

Scale effects on headwater catchment runoff timing, flow sources, and groundwater-streamflow relations

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[1] The effects of catchment size and landscape organization on runoff generation are poorly understood. Little research has integrated hillslope and riparian runoff investigation across catchments of different sizes to decipher first-order controls on runoff generation. We investigated the role of catchment sizes on riparian and hillslope dynamics based on hydrometric and tracer data observed at five scales ranging from trenched hillslope sections (55–285 m²) to a 280-ha catchment at Maimai on the west coast of the South Island, New Zealand. The highly organized landscape is comprised of similar headwater catchments, regular geology, steep highly dissected topography, relatively consistent soil depths, and topographically controlled shallow through flow. We found a strong correlation between riparian zone groundwater levels and runoff for the headwaters, whereas the water tables in the valley bottom of the larger catchments were uncorrelated to runoff for 14 months of record. While there was no clear relationship between catchment size and new water contribution to runoff in the two storms analyzed in detail, lag times of tracer responses increased systematically with catchment size. The combination of hydrometric and tracer data allowed assessment of the runoff contributions from different parts of the landscape. Runoff was generated consistently in headwater riparian zones. This agreed also with the observed variations of tracer (¹⁸O and silica) responses for the different catchments. During wetter antecedent conditions or during larger events (>30 mm under dry antecedent conditions) hillslope and valley bottom floodplains did contribute to event runoff directly. We propose that analysis of landscape-scale organization and the distribution of dominant landscape features provide a structure for investigation of runoff production and solute transport, especially as catchment-scale increases from headwaters to the mesoscale.

INDEX TERMS: 1719 History of Geophysics: Hydrology; 1860 Hydrology: Runoff and streamflow; 1871 Hydrology: Surface water quality; 1866 Hydrology: Soil moisture; **KEYWORDS:** scale, water age, runoff generation, landscape organization

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1. Introduction

[2] The effect of different scales on hydrologic variables is one of the major unresolved issues in the hydrological sciences. Sivapalan and Kalma [1995] called for continued and sustained research on scale problems in hydrology. Much effort has been directed to the more theoretical aspects of scaling [Blöschl, 2001], but less progress has been made in experimental studies of watershed hydrology [Uhlenbrook et al., 2002]. While scaling of runoff generation processes has been cited as a major need for model formulation at the mesoscale [Uhlenbrook and Leibundgut, 2002], process hydrological research has been examined almost exclusively at the headwater catchment scale

[McDonnell and Tanaka, 2001]. More problematic perhaps is the fact that intercomparisons between different “same scale” catchments have been few and far between [Jones and Swanson, 2001], resulting in rather poor progress in determining commonalities across different catchments and catchment positions about how water and solutes are delivered to streams. Thus most current field-based research focuses on the idiosyncrasies of individual hillslopes [e.g., Freer et al., 2002], riparian zones [Seibert et al., 2003], or small catchments [Williams et al., 2002]. As a result, defining the dominant controls on runoff generation and transferring knowledge from one place to another has been difficult [Bonell, 1998].

[3] Hydrologists continue to grapple with the key question posed by Sivapalan and Kalma [1995]: “Are there certain preferred time and spatial scales at which conceptualizations of hydrological response may be feasible?” Recently, Brown et al. [1999] and Shanley et al. [2002] examined how runoff composition varies across scale. These results have so far been highly equivocal. In fact, they focus exclusively on how “tracers” behave across scale. Without detailed hydrometric information, they may only provide part of the explanation on the first-order controls on the age, origin, and flow paths of

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Figure 1. Location of the Maimai research catchment on the west coast of the South Island of New Zealand.

water from headwaters to the outlet of larger watersheds. Recent work has suggested that rather than the classic mechanisms *per se* (subsurface storm flow, saturation excess overland flow, etc.), a more tractable approach may be the isolation of key catchment units that collect and convey water to the channel, namely hillslopes and riparian zones [McGlynn and Seibert, 2003; McGlynn and McDonnell, 2003a, 2003b]. The timing of contributions from these definable units of a catchment may be a way to map and monitor contributions to flow across scale in a clear and objective manner. While the contributions of hillslopes and riparian zones to catchment runoff are often convoluted in the signal monitored at the catchment outlet at any given scale, recent approaches that isolate the response of definable landscape units has shown promise [McGlynn and McDonnell, 2003a, 2003b].

[4] Ideally, processes should be observed at the scale in which they occur [Blöschl and Sivapalan, 1995]. At our study site, the Maimai experimental watershed in New Zealand, we made observations from individual hillslope segments, to individual riparian zones, to multiple catchments of increasing size. This allowed us to investigate, in space and time, the range of hydrological processes and associated landscape features contributing to streamflow across a continuum of headwater catchment scales.

[5] Qualitatively, we know that as the size of the catchment increases, the complex local patterns of runoff generation and water fluxes tend to become more attenuated [Wood *et al.*, 1988]. Monitoring of dynamics at different scales is necessary when we want to relate the catchment outflow dynamics and composition to the internal runoff processes. We know from previous studies and recent reviews [Bonell, 1998; McDonnell, 2003] that in order to constrain a conceptualization, at any scale, one must combine physical, chemical, and isotope measures both within the watershed and at the outlet.

