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On the relationships between catchment scale and streamwater mean residence time

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Abstract

The relationship between streamwater mean residence time (MRT) and landscape characteristics is poorly understood. We used tritium (^{3}H) to define our MRT. We tested the hypothesis that baseflow water MRT increases with increasing absolute catchment size at the Maimai catchments. These catchments are simple hydrologic systems relative to many catchments around the world, with uniformly wet climatic conditions, little seasonality, uniform and nearly impermeable bedrock, steep short hillslopes, shallow soils, and well-characterized hillslope and catchment hydrology. As a result, this is a relatively simple system and an ideal location for new MRT-related hypothesis testing. Whilst hydrologists have used ^{3}H to estimate water age since the 1960s nuclear testing spike, atmospheric ^{3}H levels have now approached near background levels and are often complicated by contamination from the nuclear industry. We present results for ^{3}H sampled from our set of nested catchments in nuclear-industry-free New Zealand. Because of high precision analysis, near-natural atmospheric ^{3}H levels, and well-characterized rainfall ^{3}H inputs, we were able to estimate the age of young (i.e. less than 3 years old) waters. Our results showed no correlation between MRT and catchment size. However, MRT was correlated to the median sub-catchment size of the sampled watersheds, as shown by landscape analysis of catchment area accumulation patterns. These preliminary findings suggest that landscape organization, rather than total area, is a first-order control on MRT and points the way forward for more detailed analysis of how landscape organization affects catchment runoff characteristics. Copyright © 2003 John Wiley & Sons, Ltd.

Introduction

Scale issues pervade all aspects of catchment hydrology and biogeochemistry (Blöschl, 2001), and a number of reviews in hydrology have identified scale issues as major unresolved problems in hydrological sciences (e.g. Sivapalan and Kalma, 1995). Theoretical investigations into catchment scaling issues have outpaced field observation and empirical understanding. This is because measurements are often difficult and expensive and empiricists often do not know where to sample or indeed how many measurements are necessary to characterize a given watershed (regardless of scale). Thus, process-level research in catchments has been conducted most often at the headwater catchment scale and then extrapolated to larger scales. However, determining the first-order controls on observations even at this small and relatively simple headwater

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catchment scale has proven difficult. We lack unequivocal empirical evidence to answer basic questions of where water goes when it rains, how long water resides in the catchment, and what flowpath the water takes to the stream channel. Geochemical investigations have suggested that water contact time in the subsurface (mean residence time (MRT)) can be a first-order control on the solute concentration in the channel (Wolock *et al.*, 1997). Although numerous studies have investigated the relationship between hydrological response and basin scale (e.g. Sivapalan *et al.*, 2002), to our knowledge none has addressed the relationship between MRT and catchment size. The MRT of water molecules in a catchment from rainfall to runoff and represents the mean of a distribution of water ages (Maloszewski *et al.*, 1983). Hydrologic response time is a measure of the pressure, or perturbation response time of a catchment and is often used to describe the timing of flood peaks (Jothityangkoon and Sivapalan, 2001). With this in mind, we set out to calculate the MRT of stream baseflow and to examine how baseflow MRT might scale with basin area and other measurable catchment attributes. Although very new and rather preliminary, we hope that this Scientific Briefing may be a catalyst for more work on this important subject.

Site Description

The Maimai research watersheds are located on the west coast of the South Island of New Zealand, along the axis of Powerline Creek, part of the headwaters of the Grey River (Figures 1 and 2). The research area has been the site of ongoing benchmark hydrological research since the early 1970s (McGlynn *et al.*, 2002). The research catchments have been well characterized and successive research at this site has led to the development of a detailed perceptual model of hillslope and catchment hydrology, primarily focused on storm runoff process (Mosley, 1979; Pearce *et al.*, 1986; Sklash *et al.*, 1986; McDonnell, 1990; Woods and Sivapalan, 1999; McGlynn *et al.*, 2002; McGlynn and McDonnell, 2002a,b; McGlynn and Seibert, 2002).

A poorly permeable, well-cemented, early Pleistocene conglomerate known as the ‘Old Man Gravels’ underlies the Maimai catchments. Soils are shallow (~0·6 m), have infiltration rates of 6100 mm h^{-1} (Webster, 1977) and hydraulic conductivities of ~250 mm h^{-1} (Rowe *et al.*, 1994). Hillslopes are short (<300 m) and steep (32°) with local relief of 100 to 150 m. The topography is highly dissected with hillslopes, composed of regular spurs and linear hollows. Stream channels begin typically at accumulated area thresholds of 0·5 ha (McGlynn and Seibert, 2002). Annual precipitation is 2600 mm, of which 64% becomes runoff and 39% exits as quickflow (Sklash *et al.*, 1986). For a detailed review of historical Maimai research and more detailed hydrological analysis, see McGlynn *et al.* (2002). We examine the relationship between catchment scale and MRT at four nested catchments: the 280 ha Bedload catchment, the 80 ha PL14 catchment, the 17 ha K catchment, and the 2·6 ha M15 catchment.

