Hydrol. Earth Syst. Sci. Discuss., 11, C2613–C2626, 2014
www.hydrol-earth-syst-sci-discuss.net/11/C2613/2014/

Hydrology and Earth System Sciences
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Discussions

Interactive comment on "Robust global sensitivity analysis of a river management model" *by* L. J. M. Peeters et al.

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Received and published: 22 July 2014

Reviewer 1:

General comment: Lack of a research/scientific question / wider applicability of research

The reviewer is correct in pointing out that an explicit formulation of a research question is lacking and that the manuscript did not sufficiently place the research in a broader context or highlights its potential relevance for other researchers. The key scientific issue is the development and application of a robust sensitivity analysis method that is able to identify and quantify main linear effects as well as non-linear and interaction effects. Especially the latter two are of importance in the context of river manage-

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ment modelling as the implementation of management rules through threshold values inherently leads to non-linearity in the model response. We addressed this issue by slightly shifting the emphasis of the paper towards the methodology aspect of detection of interaction and non-linear effects. The core of the methodology is the Plischke et al (2013) density based sensitivity analysis, which we would describe as an emerging rather than a well established sensitivity analysis methodology. The novel aspect of our work is in extending this methodology to allow calculation of interaction effects and providing a strategy of sensitivity analysis which relies both on the visualisation of model results and on formal sensitivity measures.

The title is therefore changed into: Robust global sensitivity analysis of a river management model to assess non-linear and interaction effects

The last paragraph of the introduction is changed to: The goal of this study is to apply a density-based sensitivity analysis in a river management modelling context to assess its capability to identify and quantify non-linear effects and to extend the methodology to account for interaction effects. An idealised, hypothetical river management model implemented in the eWater Source platform (Welsh et al, 2013) serves as testing platform to assess the ability of the sensitivity analysis methodology to quantify the influence of a small number of forcing variables upon a variety of model outcomes. The next section presents the theoretical background and numerical implementation of the \citet{Plischke2013} global sensitivity analysis method. The river management model is briefly introduced before presenting the results of the sensitivity analysis and summarizing the findings in the discussion and conclusion sections.

Specific comments: 1. In general there needs to be a greater discussion of the model including how it was set up and calibrated - the reference provided was not a sufficient description of the model. Here are my suggestions to improve this: a) It would be good to have a schematic of the model as one of the figures. It would provide some context to the model and make it easier to understand when you are describing it in section 3.

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Replaced Fig. 1 (see attachment)

b) Why have you decided to use this model? Do other researchers use it? What can other scientists learn from applying a sensitivity analysis to this model? Moreover, why did you decide to use the simplified version - why not use the full model version? This needs to be made clear to the reader.

The eWater Source modelling framework is adopted by the Australian governmental agencies as the tool to develop the new generation of water allocation plans across Australia. As stated in the introduction, providing a comprehensive sensitivity analysis methodology to researchers and practitioners will enable them to make more robust models, increase transparency and enhance credibility of their models with stakeholders. Gaining wide support from stakeholders for these models is crucial because these plans directly affect the livelihoods of a large group of people and the health of ecosystems. These water allocation plans and river management models therefore often become part of legislation. The idealised, hypothetical model has all of the relevant complexity practitioners encounter when creating water allocation models. It therefore serves as a showcase for applying sensitivity analysis techniques to eWater Source models. Using the full version of the Murrumbidgee model was not warranted, not only because of the complexity of the system and the management rules, but, more importantly, because of legal issues with regards to model licensing and confidentiality. We added the following section to the introduction: 'River management models such as eWater Source (Welsh et al. 2013) are increasingly used, especially in Australia, in the development of basin-wide water allocation plans. As these plans directly affect the livelihood of people and the health of ecosystems, it is essential that the models underpinning these plans have wide support and are robust. It is therefore essential that practitioners have a set of tools for sensitivity analysis available, tailored to the needs of water allocation modelling.' To the 'Model Description' section, following paragraph is added: Using the full version of the Murrumbidgee model was not warranted, not only because of the complexity of the system and the management rules, but, more importantly, because of legal issues with regards to model licensing and confidentiality. The idealised, hypothetical model retains most of the relevant complexity practitioners encounter when creating water allocation models.

c) Although the model outputs are well described, the model description needs to be more informative. What are the parameters in the model? How are these calibrated? Would the results remain unchanged with a different parameterisation?

