# Submission hess-2012-318
# Response to the Reviewers' comments.

We thank both Reviewers for their comments that will allow us to improve the manuscript. As a preamble, we consider the following similar comments from the reviewers.

Reviewer #1. Comment: a) This paper is fairly well written; however it is not clear what is new in the manuscript (the word "new" is used in the manuscript referring to the calibration procedure). It seems that if the title and point of the paper is to present an approach for calibrating a groundwater model then the manuscript should demonstrate the amount of information that is provided by the tritium data. However, the calibration approach relies on a simple trial and error approach and it is not clear that the model performance was improved by the use of tritium.

Review #2. Comment: This study presents a hydrologic transport modeling simulation for the Western Lake Taupo catchment in New Zealand. The work incorporates tritium tracer data into the modeling calibration. While the manuscript is well written and quality of the modelling effort appears high, it is unclear how the tracer data is utilized in model calibration in the current presentation of the work.

Reply:
We consider the work "new" because to our knowledge, no previous work has been published on tritium modeling in *streams* using distributed parameter models (DPMs) such as the finite-difference model MODFLOW and transport model MT3DMS. The two manuscripts suggested by Reviewer #1 do not discuss the calibration of groundwater models to measured tritium in streams. Plummer et al. (2000) discussed measurements of tritium and other tracers in bores and rivers, while Szabo et al. (1996) presented tritium measurements and other tracers in bores and conducted one dimensional cross-sectional modelling of travel times.

Measured tritium data in bores have been used to calibrate groundwater DPMs (e.g. Zuber et al. 2005) and to refine groundwater pathlines using estimated MRTs (Fiennen et al. 2009; Zoellmann 2001). Tritium concentrations in bores have been simulated with particle tracking MODPATH (Elberts et al., 2012), but no work with MODPATHhas been carried out on streams. MODPATH is a post-processing program that uses a completely different mechanics of modeling tritium concentrations fromMT3DMS (Pollock 1994). In MODPATH, an advective component of groundwater flow is considered that does not simulate concentrations; tritium concentrations are obtained by taking a convolution integral of transit time distributions. MT3DMS, on the other hand, solves a transport equation in single- or dual-domain to obtain simulated concentrations. A comparison of the simulation results of these two methods for the WLTC is currently being prepared and will be submitted to HESS.

Zuber et al. (2011) identified two approaches of groundwater flow and transport model calibration to measured groundwater tracer data: 1) use of groundwater ages or MRTs estimated from measured concentrations with lumped parameter models (LPMs), and 2) use of measured tracer concentrations directly for DPMs' calibration. In our work, we use the second calibration approach by Zuber et al. (2011). In this second approach, steady-state or transient groundwater flow models are calibrated to measured groundwater heads and baseflows by adjusting hydraulic conductivity, groundwater recharge and stream bed conductance in the model. Then, a contaminant transport model is calibrated to a groundwater tracer adjusting aquifer porosity and dispersivity, and making some additional adjustments to the flow model parameters (Zuber et al. 2011).

In our study, we are attempting to merge existing modelling techniques with available tritium to gain some insights in groundwater transit times in streams and are not inventing “new calibration methodology”. Instead, we use measured tritium time series data in streams at baseflow as calibration target for the transport model following the second approach by Zuber et al. (2011). In our model, all stream flow is in baseflow conditions and originates from groundwater contributions. This is a common assumption used in the field of groundwater modeling when baseflow conditions are simulated with steady-state ortransient groundwater flow models. For the transport model, the tritium calibrated transport model was calibrated with simple calibration techniques due to inability of Visual MODFLOW software (SWS 2010) to use parameter estimation sophisticated calibration techniques of PEST parameter estimation (Doherty 2012). The tritium calibrated model was used to simulate groundwater ages and obtain MRTs in streams. The simulated MRTs with DPM can be compared to MRTs estimated with LPMs and can allow a relative comparison of the first and the second approaches by Zuber et al. (2011). As Reviewer #2 stated in his comments, this is an “extremely active field of research” and we think that our manuscript contributes new material to this research field.