Figure 1. Maimai research site

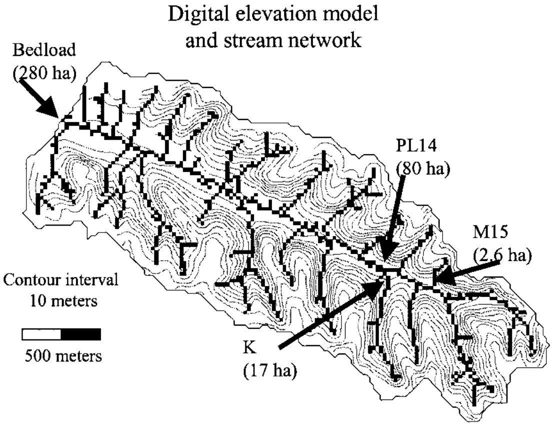

Figure 2. The Maimai valley and selected research catchments

Methods

Tritium has been used to compute MRT since the 1960s, and it has been used for age dating water in two ways: first, as a marker of global tritium peaks that arose principally from nuclear weapons testing in the atmosphere from the 1951 to 1976 (Clark and Fritz, 1997); second, as a decay from a continuous cosmic input. The first approach is now becoming 'past due' as the definition of the bomb peak is diminished due to the relatively short half-life (12·41 years). This is certainly true in our study catchment in New Zealand, where tritium concentrations in the atmosphere peaked in the 1960s and bomb tritium peaks were an order of magnitude lower than in the Northern Hemisphere, disappearing from the New Zealand atmosphere and surface waters by about 1990 (Uwe Morgenstern, personal communication, 2002) (Figure 3). Thus, the New Zealand atmosphere today is close to its pre-nuclear background tritium level (i.e. tritium generated only by cosmic rays in the atmosphere). Although traces of tritium may be present in moisture evaporated from the sea, the lack of any nuclear power plants or similar sources in-country means that contamination of the natural cosmic inputs are slight to negligible. Therefore, the second approach—decay from a continuous cosmic signal—is a viable approach at our research catchment.

One important additional reason supporting the viability of tritium as an age dating tool at Maimai is that the New Zealand Institute of Nuclear and Geological Sciences can achieve a detection limit of 0·03–0·04 TU (95% confidence interval) due to sophisticated tritium enrichment and the low-tritium environment in New Zealand (Taylor, 1994). Before measurement by liquid scintillation counting, we enriched the tritium concentration in samples by a factor of about 80 by means of electrolysis. The enrichment factor was determined accurately for each sample by measuring the deuterium concentration before and after enrichment. Using deuterium to determine the tritium enrichment to higher accuracy reduced errors from ±0·07 TU to ±0·05 TU for tritium concentrations of 2 TU (Uwe Morgenstern, personal communication, 2002). Monthly tritium measurements in rainfall were made at the closest long-term tritium measuring station to our site at Kaitoke, near Wellington, approximately 150 km north of Maimai. These data were used to estimate the tritium input concentrations at Maimai (Figures 3–5). Kaitoke rainfall tritium

