Response to the comments on the manuscript (**HESSD-2019-278**) "**Basin-scale multi-objective simulation-optimization modeling for conjunctive use of surface water and groundwater in northwest China**" by Jian Song, Yun Yang, Xiaomin Sun, Jin Lin, Ming Wu, Jianfeng Wu, and Jichun Wu

Note that the following text in Arial Narrow font denotes Referee's comments and in Times New Roman font denotes our response to the comments in the discussion. In our resubmission, the marked PDF file (HESSD-2019-278-Marked.pdf) has clearly indicated all changes to the original manuscript, tables and figures. Also, in the PDF file, marked in ~~a green strikethrough font~~ is the text that should be removed from the original manuscript and marked in a red font is the text that has been added to the revision. In addition, Line number(s) mentioned below can be referred to as that line numbering in the marked revised manuscript.

Response to Referee Dr. Joseph Kasprzyk's Comments

I am serving as a requested referee for this manuscript. The paper presents a new optimization algorithm, linked to hydrological models for the purpose of informing water management in China. Overall, the paper does provide an interesting case study. However, the authors could do a better job of contextualizing their work relative to the state-of-the-art literature in this field, summarized in my general comments below. I also provide specific comments referencing lines in the manuscript itself.

[Response] We appreciate Dr. Joseph Kasprzyk's insightful comments and constructive suggestions. We have fully addressed his concerns into the revised manuscript and given a point-by-point response as below.

General comments:

I. The need for a new MOEA should be justified. Moreover, since MOEAs are typically designed for general case studies outside of water management, the authors should indicate whether the new algorithm is available for use.

[Response] Indeed, several state-of-the-art MOEAs (*e.g.*, ε-NSGAII (Kollat et al., 2006), MOEA/D (Zhang and Li, 2007), NSGAIII (Deb and Jain, 2014), Borg (Hadka and Reed, 2013), etc.) have been tested on the standard test problems even on the real-world problems and achieved the promising results in solving many-objective problem. However, due to the diversity and complexity of real-word decision-making problems, efforts should be made to develop the advanced MOEAs (**Lines 127-134**). Moreover, the aim of our research is to

construct an effective many-objective optimization framework for water resources management in arid inland basin rather than implement comparative study of the state-of-the art MOEAs to justify the optimality of the algorithm.

Certainly, we acknowledge that the performance of ε-MOMA has to be tested to prove the availability for general case studies. Considering the reviewer's concerns, we have investigated the performance of ε-MOMA by the benchmark test problems in **Section 2.2.2** (*i.e.*, 3 to 6-objective DTLZ1 and DTLZ3 problems) (Deb et al., 2002). Results show that ε-MOMA can provide reliable and diverse Pareto-optimal solutions in addressing many-objective optimization problems (**Table S1** in the **Supplementary Materials**). Meanwhile, the case study further shows the potential of ε-MOMA for the real-world water resources management.

Deb, K., Jain, H.: An evolutionary many-objective optimization algorithm using reference-point-based nondominated sorting approach, Part I: solving problems with box constraints, IEEE Trans., 18(4), 577-601, https://doi.org/10.1109/TEVC.2013.2281535, 2014.

Deb, K., Thiele, L., Laumanns, M., Zitzler, E.: Scalable multi-objective optimization test problems, in: proceeding of the congress on evolutionary computation (CEC-2002), 825-830, 2002.

Hadka, D., and Reed, P.M.: Borg: an auto-adaptive many-objective framework, Evol. Comput, 21(2), 213-259, https://doi.org/10.1162/EVCO_a_00075, 2013.

Kollat, J. B., Reed, P. M.: Comparing state-of-the-art evolutionary multi-objective algorithms for long-term groundwater monitoring design, Adv. Water Resour., 29(6), 792-807, 2006.

Zhang, Q., Li, H.: MOEA/D: A multiobjective evolutionary algorithm based on decomposition, IEEE Trans. Evol. Comput., 11(6), 712-731, https://doi.org/10.1109/TEVC.2007.892759, 2007.

II. I would like to see more description of the optimization in general, since the calibration of hydrological models is not really the focus of the analysis.