[6] Much of the scale-related research published in the last 10 years has relied on hydrological modeling, rather than empirical hydrology and data collection across multiple nested scales. Arguably, theoretical investigations of catchment scaling have outpaced field observation and understanding [Robinson *et al.*, 1995]. While both

approaches are necessary in order to increase our understanding of hydrological processes and scaling, future advances in hydrological modeling will perhaps grow most rapidly if grounded in physical observation, empirically based relationships, and process understanding [Blöschl, 2001; Seibert and McDonnell, 2002]. We present investigations of runoff dynamics at various spatial and temporal scales. We address the first-order controls on water and tracer fluxes at different scales and discuss how these fluxes combine at the outlet of the largest catchment (280 ha). On the basis of four partly nested catchments of various sizes and a hillslope where runoff was measured along a trench excavated down to bedrock, we tested the null hypothesis that the largest catchment scale is simply a linear superposition of its many subcatchments. Within this context, we address the following questions: (1) What are the time lags in storm flow response to rainfall across scale? (2) How do antecedent wetness and storm size influence scale-related patterns? (3) How does water table response differ in riparian zones and at riparian zone – hillslope breaks as one moves up in scale? (4) Do conservative environmental tracer responses correspond with the observed streamflow dynamics? (5) How do runoff components as determined by hydrograph separations vary across scale? We combined hydrometric observations with isotopic-chemical tracing approaches, as advocated by McGlynn *et al.* [1999] and Burns [2002] in the Maimai research catchments in New Zealand. These watersheds are well suited to addressing these questions due to their relatively “simple” hydrology with a lack of seasonality, consistently wet conditions (soils are usually within 10% of saturation), shallow soils, rapid responses to rainfall, nearly impermeable bedrock, and highly organized landscape structure [McGlynn *et al.*, 2003].

2. Site Description

[7] The Maimai research catchments are a set of watersheds located along the axis of a valley that forms the headwaters of the Grey River on the west coast of the South Island of New Zealand (Figure 1). Average annual precipitation is 2600 mm and runoff ratios are 64% annually, with 39% as quick flow [Pearce *et al.*, 1986]. Soil depths are shallow, average 0.6 m, and overly Old Man Gravels, a poorly permeable early Pleistocene well-cemented conglomerate. Hillslopes are short (<300 m), steep (34°), have local relief of 100 to 150 m, are composed of regular spurs and linear hollows, and are consistent across catchment scales. Riparian areas, on the other hand, scale with increasing catchment size. Riparian zones are narrow in the headwaters and increase in width with catchment area (Figure 2 and Table 1). The median riparian width at the Maimai Bedload catchment is 6 m (typical of ~3-ha catchments), the mean is 20 m (typical of 15–30-ha catchments), and the maximum is 163 m (floodplain riparian zone at the catchment outlet) [McGlynn and Seibert, 2003].

[8] Maimai is a highly organized landscape comprised of similar headwater catchments. The geology and soil depths are relatively uniform and the topography is steep and highly dissected. Maimai has a long history of hillslope hydrological research in well-characterized sub-5-ha research catchments; therefore Maimai is a favorable site for investigation of hydrological processes across scales (for

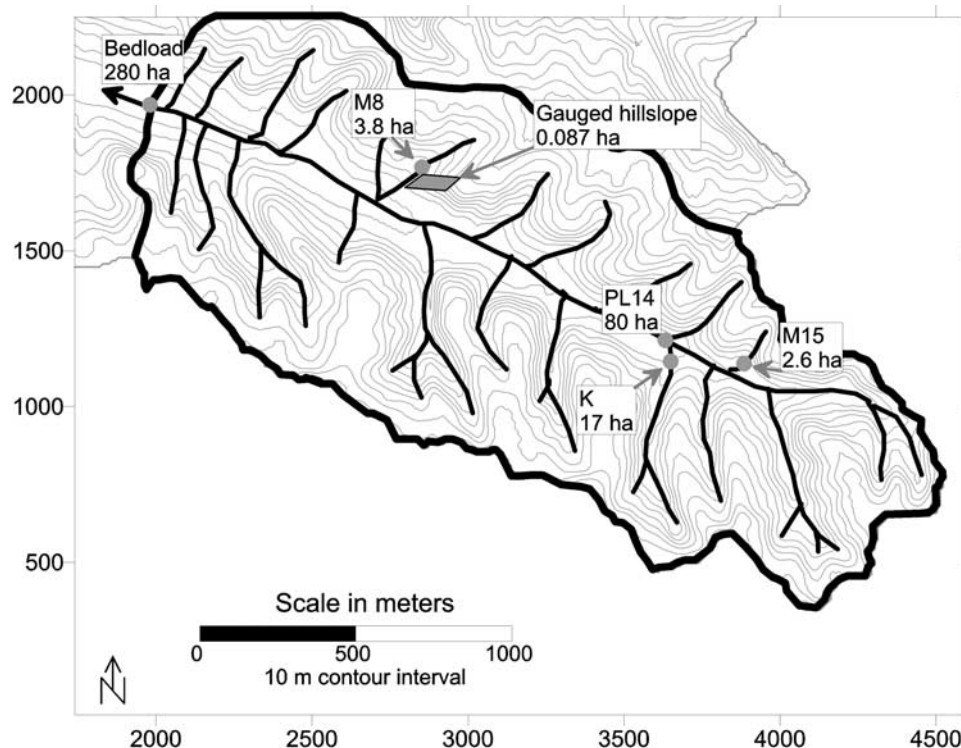


Figure 2. Topography and gauging locations along the stream network at five spatial scales including the Bedload (280 ha) catchment, the PL14 catchment (80 ha), the K catchment (17 ha), the M15 catchment (2.6 ha), and the gauged hillslope (0.087 ha).

detailed site characterization and a review of previous research at the Maimai catchments related to the evolution of a detailed perceptual model of hillslope runoff generation, see McGlynn *et al.* [2002]). The four watersheds used in this study range from 2.6 to 280 ha (Table 1 and Figure 2). The study period was 1 March 1999 to 25 May 2000.

