

Reply to Editor and Reviewers

Manuscript #: hess-2015-84

Title: Water savings potentials of irrigation systems: dynamic global simulation

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Dear Editor and Reviewers,

We thank both reviewers for carefully reading our manuscript and providing sharp, reasonable, and encouraging comments.

We have revised the manuscript according to these comments. Amendments we have made and comments from our side are listed hereafter (page and line numbers refer to the original manuscript). Please note that we have change the title towards “Water savings potentials of irrigation systems: global simulations of processes and linkages”.

In addition, we have rerun the model simulations and replotted some figures due to a new river system input file that better supports the reservoirs module. This has negligible effects on the results, yet slightly alters displayed numbers. Now we present results based on the latest and conceptually sound LPJmL version.

We hope the manuscript has been improved to the extent that it can now be considered for publication in HESS.

Yours faithfully,

Jonas Jägermeyr (corresponding author)

Comments from Referee #1

I found the paper to be well written and the research to be of such high quality and presentation that I recommended this paper be highlighted in HESS. The dataset provided in this manuscript is of critical importance to understanding water availability and use at the global scale and I would expect this paper to have immediate impact in the global modeling community. I also commend the authors on providing an evaluation of their simulation results in the context of past values reported in the literature (Section 3.4) and in providing a discussion of the modeling issues that were encountered (Section 4.2). I have no substantial comments but I do have a few minor comments on the manuscript that I have provided below.

- We are very grateful for your positive and motivating comments and for suggesting to highlight this paper in HESS.

Detailed comments:

p. 3597, line 8: Change “referred to” to “referenced”

- Thanks for this correction, the revised manuscript will be changed accordingly.

p. 3597, line 9: Change “but” to “yet still”

- Thanks for this correction, the revised manuscript will be changed accordingly.

p. 3597, line 16: Add a reference to LPJmL. The “(see below)” phrase had be look for a section later in the paper titled LPJmL but it was not clear where the discussion of the model can be found later. A reference here would rectify that. Also, add a reference after PCR-GLOBWB. Consider adding a sentence at the end of the statements about these two models to explain why LPJmL was then selected for these simulations.

- In section 2.2 we provide the description of LPJmL including all necessary references. The reference for PCR-GLOBWB was originally given at the end of the sentence, we've now moved it right behind the model name.

We have rephrased this passage, the revised manuscript will read: “To our knowledge, besides LPJmL, PCR-GLOBWB (Wada et al., 2014) is the only global model that intrinsically partitions applied irrigation water into daily evapotranspiration and percolation losses per unit crop area based on surface and soil water balance, yet only for two crop classes without partitioning beneficial and non-beneficial water consumption. LPJmL as described herein now solves the complex irrigation water balance with considerable spatial and temporal detail (see section 2.2).”.

p. 3598 line 23 to p. 3599 line 2. This sentence should go in Section 2.2 and not in Section 2.1.

- Thanks, it fits indeed better to section 2.2; the revised manuscript will be changed accordingly.

Sections 2.2 and 2.3 titles: Add to the end of the section title “. . .in LPJmL”. Then it is clear to the reader where the discussion of the LPJmL model is located in the paper.

- The revised manuscript will read: “2.2 Suitability of the dynamic process model LPJmL to simulate irrigation systems”, “2.3 Implementation of the new irrigation scheme in LPJmL”

p. 3604, lines 20-27: Please give another 1-2 sentences about crops C4 and C3. Add a reference to the classification. I had to look this up to understand what the differences are and where this designation originates

- We will add the reference (Amthor 1995) and make this section more self-explanatory. The revised manuscript will read: “C4 crops (maize, tropical cereals, sugarcane) are less sensitive to drought stress, because in contrast to C3 crops, they use a more efficient enzyme on the pathway of CO₂ fixation (Amthor, 1995).”

We agree that the concept of C4/C3 CO₂ fixation pathway is not known to all potential readers. The manuscript clearly has to be self-explanatory, on the other hand however, readers are already confronted with a long and detail-rich manuscript and we try to keep it as compact as possible. With the reference for further reading, we hope that the rephrased passage finds a balance between both.

p. 3608, line 6: Instead of “new irrigation scheme” be specific about the scheme used so it is immediately clear to the reader.

- Thanks, we will make the text more explicit, the revised manuscript will read: “Global irrigation water withdrawals simulated with our newly developed, process-based irrigation scheme are 2396 km³ per year...”.

p. 3608, line 7: Use a semi-colon instead of a comma after “2009”

- There is no comma after “2009” in the original manuscript. We think it is reasonable to separate both sentences by full stop.

p. 3608, line 15: Should read “However, on a global average”

- Thanks, the revised manuscript will be changed accordingly.