We agree with the reviewer that the model description is rather succinct. This was a conscious choice as to keep the focus of the paper on the methodology rather than the model. Unlike rainfall-runoff models or land-surface models, the goal of this model is not to predict flow at ungauged locations or in the future. The goal of water allocation models is to evaluate different management scenario's of regulated river flow and how these can be affected by changes in flow conditions. The calibration of such water allocation models focuses mainly on achieving the best possible water balance, particularly in the regulated flow range, in doing so the primary objective of the calibration process is concerned with the assignment of reach fluxes and thus minimising the unexplained component of the loss/gain within each river reach. The various fluxes are taken from the calibrated Murrumbidgee model and therefore are at least representative for the system. In order to be able to compare against observed data we would need to match the changes in water sharing and management plans over time. In this model water sharing rules are selected that are yet to be put in effect into this particular valley. So even though the gauges in the model represent actual sites there is no way of comparing against observed data.

2. As you are assessing the sensitivity in the forcing factors, I felt more information needed to be given for the inflow and climatic data. For example, did you use daily data? What is the total length of the time series for the climatic and inflow data? What is the quality of this data?

The first section of the model description section is rewritten: 'The case study is a hypothetical river system model (Fig. 1), based on a simplified version of the Murrumbidgee River Model in New South Wales, Australia (Dutta et al., 2012; Podger et al., 2014). Using the full version of the Murrumbidgee River Model was not warranted, not only because of the complexity of the system and the management rules, but, more importantly, because of legal issues with regards to model licensing and confidentiality. The idealised, hypothetical model retains most of the relevant complexity practitioners encounter when creating water allocation models. In the model, water is routed from a storage reservoir through three river reaches. Routing starts in reach 1 at the storage reservoir with hydropower generators that receive water from a single tributary inflow. In Reach 1, water is taken from the system for town water supply and irrigation and water is received from unregulated rain-fed tributaries. From the Upper Gauge at the end of Reach 1, water is routed through reach 2. In this reach, interaction with groundwater is taken into account by an exchange flux. As in reach 1, water is received from unregulated, rain-fed tributaries and water is taken out for irrigation and town water supply. In addition to these offtakes, water is diverted into an off-river wetland system. Reach 3 starts at the middle gauge and is similar to reach 2. It also has offtake for town water supply, irrigation and off-river wetlands and receives inflow from rainfed tributaries. Groundwater-surface water interaction is not taken into account in this reach. Each reach has a term representing unaccounted losses. The loss relationships are taken from the more complex model. The total travel time from headwater to end- of- system is 18 days (3 days reach 1, 6 days reach 2 and 9 days reach 3). These values, together with the other parameters influencing routing of water are also taken and aggregated from the more complex model. Daily timeseries of rainfall and evaporation from 1895 to 2006 are obtained from SILO (http://www.longpaddock.qld.gov.au/silo/) for sites representative of each of the three reaches to simulate inflow from tributaries and compute irrigation demand. Inflow into the main storage in the model is taken from daily gauged data from 1895 to 2006. The town water demands are based on a fixed annual pattern (8:8, 3:0 and 1:2 106m3=year for 155 reaches 1, 2 and 3 respectively). Irrigation demands are based on a reach-based aggregation of irrigation use as well as

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rationalising crop types. There are environmental demands for the wetlands in reach 2 and 3, which are designed to establish and maintain favorable habitat conditions for indigenous fauna and flora (Janssen, 2012).

3. The range of multiplier for each variable described in the result section needs to be better justified – why have you chosen a range of 0.5 – 1.5? The size of your ranges can have a big impact on your results (for example see Wang et al, 2013). Generally, I think that using a multiplier is unrealistic for a weather time series and you should use a more realistic model to perturb the weather time series (for example see Baroni and Tarantola, 2014)

