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Reply to "Comment on groundwater age, life expectancy and transit time distributions in advective–dispersive systems: 1. Generalized reservoir theory" by Timothy R. Ginn

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We thank T.R. Ginn for his interest in our recently published article [1] on the subject of groundwater age modelling and reservoir theory. In his previous comment [4], T.R. Ginn expresses concern about some conceptual inconsistencies in the formulations presented in our work. We basically agree with the fundaments of his comments, and we wish to continue the discussion.

The first part of T.R. Ginn's comment relates that our definition of the groundwater age pdf, $g_A = g_A(\mathbf{x}, t)$, requires distribution over a specific probability space. This is what one can find in his article of 1999 [3], in which the age pdf is distributed over the age dimension, say τ, such that $g_A = g_A(\mathbf{x}, t, \tau)$ corresponds to the transient age pdf, which may fluctuate along the time coordinate t when, for example, significant flow modifications occur. The main motivation which led us to work with steady-state age pdfs, related to steady-state flow regimes, is to be able to benefit from both forward and backward residence times in the context of the reservoir theory, and further more to combine these two variables (age and life expectancy as defined in [1]) for calculating total residence time distributions within the aquifer. This strong hypothesis might have been more emphasized in our article, in order to make a clear distinction between the special case of the (steady) groundwater age distribution we have presented, and the general case of the transient age distribution presented by Ginn [3], and others (e.g. see [2]). We fully agree with the fact that, on the one hand, "steady-state flow does not necessarily yield steady-state groundwater ages" and that, on the other hand, simulating the transient evolution of groundwater age distributions in the time coordinate t can be of high importance, depending on the hydrogeological problematic. However we have the conviction that we explicitly stated in our article that we make the hypothesis of steady-state velocity fields within which the age pdfs at any location of the system are at equilibrium. With this we mean that a steady-state flow regime is installed since at least the time-span required by the slowest particle to reach the most remote discharge zone. Given that, and as pointed out in the previous comment, the time coordinate t and the age dimension τ can be taken as identical, and thus the transport equation for the steady-state age pdf results in an advection–dispersion equation of transient nature. On this occasion, we also wish to mention our lack of comprehension about T.R. Ginn's choice of using steady-state velocity fields as an assumption for introducing the general equation for groundwater age transient-state distributions (Eq. (14) in [3]). To our point of view, this general equation then loses somehow its generality, since it just can be used to simulate the temporal evolution of the age pdf towards an equilibrium state in an equilibrated flow regime. Finally, it seems obvious that, since we use the steady-state groundwater age distribution equation from the beginning until the end of our article, the derivation of temporal moment equations from this equation can only yield steady-state

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moment equations, as for instance the steady-state form of the mean age equation already introduced by Spalding [6], and latter on by Goode [5], Varni and Carrera [7], or Ginn [3], with extension to transient-state.

The second comment of T.R. Ginn focuses on the way we introduced age as a random variable, even though the adopted models remain fully deterministic (as mentioned in the first sentence of our abstract), i.e. without any randomness of the parameters and boundary conditions. Firstly, we may argue that the term "probabilistic" can have various significances and that in any case, the function g_A makes it possible to calculate, for example, a probability that the age of water lies between two given values (say t_1 and t_2) or alternatively the fraction of the molecules in a water sample with ages contained in the time interval $\Delta t = t_2 - t_1$. Our boundary value problems are conditioned by the use of a time-Dirac delta function for the zero-age flux condition, the Dirac function being by definition a statistical distribution. Consequently, it seems logical to us to report the calculated distribution of groundwater age by a probability density function, or statistical frequency distribution, and to make use of classical elements of descriptive statistics and probability. Secondly, even if this has not been a subject in our article, nothing prevents the modeller from adding randomness in the characterization of parameters and/or boundary conditions in order to carry out a probabilistic analysis of groundwater age. Moreover, as in Ginn [3], our models are of advective and dispersive type (excluding reaction terms), and they make use of the Fickian constitutive theory for diffusion and dispersion to express diffusive flux as a way of describing diffusive and pore-scale dispersive processes. We do not think that the choice between a fully stochastic approach or a classical deterministic approach employing macro-dispersion as a way of accounting for the uncertainty in the transport prediction (mixing) is a subject that needs to be debated further in the present discussion.

To conclude the present reply, with complete awareness of the strong hypotheses inherent in our article (which to our point of view have been justified enough with respect to the aim of our work) we think that T.R. Ginn's comments can put light on some confusion that could arise from a lack of distinction between the age probability space and the time coordinate, and are beneficial for any future attempt of expansion of our approach.

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