## Reviewer 1

### Major Comments:

*Comment:a)This paper is fairly well written; however it is not clear what is new in the manuscript (the word “new” is used in the manuscript referring to the calibration procedure). It seems that if the title and point of the paper is to present an approach for calibrating a groundwater model then the manuscript should demonstrate the amount of information that is provided by the tritium data. However, the calibration approach relies on a simple trial and error approach and it is not clear that the model performance was improved by the use of tritium.*
Response:See our response above.

*b) Also, there is no information provided to allow the reader to assess how well the model is calibrated (contour maps showing measured versus simulated head or 1:1 plots, fits statistics, etc.).*
Response:We will add the requested RMS calibration statistics for the groundwater levels, flows and tritium concentrationsto our paper, as was also requested by Reviewer #2.

*c) Additionally, calibrating a steady-state model is typically one step toward calibrating a transient model. The other issue is that the transport model is run as transient; however, the flow model is steady state. Justification and limitation of this approach need to be stated.*
Response:We agree that developing a transient groundwater flow model would be the next stepfor this modeling exercise, but lack of field data would not allow us to construct a transient model at present.Atransient groundwater flow and tritium transport models arecurrently being developed in a different study (the Ruataniwha Plain, NZ). Therefore, we will add a statement of steady-state approach limitation in the discussion section.

*d)Additionally, important information is left out, and this leaves the reader wondering if many of the approaches and assumptions are justifiable. For example, the model is constructed assuming that all the flow in the river originates as groundwater. However, this assumption is not stated or* *justified.Also, the median flow is used as a calibration target; however, this does not seem like a reasonable approach for estimating the steady state groundwater discharge to the stream, even if all streamflow originates as groundwater.*

Response:We stated that our steady-state model describes river flow in baseflow conditions when flow originates from groundwater contributions.This is a typical assumption used in the field of groundwater modeling when baseflow conditions are simulated in a steady-state or transient model. The median valueshave better representation of skewed distributions.

*Comment:Considering there are already several great examples of the use of tritium for constraining and calibrating groundwater models, I don't find this paper to be a very useful contribution to the literature (e.g., Plummer et al., 2000; Ground Water Journal; Szabo et al., 1996, WRR).*

Response:This comment is not clear to us. To our knowledge, no previous work has been published on tritium modeling in streams using distributed parameter models. , see our reply above. The two manuscripts suggested by Reviewer #1 do not discuss the calibration of groundwater models to measured tritium in streams (see above). The papers refer to a manuscript by Boronina et al. (2005) that discusses modelling tritium in an aquifer and a groundwater driven spring with groundwater flow MODFLOW and particle tracking PMPATH model, which is an alternative to USGS particle tracking model MODPATH. We added this new reference to our manuscript.We have not found any papers discussing tritium calibration in streams using DPMs such as the groundwater flow and transport MT3DMS model orsimulating groundwater age with MT3DMS using tritium calibrated DPM.

*Comment:Finally, the paper lacks discussion of the approach, results, and assumptions.Below I am including specific points illustrating my overall statements stated above, aswell as, indicating additional significant issues with the manuscript.*

Response:To clarify these points, we will add some explanations to our manuscript. The software limitations are presented in the manuscript (P9747L21-25; P9750L11-21) and will be added to "Concluding Remarks" section. We will expand the "Concluding Remarks" section with discussion from the "Tritium results" section. We will briefly mention our use of the standard codes, which can be found elsewhere. In our study, we are using off-the-shelf package U.S. Geological Survey finite-difference code MODFLOW-2000 (McDonald and Harbaugh, 1988; Harbaugh et al. 2000) to model groundwater levels and base flows andfinite-difference code MT3DMS v. 5.2 to model tritium concentrations in groundwater and baseflows. The MT3DMS modelwas developed by Zhang (1990) on U.S. Corps of Engineers funding to simulate advection, dispersion, and chemical reactions of contaminants ingroundwater systems.

