DETERMINATION OF BASE FLOW RESIDENCE TIMES WITHIN THE PIEDMONT PROVINCE OF GEORGIA USING LONG-TERM TRITIUM (^{3}H)VARIATION

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Abstract. An algorithm utilizing measured temporal tritium (^{3}H) variation in selected Piedmont basins is developed for the computation of subsurface residence times of shallow ground water comprising stream base flow. This algorithm accounts for the effects of radioactive decay, the mixing of shallow subsurface water with precipitation, and ground-water flux to streams (base flow). The input data required include at least two ^{3}H measurements made at least a decade apart in base flow for a given stream and the long-term ^{3}H input in regional precipitation. The resulting residence times (which are the inverse of the ground-water flux to stream base flow) are sensitive to small changes in measured ^{3}H concentrations. The accuracy of modeled residence times is limited by analytical uncertainties in the measurement ^{3}H to ~±5 years. ^{3}H concentrations within the Upper Oconee and Ocmulgee Basins in the Georgia Piedmont Province varied between 20-30 T.U. during the early 1990s. These concentrations have declined to ~5-10 T.U. in the mid-2000s. ^{3}H input to these basins from precipitation has been generally < 6 T.U. during the interval between sampling periods. Model results indicate that the best fitting residence times of stream base flow in these Piedmont basins is between 14-18 years. These values are consistent with ground-water residence times determined by tritium-helium dating.

BACKGROUND

Tritium (^{3}H) generated by the atmospheric testing of thermonuclear weapons during the 1950s and 1960s has long been used to trace and age-date water throughout the subsurface. The utility of ^{3}H as an indicator of ground-water age is based upon its occurrence as part of the water molecule and its half-life of 12.4 years. A new method for utilizing decadal scale ^{3}H variation for modeling the residence time of shallow ground water in stream base flow is described and applied to streams within the Upper Ocmulgee and other nearby basins within the Georgia Piedmont. Stream water is the dominant drinking water resource within the Piedmont Province. Base flow on average comprises ~50% of total annual stream flow and in dry years provides ~70-80% of the total stream flow within this region (Rose and Fullagar, 2005). Constraining the base flow residence time can lead to a better understanding of ground-water flux rates, the hydraulic properties of the regolith and other important aspects of Piedmont hydrology.

METHODS

Forty-seven stream base flow samples from the Ocmulgee Basin (Yellow River, Ward Creek, Pole Branch Creek, and Falling Creek) were analyzed for ^{3}H content during the early 1990s (Rose, 1993 and 1996). Thirty-three similar samples were acquired from these basins and several additional streams within the Chattahoochee and Oconee basins during the period between 2003-2006 (Rose, 2006). Stream samples were collected under base flow conditions using a polypropylene sampler and major ion solute concentrations were determined by conventional methods (Rose, 2006).

^{3}H concentrations within the earlier and later sets of samples were measured respectively by the Alberta Environmental Isotope Center and the University of Waterloo Environmental Isotope Laboratory. Both laboratories used electrolytic tritium enrichment methods followed by beta-counting that produced comparable results. The reported errors (±1 std. dev.) associated with these measurements were typically < 1.5 T.U. (1 T.U. = 1 Tritium Unit = 1tritium atom in 10^{18} atoms of hydrogen in water). ^{3}H input concentrations in past rainfall from the period between 1962-2004 were acquired from the USGS (Robert Michel, 2005 personal communication). These input data were averaged from the major southeastern U.S. monitoring locations (Washington D.C., St. Louis, Cape Hatteras, and Ocala) and recent data from the Panola Mountain Research Watershed near Atlanta.

ALGORITHM DESCRIPTION

A simple mixing model (shown in Figure 1) was devised to analyze the effects of past ^{3}H input, radioactive decay, and the steady-state flux of shallow ground water to stream base flow. The flux of water [q] (proportional to the volume of the subsurface storage reservoir [V]) is used as follows to calculate a mean residence time [t_{mean}] of ground water comprising base flow:

$$t_{mean} = V/q \qquad [1]$$

It is likely that a variable mixture of more than one year of rainfall is input to the saturated zone from the vadose zone. This uncertainty is incorporated by the creation of an “upper precipitation reservoir” that is roughly analogous to the vadose zone. This reservoir receives a mixture of decay-corrected rainfall ranging from 0-30 years. This age range is *not* equivalent to the “residence time” of ground water in the saturated zone or “mixing reservoir”. It was determined that the age of water in this upper reservoir had little effect upon modeled residence times and a 20-year mixture of decay-corrected rainfall was used for most modeling scenarios.

