Understanding transit times in dynamic environments

Ian Cartwright (Monash University)

Here are some ideas that I was going to discuss at EGU2020. I have not tried to replicate the presentation or write a paper, but just to present a few thoughts and hopefully stimulate some discussion.

There have been many studies that have estimated the mean transit times of water that contributes to streamflow. Techniques that compare the degree of attenuation of stable isotope ratios or Cl concentrations between rainfall and the stream commonly using lumped parameter models (Hrachowitz et al., 2010; Kirchner et al., 2010; Maloszewski, 2000; McGuire and McDonnell, 2006). There are several well-recognised potential issues with this approach, such as:

- Whether this approach misses the contribution of older water (McDonnell et al., 2010; Stewart et al., 2010)
- The impact of mixing of water with distinctly different ages (aggregation) (Kirchner, 2016a)
- The availability of long and detailed monitoring data

This approach also commonly is used to estimate a single mean transit time for a catchment, whereas streamflow may be sustained by water with different transit times at different conditions (intuitively one would expect younger water to sustain streamflow during the wetter months as the catchments "wet up"). This presents an issue for the use of lumped parameter models based on seasonal tracer cycles (Kirchner, 2016b). More importantly, documenting how mean transit times vary over the hydrological cycle helps determine how catchments respond to rainfall both over longer timescales (months to years) or during individual high flow events.

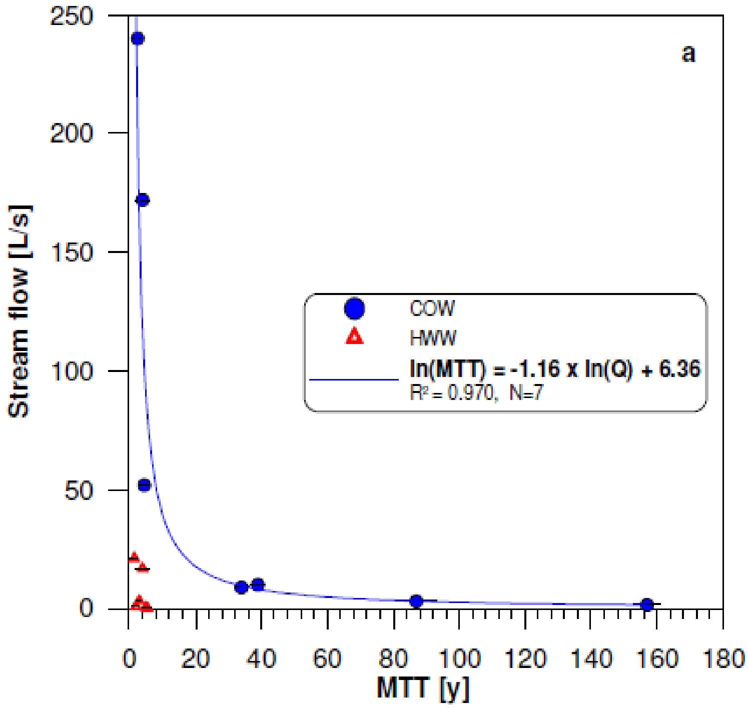
In the southern hemisphere, lower levels of atmospheric tritium (^{3}H) were released during the 1950s and 1960s nuclear tests (the bomb-pulse) than in the northern hemisphere. The relic bomb-pulse ^{3}H activities in southern hemisphere waters have now largely decayed to levels below those of modern rainfall (Morgenstern et al., 2010). This allows ^{3}H to be used in a more straightforward manner to estimate residence or transit times from individual samples in a similar way to how other radioisotopes (e.g. ^{14}C or ^{36}Cl) are used in much older waters. This analysis often employs similar lumped parameter models (although numerical models such as FeFlow can also be used: Cartwright et al., 2018b); however, it is the decay of ^{3}H that is used to estimate transit times not the smoothing of an input function. Several of the issues outlined above remain (especially aggregation: Stewart et al., 2017) and there are questions around the importance of seasonal recharge that can have significantly different ^{3}H activities to annual activities (Morgenstern et al., 2010). It is also not possible to use time series ^{3}H observations that commenced in the last few years to assess the reasonableness of the lumped parameter model as the ^{3}H vs. time trends (as the various lumped parameter models produce closely similar trends (Cartwright and Morgenstern, 2015).

The calculated mean transit times have significant uncertainties (probably 25 to 30% even under ideal conditions); however, the fact that water with higher ^{3}H activities is younger than water with lower activities is useful. Below there a few examples of how this has been applied to stream waters in southeast Australia and New Zealand. Especially in the Australian catchments, the mean transit times at low streamflows are commonly a few decades to centuries (probably due to high evapotranspiration rates that limit recharge and the high storage capacity of the deeply-weathered regolith). Mean transit times at higher streamflows may also be several years. The use of combined geochemical tracers suggests that different water stores from within the catchments (e.g. soil water, perched water tables, and interflow) augment baseflow during high flows (Cartwright et al., 2018a, 2020; Cartwright and Morgenstern, 2018; Howcroft et al., 2018).