3. Methods

3.1. Hydrometric Recording

[9] We measured rainfall at the base of the trenched and gauged hillslope positioned near the center of the longitudinal axis of the 280-ha catchment and recorded rainfall at 5-min intervals (Figure 2). The rain gauge was colocated with a sequential sampler for discrete sampling of each 5 mm of rainfall at the base of the gauged hillslope. Another rain gauge was located at the upstream head of the valley for corroboration of rainfall totals and dynamics. Annual total rainfall differences at our site were reported by Pearce *et al.* [1976] as 110 mm out of 2600 mm of rainfall annually, with 4% more rainfall toward the head of the valley.

[10] Runoff was measured using 90° V notch weirs at the 2.6 and 16.9-ha catchments, a rectangular weir at the 80-ha outlet, and a Cipoletti weir at the 280-ha catchment. Stage at each weir was measured and recorded with capacitance rods (manufactured by Trutrak, New Zealand). We reactivated the hillslope trench (located in the M8 catchment) excavated by Woods and Rowe [1996] [see also Woods and Sivapalan, 1997; McGlynn and McDonnell, 2003a, 2003b] to gauge and sample hillslope runoff. We instrumented 8.5 m of the original 30-m trench (troughs T8–T12). Runoff from each 1.7-m trench section was collected in gutters sealed to the

bedrock surface at the trench face and measured with 1 liter tipping buckets at 5-min intervals (see Woods and Rowe [1996] for a detailed description). Flow proportional sampling of hillslope runoff was accomplished by subsampling (diverting) six mL from each one L bucket tip from high flow trough T11 and low flow trough T8. See McGlynn and McDonnell [2003a, 2003b] for trench instrumentation and sampling details.

[11] We monitored groundwater table dynamics in 45 wells over the 15 months of this study. Wells were distributed in major landscape unit types of the Maimai catchments including riparian areas of increasing width from the headwaters to the 280-ha catchment outlet and hillslope positions representing convergent, planar and divergent slope sections. Our wells were distributed over wide riparian floodplain positions upstream of the Bedload weir (280 ha), transitional riparian-floodplain positions at the head of the main stem of the Maimai valley upstream of the PL14 weir (80 ha), moderate-width riparian zones upstream of the

Table 1. Catchment Scale, Riparian Area, Hillslope Area, and Riparian Zone as a Percent of the Catchment Area

Catchment	Total Area, ha	Riparian Area, ha	Hillslope Area, ha	Riparian, %
Planar hillslope	0.0055	0	0.0055	0
Hillslope hollow	0.0285	0	0.0285	0
Full hillslope unit	0.087	0	0.087	0
M15	2.6	0.06	2.58	2.3
K	17	0.52	16.38	3.2
PL14	80	4.5	75.5	6
Bedload	280	33.5	246.5	12

Table 2. Event Runoff, ^{18}O , and Silica Dynamics for Two Storms at Five Spatial Scales

Catchment	Event 1 ^a				Event 2 ^b			
	Total Runoff, mm	New Water Contribution, mm	New Water Contribution, %	Runoff Ratio	Total Runoff, mm	New Water Contribution, mm	New Water Contribution, %	Runoff Ratio
Hillslope (0.09 ha)	0.22	0.008	4	0.008	18	1.3	7	0.26
M15 (2.6 ha)	6.4	1.5	23	0.24	40.4	14.1	35	0.58
K (17 ha)	5.2	1.4	27	0.19	36.1	10.4	29	0.52
PL14 (80 ha)	7.6	1.2	16	0.28	43	10.9	25	0.61
Bedload (280 ha)	5.9	1.2	21	0.22	42.2	16.4	38	0.6

^a13 May 12:00 to 15 May; P = 27 mm.^b15 May to 19 May; P = 70 mm.

K weir (17 ha), narrow riparian zones upstream of the M15 weir (2.6 ha), and in hillslope positions in each catchment and upslope of the gauged hillslope trench (Figure 2). Well water table levels were measured every 15 min using capacitance rods (manufactured by Trutrak, New Zealand). All hydrological measurements were made over the entire 15 month study period. Data reported in this paper draw from the entire record of hydrological data, but focuses on two intensively monitored, successive rainfall events.

3.2. Geochemical and Isotopic Sampling

[12] We monitored ^{18}O and silica dynamics at each catchment outlet and the gauged hillslope to compare natural tracer response with runoff hydraulic response. Samples for chemical and isotopic analysis were collected in 250 ml high-density polyethylene bottles. Subsamples for chemical analysis were passed through 0.45 μm glass fiber syringe filters. Cation samples were acidified to a pH of 1.0 to 1.5 with HCl prior to analysis for H_4SiO_4 concentrations by direct-coupled plasma emission spectroscopy. Analytical precision for H_4SiO_4 was 0.8 $\mu\text{moles/l}$. An unfiltered aliquot was subsampled for $\delta^{18}\text{O}$ analysis at the USGS Stable Isotope Laboratory in Menlo Park, California, by mass spectrometer and reported in ‰ relative to VSMOW with a precision of $\pm 0.05\text{‰}$.

