Hydrol. Earth Syst. Sci. Discuss.,
doi:10.5194/hess-2016-41-AC2, 2016

Hydrology and Earth System Sciences
Open Access
Discussions

Interactive comment on "Projected impacts of climate change on hydropower potential in China" *by* Xingcai Liu et al.

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Received and published: 3 May 2016

We are grateful for the thoughtful comments from the reviewer. We write responses to all comments point-by-point as provided below.

General comments
The authors projected Gross Hydropower Potential (GHP) and Developed Hydropower Potential (DHP) of China using the global runoff dataset developed by the ISI-MIP project. The dataset includes global gridded runoff field simulated by 8 global hydrological models for 5 climate models and 2 emission scenarios. They analyzed the spatial and temporal distribution of changes in GHP and DHP in China. Although hydropower is a fundamental source of energy, analyses utilizing macro scale hydrological model have been seldom reported. This report has potential to advance this research field.

As is commonly seen in macro scale hydrological simulations, this study is based on several strong assumptions. I have not been fully convinced by the validity of some of these assumptions. This is partly due to the assumptions themselves, but largely due to lack of discussion. Details are noted below.
First, overall discussion on the background mechanism for the results is lacking. The results the authors obtained are well presented, but why and how they were obtained is little described. The Discussion Section should be largely expanded to include the mechanisms. Second, the term (and the model) of DHP should be revisited. What does "developed potential" mean? Which is more close to hydropower generation or technical hydropower potential? If DHP is different from any important indicators in the real world, how should we interpret the results? Without clarification of DHP, it is not clear what was calculated and what for. Third, the quality in runoff field of ISI-MIP should be well discussed. Since the global hydrological models participated in ISI-MIP have not been calibrated except the WaterGAP model, it must be carefully discussed that how the biases in runoff propagate to the results. Fourth, as far as I understood, the authors assigned the national total Installed Hydropower Capacity (IHC) into 447 major reservoirs. Since this might significantly overestimate IHC at individual reservoirs, the validity of this treatment should be validated and discussed. It might be a good idea to start with comparing reported installed hydropower capacity at individual reservoirs with the authors' estimation.
Response: Thanks for the suggestions and comments.
(1) We have extended the description of methods in the sections 2.2 and 2.3 and the Discussion on the interpretation of the results in the revised manuscript (please also refer to the question on Page 11 Line 22).
(2) We have further clarified the term of DHP in the revised manuscript. DHP in this study refers to hydropower potential at the developed plants. The changes of potential of hydropower generation are usually determined by streamflow and hydropower capacity (Lehner et al., 2005). Since we could not predict the development of hydropower technology and capacity, we only present the changes in DHP resulted from

the streamflow variation. We assessed *hydropower potential* in this study generally to highlight the necessity of considering the impact of climate change in hydropower development and planning in China.

(3) We agree that the non-calibrated model data may result in considerable biases in the GHP/DHP estimates. In the revised manuscript, we have extended discussion on the uncertainty of GCM and GHM models to remind the readers of the possible biases and the importance of calibration to the models. Note that we did not use WaterGAP model in this study because the WaterGAP model did not provide daily runoff, which was used for GHP estimation. We have added a brief discussion on the current state of the global hydrological models and the calibrated model such as WaterGAP may show better agreement in the historical period.

(4) We agree with the reviewer that it could be a source of uncertainty and we actually address it. We obtained IHC data at provincial level in China and assigned the IHC values to individual reservoir at each province. We have compared the adjusted IHC with the reported values at some reservoirs and briefly discussed the potential errors in the assignment of IHC values in the manuscript in section 2.3. The adjusted IHCs correspond well to the reported values for the reservoirs that storage capacity is highly related to hydropower capacity; e.g., the relative error is less than 1% for the adjusted IHC of the Three Gorge Reservoir, but is more than 50% for the Gezhouba hydropower station. In the supplemental material, two experiments with different IHC values were performed to show the sensitivity of DHP estimates to the deviation of IHC (Figure S14). Collection and validation of the IHC of individual reservoirs should be important to reduce uncertainty in the DHP estimates in the future work. We now highlight early, in the description of the setup, how this source of uncertainty is addressed later in the discussion and the supplemental material. The discussion already refers to this supplemental material.

Lehner, B., Czisch, G., and Vassolo, S.: The impact of global change on the hydropower potential of Europe: a model-based analysis, Energy Policy, 33, 839-855, 10.1016/j.enpol.2003.10.018, 2005.

Specific comments

Page 6 Line 7," DHP = min (Rm x h x g, IHC)": I found that this equation primarily expresses hydropower generation. Why was this termed "Developed Hydropower Potential", not hydropower generation? If DHP is not hydropower generation, then what is this correspond to in the reality?