[Response] Comment accepted. We have made detailed explanations to present the algorithmic process step by step in **Section 2.2.1**. The hydrological model, as a prerequisite for the simulation-optimization method, has to be calibrated to reflect the responses of water resources system under the management schemes. Considering the referee's concern, we have briefly stated the calibrated results of key state variables in **Section 3.2** and put the results in the **Supplementary Materials** as shown in **Fig. S1**. Moreover, the analysis of water balance in Bosten Lake paves the way for the construction of management model.

III. The results should be generalizable to a broader context. What are the take-home messages for the HESS audience? This is hinted at in the Conclusion, but could be better motivated in the Introduction.

[Response] The point is well taken. The study results show that Pareto-optimal solutions considering environmental and socioeconomic factors can be achieved for the basin-scale water resources management involving complicated groundwater-river-lake interactions. Meanwhile, due to the water scarcity and climate change, the conservative water management options may be implemented to sustain the fragile ecosystem in the arid inland basin. Considering reviewer's concerns, we have added necessary explanations in the section "Introduction" to present the motivation (**Lines 53-57**) and the general results (**Lines 198-204**).

Specific comments, where line numbers refer to the PDF version of the HESSD paper:

1. The authors should consider editing lines 25-29 to clarify the novelty of the paper. A study of one basin in China may not be compelling to an international audience, so if there is something new about the coupling of optimization to model, that should be highlighted. The same comment is relevant for the introduction; the scientific contribution of the paper is not sufficiently stated.

[Response] Comment accepted. We appreciate the reviewer's insight and have modified the statement in Abstract (**Lines 24-33**) and the section "Introduction" (**Lines 177-183**) in the revised manuscript to clearly present the contribution of the study.

2. line 48: There are several grammatical errors in the beginning of the paper ("In arid and semi-arid basin,") as well as a disconnect between talking about water management in general and moving quickly to the specifics of China. A native English speaker should proofread the manuscript throughout.

[Response] Comment accepted. We have modified the statements (**Line 53**). To avoid the disconnect raised by the referee, we have reorganized the statements in the Introduction. Firstly, we have clarified the need for water management in the arid inland basin (**Lines 53-65**); Second, we explained the meaning of many-objective optimization framework in the water resources management and planning (**Lines 81-110**) and the optimization techniques (**Lines 111-139**). After that, we introduced the specifics of water resources development in Yanqi Basin (**Lines 145-161)** to explain the suitability of the case study. As for the language problem, a native English speaker is difficult for us to find. However, in the revised manuscript, one of the co-authors who ever worked as a visiting scholar in the USA for several years has made extra efforts in current revision to correct the grammatical and wording errors.

3. line 73-74: "to tackle intricate SW and GW management model": Is this a typo? I think the intended word might be "SW and GW management problems". Also "tackle" is probably not an appropriate word to use.

[Response] Comment accepted and change made **(Lines 90-94**).

4. line 77: Before the first mention of "bi-objectives", the authors should provide a very brief introduction to optimization. Otherwise, readers may be confused by what is meant by "objective" throughout this paragraph.

[Response] The point is well taken. We have added necessary explanations to briefly introduce the process of simulation-optimization approach (**Lines 83-87**).

5. When introducing MOEAs, it would be good to cite Maier et al (2019), which is an introductory overview appropriate for readers to be introduced to the topic.

[Response] Comment accepted and change made as suggested (**Lines 113-114**).

6. lines 102-113: I am glad the authors have brought up some recent and relevant topics in many-objective optimization. However, the paragraph was confusing and will be difficult for readers to follow. For example, the Borg algorithm is briefly mentioned, but there is no clear transition to the next algorithm ("In order to enhance the local optimality..."). Did Sindya et al. add to Borg or create a new algorithm? Moreover, it is unclear whether the authors made a new algorithm, and whether it builds on the work of Hadka and Reed and Sindhya. Moreover, given that these new algorithms have been extensively tested (e.g., Reed et al 2013), it is worth justifying why a new algorithm is needed.

[Response] In the revised manuscript, we have firstly stated the difficulty in the many-objective optimization (*i.e.*, the domination-resistance phenomenon) (**Lines 114-117**). Then we presented two kinds of state-of-art MOEAs by which an attempt to alleviate the difficulty is feasible (**Lines 117-127**). Finally, we proposed a new MOEA, named epsilon multi-objective memetic algorithm (ε-MOMA), which utilized several advanced techniques from Borg and a local search operator to enhance the capacity of evolutionary search.