3.3. Hydrograph Separation

[13] Runoff from each catchment, including the gauged hillslope, was separated into new and old water components based on traditional two-component hydrograph separation methods (equations (1)–(3)).

$$Q_t = Q_o + Q_n \quad (1)$$

$$\frac{Q_o}{Q_t} = \frac{(C_t - C_n)}{(C_o - C_n)} \quad (2)$$

$$\frac{Q_n}{Q_t} = \frac{(C_t - C_o)}{(C_n - C_o)} \quad (3)$$

C is the $\delta^{18}\text{O}\text{‰}$ of each component, and the subscripts *o*, *n*, and *t* refer to old, new, and total streamflow, respectively. Base flow prior to the first event and water in the vadose and phreatic zones sampled across a range of catchment positions were quite uniform (-5.8 to -6‰). Therefore base flow $\delta^{18}\text{O}$ was used as the old water concentration. The

rainfall or new water component was incrementally weighted based on the incremental mean weighting method [McDonnell *et al.*, 1990] for each monitored event.

4. Results

4.1. Analysis of Two Events

[14] We intensively monitored two rain events over a 6-day period. Antecedent wetness conditions were relatively low for event 1 (27 mm event), and significantly higher for event 2 (70 mm event), which followed less than 36 hours (h) later. The precipitation amounts in the preceding 14 and seven days were 17 and 7 mm for event 1 and 44 and 34 mm for event 2. Rainfall totals for event 1 and 2 exceeded 82% and 92% of all events over a 13-year period and 46% and 75% of events greater than 7 mm over the same period [McDonnell, 1989]. During the 15 months of hydrological monitoring in this study, 48 runoff events were recorded with peak runoff rates in excess of 0.5 mm/hr, 26 events in excess of 2 mm/hr, and 8 events in excess of 4 mm/hr. Peak runoff rates observed in events 1 and 2 were indicative of frequent small events under low antecedent wetness conditions and less frequent large events under higher antecedent wetness conditions.

[15] Runoff ratios (defined as total runoff during the event divided by total rainfall as calculated from the first response to storm rainfall to the break in slope on the recession) were variable between catchments and were not directly related to catchment scale (Table 2). In event 1, runoff ratios ranged from 0.19 to 0.24 among the four larger catchments, whereas little runoff was observed from the gauged hillslope (runoff ratio = 0.008). The timing of runoff response to rainfall was directly related to catchment size (Figure 3) with the smallest catchment (M15) reacting most quickly. The lag in initial response between the smallest and largest catchment (M15 and Bedload) was ~ 3 h. Runoff peaks were similarly lagged with a difference of ~ 2 h between M15 and Bedload (Figure 4).

[16] In event 2, runoff ratios were more than double those of event 1 and ranged from 0.52 to 0.61. Total gauged hillslope runoff was roughly half of that observed at each catchment scale. Similar to event 1, the smallest catchment (M15) reacted most quickly to precipitation followed by each successively larger catchment (Figure 3). The lag in initial response between M15 and Bedload was 1 h. Runoff peaks were relatively synchronous from the 3 smallest catchments. We recorded a 1:00 h lag between the smallest

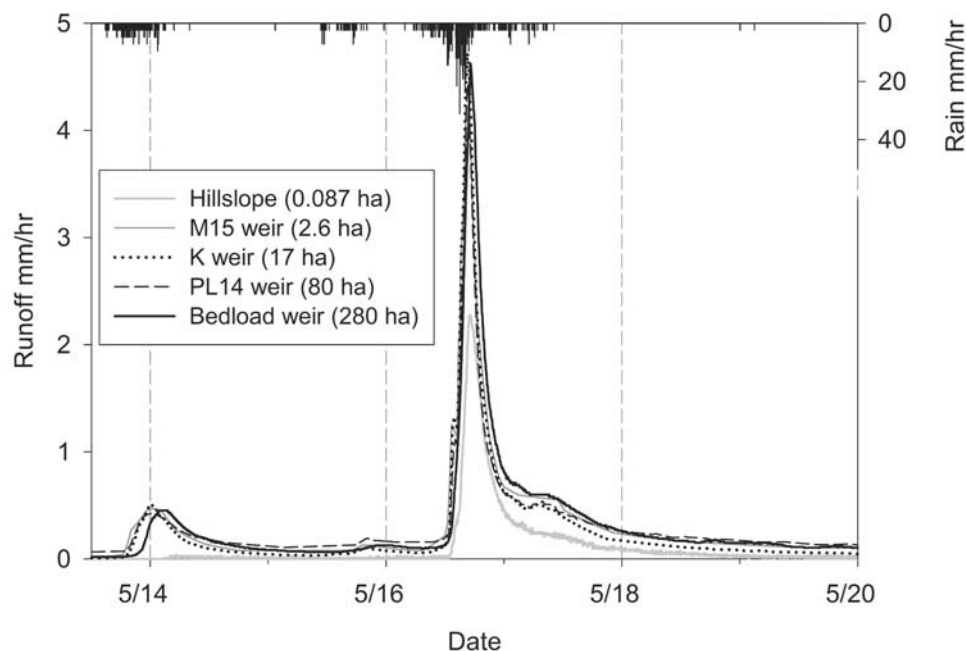


Figure 3. Hillslope and catchment runoff for events 1 and 2 in response to 27 and 70 mm of precipitation, respectively.

