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Hydrology and
Earth System
Sciences
Discussions

Interactive comment on "Assessing the added value of high-resolution isotope tracer data in rainfall-runoff modelling" *by* C. Birkel et al.

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AUTHOR RESPONSE

We are grateful to the two reviewers for clearly reading the m/s carefully and giving useful suggestions and feedback that identified weaknesses in the original m/s. In particular we are grateful to the reviewers for highlighting several areas where our approaches were not fully justified and our methods were unclear. We are pleased that Reviewer 1 recommended publication subject to relatively moderate revision, and we appreciate that Reviewer 2 had a number of concerns that needed more substantial clarification. In this revised m/s we have undertaken a major revision, incorporating the required changes to the text and – as far as possible - additional analysis as recommended by the reviewers. We detail below how we have addressed almost all the review comments below. In the few places where we have not, we provide the reasons why.

Response to Reviewer 1 general comments: Reviewer 1 "...it is somewhat confusing if the authors are trying to show 1) the isotope can improve "rainfall-runoff simulation" or 2) the isotope can improve "tracer simulation"..." The intention of this study was not specifically to improve either runoff or tracer simulations (in terms of achieving a higher value for an objective function). A more specific objective was to explore the value of tracer data in aiding hydrological modelling through improving process interpretation, parameter identifiability and simulation uncertainty. The simple approach presented is an attempt to assess the value of using high-resolution isotope data for interpretation and modelling of catchment hydrology. The end of the introduction will be modified in the revised m/s to state "This study was undertaken to examine the use of high-resolution isotope time series for the conceptualization of hydrological flowpaths and the effect on calibration and evaluation of a simple, conceptual flow-tracer model. A particular focus was the basic attempt to account for the errors and uncertainties associated with the fundamental data used in the modelling analysis of isotope variability in precipitation and streamflow."

1. Uncertainty bands are subjectively defined for both the discharge and isotope objective function according to the highest achievable values for the model simulations, for which behavioural parameter sets can still be found. Therefore, we believe that it can be comparatively demonstrated whether or not inclusion of the isotope objective function into the evaluation process further constrains parameter sets of the flow-tracer model. The evolution of constrained parameter sets is illustrated in Table 6 and begins with the initial parameter sets, moving on to the parameter sets of the calibrated flow model and then showing the effect of including a second objective function (for isotopes) into model calibration. The procedures for multi-criteria calibration and calculation of uncertainty bands have been clarified (see specific comment below). A modified Figure

5, where we now show the estimated model uncertainty for the flow model in comparison to the constrained uncertainty of the multi-criteria calibrated flow-tracer model, has been included in the revised manuscript. We also modified p6231::l23 in the discussion section 6.4 to “Although sensitivity could only be subjectively evaluated, Figure 6 shows that model parameters are largely identifiable even if that depends to a certain degree on the objective function applied (Fenicia et al., 2008b). The parameters defining the isotope mixing volumes were found to be less identifiable (Fig. 7) than the flow parameters due to a poorer performance of the isotope simulations. Absolute quantification of sensitivity and uncertainty was beyond the scope of this simple approach.”

2. The daily tracer data clearly show that during rainfall event extremes in the stream isotope response occur that correspond with extremes in the precipitation isotope input, indicating an unmixed portion of isotopes reaching the stream. This process should therefore be considered in the model structure. Much of this information is lost in the weekly isotope dataset (Figure 2 and 4, modified Table 2). The loss of water at the study site compared to the catchment outlet, presumably due to a regional groundwater recharge, was calculated from the water balance for the study site (section 2 Study site). We therefore developed a simple, but process-oriented model that could explain the observed phenomena. Furthermore, the additional parameters are (subjectively) identifiable from the maxima when parameter values are plotted against the performance measures (Fig. 6).

