 in lines 20, 21, 24
C154 p. 671, line 4: the reference is not complete, it is given above
p. 671, line 18: there is a backslash that needs to be removed
same page, line 22: please check with the journals' policy, but links to pdf should most likely not be made
Figure 8: I would imagine that it is easier to compare if the axes (x,y) have the same maximum value. Now they have 6000 and 8000.

Comment by authors: typos and figures have been corrected. The PDF link has been deleted. The following references have been considered in the revised version of our manuscript. We would like to thank reviewers for pointing out to many of them.

Chapagain, A. K. and Hoekstra, A. Y.: The blue, green and grey water footprint of rice from production and consumption perspectives, Ecol. Econ., 70(4), 749–758, 2011.

Ercin, A. E., Aldaya, M. M. and Hoekstra, A. Y.: Corporate water footprint accounting and impact assessment: the case of the water footprint of a sugar-containing carbonated beverage, Water Resour. Manag., 25(2), 721–741, 2011.

Ercin, A. E., Aldaya, M. M. and Hoekstra, A. Y.: The water footprint of soy milk and soy burger and equivalent animal products, Ecol. Indic., 18, 392–402, 2012.

Hoekstra, A. Y. and Mekonnen, M. M.: The water footprint of humanity, Proc. Natl. Acad. Sci. USA, 109(9), 3232–3237, 2012.

Jensen, M. E.: Beyond irrigation efficiency, Irrigation Sci., 25(3), 233–245, 2007.

Lankford, B.: Fictions, fractions, factorials and fractures; on the framing of irrigation efficiency, Agr. Water Manage., 108, 27–38, 2012.

Mekonnen, M. M. and Hoekstra, A. Y.: A global and high-resolution assessment of the green, blue and grey water footprint of wheat, Hydrol. Earth Syst. Sci., 14, 1259-1276, 2010a.

Raes, D., Steduto, P., Hsiao, T. C. and Fereres, E.: AquaCrop The FAO Crop Model to Simulate Yield Response to Water: II. Main Algorithms and Software Description, Agron. J., 101(3), 438–447, 2009.

Steduto, P., Hsiao, T. C., Raes, D. and Fereres, E.: AquaCrop—The FAO crop model to simulate yield response to water: I. Concepts and underlying principles, Agron. J., 101(3), 426–437, 2009.