Response to comments

Anonymous Referee #1

1) **The motivation is clear and focused, but links to broader literature are missing from the introduction. Is this the first time that multi-objective analysis has been applied to a water-energy-food nexus problem? The advantages of MOEAs over classical optimization approaches are discussed well, but more reference should be made to the implications of this approach for this particular type of problem.**

Author response:

To our knowledge this is only the second time this approach has been applied to such a problem – the first being our paper on the Jaguaribe Basin of Brazil cited earlier in the Introduction (Hurford et al., 2014). We propose to add and amend the following text in the second to last paragraph of the Introduction accordingly:

Original text – Introduction of proposed irrigation schemes in the Tana's delta provides a novel approach to investigating the impacts of different investment decisions – by assessing their impact on Pareto-optimal trade-offs.

Proposed text – The same approach was first applied with different objective functions to a water, energy and food (WEF) security problem and re-operation of dams in Brazil's Jaguaribe basin by Hurford et al. (2014). The novel contribution of this paper lies in investigating the impacts of different irrigation investment decisions alongside reservoir re-operation – by assessing irrigation investment impacts on Pareto-optimal trade-offs. The approach could augment conventional economic cost-benefit analysis for addressing WEF problems, which often involve multiple stakeholders. Considering multiple objectives helps consider wider aims such as equity and sustainability of future plans. Visualisation of the trade-offs between many objectives facilitates a more intuitive understanding of the cost-benefit (i.e. sacrifice-gain) relationships between them.

2) **The same goes for the conclusion. How does this improve on prior studies in the Tana Basin? Are there broader implications of using this approach for the field of water-energy problems?**

Author response:

In order to relate the points about comparing to previous work on the Tana and improvements of this approach, in addition to the broader implications, we propose to add the following text to the Conclusion:

This finding concurs with other work on the Tana basin suggesting implementation of large irrigation schemes would impact heavily on the delta's ecosystem services (Duvail et al., 2012). The visual trade-off analysis used here helps improve understanding and communication of the incremental impacts management and investment decisions have. This approach is appropriate for linked water, energy and food (WEF) systems where management and planning decisions imply a complex distribution of benefits between actors and sectors competing for resources. The approach simultaneously identifies a wide range of decisions which cannot be improved upon without decreasing some benefit, and visualises the outcomes for different stakeholders. Because the approach links integrated simulation models to a separate search algorithm there is potential to use this approach with a wide range of system simulators.

3) **The figure sequence is logically constructed and informative, but a bit long. It may be possible to combine several figures as subplots: - Figures 3 and 4 - Figures 5, 6, and 7 - Figures 12, 13, and 14 This would reduce the number of figures from 14 to 9. The suggested combinations are usually discussed in the same or adjacent paragraphs, so it should not alter the narrative at all.**

Author response:

Thank you; we propose to combine the figures suggested by the reviewer as subplots to reduce the length of the figure sequence.

4) **There is some confusion throughout about the term "Pareto-optimal". The authors note in Section 3.2 that these solutions are "only approximately Pareto-optimal", which is of course a requirement of black-box heuristic optimization – we don't know where the true "optimal" solutions are. This should be made clearer up front. For example in the abstract, replace "to identify the Pareto-optimal tradeoffs" with "to approximate the Pareto-optimal tradeoffs", etc.**

Author response:

We propose to take the reviewer's suggestion of replacing "to identify the Pareto-optimal tradeoffs" with "to approximate the Pareto-optimal tradeoffs" in the abstract. Furthermore, we propose changing the following sentence in the abstract "Full implementation of the proposed schemes is shown to be Pareto-optimal, but at high environmental and social cost" to "Full implementation of the proposed schemes is shown to come at high environmental and social cost" to avoid confusion at this early stage. Additionally, "The solutions cannot be mathematically proven to be Pareto-optimal, but the evolution of the solution set can be visually analysed for convergence on and diversification across the Pareto-approximate surface." is proposed as the second sentence in the first paragraph of the methodology.

5) **Use of the term "visual analytic plots" to describe the tradeoff surfaces in Figures 3, 5, and 8-12 is a bit vague. Surely there are other plotting styles that fall under the heading "visual analytics". Perhaps there is a more specific term such as "tradeoff plots" or "multiobjective plots" that could be used.**

Author response:

We appreciate the point that visual analytics are a broad class of tools of which our trade-off and other plots are a narrow set. Previous authors using the same tools have referred to these as interactive trade-off visualisation (e.g. Kasprzyk et al. 2009) but we propose to amend our text to use "trade-off plots" for conciseness.