Minor Comments:

*P9744 L20-22:*

*Comment: The comment regarding limited understanding of the dynamics of the groundwater component that transmits much of the water from rainfall to streams is somewhat misleading. For one, the groundwater component in streams is highly variable from region to region and depends on one's definition of groundwater. For example, one might consider shallow subsurface stormflow as groundwater; however this water is very young. Dispersion and mixing with GW discharge to shallow soils can make new water look old. For this problem, tritium does not help because it suffers from the same issues related to mixing. Thus, the debate is not satiated by the use of tritium, which has been applied to these problems for decades (e.g., Szabo et al., 1996, WRR; Plummer et al., 2000, Ground Water).*

Response:The reviewer's comment illustrates some of the uncertainty associated with the dynamics of the groundwater component in streamflow generation. True, groundwater input is highly variable between regions and shallow subsurface stormflow (in the form of perched groundwater) can sometimes be considered groundwater. Nevertheless tritium can provide unique information, e.g. 'dispersion and mixing with groundwater discharge' cannot make new water look old unless the mixture contains a high proportion of water with low tritium concentration, in which case the mixture really is oldnot just looks old.

*P9745 Lines 8-10:*
*Comment: This sentence is misleading. As shown by Szabo et al., 1996, WRR, tritium was an effective tracer for GW model calibration when the effects of the bomb pulse were still apparent.*
Response:
We can probably concede this point, although Szabo et al., 1996, used $^{3}H$-$^{3}He$ measurements, not $^{3}H$ measurements alone.We agree that tritium as used by Szabo et al., 1996 was an effective tracer for GW model calibration when the effects of the bomb pulse were still apparent, particularly as Szabo et al. used $^{3}H$-$^{3}He$ measurements in groundwater.

*P9745 Line 13:*
*Comment: A sample of water typically contains a distribution of ages, especially stream water. It is not accurate to refer to the "age" of a water sample without some kind of qualifier (e.g., mean age).*
Response:We have changed this to mean age or MRTas originally intended. These distributions were obtained by direct simulation of groundwater agewith DPMs.

*P9747 Lines 17-20:*
*Comment:Is there no overland runoff or shallow subsurface storm flow? If not then this should be stated. Recharge=Precip-ET typically works when averaged over a basin but notusually for each model cell due to runoff in the uplands where Kv is typically small. Also, there is the issue of subsurface storm flow that really is not recharge. Also, is there phreatophyte ET in these basins? If so, then one cannot subtract ET from precipitation to calculate recharge.*
Response:
We do not account for overland run-off and subsurface storm flow in the hydrological balance in our steady-state MODFLOW model, on the basis that these processes contribute to quickflow and our model describes baseflow which is commonly considered to be dominantly from groundwater sources (see below). In our study, we adopt a simple water balance procedure of groundwater recharge estimation for steady-state regional models without sufficient time series field data (Sanford 2002). The effect of phreatophytes is already incorporated into the evapotranspiration component of the catchment water balance.
*P9747 Lines 25-29:*
*Comment:If one uses the median flow in the river then this likely includes water that does not flow through aquifers, unless there is no surface water or shallow subsurface stormflow reaching the streams. However, in your simulations you are assuming the all of this flow travels through the aquifers. Why use the median streamflow as a calibration target? The long term average discharge to streams (steady state) reflects the long term sum of streamflow divided by the measurement period (mean). The median may or may not reflect the long term average GW discharge to a stream, even if precipitation minus ET equals groundwater recharge. Also, are there phreatophytes in the basin? If so, then recharge will be greater than precipitation minus ET because ET occurs after recharge has occurred. If there is a component of streamflow that does not come from groundwater then this cannot be simulated with the MODFLOW model described in this manuscript.*

Response:
We calibrated the groundwater flow model to river baseflows, see Sanford (2002). The median values were used to represent a skewed distribution of the observation values. We thank Reviewer for the useful comment. The topic of groundwater recharge estimation is not included in this paper.