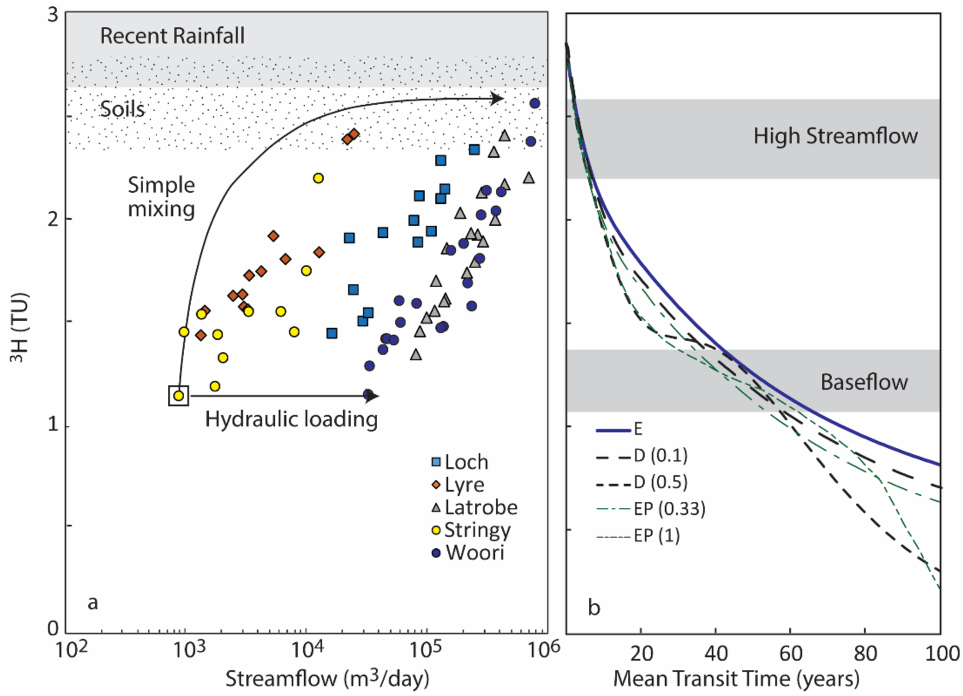
This approach will become possible in the northern hemisphere in the next few years or decades. Even now it is possible to use time-series ^3H to estimate mean transit times at different flow conditions (Gusyev et al., 2016). It would also be desirable to be able to use multiple methods to assess changes to transit times with flow. Perhaps due to the similarity of approach, possible comparison of the results of lumped parameter models applied to ^3H and stable isotopes or Cl is often discussed. However, alternative approaches such as flux tracking (Hrachowitz et al., 2013) or applications of StorAge Selection (SAS) functions (Benettin et al., 2015; Botter et al., 2010) that capture the time-variance of mean transit times mat be more appropriate comparators. There are several questions that such comparisons could address:

- Is there input of older water in the catchments that are not immediately obvious from the flux tracking or SAS analysis (due for instance to attenuation or the length of the input record)?
- What level of temporal variability do the different techniques resolve (intuitively, one would think that the tritium record would record longer wavelength variations)?
- How do the techniques resolve spatial variability in nested catchments (and are these as important as temporal variability)?
- What timescales are interesting and useful for different purposes?
- Should we be making more of an effort to analyse water from the different catchment stores (soils, interflow, groundwater etc) to better understand their contributions at different streamflows?

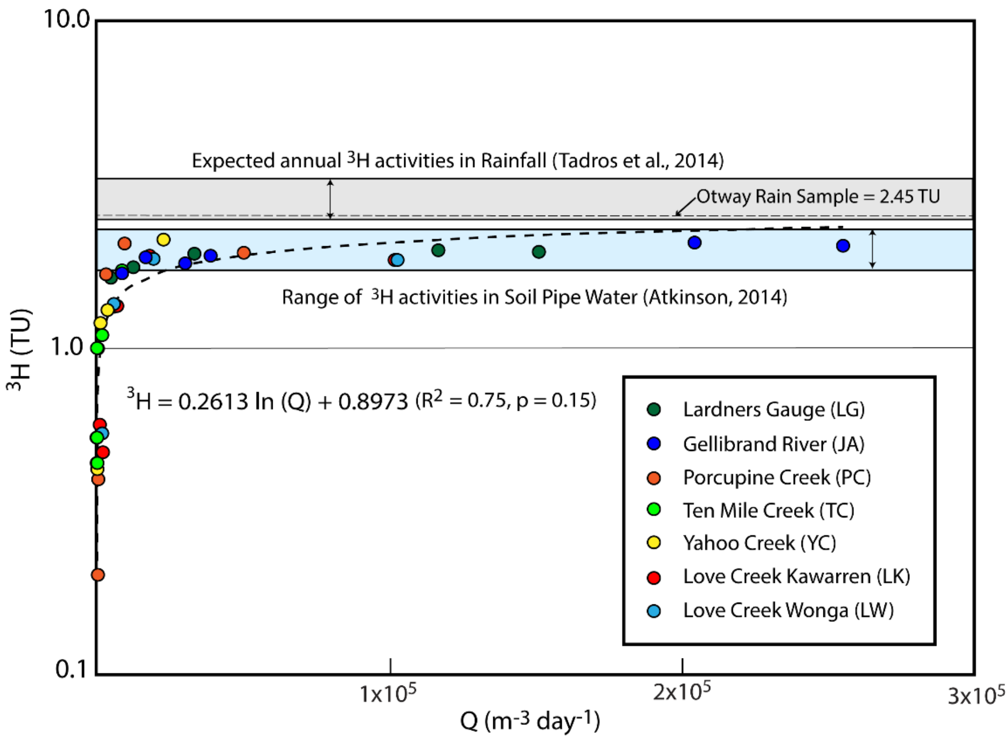
Addressing these may help in the continuing efforts to understand catchments.