Specific comments of reviewer 1 (page ##:: line##): 1. p6215::l1. Corrected. 2. The need to better explain the multi-criteria procedure in section 4.2.2 Model application is incorporated in the revised m/s as follows: “A stepwise, multi-criteria calibration (Khu et al., 2008) was used to evaluate the behaviour of the model under measurement uncertainty. The procedure can be summarized as follows: (i) Monte Carlo (MC) random sampling with 10,000 iterations was used to assign parameter values to model simulations. Efficiency criteria for flow and tracer simulation were evaluated for each iteration of the MC run. (ii) On the basis of the results from (i) efficiency criteria thresh-

olds for flow and tracer were established to identify the best parameter sets for the 10,000 simulations. (iii) Ranges of parameter values were initially constrained according to the sub-set of simulations that satisfied efficiency criteria thresholds for flow simulation (multi-criteria modes). A further 10,000 MC simulations were run using the constrained parameter ranges identified in (ii). From these simulations, 445 parameter sets that achieved the assigned criteria thresholds were used to calibrate the flow model. Maxima and minima of simulated flow at each time-step, across all acceptable parameter sets, were extracted to define uncertainty boundaries for flow simulation. (iv) Ranges of parameter values were constrained according to the sub-set of simulations that satisfied efficiency criteria thresholds for both flow and tracer simulation (multi-criteria measures). A further 10,000 MC simulations were run using the constrained parameter ranges identified in (ii). From these simulations, 24 parameter sets that achieved the assigned criteria thresholds for both flow and tracer were used to calibrate the tracer model. Maxima and minima of simulated tracer at each time-step, across all acceptable parameter sets, were extracted to define uncertainty boundaries for tracer simulation.”

3. P6222::l11. The calibration of the CIM model against weekly data is better explained in the revision as follows: “We evaluated the performance of the multi-criteria calibrated best-fit parameter set applied to the model against weekly tracer data. The tracer efficiency for the weekly data improved on average by 10% for all three performance measures applied. The Nash-Sutcliffe criterion for deuterium D_NS increased from 0.54 (daily) to 0.58 (weekly), for example. This is mainly due to the averaging effect of the isotope dynamics in stream water over the coarser temporal resolution, which makes it easier to achieve a high value for the objective function compared with a temporally variable response. Errors in the temporal dynamics of the simple model are accentuated when comparing against the higher resolution data. Hence quantitative demonstration of the benefits of the higher resolution data is difficult.”

4. The description of the model structure is clarified in the revised m/s as presented

below (pdf supplement), through modified text for section 4.2.1 Model concept, a modified version of Figure 3 (attached below) and an explanation of all equations in the text rather than in a table.

Reviewer 2 general comments: 1) The title was criticised as too general and as promising too much. We hope that this reflects the lack of clarity in the original m/s. We feel that the title is appropriate and hopefully is now justified by the clearer exposition of the approach in the revision. 2) “Low-parameter model” will be changed throughout the revised manuscript to “simple, conceptual model”. 3) The reviewer was incorrect to say that “most” references in the introduction came from the authors, the majority did not. However, three group citations will be removed from the revised m/s to address any accusation of biased self-citation. We believe that work from our group has only been cited where appropriate and has underpinned the different strands leading to the development of this study. The reviewer also implies we have missed certain key references, but unfortunately doesn’t specify which. Nevertheless, we also added citations from Wagener (2007), Kirchner et al. (2004) and Fenicia et al. (2008) to give a wider range of background material. 4) Objective 2 was stated as too strong and objective 1 declared as not a proper objective itself. We therefore, will rephrase objective 1 to “To generate a tracer data set that would enable the benefits of high-resolution data to be assessed”. Therefore, we maintain a total of four objectives for this paper as we feel the acquisition of such a high resolution data set is a non-trivial issue and a legitimate effort. In the introduction we mention that there have been conceptual flow-tracer models (among others: Stadnyk et al., 2005; Dunn et al., 2008 and Fenicia et al., 2008) on which we base our approach, but it was still necessary to write and test a suitable code to permit a logical step-wise assessment of the flow and isotope processes for this catchment. Therefore, the second objective (p6210) is now “to develop a conceptual flow-tracer model suitable for simulating water and isotope fluxes in the study catchment, with minimal parameters.”

5) Daily model time step is now included in first phrase and throughout section 4.2.1.

6) The decision to only use D/H for this study was taken based on the interdependence of oxygen-18 and better instrument precision for deuterium. A study to look at the processes, such as fractionation, that explain the interrelation between both isotopes, was beyond the scope of this paper. 7) It was assumed that error introduced by spatial variability in precipitation could be neglected in this catchment, due to its small size and little relief. This assumption is supported by an analysis of the water balance of the larger scale Lunan catchment (122 km2) which gave a closed balance between the measured precipitation, ET and runoff. The measurement error of daily precipitation volumes was pragmatically approached by combining data from the (adjacent) tipping bucket gauge and isotope rain sampler to form an averaged time series with error estimate for the analysis.