Abstract original text: Visual analytic plots allow decision makers to assess multi-reservoir rule-sets and irrigation investment options by understanding their impacts on different beneficiaries.

Abstract proposed text: Trade-off plots allow decision makers to assess multi-reservoir rule-sets and irrigation investment options by visualising their impacts on different beneficiaries.

Introduction original text: Several authors have demonstrated the use of visual analytics for analysis of trade-offs revealed by MOEA…

Introduction proposed text: Several authors have demonstrated the use of trade-off plots to analyse solutions revealed by MOEA…

Methodology original text: Visual analytic plots are built to help understand the trade-offs

Methodology proposed text: Trade-off plots help understand and communicate the trade-offs implied by different management decisions.

Visual analytics original text: We use visual analytics (Keim et al., 2008) to interactively explore the trade-offs between competing objectives, and add analytical and non-optimised information to the trade-off surface to highlight information about the results. Visual analytics provide a broad perspective on the multiple objective performances and operating policies which produced them. Large sets of Pareto-optimal solutions can be analysed in plots with high information content facilitating more informed deliberation and decision-making (Kollat and Reed, 2007;Lotov, 2007). The visual analytic plots below aim to help make decisions about the preferred balance of benefits by showing how different societal goals trade-off against each-other. Any selected solution point from the trade-off curve/surface represents the performance achieved for all objectives by a specific set of decision variables (a 'policy').

Visual analytics proposed text: We develop trade-off plots built using interactive visual analytics (e.g. Kasprzyk et al., 2009;Kollat and Reed, 2007;Keim et al., 2008) to explore trade-offs between competing objectives and other relationships, adjusting the information displayed to highlight different features. Interactive trade-off visualisation provides a broad perspective on the multiple objective performances and decisions which produced them. Large solution sets can be analysed in plots with high information content facilitating more informed deliberation and decision-making (Kollat and Reed, 2007; Lotov, 2007). The figures below and the animations in the supplementary material illustrate how trade-off visualisation helps balance water benefits by showing how different goals trade-off against each-other. Any selected solution point from the trade-off curve/surface represents the performance achieved for all objectives by a specific set of decision variables (a 'policy').

Discussion original text: Visual analytic plots allow an interactive and intuitive understanding…

Discussion proposed text: Analysing trade-offs visually fosters an intuitive understanding...

Conclusions original text: Decision makers can use the information presented in visual analytic plots to trade-off the various gains and sacrifices according to their preferences.

Conclusions proposed text: Decision makers can learn about the consequences of policies or investments by directly viewing their joint impacts on several objectives and trade-off the various gains and sacrifices according to their preferences.

6) **Some details of the optimization itself are glossed over. Is there evidence that 100,000 model evaluations were sufficient? Were multiple trials performed? In Section 4, Line 10 the authors note: "The two cases presented here each converged..." is there evidence of convergence? Typically it's difficult to make such claims with heuristic optimization techniques.**

Author response:

We understand that the details of the optimisation were insufficient and propose to revise the text.

Original text - Although the computational burden of MOEA optimisation is high, this was mitigated by the use of parallel computing. The two cases presented here each converged sufficiently using 48 2 GHz processors over 1.75 hours.

Proposed text – The search process requires many simulation runs and was carried out using a university clusters. The two cases presented here each completed 100,000 function evaluations (each function evaluation is a 42-year simulation) in 1.75 hours using 48 2GHz processors. Visual analysis of the search progress and a random seed analysis (e.g. Kollat et al., 2008) testing 50 iterations of the same optimisation process confirmed that 100,000 evaluations were sufficient to approximate the Pareto optimal set and only diversification of results would be gained by extending the search. If decision makers focus on a relatively small area of the initial trade-off surface, an extended search could be undertaken to help diversify the options over that limited area.