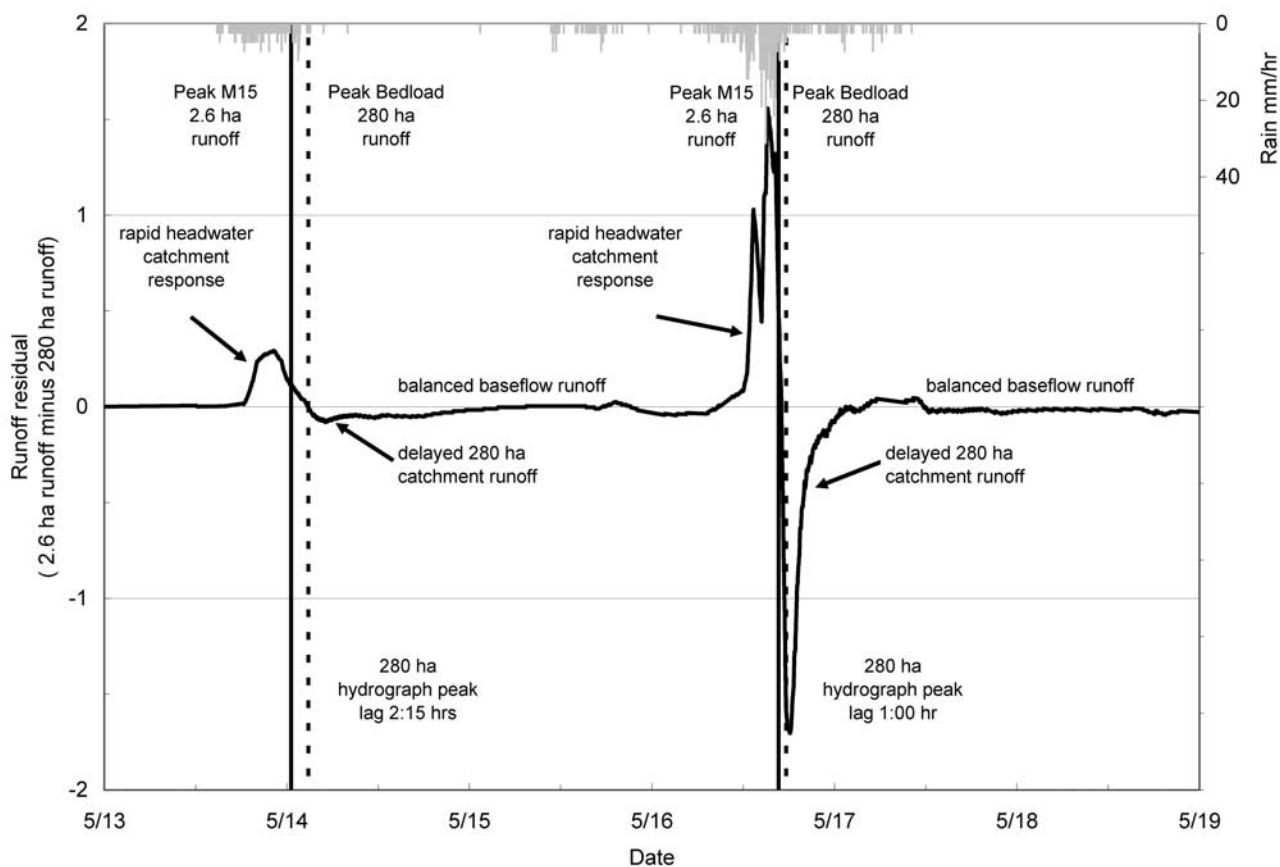


Figure 4. Runoff residual for the headwater M15 catchment (2.6 ha) runoff minus the Bedload catchment (280 ha) runoff. The difference in the specific runoff between the two catchments shows the relationship between the headwater and large catchment hydraulic responses for two storm events; one small event during low antecedent conditions and a second large event during higher antecedent conditions.

catchment (M15) peak and the largest catchment peak (Bedload) (Figure 4).

[17] Plotting the difference in specific runoff between 2.6 and 280-ha catchment for events 1 and 2 shows the divergence of runoff responses more clearly (Figure 4). Runoff increased more quickly and at a higher rate in the

smaller catchment. Following runoff peak in the 280-ha catchment (~ 2 h after the 2.6-ha catchment peak) specific runoff was first slightly higher for the larger catchment and then equal until the second event. In event 2 the smaller catchment again responded more rapidly and specific runoff was smaller for the 280-ha catchment until the runoff peak. However, the runoff from the 280-ha catchment was greater on the falling limb. The lag between the 2.6-ha and 280-ha runoff peaks was 1 h for event 2 (~ 1 h less than in event 1). Specific runoff was similar for both catchments both ~ 7 h before the event 2 peak and from 7.5 h after peak runoff.