Comments from Referee #2

Dear Editor and Authors, In this paper, the authors developed a global map of irrigation system for the first time. The irrigation system was categorized into three, namely surface, sprinkler, and drip irrigation. Then, they modeled the irrigation application of each system and incorporated it into the LPJmL global hydrological model. These works enabled the authors to simulate detailed hydrological simulation in irrigated cropland, which provided new insights into irrigation efficiency of the world. I believe this study is well designed and presents novel data and results on global hydrology. Although the draft is basically well prepared, I observed some parts are unclear and need revision. See below for detailed comments. I recommend this paper be published after moderate revision.

- Thank you very much for carefully reading our manuscript and the positive review.

Before we reply to the detailed comments, we would like to briefly elaborate on the principle of “dynamic” modeling as we understood it in the original manuscript. Our model represents detailed fundamental biophysical process dependencies that are interlinked and thus affect each other's behavior. Functional dependencies in LPJmL are not “static”, i.e. parameterized for certain conditions, but are sensitive to the mechanistic interplay of underlying processes and thus generate feedback mechanisms. Physical properties hence change “dynamically” over time, updated at a daily simulation time step. As a result, such a model is more likely to produce reasonable results under altered bounding conditions (e.g. climate change), compared to a static equilibrium model (i.e. predetermined by statistical relationships).

Based on this process-based modeling capacity, we are able to investigate spatio-temporal heterogeneity in the performance of irrigation systems due to climate, landuse, soil, and vegetation dynamics; i.e. the irrigation water balance and thus irrigation efficiencies are computed at the daily time step, explicitly in space and time, despite the fact that inputs of land-use and irrigation systems distributions are updated at the annual time step.

To make this concept easier to understand, and to clearly conduct how we understand the principle of process-based modeling, the following passage in the introduction will be rephrased in the revised manuscript, page 3596, line 25: “Advanced estimates of global agricultural water consumption, and of water saving and water productivity potentials at basin level require a spatially and temporally explicit and process-based simulation of the irrigation water balance. That is, the performance of irrigation systems is represented mechanistically, in direct coupling with vegetation dynamics, climate, soil, and land-use properties.” In addition, we will generally replace “dynamic” by “process-based”, following your implicit suggestion that our overall modelling approach is not fully dynamic (but relies e.g. on seasonally fixed distribution of land use patterns and irrigation systems). We will also change the title towards “Water savings potentials of irrigation systems: global simulations of processes and linkages”.

Detailed comments:

Page 3594 line 5 “due to climate and other biophysical dependencies”: The statement is a bit unclear because these terms cover quite broad range of aspects, particularly the latter part. Specify

(narrow down) what were explicitly taken into account in this modeling. I observe this study mainly dealt with irrigation water partition into transpiration, evaporation, interception, and return flow.

- Thanks, we agree that this formulation is quite broad. However, due to space constraints within the abstract we need to be brief here, and factors that influence the results are listed one sentence later (page 3594 line 12). Nevertheless, we will rephrase page 3596 line 25 to be more specific about what was explicitly taken into account. We hope that the revised manuscript finds a balance between abstraction and transparency here.

Page 3594 line 8 “dynamic representation of three major irrigation systems”: I have read this draft three times, and I am still confused what “dynamic representation” stands for. The term “dynamic” gives me an impression that something grows/varies by time, but as far as I understand that the irrigation system was fixed during simulations except three sensitivity studies (i.e. All-surface, All-sprinkler only, and All-drip). Do you mean “explicit representation. . .” or “modeled and parameterized three major irrigation systems” here?

- Please see our general comment above. Here you are right indeed, the irrigation system is fixed (at least for one year, if the area of irrigated cropland changes, the spatial distribution of irrigation systems is adjusted, see Supplement), but the performance of irrigation systems is dynamically simulated, i.e. updated daily in direct coupling with the above-mentioned processes. Nevertheless, to avoid confusion and to improve explicitness, we will generally replace the term “dynamic” by “process-based” throughout the revised manuscript.

Page 3594 line 11 “dynamically retrieved”: Similar to above, I couldn’t clearly understand what does “dynamically retrieved” indicate.