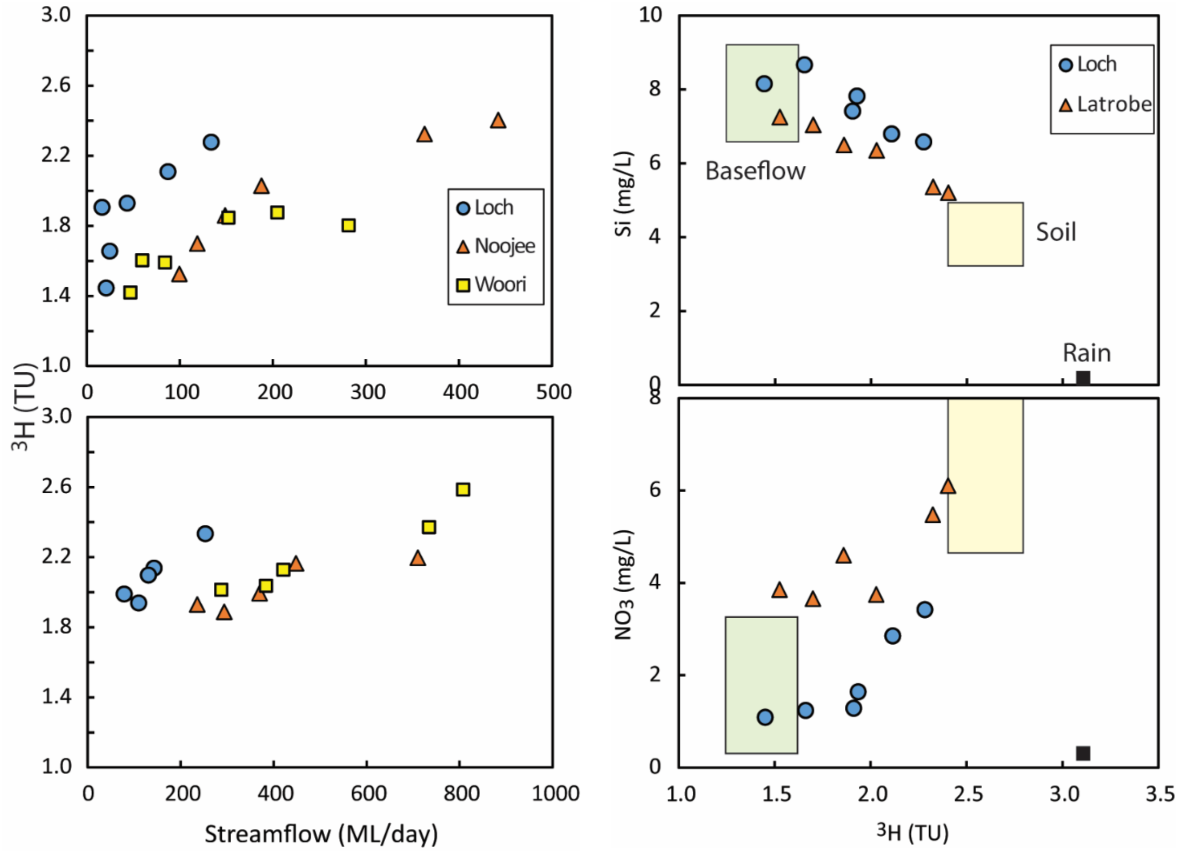
Large variation of mean transit times with streamflow from the Toenepi catchment in New Zealand determined using lumped parameter models (Morgenstern et al., 2010).



Variation of ^{3}H activities vs streamflow and the estimated mean transit times at low and high flows in streams from the Latrobe and Yarra catchments (Australia). Water at the lowest flows has mean transit times of a few decades (Cartwright et al., 2020).



Variation of ^{3}H activities vs streamflow (Q) in the Gellibrand catchment of southeast Australia. The mean transit times of the waters with the lowest ^{3}H activities are <100 years. The maximum 3H activity is always below that of modern rainfall but is similar to water from the soils and macropores (Howcroft et al., 2018).



Variation of ^3H activities vs streamflow over two storm events in the Latrobe and Yarra catchments of southeast Australia. The major ion geochemistry implies that water displaced from the soils may be an important contributor at high streamflows (Cartwright and Morgenstern, 2018).

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