4.2. Water Table–Runoff Relationships in Riparian and Hillslope Positions

[18] The groundwater level–runoff relationship for the full 15 months of record varied among the wells but similar patterns were found within the different landscape units. The relationships shown in Figures 5 and 6 are examples from typical wells. We found that water table–runoff relationships varied significantly between sites and as a function of antecedent wetness and event size in riparian floodplain positions at the 280-ha catchment scale and in hillslope position at the sub-0.1-ha scale. Counter-clockwise hysteresis was pronounced in the 280-ha riparian floodplain positions indicating that local groundwater response lagged catchment runoff response. In riparian sites between the 80-ha catchment scale and the first-order catchment scale (>0.5 ha), the relationship between water table and runoff was consistent throughout the year and across a range of antecedent conditions (Figure 5) and showed minimal hysteresis in the water table–runoff relationship. Head gradients in each riparian and hillslope position (determined by 3-point water table slope calculations) were toward the stream channels perpendicular to elevation contours (within 15°).

[19] At the 280-ha catchment high runoff rates were not necessarily related to increased water tables. In fact, the largest runoff event of the 15-month period (peak flow of ~ 10 mm/h) was associated with a water table elevation of 0.5-m below the ground surface, a level that was exceeded during 2% of the study period (including base flow). At the 280-ha scale riparian/floodplain zone, water tables hardly rose during event 1 whereas water tables rose to the ground surface during event 2 (albeit on the falling limb of the event hydrograph) and a significant hysteresis in the water table–runoff relationship was evident (Figure 5). In the subcatchments the water tables and runoff were strongly correlated with sharp increases in runoff as the water tables approached the ground surface (Figure 5). Hysteresis was not significant for these cases.

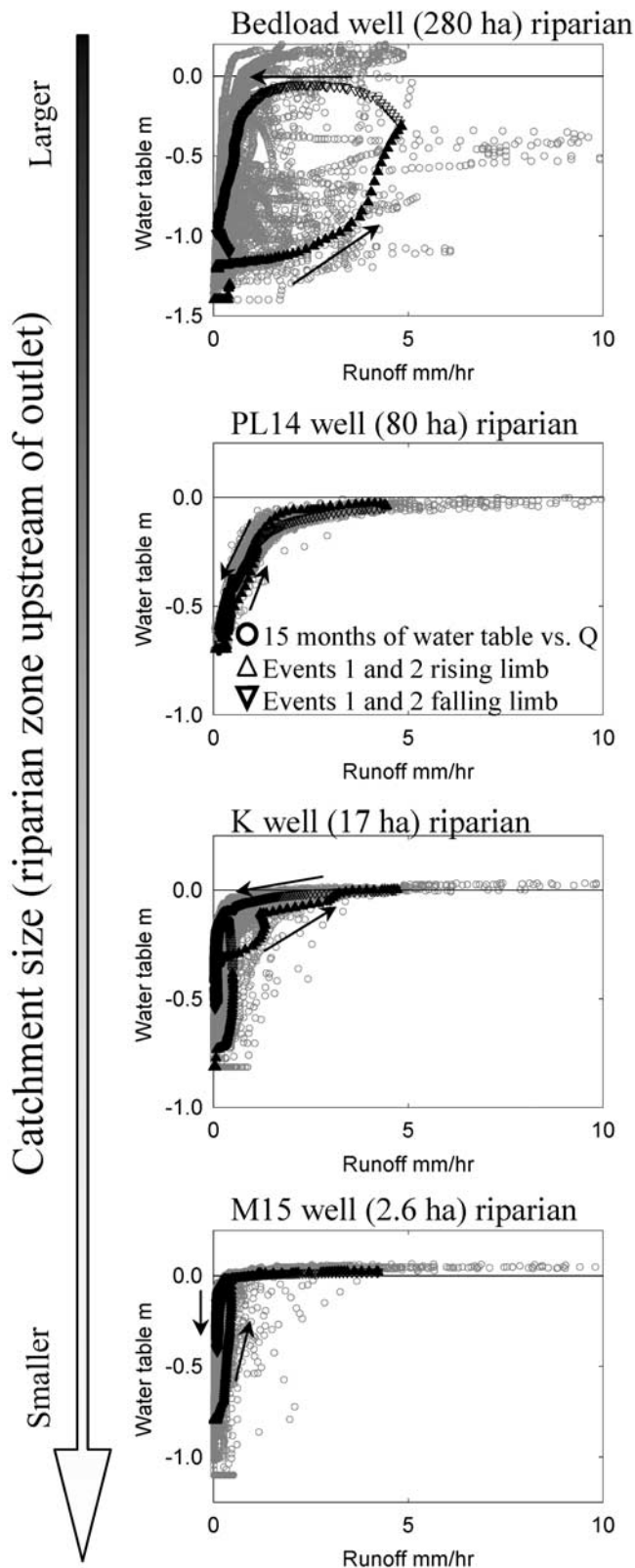


Figure 5. Fifteen months of water table versus catchment runoff reported at 15-min intervals (shaded open circles) with events 1 and 2 (13 May 12:00 to 19 May) superimposed and reported at 5-min intervals. Solid triangles (pointed up) represent the relationship on the rising limb of each event hydrograph; open triangles (pointed down) represent the falling limb. Note that little water table response or hillslope runoff was observed in event 1.