Sindya et al. (2013) proposed a hybrid framework for evolutionary multi-objective optimization and overcame some shortcomings of MOEAs (*e.g.*, slow convergence, inefficient termination criterion, etc.). In this study, we cited the work of Sindya et al. (2013) to show the efficiency of the hybrid framework (*i.e.*, memetic algorithm) for multi-objective optimization.

As stated in **Lines 127-134**, the state-of-the-art MOEAs have been extensively used in the optimization problems, however, the complex real-world problems still show the deficiency of some advanced MOEAs. For example, Zheng et al. (2016) implemented the comparison of three MOEAs (NSGAII, SAMODE, Borg) in the water distribution system design. Results show NSGAII exhibits a more robust performance than other MOEAs. Borg converges quickly to the Pareto-optimal front whereas decreases the diversity of Pareto solutions.

As stated in the response to **General Comment I** above raised by the referee, this study has supplementarily exploited classical DTLZ problems to test the performance of ε-MOMA in

Section 2.2.2. The optimization results show the potential of our algorithm (**Table S1** in **Supplementary Materials**) and it can be applied to solve basin-scale water resources management. Certainty, the performance of the algorithm needs to be validated on the challenging real-world problems, that's our focus in the future.

Sindhya, K., Miettinen, K., Deb, K.: A hybrid framework for evolutionary multi-objective optimization, IEEE Trans., 17(4), 485-511, https://doi.org/10.1109/TEVC.2012.2204403, 2013.

Zheng, F., Zecchin, A.C., Maier, H.R., Simpson, A.R.: Comparison of the searching behavior of NSGA-II, SAMODE, and Borg MOEAs applied to water distribution system design problems, J. Water Resour. Plann. Manage., 142(7), 04016017, https://doi.org/10.1061/(ASCE)WR.1943-5452.0000650, 2016.

7. line 114: The section would benefit from a better transition between the MOEA material and the GW modeling material. Also, since the GW modeling is being done in the context of decision making, I would like to see a clearer discussion of the decision variables and objectives of the optimization as the problem is being introduced.

[Response] Comment accepted. We have made revisions in the paragraph to highlight the details of optimization model (**Lines 172-177**) and deleted the redundant statements of simulation model **(Lines 161-172)**.

8. line 125: Ideally, a paragraph would express one idea at a time. Here, the authors have transitioned from discussing their method to providing details about their case study. This material should be separated.

[Response] Comment accepted and change made as suggested **(Lines 184-185)**.

9. line 168-169: What is meant by "decision makers" here? In many systems, different people make decisions about the irrigation diversions, lake storage, and groundwater pumping. Without a clear context for decision making, this section is too vague.

[Response] In **Section 2.1**, our purpose is to state the general problem formulation for conjunctive management of surface water and groundwater in the arid inland basin. The decision makers in this study refer to the local water resources authority in the local government. Considering the referee's concerns, we have made necessary revisions for the context of decision making in the revised manuscript (**Lines 230-232**).

10. line 179-186: There is some repetition here compared to the introduction. Although I agree with the points about nonlinearity, nonconvexity, etc., it is more useful at this point in the paper to explain the details of the proposed new algorithm.

[Response] Comment accepted. To clearly state the algorithmic process and investigate the performance of the algorithm, we split the section into **Section 2.2.1** "Main algorithmic structure" and **Section 2.2.2** "Benchmark test". In **Section 2.2.1**, we have deleted the repetition (**Lines 245-250**) and presented process of the proposed algorithm step by step (**Lines 252-290**).

11. Is this the first introduction of the e-MOMA algorithm? If not, it would be very helpful to have a citation to the original reference, since there is not enough detail given here. At the least, the authors should justify how their algorithm differs from Hadka and Reed, and others.

[Response] The ε-MOMA is a new MOEA and firstly applied to solve many-objective optimization problems. As stated in the response to specific **Comment #10** above, we have added the process of the algorithm step by step. The basic framework of ε-MOMA is similar to the traditional NSGAII with significant change in recombination operators and ε-dominance archive from Borg and a local search operator. Borg includes an adaptive population sizing operator that is not used in the proposed algorithm. The strategy adapts the population size in terms of archive size which is considered as a metric of complexity of problems. However, population size will be dramatically increased along with augmentation of archive size, which probably results in a large number of function evaluations. In simulation-optimization method, for CPU-intensive simulation model, this strategy may lead to unaffordable computational burden.