The range of these multipliers is inspired by previous work on historical hydrological conditions and future conditions, taken into account climate change, for the Murray Darling Basin in Australia (Leblanc et al.2012). The 0.5 to 1.5 ranges encompasses the historical and expected change in rainfall and inflow. You are correct that more elaborate methodologies are available to perturb weather time series. In this study however, the model outcomes of interest are metrics that integrate the simulated time series of simulated flow. As such, we are interested in changes in total flow in or out the model, rather than in changes of the timing of flow. A more elaborate perturbation would indeed enable us to assess the impact of timing of flows, such as duration and frequency of floods and droughts. However, in this paper, where the focus is on the sensitivity analysis methodology rather than the model results and predictions, we judged that incorporating a more complex perturbation method would detract the attention of the reader away from the main message. We have updated the first section of the results section to reflect the above: In the sensitivity analysis, the three main forcing variables are considered; the system inflow (Inflow), the precipitation (Rain) and the potential evapotranspiration (PET). The latter two affect the inflow into the reaches and the irrigation demand. Inspired by the work of Leblanc et al. (2012), the forcing variables are changed through a multiplier to the corresponding input time series with the range of the multiplier for each variable is to be between 0.5 and 1.5. This range

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encompasses both historical variation in hydrological input and output, as well as the expected change under various climate change models and scenario's. While elaborate schemes are available to perturb hydrological time series, this is not warranted in this study as the focus is on metrics that integrate the entire flow time series. As such emphasis of the research is on interested in changes in total flow in or out the model, rather than in changes of the timing of flow.

4. In the results section, you compare each daily time series from the changed forcing data with a randomly selected reference simulation. I have a few concerns about this. Firstly, I do not see the relevance of using a randomly selected reference simulation and this needs to be better justified - why is there no comparison with observational data? Secondly there are no screening procedures for poor model simulations and this could greatly affect the results (see Pappenberger et al, 2008 for a nice discussion of this).

As stated earlier, the goal of the model is not to predict flow at ungauged location or in the future, but to evaluate management scenario's. As we are working with an idealised, hypothetical scenario, there are no physical gauges that correspond to the gauges simulated in the model. It is therefore not possible to directly compare model results with observations. An alternative option, often used in model calibration and uncertainty literature, is to select a random model realisation as the hypothetical 'truth' and treat the simulated results, optionally with an added error term representing observation error, as error. We made the decision not to treat the randomly selected model realisation as 'truth' or observations to avoid having the focus of the discussion shift towards finding the realisations that have the smallest least square sum of residuals. By choosing a randomly selected reference simulation we are able to visualise and analyse the sensitivity of the model in general. With regards to the second comment, you are absolutely right that a screening of behavioural simulations can change the results of the sensitivity analysis. However, developing a set of screening rules implies formulating an objective function. While this can be straightforward for rainfall-runoff models, it quickly becomes a challenging issue, as is vividly illustrated by the ongoing debate in literature on this topic (e.g. Montanari & Koutsoyiannis, 2012 and the comment by Nearing, 2014). This issue is exacerbated by the fact that we are not only interested in simulating flow, but also want the socio-economic and environmental impacts. As the sensitivity analysis shows, they respond differently to changes in the forcing data, which implies that they are determined by different aspects of the hydrograph. Any screening procedure or objective function needs to be tailored to be able to capture all of these aspects of the hydrograph. In order not to bias our interpretation by choosing a potentially ill-suited objective function, we opted to take a single reference realisation and compute the difference with the other simulations by using equation 7 to have an as general and robust estimate of the time series difference. To reflect this discussion in the paper, the sentence below Eq. 7 is replaced with: The choice of this metric is motivated by the fact that, since the case study is an idealised, hypothetical model, it is not possible to directly compare the results with observations. In addition to this, and more importantly, the variety of model outcomes examined in this study are more than likely to be affected by different aspects of the hydrograph. Similar to choosing an objective function in traditional calibration or a likelihood function in uncertainty analysis, such metric needs to be tailored to be able to capture the relevant aspects of the hydrograph. Choosing an ill-suited metric can have huge consequences for the sensitivity analysis, calibration or uncertainty analysis, as pointed out in Montanari and Koutsoyiannis (2012) and Nearing (2014). The metric presented in Eq. 7 is designed to provide an as general and robust as possible measure of the difference between two time series as not to bias the interpretation of the sensitivity analysis.

5. The discussion section needs expanding with greater reference to previous works – are the results similar to what has been found in the past? What is the significant outcome?

