Water resources trends in Middle East and North Africa towards 2050

By P. Droogers, W. W. Immerzeel, W. Terink, J. Hoogeveen, M. F. P. Bierkens, L. P. H. van Beek, and B. Debele

Overall

I would like to thank the editor and the reviewers for the overall very positive comments on our manuscript and acknowledge their time spent on providing constructive comments. Below are detailed comments to the two reviewers. For the further editing process two items are important: (i) we've modified the title slightly based on comments, (ii) the name of the last author was wrong and the correct name can be seen in the revised manuscript.

Anonymous Referee #1

This paper attempts to assess the impacts of climate change on water resources availability in the MENA region using a physically-based distributed hydrological model coupled to a water allocation model. The study gives due respect to changes in socio-economic conditions in comparison to impacts of climate change. I see this paper as a valuable contribution to the assessment of climate change and development scenarios on large and less well studied region. It is not clear, though, if the used models are suitable for a hyper-arid region where most of the rain falls in the form of intense and short storms causing flash floods in many times that may not be well-captured by daily time steps. In addition, I have some comments on the approach in addition to some specific comments as follows;

We would like to start with appreciating your time spent on reviewing our manuscript. We thank you for the overall comment that this paper is "*a valuable contribution to the assessment of climate change and development scenarios on large and less well studied region*". We will address your main concern regarding the suitability of the models used in the revised version of the manuscript and will provide a more detailed reply under the specific comments you raised under P4393. Also other issues raised by you will be addressed here.

P4382
L5: use "physically" instead of "physical"
Corrected.

L8: use "Sectoral" instead of "Sectorial" and throughout
Corrected.

L10-12: I do not understand how the shortage in 2050 (199 km3/yr) can be larger than the total demand (132 km3/yr) - please clarify?
This was wrongly stated as we combined "increased to" and "increased by". Corrected in the manuscript.

L 11, 14: use units of (km3/yr) instead of (km3)
Adjusted.

P4384
L22-23: Latitudes and Longitudes are interchanged by mistake - Add a reference to Fig. 1

Corrected. Reference added.

L25: add "of the area" after "about 85%"
Adjusted.

P4386
L5-10: there is no debate about the flows of the Nile: the average natural flow is 84 km3/yr (for the period 1901-1950) and the number was used in the design of the High Aswan Dam (HAD) and to establish a treaty between Egypt and Sudan in 1959 allocating 55.5 km3/yr to Egypt and 18.5 km3/yr to Sudan while the remaining 10 km3/yr are considered to be lost to Evaporation from lake Nasser which was formed after the construction of the HAD - check (Abu-Zeid and El- Shibini, 1997).
We've included this reference and these statements. However, we've not taken out the Molden publication which is claiming such a debate. The objective of this section was not to dispute these numbers, but to provide a short overview of the scientific literature.

L18: The model will not "combine" supply and demand, it will rather simulate the allocation of supplies to demands according to the given rules and constraints - please rephrase.
Adjusted.

P4385
L11: Iran is not an Arab country - but it is still in the Mashreq region of MENA - rephrase to remove the confusion
Corrected.

L16: in search "for" instead of "of"
Corrected.

L29: do you consider "springs" as surface water sources?
This is a reference to FAO (2006) who indeed consider springs as surface water source. Clarified in the text.

P4389
L21-22: There are some problems with Hydro1K datasets in flat areas like the Sudd Swamps in Sudan - these limitations should be noted especially that the MENA region has large flat areas.
We've included a statement on this potential error.

P4390
L5: define what you mean by "crop factors"
Defined in the manuscript.

L11: was the "formal accuracy assessment" part of the current study? If so then report on the results, if not refer to the study.
Reference added.

P4392
L18: the scenario with the largest emissions is A1FI not A2 - refer to IPC SRES report.
Corrected and reference included.

L21: explain why you selected the "9" best performing scenarios - there is a large debate on the definition of "best" which needs to be referred to
Clarified and reference added.

L24: A short paragraph on the downscaling method is required in addition to the mentioned references
Paragraph included and additional reference added.

P4393

Model Validation: I do not see that validating using long-term average discharge is sufficient at all. This only takes care of the water balance and ignores both seasonal and inter-annual variability which are very important aspects of the assessment and puts the whole approach in jeopardy. Why waste effort coupling a hydrological model (using a daily time step) to a water allocation model (using a monthly time step) and then validate that model using long-term average flows? I understand there are always data limitations but seasonal patterns from available data can still be used to provide better validation!

We realize that our study does not follow a classical approach by only trying to mimic historic observations. We've included additional references to the model and its performance. Moreover, we've discussed in the manuscript that a daily model is still required: (i) annual flows would not be correct, (ii) daily projections are needed for the analysis of the future.

L9-13: please discuss more the issues of relative and absolute model accuracy and show some evidence - the statements given is speculative.

We've added two additional references to support this statement.

Fig. 5: flow stations need to be mentioned along with river names - e.g. White Nile appears three times! Black and White Volta do not contribute to the water resources of MENA, explain why they are included in the calibration/validation

Figure is adjusted and discussion on Volta is added.