*P9748 Lines 16-17:*
*Comment:What is meant by deduced in this context? It would help if the authorsexplained what a tritium measurement in surface water represents?*
Response:
The explanation of the input function derived by Morgenstern and Taylor (2010) has already been provided by Morgenstern et al. (2010), and further discussion is beyond the scope of our manuscript.We will add the Morgenstern et al. (2010) reference to the manuscript.

*P9748 Lines 22-23:*
*Comment:Here again, the authors are making assumptions about what a tritium sample from surface water represents without explaining these assumptions. It seems that due tomixing of a wide range of water (runoff, subsurface stormflow, groundwater flow, hyporheic flow, banks storage, etc.) that matching tritium in surface water would be very non-unique and not provide a very good constraint on the distribution of residence times. A discussion is warranted on these issues in order to propose this approach for model calibration. It is not clear how much information is provided by the tritium data.*
Response:
The tritium sampling in streams was carried out during baseflowconditions, when streamflow is commonly considered to be sourced predominantly from groundwater sources. The hydrological community is somewhat divided on the importance of groundwater sources in supplying streamflow, but our experience with New Zealand streams and the use of tritium in particular on these streams has confirmed our view that groundwater plays a dominant role in supplying baseflow.

*P9749 Lines 22-23:*
*Comment:Please explain why you chose these values, especially the longitudinaldispersivity.*
Response:The dispersivity values are obtained from local tracer studies and published literature. These values are typical forMT3MS transport models, see Lautz and Siege (2006) and were selected as starting values prior to the transport model calibration. The dispersivity and porosity values are constrainedin the model calibration with the use of a groundwater tracer, seeZuber et al. (2011).

*P9751 Line 3:*
*Comment:what aspects of the transport model were fine-tuned?*
Response:The measured tritium values at the bomb-peak served as additional calibration targets of the modeled tritium concentrations. This point can be illustrated in Figure 3. The Kuratau catchment has 1960-1970 and 2001-2007measured tritium data, whilethe other four catchments only had 2001-2007 tritium data. Therefore, the simulated tritium concentrations in Kuratau river catchment are constrained during the bomb-peak by 1960-1970 tritium measurements. The absence of 1960-1970 tritium data for the other four catchments does not allow us to be certain of modeled tritium concentrations during the bomb-peak period. Also, there was no measured tritium data for 1980-1990for all five river catchments. This lack of measured data causes some ambiguity of the modeled tritium values. A similar situation holds in the Northern Hemisphere, where tritium concentrations in groundwater are rapidly declining and have not yet

returned to the natural tritium levels of the pre-bomb era. This means itwill be important to sample tritium concentrations in Northern Hemisphere streams in order to constrain modeled tritium concentrationsin the future, see Stewart et al. (2012).

*P9751 Lines 9-11:*
*Comment:Why doesn't the model match the bomb-peak? Please provide explanation.*
<u>Response:</u>Please see the comment above.For 1960-1970, the modeled tritium concentrations for Kuratau and Whanganui have similar spike in Figure 4, while the modeled tritium concentrations for the Omori river catchment are below and Whaihaha and Whareroa are above the modeled concentrations for Kuratau. These differences in modeled tritium concentrations can be attributed to different flow path in those catchments and it was shown by modeled groundwater age in Figure 5.

*P9753 Lines 1-2:*
*Comment: One cannot model concentrations of nitrate in a stream using a large scale groundwater model. Hyporheic and floodplain zone processes are important processes affecting nitrate concentrations and these processes cannot be simulated with a coarse MODFLOW models as suggested in the manuscript.*
<u>Response:</u>It is standard practice to use groundwater flow and transport models to predict nitrate concentration in streams (Abrahms 2012). Each model cell can be assigned a nitrate attenuation rate that is specific to the stream-aquifer properties represented by that cell. The uniform 80 m horizontal and 20 m vertical cell sizes of our regional model are a relatively fine resolution compared to the typical 100-500 m cell size resolution of regional models. The software limitation and numerical run times did not allow us to select finer grid resolution.However, site-specific hyporheic and floodplain zone processes require DPMswith very fine scale.Lautz and Siegel (2006) represented their study area of 80 km$^2$ by uniform 0.5 m uniform horizontal grid spacing and variable grid spacing with about 1 m vertical discretization and modeled surface and groundwater mixing in the hyporeic zone using groundwater flow MODFLOW and transport MT3DMS models (McDonald and Harbaugh 1988; Zheng and Wang 1999).