- Please see our general comment above. The performance of irrigation systems strongly depends on downstream effects along a river system. “Dynamically retrieved irrigation efficiencies” means that the feedbacks of impacts from system types, crop types, climatic and hydrologic conditions, and overall crop management are all accounted for. This will be clarified in the revised introduction.

Page 3596 line 27 “a dynamic simulation of irrigation systems”: Again and again, what is dynamic simulation? What is “static” simulation?

- Please see our general comment above. In the revised manuscript we will rephrase this section to make clear that it is the performance of irrigation systems, not its distribution, which is dynamically simulated.

Page 3597 line 15 “To our knowledge, besides LPJmL, PCR-GLOBWB is the only global model that calculates daily evapotranspiration and percolation losses per unit crop area based on surface and soil water balance”: It is not very clear what this mean. Without surface/soil water balance calculation, actual evapotranspiration couldn’t be estimated. For example, the H08 global model (Hanasaki et al., 2008, HESS) solves surface water and energy balance of irrigated cropland (expressed as a sub-grid cell) explicitly.

- What we want to refer to here is that irrigation water is intrinsically partitioned by the model into evapotranspiration and return-flow, i.e. irrigation efficiencies are simulated mechanistically through solving the irrigation water balance. H08 solves the water and energy balance (as LPJmL), but it uses static irrigation efficiency values to convert crop water demand to actual withdrawal demand (Hanasaki et al. 2008). To make this section clearer, we will rephrase it as follows: “To our knowledge, besides LPJmL, PCR-GLOBWB (Wada et al., 2014) is the only global model that intrinsically partitions applied irrigation water into daily evapotranspiration and percolation losses per unit crop area based on surface and soil water balance, yet only for two crop classes without partitioning beneficial and non-beneficial water consumption. LPJmL as described herein now solves the complex irrigation water balance with considerable spatial and temporal detail (see

section 2.2).”

Page 3600 line 3 “defined as beneficial consumption (W_{bc})”: What are the differences between W_{bc} and T (transpiration)? Clarify the relationship between these two.

- “Beneficial consumption” and “transpiration” relate to the same quantity of water throughout this manuscript, but the term beneficial consumption describes a component of the irrigation water balance, while transpiration describes the biophysical water flux. Both are defined on page 3602 line 4: “Beneficial water consumption, i.e. transpiration, is calculated as...”, also see Figure 1.

Page 3603 line 25 Equation 9: I am curious about the physical meaning of “ $W_{sat}-W_{fc}-W_{pwp}$ ”. Actually, I expected “ $W_{sat}-W_{fc}$ ” here.

- Thank you very much for carefully reading the manuscript, this is indeed a typo. The formula in the model code is calculated as “ $W_{sat}-W_{hc}-W_{pwp}$ ”, where W_{hc} is absolute water holding capacity, which is defined as “ $W_{fc}-W_{pwp}$ ”. Accordingly, the formula in the manuscript must read, as you correctly commented: “ $W_{sat}-W_{fc}$ ”. The revised manuscript will be changed accordingly, results and figures remain unaffected.

Page 3605 line 17 “Development of new input dataset for grid-level irrigation system distribution”: This part is one of the most important points in this work, but it seems validation is completely missing. I understand it is difficult to obtain ground-truth data globally, but at least qualitative discussion could be presented for some parts of the world. For example, does the authors’ map explain the general pattern of actual irrigation system distribution of Europe?

- This is a very important point. The validation of the new map of subnational distributions of irrigation systems (Figure 3) remains a challenge, because the lack of such data was actually the motivation to develop it. This new map is based on two data sets, as described on page 3605, line 18pp and in the Supplement. The distribution for each country (percentage share of each of the three simulated systems, e.g. 30% surface, 60% sprinkler, 10% drip) is retrieved from (FAO 2014). The spatially explicit crop areas that are actually equipped for irrigation, are retrieved from (Siebert et al. 2015). Therefore, overall regional patterns of irrigation system distributions are in accordance with the recent literature and national statistics. Thus, we represent in line with those statistics that e.g. Greece (25%) and Spain (48%) have larger shares of drip irrigation than Germany (1%), see Table S1.

Our advancement is to distribute spatially the different irrigation systems within each country, following the distribution of crop types and their common irrigation system (Table 2). In regions with relatively small countries, as for instance across Europe, our approach works well and leads to results that are in line with national statistics but provide much more spatial detail. This approach is challenged, however, if to deal with very large countries providing only a single national share of irrigation systems, e.g. USA, China, Brazil. We tried to collect subnational data on the distribution of irrigation systems from many sources, e.g. Siebert et al. (2013), who present detailed information and individual references for each country, or FAO (2012), who present detailed water management information for major river basins. But we did not succeed to collect data on the actual distribution of irrigation systems at the subnational level.