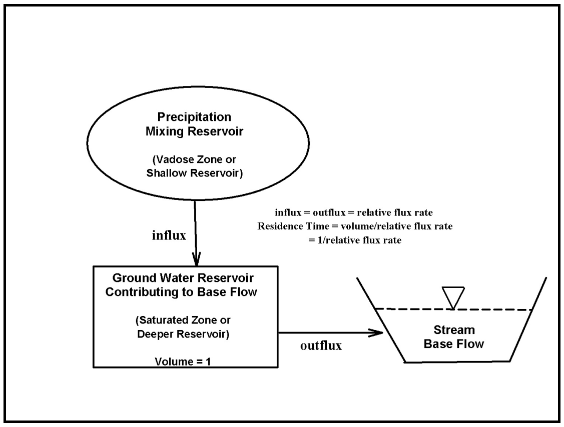

Figure 1. Schematic of mixing model employed in algorithm

The algorithm devised for estimating residence times of shallow base flow is summarized by the following equation:

$$^3H_{ts} = \{(1-q')\,^3H_{ts-1}[e^{-\lambda(ts)}]\} + q'\,^3H^*_{ts} \qquad [2]$$

where:
$^3H_{ts}$ = [^3H] in the “mixing reservoir” at a given time step
$^3H_{ts-1}$ = [^3H] in the “mixing reservoir” at previous time step
ts = time step
$^3H^*_{ts}$ = ^3H input concentration in “influx” reservoir
λ = decay constant for ^3H (12.41 y)
q’ = relative flux = volume of water in flux during a given period of time relative to total volume of water that is stored in the saturated zone (mixing reservoir)

Equation 2, although linear, does not explicitly account for the type of mixing that occurs within either the saturated or unsaturated zones. The algorithm merely facilitates the mixing of a given fractional input of water from the vadose zone (q’) with a complementary fractional volume of water that has been previously stored in the saturated zone. This algorithm is used to derive a modeled $^3H_{ts}$ concentration at a series of time steps. Although residence time does not explicitly appear in Eqn. 2, it is equivalent to the inverse of the relative flux (q’). For example, given an annual relative flux of 0.1 from the upper reservoir to the saturated reservoir (which due to steady-state considerations is equal to the relative flux from the saturated reservoir to base flow), the residence time for ground-water base flow is 10 years.

The model tritium concentrations ($^3H_{ts}$) were computed for a range of volume replacements (q’) typically between 0.2 (i.e. a residence time of 5 years) and 0.02 (residence time = 50 years).Typically 15 time-steps were used for each flux rate to represent the period between the end of 1991 and the beginning of 2005, bracketing the period of sample collection.

RESULTS AND DISCUSSION

Tritium concentrations within study area stream base flow varied between ~ 15-30 T.U. during the early 1990s. By the middle 2000s these concentrations declined to ~6-10 T.U. (Table 1) and there was no longer significant seasonal variation at a given location, as was the case during the earlier sampling period. ^3H concentrations in southeastern precipitation during the past two decades have declined to near background values and decay-corrected values have been typically <6 T.U.

The resulting relationship between modeled ^3H concentrations (i.e. those at the final time step) versus residence time (inverse of flux) resembles a logarithmic function (see Figures 2 and 3). High rates of flux (short residence times) result in low ^3H concentrations in that base flow would be comprised of a high proportion of recently recharged, tritium deficient rainfall. Conversely, low rates of flux would be characterized by relatively high proportion of bomb test-era ^3H. The model results show that seemingly small differences of ^3H (~5 T.U.) at the final time-step correspond to a significantly large difference in associated residence times (i.e. ~50 years). Given enough time (i.e. >100 years) the curves shown in Figures 1 and 2 would eventually bend down and approach zero. However, there is independent evidence that suggests shallow ground water in this setting is far younger than this and therefore the “tailing” end of these curves was not considered.

The algorithm was tested for its sensitivity to the inherent uncertainties associated with measuring ^3H concentrations at low concentrations. The results for Ward Creek, a first-order stream in the Upper Ocmulgee basin, were used to test the effects of this and other uncertainties.

The reported ^{3}H concentration for this was stream in 2005 was 7.7 ± 0.8 T.U. This error is typical of the precision inherent to beta-counting methods. The model ages that correspond to ^{3}H concentrations between 6.9 and 8.5 T.U. are between 14 and 24 years with a best fit residence time (corresponding to 7.7 T.U.) of 18 years (Figure 2). The ten-year range of ages associated with the analytical error approximates the limits of accuracy inherent in this model.