*P9753 Lines 11-12:*
*Comment: I assume these are simulated groundwater age distributions, please clarify.*
<u>Response:</u>Yes.,The groundwater age distributions in Figure 4 were obtained by direct simulation using the tritium calibrated MT3DMS model.

*P9755 Lines 5-6:*
*Comment:It is not clear what is "new" about this calibration. Folks havebeen using tracers with MODFLOW and particle tracking for decades. This seems likea very simple trial and error type calibration procedure.*
<u>Response:</u>The Reviewer has missed the purpose of the manuscript, see our opening statement. In our work, we are not inventing a new calibration methodology. Zuber et al. (2011) outlined step-by-step calibration approach of groundwater flow and transport models. Instead, we are demonstrating the use of measured tritium data in streams using the second calibrationapproach outlined by Zuber et al. (2011). Sophisticated calibration techniques with PEST (Doherty 2012) were considered, but could not be used in this study due to Visual MODFLOW limitations (SWS 2010).

*P9755 Lines 17-18:*

*Comment:Measuredhow? This seems strange because measurements of aquifer properties are typicallylocal values and model values represent effective values for large grid blocks.*
Response:Yes, the field values of hydraulic conductivity are typically determined from pump tests and other field studies in the local scale.For large regional models, aquifer parameters obtained from groundwater flow and transport model calibration are usually needed to be within the range of field measured values.

*Technical corrections*
*Comment: Figure 4: These are simulated ages, correct?*
Response:Yes, these are simulated groundwater age distributions with MT3DMS.

*P9751 Line2:*
*Comment:"mode" should be "model"*
Response:We fixed the typo.

*P9752 Line 16: "pattern" should be "patterns".*
Response:We fixed the typo.

## Reviewer 2

General Comments:

*Comment:This study presents a hydrologic transport modeling simulation for the Western Lake Taupo catchment in New Zealand. The work incorporates tritium tracer data into the modeling calibration. While the manuscript is well written and quality of the modelling effort appears high, it is unclear how the tracer data is utilized in model calibration in the current presentation of the work.*
Response:We addressed this comment in our opening statement.

*Comment:This is a major concern as incorporation of tracer (specifically tritium) data in model calibration seems to be the central focus of the study and the central novel aspect. Specifically, at P9751 L1 the authors state that measured tritium values were 'essential' to fine-tune the model. Yet, no information on how calibration was carried out is given. Was some off-the-shelf package used? Was calibration approached in a multi-parameter sense or were parameters handled one at a time? How was the potential information from the tritium tracer balance to the direct information available from groundwater observations and outflows? Incorporation of tracer data into model calibration is an extremely active field of research, so the authors must give more insight to the methodology they are proposing with this study.*
Response:
We followed the second calibration approach described by Zuber et al. (2011) to use sampled tritium concentrations in streams during baseflow conditions. In both approaches by Zuber et al. (2011), a groundwater tracer is required for the groundwater flow and transport model calibration and needs to meet these conditions: 1) defined input concentrations to groundwater system, 2) non-reaction with aquifer materials and dissolved chemicals in groundwater, and 3) accurate measurements at sampling points of monitoring bores and streams. Many groundwater tracers have been sampled in bores and their applicability to characterize groundwater flow and

transport in aquifers is well-established. However, the choice of a calibration tracer is not obvious for streams. The gaseous tracers such as SF6, CFCs, and 3H-3He, which have with well-defined atmospheric concentrations,cannot be easily applied as a calibration tracer for DPMs due to open atmosphere-exchange in stream waters. The dissolved chemicals such as chloride, sulphate, and nitrate measured in stream are lacking input information at the groundwater table and can undergo chemical reactions in the aquifer and stream waters (McMahon et al. 2010).