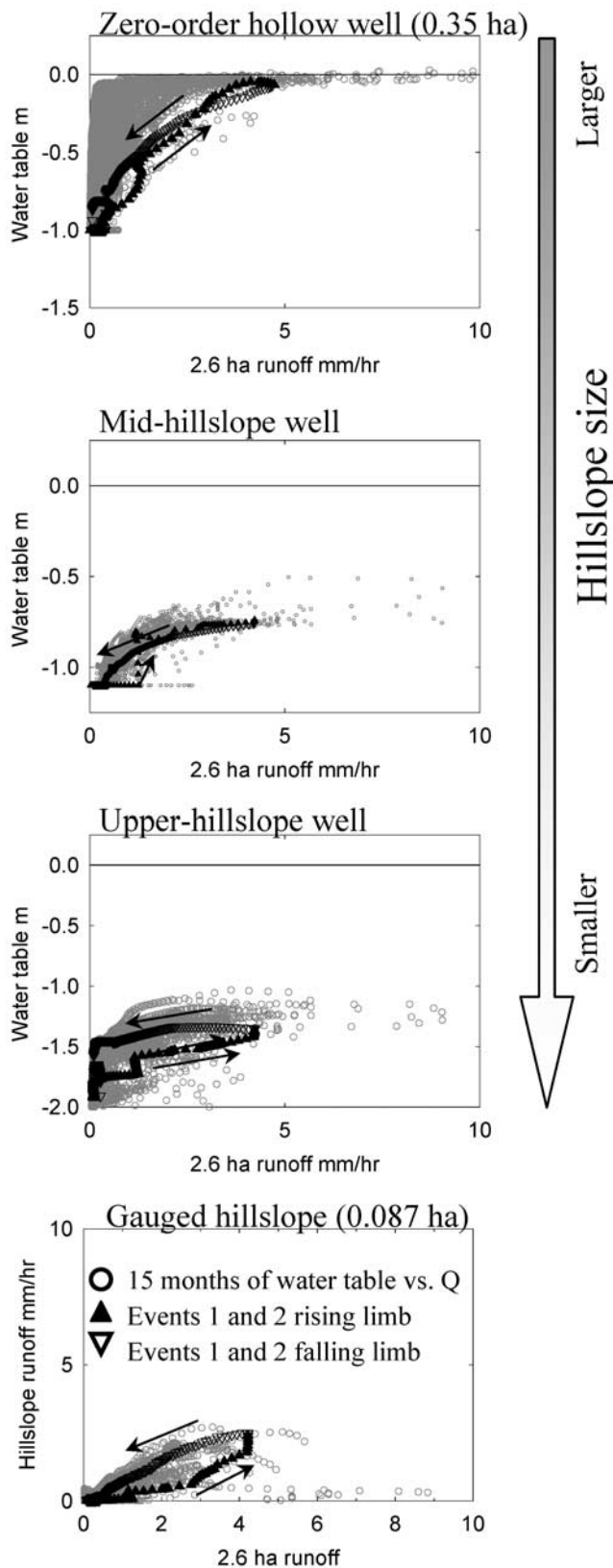


Figure 6. Fifteen months of hillslope water table versus 2.6-ha catchment runoff in the top three plots moving from a zero-order hollow upslope to midslope and upper hillslope positions. The bottom plot (gauged hillslope) shows the relationship between gauged hillslope runoff (the range of hillslope geometries) and 2.6-ha catchment runoff.

[20] Water table and runoff were not as closely linked at the monitored hillslope as in the headwater riparian zones and greater ranges of water table heights were observed for the same runoff rate (Figure 6). At the zero-order hollow well (<0.5 ha), the water table discharge relationship was intermediate between those observed in the riparian zones of the sub-80-ha catchments and those observed at mid and upper hillslope positions (Figure 6). In event 1, no hillslope water table development or hillslope runoff was observed. In event 2, water tables developed and runoff from the gauged hillslope showed distinct hysteresis in its relationship to the 2.6-ha catchment runoff. We observed lower rates of hillslope runoff on the rising limb than on the falling limb for the same catchment runoff level (Figure 6, bottom plot).

4.3. Tracer Response

[21] The rainfall events caused runoff $\delta^{18}\text{O}$ deflection from base flow (Figure 7). Contrary to $\delta^{18}\text{O}$, which was quite uniform over the catchment, silica concentrations varied considerably and were roughly twice as high in riparian zone water than in hillslope water. During events 1 and 2 silica concentrations decreased (Figure 7). Total lag times to the peak of $\delta^{18}\text{O}$ and silica concentration relative to the initial response in the 2.6-ha catchment varied between 4.5 and 13 h for the different catchments in event 1 and 4.5 to 8 h for event 2 (Figure 8). The lag times increased consistently with catchment size. The 2.6-ha catchment responded most rapidly and concentrations peaked first, whereas the peak was reached $\sim$ nine h later in the 280-ha catchment for event 1. In event 2, lag times were shorter for both $\delta^{18}\text{O}$ and silica concentrations. For event 2 lag times for silica concentrations were 1–2 h longer than $\delta^{18}\text{O}$ for all catchments.