L13-22: I do not see a good match for the Nile neither the Blue nor the White - note that you are only comparing long term averages and if the model cannot get a very close match, then it casts doubts on its performance in terms of seasonal and inter-annual variability. There are many good models of the Blue Nile and the Atbara and they are not difficult to model (e.g. (Conway, 1993) and (Elshamy, 2008))

Important for the study was to have one similar approach for the entire MENA region to avoid study outcomes depending on model differences. We've included your recommendations in the manuscript.

L15: non-calibrated model results are not shown

A whole section on model performance, before and after model fine-tuning were included. In fact, model calibration was done in previous studies of the PCR-GLOBWB. We've added additional references and have change the incorrect wording of "calibration" to "model performance".

L24-27: EL-EKhsase lies on the main Nile in Egypt upstream the delta. Therefore irrigation abstractions in the delta will not affect its flows as mentioned. There are of -course abstractions along the Nile from Khartoum to El-Ekhsase in Sudan and Egypt. Moreover, if Geizera scheme is not completely included then it will affect the Blue Nile flows at Khartoum and the main Nile downstream while the authors claim that the simulation of the Blue Nile is very good - this is inconsistent. There are other smaller schemes in Sudan (e.g. Rahad). Contact Nile Basin Initiative for information.

Thanks for these detailed insights. Based on this knowledge combined with NBI information we have updated this section in the manuscript.

P4394

L1-3: The Sudd wetland losses should affect the White Nile - another contradiction with the previous statement that the model performance is very good for the Nile.

See previous point: adjusted in the manuscript.

P4395

L25: The authors mentioned a significant decline in groundwater recharge (P4394 L17) while here it is mentioned that groundwater supply shows a slight decrease despite the increase in demand. Please explain.

Groundwater plays a smaller role compared to surface water. So a significant decline in groundwater only, plays a relatively minor role in total water supply. We've made this clearer in the manuscript.

L27: It is not logical (as stated) that urban and industrial demands are not affected by climate change - temperature increase will affect those demands. Industrial demands include cooling water requirements and domestic demands include bathing to overcome heat stress.
We've modified this in the manuscript and indicated that these affects are likely but will be minor compared to other impacts.

P4396
L15-16: water shortage does not depend only on observed precipitation and temperature but also on demand parameters like population, consumption rates, etc.
This sentence is not complete as all these components are included in the study. The only issue we wanted to raise is that these numbers are based on observations and not on climate projections. Adjusted in the manuscript.

P4397
L4: better rephrase "contribution of merely climate change" to "contribution of climate change alone"
Adjusted.

L13: explain why demands are less under wet projections
Explained in the text: more precipitation.

P4398
L23: It is not clear what you mean by "the desired required accuracy of projections"
It is not our statement but a quote from the given reference. We've further explained this in the manuscript.

P4399
L2-3: Explain why the increase in unmet demand is related to hydrological non-linearity. In my opinion it is related to the amount of unmet demand currently (which is relatively small compared to the future and thus diving a large number by a small one gives a large ratio)
This is exactly what we meant by non-linearity. We've used your wording to clarify this in the manuscript.

L13-23: relate the results obtained in this study to those presented from earlier studied mentioned.
Included.

L18: add "EACC" after the study name such that it is clear when the abbreviation is used later
Included.

References
Abu-Zeid, M. and El-Shibini, F.Z., 1997. Egypt's High Aswan Dam. Water Resources Development, 13(2): 209-217.
Conway, D., 1993. The development of a grid-based hydrological model of the Blue Nile and the sensitivity of Nile river discharge to climate change, University of East Anglia.
Elshamy, M.E., 2008. Assessing the Hydrological Performance of the Nile Forecast System in Long Term Simulations. Nile Water Science & Engineering Magazine, 1: 22-36.

Anonymous Referee #2

General comments:
The work by Droogers et al. is an interesting study that aims to estimate the water shortage in the MENA region in 2050 as a result of a combination of climate change and other socio-economical factors. It is a very well written paper and deals with a very interesting research topic for the region. The manuscript could be enhanced by adding some more detail results on the validation of the hydrological model for this arid region. Specific comments:
I would like to start thanking you for spending time on reviewing this manuscript. We acknowledge the fact that you see this paper as "*very well written paper and deals with a very interesting research topic for the region*". Detailed reply on your comments is provided here.

P 4382:
Line 9-11: "Results show that total demand in the region..." The demand (132 km3yr-1) is lower than the shortage (199 km3yr-1), is this right? It should probably say: "... will increase by 132 km3yr-1" (as it says in page 4395).
This was indeed wrongly stated as we combined "increased to" and "increased by". Corrected in the manuscript.

Line 22: Include also the average renewable water resources per capita value for SubSaharan Africa, as several countries of this region are included in your model.
information added to the manuscript.

P 4383:
Line 22: "The study argues..." is repeated in two consecutive sentences. Change one of them.
Changed.