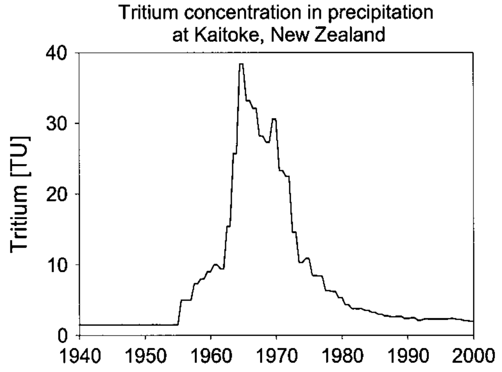

Figure 3. Tritium concentration in precipitation at Kaitoke, New Zealand

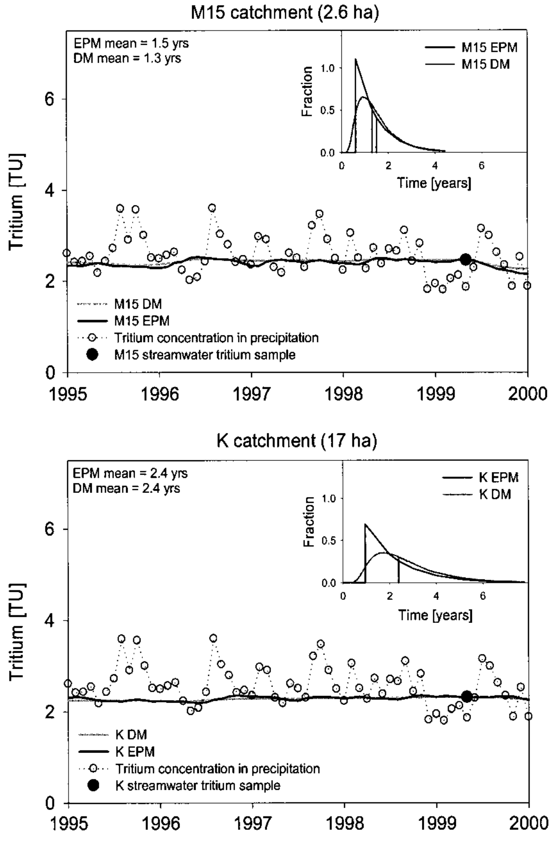

Figure 4. Tritium concentration in precipitation at Kaitoke, New Zealand, scaled by a factor of 1·1. M15 and K catchments exponential piston-flow model (EPM with 60% mixing) and dispersion model (DM) fits and associated mean ages. The stream samples are shown as solid circles. The inset plots show the mean age and age spectra for each model at each catchment

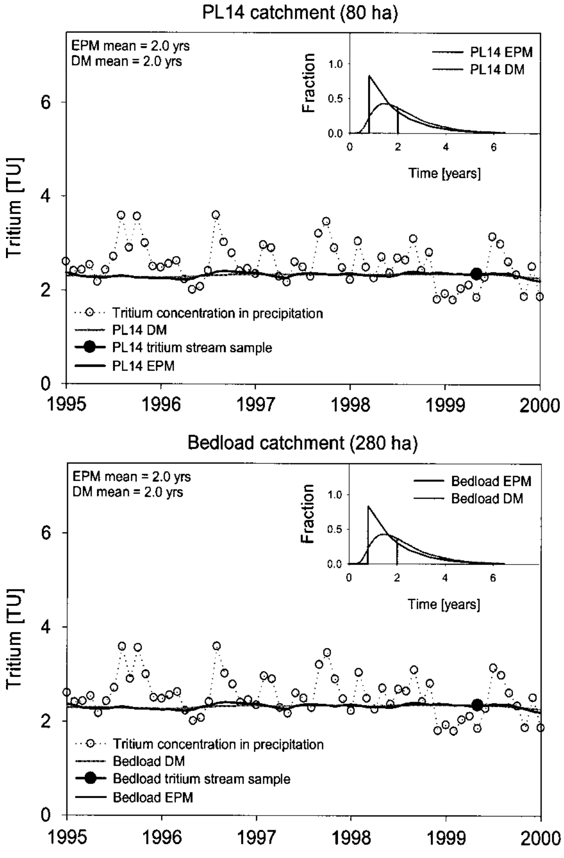

Figure 5. Tritium concentration in precipitation at Kaitoke, New Zealand, scaled by a factor of 1·1. PL14 and Bedload catchments exponential piston-flow model (EPM with 60% mixing) and dispersion model (DM) fits and associated mean ages. The stream samples are shown as solid circles. The inset plots show the mean age and age spectra for each model at each catchment

concentration averaged 2·4 TU for 1995–98. Rainfall at Maimai was estimated to be a factor 1·1 higher in tritium based on a standard latitude adjustment. Hence, tritium concentration was 2·6 TU for Maimai rainfall from 1995 to 1998. The mean streamwater ages were calculated using the standard decay equation, assuming the initial tritium concentration was 2·6 TU:

$$t = -\left(\frac{1}{\lambda}\right)\ln\left(\frac{C_t}{C_0}\right) \qquad (1)$$

$$\frac{1}{\lambda} = 17{\cdot}9 \qquad (2)$$

where t is the mean age, C_0 is the initial concentration, C_t is the concentration after decay for t years, and λ is the decay constant for tritium (Clark and Fritz, 1997). (Note that, even if the initial concentration differed somewhat from this estimate, the relative ages would still be in the same order.)