12. line 253: The discussion of the Ecological Water Conveyance Project is interesting. I'd like to see it integrated better within the text. Is this study supporting that analysis?

[Response] The point is well taken. In northwest China, Tarim River, the longest inland river in China, is a typical meandering river that sustains the fragile ecosystem in the basin. However, in the past decades, many tributaries of Tarim River have lost the surface hydraulic interaction with the main stream due to sharply increased water demands. Therefore, Tarim River basin has undergone serious ecological degradation (*e.g.*, land desertification) especially in the lower reaches of Tarim River. In order to restore "Green Corridor" in the lower reaches of Tarim River, Chinese government has implemented the water-conveyance project since 2000 to increase the recharge of groundwater system and raise the local groundwater levels. The project transferred water from Bosten Lake to the Daxihaizi Reservoir and then to the lower reaches of the Qiwenkur River, a large tributary of the Tarim River, and finally to the Taitema Lake (Chen et al., 2010; Yao et al., 2018). Considering the reviewer's concerns, we have added some necessary explanations in the revised text (**Lines 354-360**).

Chen, Y., Chen, Y., Xu, C., Ye, Z., Li, Z., Zhu, C., Ma, X.: Effects of ecological water conveyance on groundwater dynamics and riparian vegetation in the lower reaches of Tarim River, China, Hydrol. Process., 24, 170-177, https://doi.org/10.1002/hyp.7429, 2010.

Yao, J., Chen, Y., Zhao, Y., and Yu, X.: Hydro climatic changes of Lake Bosten in Northwest China during the last decades, Sci. Rep., 8, 9118, https://doi.org/10.1038/s41598-018-27466-2, 2018.

13. Equations 3-5: Why were different metrics used for different variables?

[Response] The Nash-Sutcliffe Efficiency (NSE) criterion is a popular method to evaluate model efficiency when the state variables change over time as showed in **Fig. S1a-S1c**. Root mean square error (RMSE) and correlation coefficient (R) are generally used to show goodness-of-fit of calculated and observed variables over the entire stress period as shown in **Fig. S1d**.

14. line 322-323: This statement should be justified. It speaks to the wider question of how the hydrological modeling is serving the ultimate goal of the management problem, as well as the general contribution of the paper itself. If the focus of the paper is too diffused, it becomes hard to follow its details.

[Response] In this study, we firstly built simulation model to evaluate the effect of water management practices on the water resources system. As stated in the revised manuscript (**Lines 423-429**), the water balance of Bosten Lake was calculated by the well-calibrated model and then we found the significance of surface runoff inflow to lake. Therefore, the surface runoff can be considered as the management objective. The analysis paves the way for construction of the management objective. Meanwhile, the contribution of the inflow from Kaidu River to Bosten Lake is close to the result from the previous work of Guo et al. (2015) and Yao et al. (2018).

Guo, M., Wu, W., Zhou, X., Chen, Y., and Li, J.: Investigate of the dramatic changes in lake level of the Bosten Lake in northwestern China, Theor Appl Climatol, 119, 341-351, https://doi.org/10.1007/s00704-014-1126-y, 2015.

Yao, J., Chen, Y., Zhao, Y., and Yu, X.: Hydro climatic changes of Lake Bosten in Northwest China during the last decades, Sci. Rep., 8, 9118, https://doi.org/10.1038/s41598-018-27466-2, 2018.

15. line 348: To what extent can the groundwater extraction rate be controlled? In some systems, farmers have juristiction on how much to pump. If there is an implicit assumption about a set of water managers who can dictate water usage, this should be stated.

[Response] The purpose of the study is to provide suggestions for water managers in local water resources authority. Indeed, some schemes in the Pareto-optimal solutions may be

unfeasible for the stakeholders due to the greater extent of regulation of the existing water management scheme. However, a significant advantage of multi-objective optimization is to provide diverse and alternative schemes. The water managers can select the suitable scheme among the Pareto-optimal solutions in terms of specific demands for water management practices. In the optimization, the range of decision variables is specified according to the potential of water use in the irrigation districts or diversion point recorded in the reports of local water resources authority.

16. lines, 353, 357, etc.: Is there a citation to the water price data? Or was this just an assumption?