Response: We emphasized that DHP is a potential because actual hydropower generation is affected by more than discharge and IHC, i.e. energy demand, electricity price, environmental discharge not going through the turbines, etc. It therefore could not correspond to a hydropower production in the actual operations.

Page 6 Line 8 "h=S/A": Fekete et al. (2010) expressed reservoirs as tetrahedrons in their model. What are the advantage and disadvantage of the authors' expression (cylinder)?

Response: The cylinder is a simple assumption. It means that in our analysis, we have a linear decrease in head as the reservoir volume decreases. In Fekete et al. (2010), the change in head is slower at first when volume decreases. Based on those simple assumptions, it means that for small to medium changes in inflow, our modeling framework will detect larger changes in DHP than Fekete et al. Beyond an unspecified threshold in decrease in inflow, which will vary for each reservoir, Fekete et al. assumption will be more aggressive and non-linear on the estimate of changes in DHP. The tetrahedrons may be a better approximation for the reservoirs located at the rivers with high stream gradients. It is beyond the scope of this analysis to quantify this uncertainty but we added this discussion in the Discussion section and highlight the differences in DHP assessed in this analysis and in other papers (e.g. van Vliet et al. 2016).

van Vliet, M. T. H., Wiberg, D., Leduc, S., and Riahi, K.: Power-generation system vulnerability and adaptation to changes in climate and water resources, Nature Clim. Change, 6, 375-380, 10.1038/nclimate2903, 2016.

Page 6 line 15 "no IHC data associated with the GRanD reservoirs" World Register of Dam by International Commission of Large Dams (http://www.icold-cigb.org/) includes

Electric Capacity of individual dams.
Response: Thank you for the information. IHC is missing in many reservoir entries in the ICOLD database. We added the following statement. "Despite World Register of Dam by International Commission of Large Dams (http://www.icold-cigb.org/) includes Electric Capacity of individual dams, many reservoir entries are missing. Therefore, we used the following approach to represent the IHC at our aggregated reservoirs.

Page 6 line 18 "Then the adjusted provincial IHC. . ." As far as I understand, this study deals with storage and discharge for 447 reservoirs in China, while IHC for all the nation. This discrepancy could make Rm x h x g substantially smaller than IHC, hence it may have influenced the results. This point should be clarified here.
Response: We assigned IHC of provinces (not the nation) to each reservoir according to the storage. The IHC data was collected before 2004, which is close to the GranD database. We have checked that many large reservoirs built in 21st century were not included in the GRanD database. The assignment definitely may bring biases to the DHP estimation (not necessarily smaller than IHC). The experiments with 0.9*IHC and 1.1*IHC should be helpful for addressing the uncertainty resulted from the IHC assignment, and we have further clarified it in the revised manuscript.

Page 11 Line 22. I got a general impression that the Discussion Section is superficial. Since the Results Section only introduces the numbers that authors obtained, actually I expected detailed discussion on the background mechanisms of model behaviors and interpretation of the results, but these are seldom provided in the current form of the manuscript. The contents of this section should be substantially added.
Response: Thanks for the suggestion. We have extended the Discussion section in the revised manuscript. The hydropower potential in this study was assessed based on multimodel simulations of runoff and discharge under different climate change scenarios. The assessment of hydropower potential changes is based on the linkages of climate, streamflow and hydropower. Therefore, the projection of streamflow by the GCM-GHM combinations will directly affect the estimation of hydropower potential.

Though the ensemble mean of projected GHP of China for the historical period is relatively close to the reported data, there is large discrepancy among GHMs. During the historical period, discrepancy in hydropower potential is much smaller among GCMs because the GCM climate data is bias-corrected to a historical reference. It implies that validation or bias-correction may be helpful to reduce the uncertainty in the projections of GHMs. However, the GCM uncertainty predominates future GHP changes at most areas in China.
The uncertainty in the streamflow projections also propagate to the estimation of DHP. Though a universal reservoir regulation is applied to all modeled discharge, there is still a large spread across GCM-GHM combinations. The large uncertainty in DHP should be mainly due to the large discrepancy of GCM climate data since the reservoirs used in this study are mostly located in areas with low model agreements in future discharge projections (see Figure 1 in Schewe et al., 2014). This also partly explains why the total DHP (Figure 5) shows larger spread than total GHP (Figure 3) of China.

Schewe, J. et al., 2014. Multimodel assessment of water scarcity under climate change. Proc. Nat. Acad. Sci. U.S.A., 111(9): 3245-3250. DOI:10.1073/pnas.1222460110

Page 12 Line 10 "most regions show poor agreement between models": In terms of what? Magnitude or signs? What are the results of the WaterGAP model or the only model with calibration?
Response: The agreement here means signs of the GHP changes. We specified it in the statement. We did not use the WaterGAP model in this study because the WaterGAP model did not provide daily runoff, which was used to estimate the GHP in a routing model at daily step.