For the terrain-based portion of the analyses, we used a 20 m digital elevation model to extract catchment area. We then employed the approach of McGlynn and Seibert (2002) to compute the median sub-catchment size for each watershed. Our intention was to highlight the landscape organization and network structure at each catchment scale sampled to explore possible relationships between catchment organization and MRT. The stream network for the Maimai catchments was computed using a creek-threshold-area method using digital data with a grid size of 20 × 20 m^2. Based on field surveys, the creek initiation threshold area was estimated as 0·5 ha. We then determined the local sub-catchment area for each stream segment (i.e. each grid cell flagged as stream). For each of the four catchments, we compiled distribution functions of sub-catchment areas from this spatial information.

Results

The calculated MRTs in Table I are based on the widely used piston-flow model system response function, as described by Maloszewski and Zuber (1996) and reviewed by Turner and Barnes (1998). Comparison between the piston-flow and another widely used system response function, the exponential (i.e. well-mixed) model, showed that the MRTs only begin to diverge for residence times greater than 2 years, for constant initial tritium concentrations. MRT estimates of less than 2 years were effectively the same

Table I. Catchment scale, median sub-catchment area, raw data (TU), mean streamwater age for each catchment sampled, and the uncertainty in computed MRT values due to potential errors in tritium measurements. Each stream was sampled on 30 April 1999

Catchment scale (ha)	Median sub-catchment area (ha)	Streamwater samples ±0·05 (TU)	MRT (years)	Error (±) [years]
280	3·1	2·36	1·7	0·4
80	3·9	2·36	1·7	0·4
17	8·2	2·31	2·1	0·4
2·6	1·2	2·45	1·1	0·4

between the two models. The difference in simulated concentrations was 0·01 TU at 2 years, 0·03 TU at 3 years and 0·04 TU at 4 years for the two mixing models. We focus on the results of the piston-flow model based on average tritium inputs over the period 1995–98, but additionally report results from the exponential piston-flow model and dispersion model applied with monthly tritium input data for corroboration. Inspection of the monthly tritium variations over the 5 years prior to stream sampling (Figures 4 and 5) and simulation with the exponential piston-flow model (60% mixing) and the dispersion model indicates that absolute ages of the stream water are a factor 0·3 years older than those ages calculated using the average tritium input and the piston-flow model, although the relative ages are the same. We argue that even though the detailed month-to-month or storm-to-storm tritium values may be different between the Kaitoke site and Maimai, the 1995–98 average Kaitoke data (multiplied by the scale factor 1·1) are a more reasonable approximation of the pattern of input. Similarly, results from both system response function approaches are shown to demonstrate that the trend in mean ages is comparable regardless of the method chosen. It is important to note, however, that application of these approaches to dating of young waters (<3 years) can probably only be accomplished in maritime areas of the Southern Hemisphere at present. The tritium concentrations in the Northern Hemisphere still have major seasonal variations that are likely to obscure any changes due to decay in a 1–2 year period.

The MRT estimates based on tritium analysis varied between about 1 and 2 years for the four catchments (Table I). We sampled stream baseflow at each of the gauged Maimai catchments during annual low-flow conditions ($\sim$0·04 mm h^{-1}) on 30 April 1999. We found that MRT increased from the M15 catchment (2·6 ha) to the K catchment (17 ha) (from 1·1 years to 2·1 years). However, MRT did not continue to increase with catchment size up to the PL14 (80 ha) and the Bedload (280 ha) catchment scales (both 1·7 year MRTs), suggesting a more complex water age–catchment size relationship. Our results showed no correlation between MRT and absolute catchment size (Table I), as the two largest catchments' MRTs were intermediate between the two smallest catchments' MRTs.

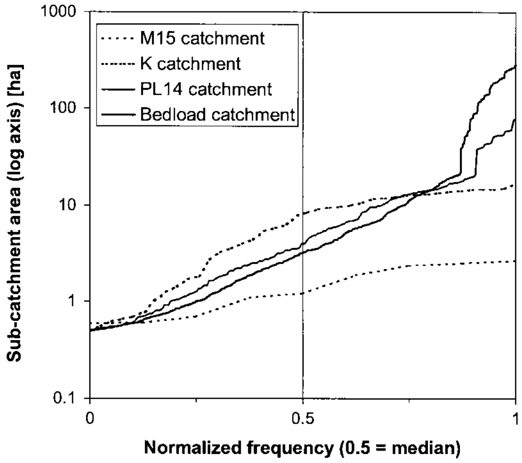

Figure 6. Cumulative normalized frequency distributions of sub-catchment area calculated for each 20 m channel pixel along the stream network for each gauged catchment. Note the logarithmic y-axis scale