7) **Figure 2 (showing the decision variables for the piecewise linear release curve) is very helpful. Is there any reason to choose a piecewise linear function here rather than a smoother function? (except perhaps ease of use). Would performance be any different?**

Author response:

We are pleased the referee found the figure depicting the release rule curve helpful. IRAS-2010 has a feature for implementing the standard operating policy (SOP, Maass et al., 1962) for reservoirs. We used this feature to create hedging rules similar to those used by Shih and Revelle (1994) but using only present storage to decide releases. Performance may be different with other methods of constructing release rules. We propose adding the following text to clarify this to the reader:

IRAS-2010 has a feature for implementing the standard operating policy (SOP, Maass et al., 1962) for reservoirs. We used this feature to create hedging rules similar to those used by Shih and ReVelle (1994) but using only present storage to decide releases.

8) **In the conclusion, the authors mention a future exploration of uncertainty. What are the potential implications for this? Do the authors feel that uncertainty could change the recommendation made to decision-makers from this study?**

Author response:

Thank you for your interest in future work relating to uncertainty. Regarding the implications, we propose to add the following text to the relevant paragraph in the Discussion:

This paper seeks reservoir operating rules that appropriately meet water manager and/or stakeholder expectations. The rules are designed such that they produce acceptable results over a wide range of hydrological conditions (those present in the historical time-series used). The approach could be called implicitly stochastic (Labadie, 2004) since using a long hydrological time-series has encapsulated a wide range of hydrological variability. If the hydrological regime were to change in the future, or a series of new assets were put in that would strongly change the system, the study would have to be redone to adapt to new conditions.

We feel the existing statement "An ensemble analysis considering many plausible future flow series may also alter this assessment if water resources availability changes…" sufficiently addresses the question about uncertainty changing the recommendations made to decision-makers from the study. Since we have not done this work, we prefer not to comment on it more extensively.

Anonymous Referee #2

1) **At line 10 and line 16 of page1344, we can figure out two possible innovations in this study, the first is the coupling of "water resources management model" with "multi-criteria search algorithm". The second one is "visual analytic plots". However, in introduction section, no statement about the coupling model has appeared except for the advantages of MOEAs at line 16 of page 1346, and you just emphasized the benefits of visual trade-off analysis at line 1 of page 1347. This will confuse the readers that whether the coupling model is an innovations point you want to declare or it's just a inter-process. And though in section 3.2.1, you introduced the implement of the linking model, however, in latter sections, especially in discussion and conclusions sections, no more discussion about the benefits of simulation-optimization interactions has been mentioned. I think it is better to make detail statement if you want to highlight the first possible innovation point.**

Author response:

Thank you for these comments. Apologies if it wasn't clear that neither of the two points noted are innovations of this paper. Neither the coupling of a water resources management model with multi-criteria search nor the use of visual analytics to analyse the results from such a simulation-optimisation approach are novel; several papers do this in the past 5 years as described in the literature review. The innovation of this paper is in assessing the trade-offs related to irrigation investment decisions in a developing country context. We believe the additional text provided above in response to Reviewer #1's first comment addresses this point satisfactorily.

2) **I suppose the you might want to emphasize the advantages of "visual analytic plots", however at line 21 of page 1353: "We use visual analytics (Keim et al., 2008) to interactively explore the trade-offs between competing objectives, and add analytical and non-optimised information to the trade-off surface to highlight information about the results.", the visual analytics is referenced from another literature, it's not very clear that if you made some progression or just apply it to this study. It's better to make a more clear statement.**

Author response:

Thank you for this comment. We wish to emphasise the advantages of 'visual analytic plots' on page 1353, but must make clear that we are not the first to use these tools. To clarify this point we have added the following references to the first sentence of section 3.2.5 Visual analytics:

(e.g. Kasprzyk et al., 2009;Kollat and Reed, 2007;Keim et al., 2008)…

3) **At line 3 of page1348: “This wetland has specific requirements for flow variability which amounts to a major demand for water”, the meaning of it is not quite clear, I suggest you to express it more clearly and accurately.**

Author response:

Thank you. In order to clarify the meaning we propose revising the relevant text as follows:

Original text - This wetland has specific requirements for flow variability which amounts to a major demand for water.

Proposed text – The physical, chemical and biological characteristics of this wetland have resulted from the historic extent, timing duration and frequency of flood events (Mitsch and Gosselink, 2000). Maintenance of these characteristics amounts to a major demand for water, in competition with other demands.

New References

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Kollat, J. B., Reed, P. M., and Kasprzyk, J. R.: A new epsilon-dominance hierarchical Bayesian optimization algorithm for large multiobjective monitoring network design problems, Advances in Water Resources, 31, 828-845, 10.1016/j.advwatres.2008.01.017, 2008.

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