This has now been included on p6215::l18 in the section 4.1 Statistical methods: “As errors in the measurement of precipitation volumes cannot be neglected, we used the average precipitation time series of the two adjacent sampling devices (tipping bucket gauge and rain sampler) deployed in this study with a potential error estimate (Ep) of 12% (based on the percentage difference of the combined time series).” The upper and lower precipitation measurement uncertainty limits were applied to the model in order to examine the effect on flow simulation uncertainty.”

This aspect has also been included in Figure 5 and the result section 5.3.2: “For this the precipitation volume uncertainty boundaries (±12%) and isotope input uncertainties (±1.34‰ were used to calculate the isotope simulation uncertainty envelopes, which are only slightly increased compared to the pure model uncertainty and therefore not visible in Figure 5b. The uncertainty envelopes based purely on the calibrated flow model and including precipitation input uncertainty (Figure 5c) are compared against the constrained uncertainty of the multi-criteria calibrated flow-tracer model (Figure 5d). The estimated error in precipitation input results in 130mm more or less water reaching the catchment with increased total uncertainty in flow simulations. Much narrower uncertainty envelopes can be observed in Figure 5d compared to Figure 5c after incorporation of the additional isotope objective function."

Section 6.3 is now "Measurement uncertainty of precipitation, discharge and isotope data" and we included the following: "Considerable uncertainty surrounds precipitation measurement with errors of over 50% (Sevruk and Chvila, 2005) reported in some catchments. A relative error of only 12%, as the estimated percentage difference between two adjacent measurement devices, causes wider uncertainty envelopes mainly affecting the simulating of peak discharge (Figure 5c)."

8) a- The model is set up as a water balance model with integrated tracer fluxes (Eq. 5) linked to water flow and as such conserves mass of both water and tracer. Please, see response to first reviewer, specific comment 4, with the proposed clarification of the model description. b- Similar to 8a, all tracer fluxes are linked to water flow, even the loss terms such as ET and regional groundwater recharge. c- Section 4.2.1 Model concept was completely reworked in the revised m/s to correct issues with units, etc. d- This is now clarified as follows: "This reservoir is not restricted to a lower limit; subzero values indicate that the active storage is emptied by evapotranspiration and does not generate any lateral flow, and in this case the associated tracer loss is depleted from the passive storage." e- New Figure 3 in revised m/s. f- This was corrected in 4.2.1. g- Equations 5/6 from Table 3 were misleading and consequently deleted. In the revised m/s the mass balance equation 5 shows that incoming precipitation is added to the upper active storage from which estimated ET is subtracted. h- Changed to "direct runoff component enabling an unmixed portion of precipitation signature to reach the stream". i- If parameter c is included a portion of rain directly enters the stream (new Figure 3). j- The input time series were looped over 5 years to establish initial conditions (p6216::l20-21).

9) The Pearson product moment correlation coefficient between D and Q gives a negative and weak ($r=-0.32$), but significant ($p<0.05$) relation. Therefore, we have removed the statement regarding independence in the revised m/s and refer instead to an additional objective function that assesses different characteristics of the system.

10) Mass flux statistics are now included in the revised m/s in Table 3 with explanations in section 4.1 Statistical methods "The δ2H time series were summarized using basic statistic descriptors such as mean, maximum, minimum, standard deviation (Std. Dev.) and the 10th and 90th percentile to compare different sampling resolutions looking at isotope content and mass fluxes.". The new information has been added to Table 3 for comparison.

Section 5.2 has been rewritten as follows: "Table 3 summarizes the statistics of daily and weekly composite sampling resolution and weekly grab and composite sampling methods. The daily stream sampling regime captures greater variability in the deuterium, characterised by higher and lower maximum and minimum values, although comparable mean values and percentiles to the weekly sampling were observed. The data suggest the difference in sampling resolution will be most important for precipitation because of the greater temporal variability. From these differences it would be reasonable to expect that the sampling resolution will have important implications for modelling, especially when the input function forces the simulation of stream isotopes. This difference between the temporal sampling resolutions is emphasised further by comparing discharge and precipitation isotope statistics when weighted by the rainfall and runoff volumes (also summarized in Table 3). Here, the greater variability captured by the daily sampling resolution is evident in all statistical parameters."