[Response] The cost coefficients refer to the regulations of the local government. (http://www.xjyq.gov.cn/page.do?danwei=1&fenlei=4000&nian=2017&liushui=19&type=2)

17. line 406: Guidance on interpreting parallel plots should be provided.

[Response] Comment accepted and change made (**Lines 515-517**).

18. line 534: When the authors say "This study implemented...", were they implying that this occurred across the entire study? Or only in one part of the study? This should be clarified.

[Response] Comment accepted. The optimization in three runoff scenarios is the last part of the study to explore the effect of runoff change related to climate change on the water management practices in the basin. We have made some necessary revisions as the referee suggested (**Line 646**).

19. line 541-542: My impression is that hypervolume analyses are usually done to compare optimization runs with the true Pareto set. Is this known? In general, since the optimization seems to be the focus of this paper, items such as Hypervolume Analysis should be covered in the Methodology (which means that some hydrological modeling detail can be removed)

[Response] Comment accepted. For real-world optimization problems, it is computationally expensive to implement many trial runs for the reference Pareto set. In this study, we only calculate the volume of the objective space dominated by a Pareto approximate set (*i.e.*, HV_{as} defined in the **section 2.2.2**). The hypervolume indicator in the section is used to evaluate the optimality of Pareto solutions under different runoff scenarios rather than the convergence and diversity of our proposed algorithm. We have included the hypervolume analysis (**Lines 301-312**) based benchmark test and deleted the statements in the section (**Lines 653-657**).

20. line 546: "obvious" is usually not appropriate in technical writing.

[Response] Comment accepted. We have modified “obviously” as “clearly” (**Line 658**).

21. Conclusion section: The quality of writing here is much better than in the introduction. Some of this material should inform the Introduction, since this more clearly articulates the purpose of the study than the beginning of the paper did.

[Response] Comment accepted. We appreciate the reviewer's positive comment. We have added necessary statements in the Introduction (**Lines 55-57, Lines 177-180,** and **Lines 198-204**).

22. In spite of comment #21, I would like to see slightly more discussion about the management implications of this study – in the local case study as well as how the results can be transferred to other basins (especially given different legal and regulatory structures).

[Response] Comment accepted. We have added more discussion in the section "Conclusion" to present more implications (**Lines 714-719**).

23. Table 1: Was random seed analysis performed? If so, the parameters of this analysis should also be provided here. The epsilon values seem quite small – were larger epsilons attempted?

[Response] In this study, we didn't perform random seed trials and used the default setting in MATLAB for the rand number generation in which random seed is zero. We performed some optimization trials to select the epsilon value and results show the value in Table 1 is a good choice. As the epsilon value increases, it probably reduces the diversity of Pareto solutions.

24. Figure 4: If the paper is too long, I could imagine this figure could go into supplemental material. Also, I noticed that the NSE values appear in the figure but were not referenced in the text.

[Response] Comment accepted. We have presented Figure 4 in the supplemental file (**Fig. S1**). The NSE values have been added in the manuscript (**Lines 405-406**; **Line 422**).

25. Figure 9: If possible, the other solutions that are Pareto optimal in 4 dimensions but not in two, should be shown on this plot. Otherwise, the idea that the highlighted solutions fall "outside the front" will be confusing to readers. The Kollat and Reed (2007) paper referenced in this manuscript shows how to do this.

[Response] Comment accepted and change made (**Fig. 8**).

26. Figure 12: The figure would be easier to understand if the authors reminded reader what these scenarios represent (see also comment #18 – the scenario analysis could be better explained overall).

[Response] Comment accepted and change made (**Caption of Fig. 11**).

References

Maier, H.R., Razavi, S., Kapelan, Z., Matott, L.S., Kasprzyk, J., Tolson, B.A., 2019. Introductory overview: Optimization using evolutionary algorithms and other metaheuristics. Environmental Modelling & Software 114, 195–213. https://doi.org/10.1016/j.envsoft.2018.11.018.

Reed, P.M., Hadka, D., Herman, J.D., Kasprzyk, J.R., Kollat, J.B., 2013. Evolutionary Multiobjective Optimization in Water Resources: The Past, Present and Future. Advances in Water Resources 51, 438–456.

[Response] Comment accepted and these references have been cited in the revision.