References are added to: - Hughes (2014) to highlight the importance of inflow in river system models - Gallagher & Doherty (2007), Zhang et al (2013), Peeters et al

(2013) and Doherty & Hunt (2009) to illustrate the importance of parameter interaction in hydrological modelling. - Letcher (2007) as an example where interaction effects are considered important, without however providing quantitative measures to evaluate them.

6. In your conclusion you really need to highlight what is novel about the paper. There needs to be more to the paper than applying a well established sensitivity analysis to the model - what have you learnt and what can other researchers take away from the paper?

The conclusions are changed (see below) to emphasize the contribution of extending the Plischke et al 2013 methodology in combination with the visualisation of the sensitivity analysis results. Greater emphasis is given to the use of sensitivity analysis methods to improve the understanding of complex river system models and to create support with stakeholders. The density-based sensitivity analysis of Plischke et al. (2013) has been applied to a river management model representing an idealized regulated river system representative of the Southern Murray-Darling Basin in Australia to identify the main and interaction effects of three driving forces on several hydrological and socio-economic model outcomes. The extended sensitivity analysis method presented in this paper provides a quantitative measure of sensitivity of main and interaction effects and, through a combination with qualitative visual inspection of scatter plots, proved to be able to identify not only major effects but also subtle interactions, even in the presence of strong non-linearities. Due to the small dimensionality of the case study, it was possible to visualise all main effects and their interactions through scatter plots for all model outcomes. Although this will be challenging for higher dimensional problems, the visual inspection of scatter plots is an invaluable complement to the sensitivity indices. Understanding the dynamics of river system models is often not intuitive, especially in larger or basin-scale models (Johnston and Smakhtin, 2014). A robust and comprehensive sensitivity analysis is an invaluable step in model development to elucidate the often intricate interactions between driving forces, management rules and parameters. Increased understanding of the model will not only lead to improvements in calibration and prediction, it also has enormous potential in establishing credibility and understanding of models.

Technical Comments 1. P 3482 Line 3. 'will quickly results in' change results to result changed 2. P 3487 Line 25. 'are to designed to establish' remove the first to changed âĂČ Reviewer 2: General comments: 1 Put the research in a wider context, with additional applications of the model and possible intrests of applying the SA on this type of models.

We added the following section to the introduction: 'River management models such as eWater Source \citep{Welsh2013} are increasingly used, especially in Australia, in the development of basin-wide water allocation plans. As these plans directly affect the livelihood of people and the health of ecosystems, it is essential that the models underpinning these plans have wide support and are robust. It is therefore essential that practitioners have a set of tools for sensitivity analysis available, tailored to the needs of water allocation modelling.'

2 A comparison of the results of the applied density-based global sensitivity analysis with results obtained from applying other SA techniques to this model could add more scientific value to this work, as it might give additional justifications why the selected method is appropriate. Besides results, also the computation time can be a key factor in this comparison.

The reviewer is correct that comparing different sensitivity analysis techniques is a valuable exercise. We decided not to go down this path as it is very difficult to do a fair comparison of different sensitivity analysis techniques because of the often large differences in underlying assumptions and sampling schemes. For instance, methods such as variance based methods are not well suited to capture small scale non-linear effects. Elementary Effects, through their minimal sampling, will only capture We rather opted to focus the paper on extending the Plischke method to account for interaction effects and highlight it as a valid and usable method in water allocation modelling in which model results are often non-linear functions of the driving function. With regards to the computing resources, following sentence is added to introduction: 'This has the added benefit that as no model runs need to be devoted to the resampling of a base sampling, more computing resources can be directed to exploration of parameter space.'

3 Add additional information on the data and the model you have been using.

The model description is rewritten, see the reply to comment 1 of reviewer 1 for a detailed list and motivation of the changes.

4 Besides repeating the most important results, your conclusions should also "promote" your work and the added value.

The conclusion section is partly rewritten, see the reply to comment 6 for a detailed list and motivation of the changes.