Each of the catchments in this study had a different distribution and median of sub-catchment sizes (Figure 6), which were related to the structure of that catchment's drainage network and associated area accumulation pattern. At the smallest catchment scale (M15: 2·6 ha), median sub-catchment size was 1·2 ha. A similar pattern of simple area accumulation along one main channel existed in the 17 ha K catchment (Figure 6). In both the M15 and K catchments, median sub-catchment area was slightly less than half of the total catchment area because of the relatively diffuse accumulation of area along the main channel. Conversely, PL14 (80 ha) and Bedload (280 ha) were comprised of numerous small headwater catchments and exhibited a more complex network structure. The PL14 catchment was comprised of three sub-catchments similar in size to the K catchment (K is nested in PL14); however, two of those sub-catchments exhibited more a complex network structure and were comprised of numerous first-order channels. Most of the catchment area was added to the main channel via tributary junctions that drained small catchments. As a result, the distribution of PL14 sub-catchment sizes was skewed toward small headwater catchments and resulted in a median sub-catchment size of 3·9 ha. The Bedload catchment was comprised of each of the sampled nested catchments (M15, K, and PL14). Sub-catchment area ranged from 0·5 to 280 ha, but was strongly skewed toward small headwater sub-catchments. The median Bedload sub-catchment size was 3·2 ha. Analysis of sub-catchment size frequencies provided insight into characteristics of each sampled catchment: catchment area was not accumulated similarly across scales nor between catchments of similar size, despite a relatively simple network structure.

Using the results of the landscape analysis, we found a positive relationship between the median sub-catchment area measure and the tritium-based MRT estimates (Figure 7). The PL14 and Bedload catchments had similar median sub-catchment areas despite a 200 ha difference in total catchment area. The MRT was also similar for the PL14 and Bedload catchments, bracketed by the M15 catchment, which showed the smallest median sub-catchment area (1·2 ha) and youngest water, and by the K catchment, which showed the largest median sub-catchment area (8·2 ha) and oldest water. The streamwater sampled at the outlets of each of the gauged catchments was an admixture of streamwater from each of its tributaries; therefore, the composition of streamwater at each catchment outlet sampled was controlled by the distribution of tributaries, related sub-catchment area, and the associated MRT of each. Though based on limited data, these preliminary results suggest that the distribution of sub-catchment area, or some measure of this distribution (such as the median sub-catchment size), provides a stronger representation of first-order controls on streamwater age than total catchment area. The implications are twofold. First, sub-catchment size distribution might be a more suitable measure of watershed form and function than total catchment area, since it reflects catchment hillslope and channel network structure. Second, landscape organization principles might provide a framework for up-scaling (aggregation), down-scaling (desegregation), and transfer of emergent patterns in streamwater MRT.

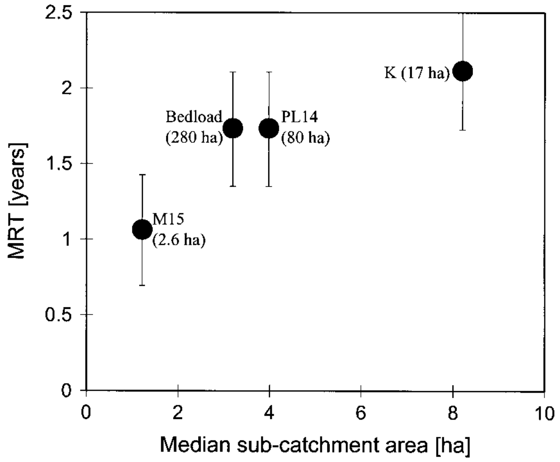

Figure 7. Mean streamwater age sampled at each catchment outlet on 30 April 1999 versus median sub-catchment size for each catchment sampled. Mean ages reported here are based on the average annual tritium input. The trend in mean ages shown here is comparable to those calculated using monthly values (Figures 4 and 5), but offset by −0·3 years

Summary

We used a tritium-based approach to quantify stream MRT in four nested catchments draining the Maimai Valley, New Zealand. We did not find a relationship between MRT and absolute catchment size. However, median catchment area, computed based on landscape analysis, showed a strong trend with MRT: the MRT increased with increasing median sub-catchment size for each catchment sampled. These results suggest that total catchment area is a poor measure of watershed function in this case, and that landscape organization is a first-order control on streamwater age. Although preliminary, these results suggest a previously not recognized linkage between landscape organization and catchment hydrology.

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