P 4385: It could be interesting to include, if available, the percentage of the region under the physical water scarcity limit.
Percentage is not known as data is available per country. We've included this comment in the revised manuscript.

P 4386:
Line 24:"... the period 2001-2010 is based on actual data on climate and water requirements." - Which is the source of the data?
We've included an entire section on the source of the current data (section 2.3.8) and put additional references.

P 4387:
Line 4: "PCR-GLOBWB can be described as a conceptual, ... model" - In the abstract and in page 4386 says "an advanced physical based model", unify please.
We've unified wording in the revised manuscript.

Line 7: "with the main difference that PCR-GLOB..."- Unify, use always PCR-GLOBWB. This occurs in a lot of places over the manuscript, PCR-GLOBWB and PCR-GLOB are used alternately.
Modified throughout the entire document.

Line 17: "This resolution is the optimum tradeoff between required detail for hydrological processes, data availability and calculation times."- Why? Include citation to previous study or defend the statement.
Citations included to confirm this statement.

P 4390:
There is no mention here nor in the description of the model (P 4387) to the input meteorological forcing data required by the model. Which data is used for the period 2001-2010? Which is the temporal and

spatial resolution of the precipitation and potential evaporation inputted?
We've included an entire section on the source of the current data (section 2.3.8) and put additional references.

P 4391:
Line 1: "Center of for International..." - Delete the "of".
Corrected.

Line 2: It refers to Colombia University, it should say Columbia.
Corrected.

Line 22: Verify that the reference is correct (I didn't found the equation in the reference).
Equitation is indeed not in reference, but this equation was used in getting results as presented in the reference. Added this into the manuscript.

Line 23: 1) Numerate the equation - (1). 2) Check the formulation of the equation. It seems to me that the "-1" should be subscript, as: IWWy-1
Equation numbering is part of editing and removed by HESS layouting. -1 should be indeed a subscript. Corrected in the manuscript.

Line 25: "where IWW is the industrial water withdrawal" - Change for: where IWWy is the industrial water withdrawal of the year y.
Adjusted.

Line 26: Change "doesn't" for "does not".
Corrected.

P 4392:
Line 21: Why nine? Explain.
Nine models were selected as a treat-off between including sufficient variation and having conceivable calculation times. Selection was based on the performance as described by Shongwe. This has been explained in the manuscript.

P 4393:
Line 1: The model performs well globally, but what about in Africa and especially in dry areas?
We realize that our study does not follow a classical approach by only trying to mimic historic observations. We've included additional references to the model and its performance, including in dry areas.

Lines 7- 9: I understand the point, but in page 4384 it is stated that one of the issues with previous studies is that they are based on annual or monthly approaches rather than the required daily approach to capture hydrological processes. It is argued that this study addresses those issues. What is the point in making a daily hydrological model if at the end the long term average hydrology is validated?
This is a very relevant comment, but we're convinced that in order to get monthly flows correctly, the daily hydrological processes have to be captured. We've included this more clearly in the manuscript that a daily model is still required: (i) annual flows would not be correct, (ii) daily flow projections are needed for the analysis of the future.

Lines 13-15: I do not agree that the there is a very good match between observed and simulated flow in every case. In the Blue and White Nile the match is not so good, especially considering that the long term average hydrology is being compared.
We've expanded the discussion on model performance and have put in additional statistics . At the same time we realize that our study does not follow a classical approach by only trying to

mimic historic observations by a model. We've included additional references to the model and its performance.

P 4394:
Lines 19-22: This statement is right. However, if the whole same study was carried out for Eastern Africa, the water resources availability for the region (which is considered external in your study) could decrease. Here you are assuming that the change (increase) of external water resources availability is only related with climate change, but it could decrease due to the contribution of population growth other socio-economical factors in Ethiopia (for the Nile) and other regions.
This is a correct observation and we have included this in the discussion. At the same time, changes in abstraction for irrigation, the major consumer, are included in our analysis.

P 4395:
Line 25: Why the groundwater supply shows only a small decrease? It says before in page 4395 Line 4, that "Groundwater recharge shows a very sharp decrease in almost all countries".
Groundwater plays a smaller role compared to surface water. So a significant decline in groundwater only, plays a relatively minor role in total water supply. We've made this clearer in the manuscript.

P 4396:
Line 26: "An increase in water shortages is projected for all countries." - Add: with the exception of Djibouti.
Added.

P 4397:
Lines 5-7: Another way to do it, which seems more straight forwards to me, is to assume that socio-economic changes would remain similar to current conditions, but climate change would occur as expected. Was this evaluated? Why you decide it to do it the opposite way? Explain.
Probably results would have been only slightly different given non-linearity in hydrological processes, but the overall message remains the same. The reason to consider a constant climate is to support de on-going policy discussions on compensating developing countries for the climate component only, so looking at total expected changes minus socio-economic changes.

Line 14: Rephrase sentence starting with: "Table 1... "
Rephrased

P 4398: Line 13: It has been validated in arid areas also?
Additional references have been added 3.1 to support this statement.