11) Section 4.1 Methods and result section 5.3.1, now clarify how the error estimation was derived from a combination of our own measurements (45 manual discharge measurements to set up the rating curve, repeated individual discharge measurements to estimate error in depth and velocity and weekly streambed control measurements) and error analysis and / or literature values. We acknowledge (p6224::l1-4) that the presented error propagation method is a simple approach based on relative errors and doesn't reflect the error variability between low and high flows. We therefore, clearly state in the revised m/s that this analysis is a first attempt to acknowledge and include measurement errors into conceptual flow-tracer modelling.

12) The total stable isotope measurement error is treated as the sum of determined and estimated absolute errors, which has been corrected in the text and for the precipitation input in Figure 5 of the revised m/s.

13) Both reviewers agreed on the need for a better explanation of the multi-criteria procedure, which has been presented above. However, the efficiency criteria thresholds defined after subjectively evaluating the parameters against performance measures (5.3.3 – Q_NS>0.85 and D_NS>0.5, for example) is not higher than the best results (Q_NS=0.87 and D_NS=0.54) presented in section 5.3.2. 14) We believe that a formal sensitivity analysis is beyond the scope of this paper (included in p6224::l23), as its primary objective is to explore the utility of the high resolution isotope data, rather than to evaluate the behaviour of the model per se. Issues of parameter sensitivity and equifinality are discussed in relation to the behaviour of the model and the assessment of relative uncertainty. However, the primary aim of the modelling was to show that by including an additional objective function (isotope time series) for evaluation and calibration, the number of accepted parameter sets can be constrained (Table 6 and modified Fig. 5) and the prediction range is narrowed. Further, the modelling helped to demonstrate the value of high resolution data in predicting the variability of the response, and the existence of a rapid flow pathway carrying unmixed event water. 15) The input uncertainty in precipitation isotopes is included in Figure 5a. The precipitation isotope measurement uncertainty boundaries (±1.34‰ were used as model input to study their effect on model simulations (Figure 5b). This is now made clear on p6220::l5. However, the effect was found to be small compared to the estimated parameter uncertainty: "For this the precipitation volume uncertainty boundaries (±12%) and isotope input uncertainties (±1.34‰ were used to calculate the isotope simulation uncertainty envelopes, which are only slightly increased compared to the pure model uncertainty and therefore not visible in Figure 5b. The uncertainty envelopes based purely on the calibrated flow model and including the error induced due to precipitation measurement uncertainty (Figure 5c) are compared against the constrained uncertainty of the multi-criteria calibrated flow-tracer model (Figure 5d)."

16) This point is explained above as both reviewers agreed on it.

Specific comments of reviewer 2 (page ##:: line##): 1) The revised manuscript has been checked and edited by the senior native English speaking authors. 2) P6210::l19. Corrected. 3) P6212::l3. It is now mentioned in the revised m/s that "actual ET was estimated using a modified Penman-Monteith equation according to Dunn & MacKay (1995)". 4) P6213::l3. The last paragraph of section 3.2 was changed to "This was used to mimic the level of available data commonly obtained from weekly or bi-weekly sampling programmes (e.g. Dunn et al., 2008b) in order to explore the level of detail lost through adopting such a strategy. This was applied within the modelling by replacing the daily deuterium with the corresponding weekly and bi-weekly mean value.", in order to clarify how the weekly resolution of precipitation samples was constructed and used in the daily time-step model. 5) We assume, that Reviewer 2 refers to the result section 5.1 Isotope response to hydrological variability, where we refer back to the database figure 2 in order to explain the hydrological and isotopic behavior over the course of the study period in the catchment. Figure 2 is first referred to in section 3.2. 6) Table 3 and 4 are merged together and clarified in the revised m/s:

Please also note the supplement to this comment:
http://www.hydrol-earth-syst-sci-discuss.net/6/C3219/2010/hessd-6-C3219-2010-supplement.pdf

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Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 6, 6207, 2009.

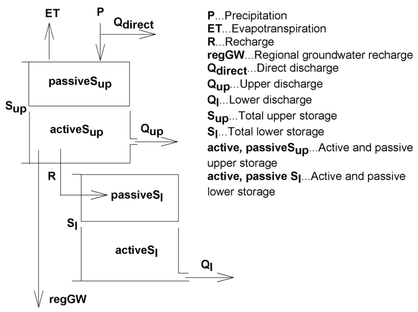

Fig. 1. Fig. 3. Structure of the Catchment Isotope model CIM showing flows and linkage of storages.