Table 1. Summary of Tritium Concentrations within Stream Base Flow Within the Georgia Piedmont Province

Basin	**Period**	**Average ^{3}H [T.U.]**	**Range ^{3}H [T.U.]**
Upper Ocmulgee[1]	1990-1991	21.9	17.3 - 30.7
Lower Ocmulgee[2]	1991-1993	18.4	13.4 - 21.1
Upper Ocmulgee[3]	2005	7.1	6.8 - 7.1
Lower Ocmulgee[4]	2005	5.9	----
Chattahoochee[5]	2005-2006	7.5	6.1 - 9.1
Middle Oconee[6]	2003 - 2004	10.2	7.3 - 16.6
Basins and Streams Sampled (n = number of samples)			
Upper Ocmulgee[1]: Yellow River, Ward Ck., Pole Branch Ck. (n = 32)			
Lower Ocmulgee[2]: Falling Creek (n =16)			
Upper Ocmulgee[3] Yellow River, Ward Ck., Pole Branch Ck. (n = 3)			
Lower Ocmulgee[4]: Falling Creek (n =1)			
Chattahoochee[5]: South Peachtree Ck., Nancy Ck. Peachtree Ck., Snake Ck., Olley Ck., Burnt Fk. Ck., Chattahoochee River at Franklin, Chattahoochee River at College Park (n = 8)			
Middle Oconee[6]: Oconee River, Indian Ck., Pond Fork Ck. (n = 22)			

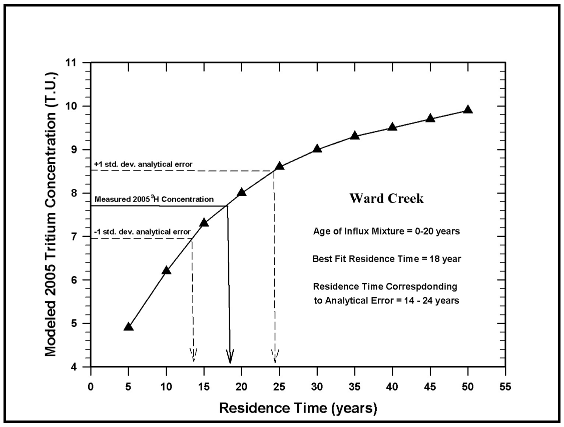

Figure 2. The effects of analytical measurement error on modeled ages for Ward Ck. base flow

Other uncertainties include our imperfect knowledge of ^{3}H concentrations in base flow during the past. Although numerous ^{3}H measurements were made during the 1990s, the inherent seasonal variability prevalent during that period precludes the input of a definitive "initial" ^{3}H concentration to these models. For example, the average ^{3}H concentration for nine measurements of Ward Creek base flow during 1991 was 23.1 ± 2.9 T.U. This standard deviation was used to test the effects of variability with respect to the "initial" ^{3}H input to the model. The resulting range of modeled ages varied between 14 and 27 years.

The age of water within the upper "precipitation mixing reservoir" (akin to the vadose zone, see Figure 1) is not certain; however, it is highly likely that it represents a multi-year mixture. In order to test the effects of this uncertainty, a range of mixtures varying between 0-30 years was used as input. The precipitation input to this region has been nearly constant for the past several decades and hence the effects of uncertainty with the respect to the age or ^{3}H content of the vadose zone resulted only in five years of difference between the modeled residence times of base flow for Ward Creek.

Ward Creek, Pole Branch Creek, and the Yellow River are within 10-20 kilometers of each other in the Upper Ocmulgee Basin and these streams were well-monitored for ^{3}H in the 1990s. Over long-term intervals the rainfall input to these hydrogeologically similar basins is assumably nearly identical. Therefore these three basins provide the best set of samples to test this model and for interpretation of its results. The measured ^{3}H concentrations for base flow in these basins during the 2005 sampling period varied only between 6.8 and 7.7 T.U. When these values were input along with the 1991 "initial" values, the resulting model ages were between 14-18 years (see Figure 3). This is less than the variation resulting from the analytical uncertainty of measuring ^{3}H. The fact that this model resulted in such a concordant set of residence times for these three hydrogeologically similar basins is encouraging.