However, irrigation efficiencies (although not ideal for comparison across various studies due to varying definitions) are somewhat better documented. Therefore, we oppose spatial patterns in irrigation efficiency simulated in this study with published local and regional studies (page 3611 line 11pp). Irrigation efficiencies depend to a large degree on the geographical distribution of irrigation systems.

We will add a new paragraph along these lines to the discussion of the revised manuscript (section 4.2).

Page 3607 line 1 “we ran three synthetic scenarios. . .”: Table 2 indicates that some combinations of CFT and irrigation system are unavailable (e.g. rice and sprinkler irrigation). Does Table 2 hold true in the “All-Drip” simulation? If “All-Drip” simulation really assume even rice paddy can be irrigated by drip irrigation, add discussion on the feasibility of implementation.

- For synthetic scenarios it is assumed that each system is respectively applied on the entire global irrigated area, irrespective of Table 2 (as described on page 3607, line 4). Yet according to Table 1, the irrigation threshold in case of rice cultivation is set to 1 (no minimum soil water depletion needed before irrigation triggered).

For this study we have decided to employ these synthetic and by definition somewhat unrealistic scenarios, because they enable to investigate spatio-temporal properties and performances (e.g. water saving potential) of the three irrigation systems. Here we focus on studying the potential of different irrigation systems, we do not focus on the feasibility of its large scale adoption. In a follow-up study we will focus on more realistic transition scenarios in order to quantify achievable opportunities in irrigation water management.

To make this passage more transparent, we rephrased page 3607 line 1: “In addition to the current distribution of irrigation systems, we ran three synthetic scenarios (hereinafter: All-Surface, All-Sprinkler, All-Drip), in which it is assumed that each system is respectively applied on the entire global irrigated area, irrespective of system suitability for crop types (Tab. 2). These scenarios were developed to investigate the global performance of each system and to provide an estimate of the effect of irrigation system transitions, they do not represent feasible transition targets.”

Page 3611 line 24 “With correlation analyses . . . in spite of multitude of confounding processes”: It is not clear what are analyzed here. Apparently the items the authors discussed here are strongly dependent each other (e.g. precipitation and return flow). The items should be “confounding” with no surprise. In the present form, I hardly found Figure 9 informative. Elaborate the intention and results of Figure 9 in detail.

- Thanks, we will move Figure 9 to the Supplement (Fig. A3) and this section will be rephrased in the revised manuscript, as follows: “With Figure A3 we can show that mechanistically simulated irrigation water fluxes (and thus efficiency patterns) follow expected biophysical dependencies. We are able to fit significant empirical relations between components of the irrigation water balance and biophysical explanatory variables, although each component is affected by interlinked processes and input variables, which themselves exhibit spatio-temporal patterns (e.g. local climatic conditions, crop type, crop phenology, *LAI*, length of the growing season, soil parameters). For instance, return flow mainly depends on *prec* and *WHC*; *WHC* is more relevant for surface systems, while *prec* appears to be most decisive for drip systems. Aboveground biomass affects soil evaporation negatively and interception losses positively. Precipitation during the growing season can lead to leaching of soil water that originated from irrigation, which can oppress efficiency indicators.

Accordingly, Figure A3 adds confidence that the newly implemented parameterization of irrigation systems in LPJmL is reasonable from a biophysical perspective and, as importantly, it supports a main finding of this study: the performance of irrigation systems is clearly governed by local biophysical conditions.”

Page 3612 line 8 “for the first time spatially and temporary explicit”: What does “temporary” mean here? Possibly, the authors meant that simulations were conducted at daily time interval, but

the present expression gives me an impression that the map of irrigation system varies by time, which is not the case.

- The original manuscript reads “temporally explicit”, not “temporary explicit”. Here it means that we are able to simulate detailed seasonal patterns, based on the daily simulation of incorporated processes, as well as on yearly adjusted inputs of land-use and irrigation system distribution (see Supplement). Although all processes are simulated explicitly in space and time, we present most global maps as 1980-2009 averages (page 3606 line 27), in order to illustrate average irrigation system properties.

Page 3602 line 25: “(Rost et al., 2008)” reads “Rost et al. (2008)”.

- Thanks, the revised manuscript will be changed accordingly.

Page 3609 line 18: remove “very”.

- Thanks, the revised manuscript will be changed accordingly.

References

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