Specific comments: 1 p3484: L4: "structured sampling" is not necessary for Sobol' SA. Random sampling is also possible for the base sampling. (Based on this base sampling, combinations of parameters are used for the calculations, which might have given you the impression of structured sampling.) changed p3484L4 to: 'Variance based methods, such as Sobol' sensitivity analysis (Saltelli & Annoni, 2010; Nossent et al., 2011), use a scheme of structured resampling of a random base sampling to decompose the variance of the metric of interest into the main effects of a parameter and interaction effects of other parameters.' 2 p3485: L27: I'm not sure if all readers will be familiar with the concept of kernels. Add some information or at least add a reference. Added reference to Devroye and Gyorfi (1985) 3 p3486: L19: Add a reference for the bootstrapping. Added reference to Efron (1977) 4 p3487: L2: You write "first order effects", but you describe a second order effect. Make sure the formulation is correct. Thank you for picking this up, the formulation is consistently changed to 'second order effect' 5 p3490: L19-20: It is not really clear how this is related to the "treshold-induced non-linear behavior". Make this more clear. The sentence is replaced with: This is because hydropower is generated by release of water from the reservoir in function of the demand and the water level in the reservoir. These management rules create a buffer to immediate impact from rainfall and inflow and also result in non-linear, threshold related behaviour. 6 p3491: Is the inflow in your catchment not rain fed? I would expect to see this from the interaction effects? Or could this be the case in other applications? The separation of inflow and rainfall in this study is because inflow relates to inflow into the upstream reservoir from the headwaters of the catchment. Rainfall relates to the precipitation inside the modelled domain. The distinction is warranted because the headwaters have a different hydrological and climatic regime than the modelled catchment and because this approach makes it possible to distinguish between the effect of inflow in the system from upstream and rainfall in the modelled area. In other studies, inflow into the system, especially from ungauged tributaries is simulated using a rainfall-runoff model and in that case, changing the rainfall would also influence the inflow. This element is however not retained in creating the idealised version of the complex Murrumbidgee model. 7 p3498: A more specific (detailed) figure of the reaches would have been more clear. Figure 1 is updated. Technical comments 1 p3487: L25: remove the first 'to' in "which are to designed to established" Changed 2 p3491: L23: Don't you mean "RAIN and Inflow" instead of "RAIN and Storage"? Yes, it is changed accordingly

References

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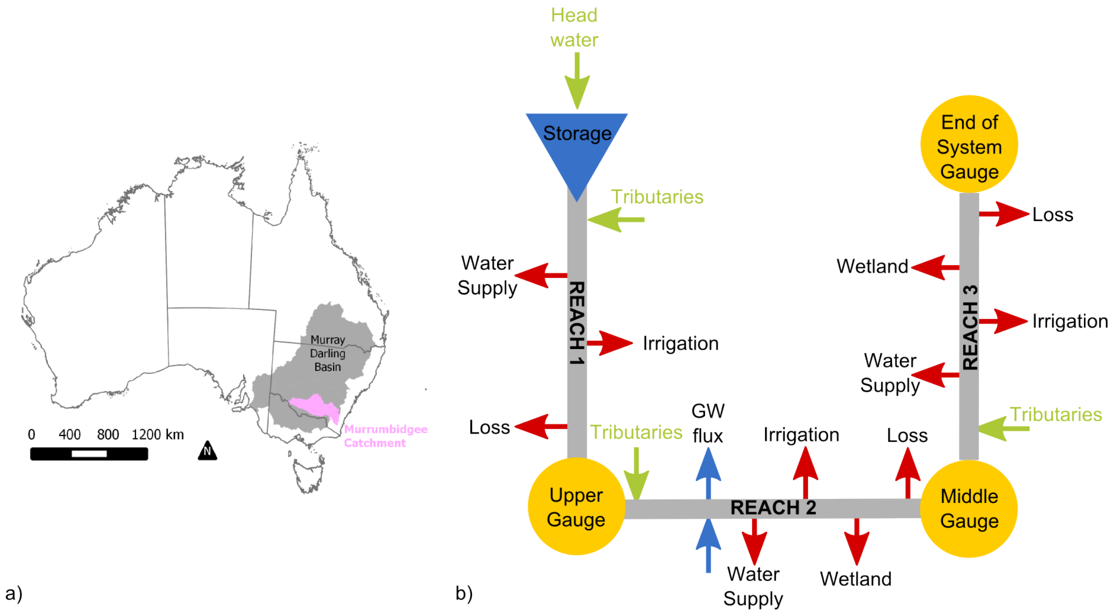

Fig. 1. a) Map showing the extent (indicated by pink shading) of the idealised river system model within the Murray-Darling Basin and b) schematic structure of the river management model

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