Page 13 Line 19 "Thus, reservoir regulation could be changed in the future to adapt to climate change": Too superficial and abstract. How should it be changed based on the findings of this study?
Response: We agree with the reviewer. Reservoir regulation rules are related to reser-

voir functions. In this study, we treated all dams as hydropower stations rather than multi-objective reservoirs. Increase of reservoir release or retain a high water level may produce more DHP. Therefore, DHP could be maximized by adjusting the monthly release, e.g. retaining a high water level seems to be easier to obtain high DHP in the dry season (see Figure S12, where β can adjust the proportions of monthly and annual inflow for monthly release). However, considering various competitive water uses, reservoir regulation is optimized for multiple objectives rather than for DHP only. Adaptation of operational reservoir operations to climate change is more complex. We have rewritten this sentence carefully to clarify the findings of this study in the revised manuscript.

Page 15 Line 5 "Relatively small changes also will occur in late spring and early summer, while large decreases will occur in other months". Why did these happen in your simulations? Basic mechanisms should be mentioned here. For instance, DHP is a function of monthly discharge (Rm) and water level (h). Which is dominant factor to produce the seasonal variation?
Response: Thanks for the suggestion. We agree with the reviewer that it would be interesting to isolate the drivers of change in DHP. Voisin et al. (2013) describes how generic operating rules affect the reservoir storage, which highlights how monthly release and water level are linked. For the specific release used in this paper (mean annual flow), a large storage capacity reservoir will react to changes in annual mean flow by decreasing its ability to fill, the head will decrease and DHP will decrease. Conversely an increase in flow will top the reservoir during certain years, increase the DHP until reaching a plateau due to the reservoir maximum capacity and induced spilling. Change in the seasonality of the flow will affect the speed at which the reservoir can fill in the Spring, therefore affecting the head. DHP production in Summer are also affected by the level of the reservoir storage on the month when the natural monthly flow is smaller than the mean annual flow (start of the operation season, see Haddeland et al. 2006 and Hanasaki et al. 2006) (see Equation 1). This additional component, which mimics the inter-annual variability in release and operations, will be impacted

by a change in inflow seasonality, possibly affecting the DHP at end of the summer. Drivers in seasonal changes in DHP vary by reservoirs and will overall depends heavily on the simplified representation of reservoir operations. The current assessment also assumes no change in reservoir operations (no adaptation) which affects the seasonal change in DHP. We have added some explanation for the result in the revised manuscript accordingly.

Voisin, N., Li, H., Ward, D., Huang, M., Wigmosta, M. and Leung, L. R. (2013) On an improved sub-regional water resources management representation for integration into earth system models. Hydrol. Earth Syst. Sci., 17(9): 3605-3622.

Page 15 Line 10 "DHPs given the current infrastructure will not be able to mitigate the hydrological changes and thus will decrease": Why and how did the authors conclude this? Would this conclusion be different if the authors modified the reservoir operation rules? Actually, the authors have conducted an elaborate sensitivity test on the parameters of operation. Some of the combination might have worked as "adaptation" to climate change.
Response: Thanks for the suggestion. We rewrote this sentence carefully in the revised manuscript. The sensitivity tests to some degree can be regarded as "adaptations" to climate change by modifying regulation coefficients, and this may alter the changes of the hydropower potential of current reservoirs. It should be noted that we do not consider other reservoir purposes in the present study (regulation for irrigation, domestic or other sectorial supply), which may increase competitive water use and then further reduce hydropower generation.

Figure 1: The figure doesn't have legend. It should be displayed what the height of bars quantitatively indicates.
Response: Thanks for the suggestion. The bars and texts at the lower left corner of the figure are the legend. We redrew the figure to make it more readable in the revised manuscript.

Figure 5: Specify the base period of these two figures. I'm a bit curious why the plots start form -4% at 2010 (largest change) and gradually "recover" toward 2100 (smallest change) for RCP8.5.

Response: The base period of these two figures is 1971-2000. The plots show the temporal changes from 2010-2084, which are 31-year moving averages of the original time serials, e.g. the data of 2010 is the mean value of 1995-2025. For a clear view, we did not show the moving averages of the 1985-2009 period. The discharge is projected to decrease in most areas China during the 2020-2050 period, and significantly recover in some areas during the 2070-2099 period (see Figure S2). The variation of discharge largely affects the DHP variability, however, there are few reservoirs located in the areas with large increase of discharge in the 2070-2099 period and the reservoir regulation may offset the effects of discharge variation to some degree. Therefore, the projected changes of DHP of China would not always coincide with those of discharge. It is not very exact that DHP change recovers toward 2100, but the annual DHP change definitely shows less decrease after 2040 and reach about -1% at late 21st century under RCP2.6.

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