Tritium seems to be the ideal conservative tracer for the calibration of a transport model. Tritium input concentrations are well established globally from the Global Network of Isotopes in Precipitation, which is run by the International Atomic Energy Agency, including many stations in NZ, the south Pacific, and Australia. As a part of the water molecule, tritium does not react with aquifer materials and is inert to dissolved chemicals and remains. This makes tritium a conservative tracer in groundwater systems apart from radioactive decay and makes tritium useable also when the bomb tritium is not present anymore. Because of its radioactive decay, tritium concentrations in groundwater are still dependent on the travel times even at constant tritium input of background concentrations (Stewart et al. 2012). A similar situation holds in the Northern Hemisphere, where tritium concentrations in groundwater are rapidly declining and have not yet returned to the natural tritium levels of the pre-bomb era.

In our study, we are using off-the shelf package U.S. Geological Survey finite-difference code MODFLOW-2000 (Harbaugh et al. 2000) to model groundwater levels and baseflows, and finite-difference code MT3DMS v. 5.2 to model tritium concentrations in groundwater and baseflows. MT3DMS model was developed by Zhang (1990) on the U.S. Corps of Engineers funding to simulate advection, dispersion, and chemical reactions ofcontaminants ingroundwater systems. The software limitations are presented in the manuscript (P9747L21-25; P9750L11-21) and will be added to “Concluding Remarks” section. We will briefly mention the the standard codes, which can be found elsewhere. For the tritium calibration part, one parameter at a time calibration was adopted. The effect of modeled tritium concentrations on model parametersis discussed on P9751,L21-25; P9752,L1-17. A multi-parameter calibration was conducted, but it was limited due to manual investigations. The details of the tritium calibration will be added to the “Tritium results” and “Concluding Remarks” sections.

*Comment:In the current presentation, the approach appears ad hoc and more-or-less as a trial-and-error method. The title and general presentation of this work leads the reader to expect a detailed explanation outlining a new or novel methodology of how to use tritium tracer data (or perhaps other tracer data) in model calibration. No information is given in this regard. This makes it impossible to judge the calibration procedure or the value added by even considering the tritium data. Beyond being ‘essential’, could there be some quantified metric of the improvement obtained by considering the tracer data? Also, how could one attempt to reproduce the work or apply the procedure to their own datasets without some more information?*
Response:The Reviewer misunderstood the purpose of the manuscript, see our opening statement.

*Comment:In addition to the above, there is apparent disconnect between the measured data and that used in the model calibration. At P9748 L22, it appears that several rivers were monitored for tritium concentrations; however, in Figure 3 only one river appears to be considered. Have I missed something here?*

Response:We did not show the measured values, because those additional points have the same tritium sampling times and would clutter the figure. We will try to incorporate those points in Figure 3 or will add another figure for the other four catchments.

*Comment:Finally, the discussion alludes to the ability to simulate nitrate within the same model framework. It is not explicitly clear how the improvements brought about by considering tritium data translate directly to improvements for nitrate predictions. What is the connection here? Are the parameterizations made to represent tritium movement and decay parallel to those for nitrate? The connection here is rather loose and could be made much stronger and more explicit in the discussion.*
Response:The tritium-calibrated transport model describes the temporal and areal variation of tritium in the system based on the relatively well-known temporal and areal input of tritium. The same model can then be applied to nitrate concentrations for different nitrate input scenarios and the outputs compared with measured nitrate concentrations (with corrections if required for processes specific to nitrate, such as nitrate reduction in specific parts of the system).Abrahms (2012) discusses nitrate contribution to streams using a spatial distribution of nitrate loading with groundwater transit time distributions obtained from the MODFLOW/MODPATH distributed parameter model. In our case, we can use our tritium calibrated MODFLOW/MT3DMS model to simulate the groundwater nitrate concentrations contributing to streams with the groundwater flow.