A slightly modified model was constructed for Ward Creek using 1950 as the "initial" year with a ^{3}H concentration of zero. The "final" year used for calibrating residence times was 1991. The modeled ^{3}H concentrations for Ward Creek base flow for this earlier period were nearly identical to the measured ^{3}H concentrations when the average residence time was 15 years. In short, both periods (1950-1991 and 1991-2005) produced concordant residence times when the appropriate sets of ^{3}H concentrations were input to this model. The computed range of residence times for base flow within the Upper Ocmulgee basin (14 -18 years) compare favorably with the limited set of tritium-helium ages made within shallow ground water at the Panola Research Mountain Watershed test site. This age range was between 6-26 years (Burns et al.,2003).

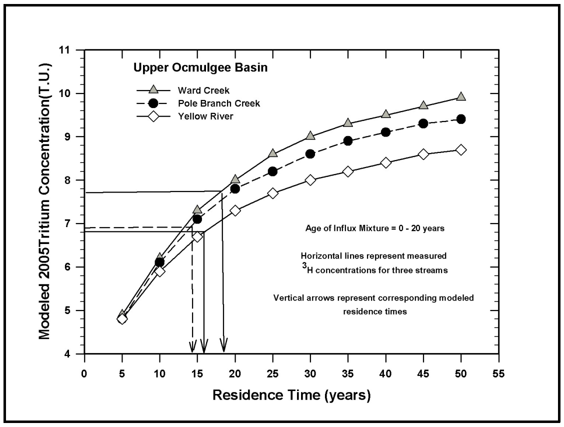

Figure 3. Modeled ^{3}H concentrations and corresponding residences times for base flow within the Upper Ocmulgee Basin.

SUMMARY AND CONCLUSIONS

We are now approaching the end of the "bomb-era" and atmospheric tritium concentrations have approached background levels. One way in which environmental tritium can still be used to quantify the residence time of ground water is to compare present concentrations of ^{3}H with past measurements in those locations where such data exist. This investigation is one of the few which have utilized ^{3}H data from two different decades in order to compute the average residence time of shallow ground water comprising stream base flow.

The algorithm used for these computations was based upon the mixing of an "upper reservoir" of decay-corrected multi-year precipitation with a "lower reservoir" comprising the saturated ground-water component to base flow. The model is steady-state in that the flux rate from the upper reservoir is equivalent to the flux from the saturated zone to base flow. The inverse of this flux rate represents the mean residence time of ground water comprising base flow.

The model produced a highly concordant set of residences times for shallow ground water from three streams within the Upper Ocmulgee Basin. Tritium concentrations generally exceeded 20-25 T.U. in the early 1990s and have declined as a result of radioactive decay and mixing with younger and relatively tritium-deficient precipitation. In the mid-2000s ^{3}H concentrations have declined to < 10 T.U. within the Chattahoochee, Ocmulgee, and Oconee basins in the Georgia Piedmont. The best range of model ages consistent with these measured values is between 14-18 years; however a range of 10-20 years is certainly plausible when considering analytical errors and other uncertainties. This age range is consistent with residence times determined by tritium-helium dates derived for shallow ground water in Panola Mountain watershed as determined by Burns et al., 2003.

Most previous isotopic studies of shallow ground water and stream water in the southeastern U.S. (e.g. Michel, 2004) have derived residence times of ~1-10 years. The longer residence times (10-20 years) computed in this study might have resulted from the significant amount of water retention that occurs within the clay-rich soils that serve as storage reservoir for shallow ground water within the Georgia Piedmont Province.

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REFERENCES CITED

Burns, D.A., Plummer, L.N., McDonnell, J.J., Busenberg, E., Casile, G.D., Kendall, C., Hooper, R.P., Peters, N.E., Beven, K., and Schlosser, P. 2003. The geochemical evolution of riparian ground water in a forested Piedmont catchment. *Ground Water* 41: 913-925.

Michel, R.L., 2004. Tritium hydrology of the Mississippi River Basin. *Hydrol. Process.*. 18: 1255-1269.

Rose, S. 1993. Environmental tritium systematics of baseflow in Piedmont Province watersheds, Georgia (USA). *J. of Hydrol.* 143: 191-216.

Rose, S. 1996. Temporal environmental isotopic variation within the Falling Creek (Georgia) watershed: implications for contributions to streamflow. *J. of Hydrol.* 174: 243-261.

Rose. S. 2006. A strontium isotopic investigation of possible sewage influx to stream base flow in the Atlanta Metropolitan Region. *Ga. Water Res. Inst. Tech. Comp. Rept. B-02-645-G8.*

Rose, S. and Fullagar, P.2005. Strontium isotope systematics of base flow in Piedmont Province watersheds, Georgia (USA), *Appl. Geochem.* 20:1571-1586.