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Threshold groundwater ages and young water fractions estimated from ^{3}H, ^{3}He, and ^{14}C

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It is widely recognized that a water sample taken from a running stream is not described by a single age, but rather by a distribution of ages. It is less widely recognized that the same principle holds true for groundwaters, as indicated by the commonly observed discordances between model ages obtained from different tracers (e.g., ^{3}H vs ^{14}C) in the same sample.

Water age distributions are often characterized by their mean residence times (MRT's). However, MRT estimates are highly uncertain because they depend on the shape of the assumed residence time distribution (in particular on the thickness of the long-time tail), which is difficult or impossible to constrain with data. Furthermore, because MRT's are typically nonlinear functions of age tracer concentrations, they are subject to aggregation bias. That is, MRT estimates derived from a mixture of waters with different ages (and thus different tracer concentrations) will systematically underestimate the mixture's true mean age.

Here, building on recent work with stable isotope tracers in surface waters [1-3], we present a new framework for using ^{3}H, ^{3}He and ^{14}C to characterize groundwater age distributions. Rather than describing groundwater age distributions by their MRT, we characterize them by the fraction of the distribution that is younger or older than a threshold age. The threshold age that separates "young" from "old" water depends on the characteristics of the specific tracer, including its history of atmospheric inputs. Our approach depends only on whether a given slice of the age distribution is younger or older than the threshold age, but not on how much younger or older it is. Thus our approach is insensitive to the tails of the age distribution, and is therefore relatively unaffected by uncertainty in the distribution's shape.

Here we show that concentrations of ^{3}H, ^{3}He, and ^{14}C are almost linearly related to the fractions of water that are younger or older than specified threshold ages. These "young" and "old" water fractions are therefore immune to the aggregation bias that afflicts MRT estimates. They are also relatively insensitive to the shape of the assumed residence time distribution. We apply this approach to ^{3}H and ^{14}C measurements from $\sim$5000 wells in $\sim$200 aquifers around the world. Our results show that even very old groundwaters, with ^{14}C ages of thousands of years, often contain significant amounts of much younger water, with a substantial fraction of their age distributions younger than $\sim$100 years old. Thus despite being very old on average, these groundwaters may also be vulnerable to relatively recent contamination.

[1] Kirchner J.W., Aggregation in environmental systems: Catchment mean transit times and young water fractions under hydrologic nonstationarity, *Hydrology and Earth System Sciences*, in press.

[2] Kirchner J.W., Aggregation in environmental systems: Seasonal tracer cycles quantify young water fractions, but not mean transit times, in spatially heterogeneous catchments, *Hydrology and Earth System Sciences*, in press.

[3] Jasechko S., Kirchner J.W., Welker J.M., and McDonnell J.J., Substantial young streamflow in global rivers, *Nature Geoscience*, in press.