Minor comments:

*Page 9, line 136:*
*Comment:P9748L1: can the authors motivate the reasoning and validity of multiplying recharge values by 0.88? Is this more than a 'fudge factor' to correct a bad model?*
Response:Adjusting groundwater recharge values is an important part of calibration of groundwater flow models. Any calibration could be called a 'fudge factor', that is how calibration works.

## **References:**

Abrams, D.: Generating nitrate response functions for large regional watersheds, PhD Thesis, Indiana University, Bloomington, 85 p., 2012.

Boronina, A., Renard, P., Balderer, W., Stichler, W.: Application of tritium in precipitation and in groundwater of the Kouris catchment (Cyprus) for description of the regional groundwater flow. Applied Geochemistry, 20, 1292–1308, 2005, doi:10.1016/j.apgeochem.2005.03.007.

Eberts, S. M., Böhlke, J. K., Kauffman, L. J., Jurgens, B. C.: Comparison of particle-tracking and lumped-parameter age-distribution models for evaluating vulnerability of production wells to contamination. Hydrogeology Journal, 20, 263–282, 2012, doi:10.1007/s10040-011-0810-6

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G.: MODFLOW-2000, the U.S. Geological Survey modular ground-water model — User guide to modularization concepts and the Ground-Water Flow Process, Open-File Report 00-92, U.S. Geological Survey, 2000.

Lautz, L.K. and Siegel, D.I.: Modeling surface and ground water mixing in the hyporheic zone using MODFLOW and MT3D. Advances in Water Resources, 29, 1618-1633, 2006.Doi: 10.1016/j.advwatres.2005.12.003

McDonald, M.D. and Harbaugh, A.W.: A modular three-dimensional finite-difference flow model. Techniques of Water Resources Investigations of the U.S. Geological Survey, Book 6, 1988.

McDonnell, J.J.:Where does water go when it rains? Conceptualizing runoff processes in headwater catchments, Birdsall-Dreiss Distinguished Lecture, Session #196, 2011 GSA Annual Meeting, Minneapolis, October 8-12, 2011.

Sanford, W.: Recharge and groundwater models: an overview. Hydrogeology Journal, 10, 110–120, 2002, DOI 10.1007/s10040-001-0173-5.

Stewart, M.K., Morgenstern, U., McDonnell, J.J., and Pfister, L.: The 'hidden streamflow' challenge in catchment hydrology: a call to action for stream water transit time analysis, Invited Commentary, Hydrological Processes, 26, 2061-2066, 2012.

Szabo, Z., Rice, D.E., Plummer, L.N., Busenberg, E., Drenkard, S.: Age dating of shallow groundwater with chlorofluorocarbons, tritium helium 3, and flow path analysis, southern New Jersey coastal plain. Water Resources Research, 32(4), 1023-1038, DOI: 10.1029/96WR00068, 1996.

Plummer, L.N., Rupert, M.G., Busenberg, E., Schlosser, P.: Age of irrigation water in ground water from the Eastern Snake River Plain Aquifer, south-central Idaho. Groundwater, 38(2), 264-283, DOI: 10.1111/j.1745-6584.2000.tb00338.x, 2000.

Morgenstern, U., Stewart, M., Stenger, R.: Dating of streamwater using tritium in a post nuclear bomb pulse world: continuous variation of mean transit time with streamflow. Hydrol. Earth Syst. Sci., 14, 2289–2301, 2010, doi:10.5194/hess-14-2289-2010.

Zuber, A., Kania, J., Rozanski, K. and Purtschert, R.: On some methodological problems in the use of environmental tracers to estimate hydrogeologic parameters and to calibrate flow and transport models, Hydrogeology Journal, 19, 53-69, 2011.

Zheng, C. and Wang, P.P.: MT3DMS: a modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems: documentation and user's guide, Report SERDP-99-1, 221 p., 1999.