4.4. New Water Response

[22] The contribution of new water (event rainwater) to runoff ranged from 16% to 27% in event 1 and did not show a relationship to catchment size (Figure 9 and Table 2). Hillslope runoff was minimal and 4% of the total runoff was new water. Timing and dynamics of new water runoff, rather than total new water percent, however, showed distinct changes with catchment size. As expected from the variations of the $\delta^{18}\text{O}$ lag times, new water runoff response time increased with catchment size. Furthermore, the peaks became damped and lagged with increasing catchment size. Most significant was the difference between the 16.9-ha and 80-ha catchments. Peak new water runoff at the 16.9-ha catchment was more than twice that observed at the 2.6-ha catchment. The difference of the new water response lag was greatest between the 80-ha and the 280-ha catchment.

[23] In event 2, new water runoff was 25% to 38% of total catchment runoff for the four catchments and 7% for the hillslope segment (Table 2). Again, the new water contribution was not related to catchment size, whereas lag times increased with catchment size (Figure 9). Compared to event 1, the response of new water runoff in event 2 was relatively synchronous among the catchments.

5. Discussion

5.1. Runoff Response Across Scale

[24] Analysis of differences in runoff rates and timing between catchments of different size showed, not surprisingly,

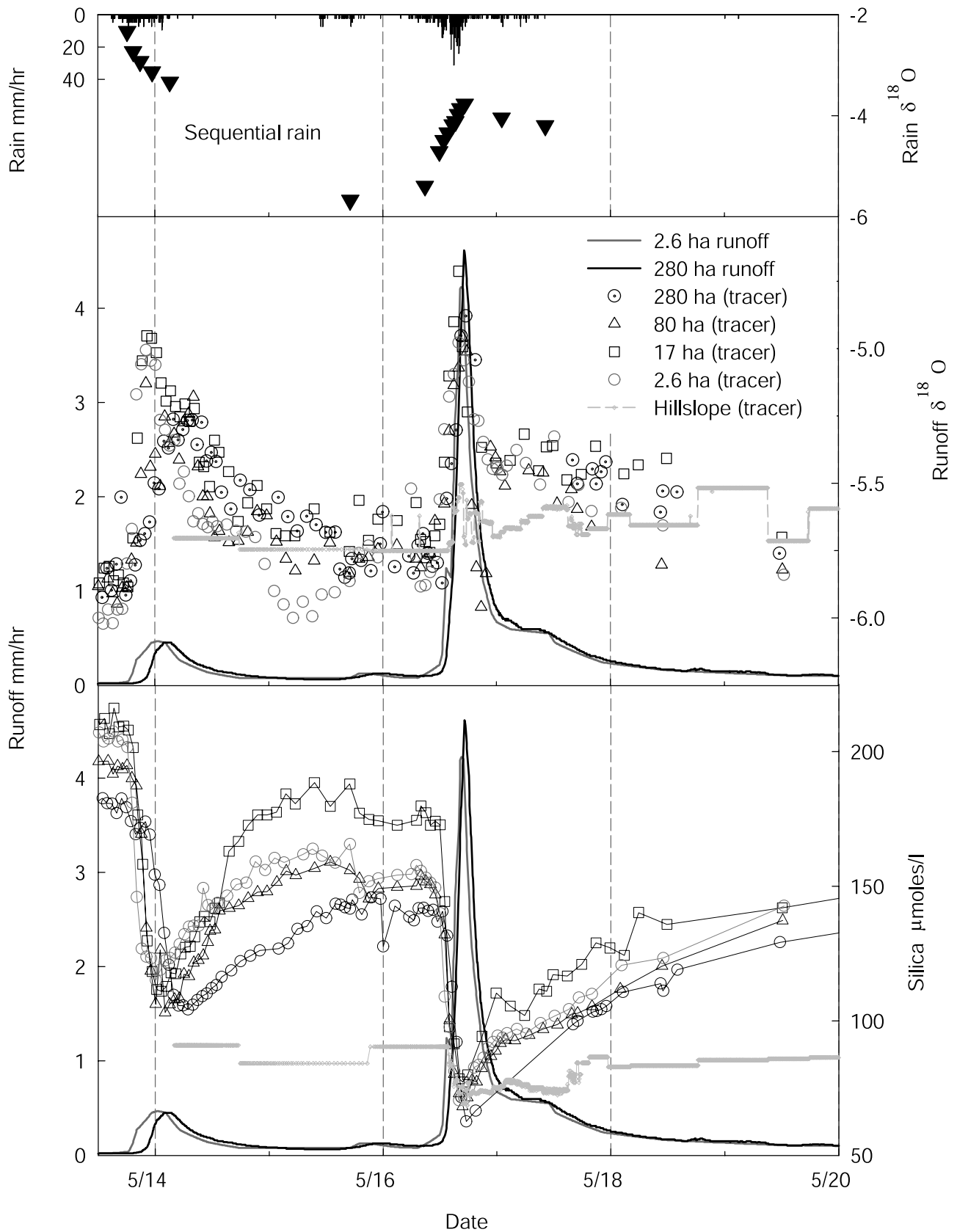


Figure 7. Storm event deflection from base flow for natural tracers ^{18}O and silica across five spatial scales from the 280-ha Bedload catchment to the 0.087-ha gauged hillslope. Runoff $\delta^{18}\text{O}$ deflections from base flow were due primarily to new rainwater proportions of storm runoff. Silica dilution was due partially to dilution by rainwater and partially due to changing sources of catchment runoff (riparian zone to hillslope zone).

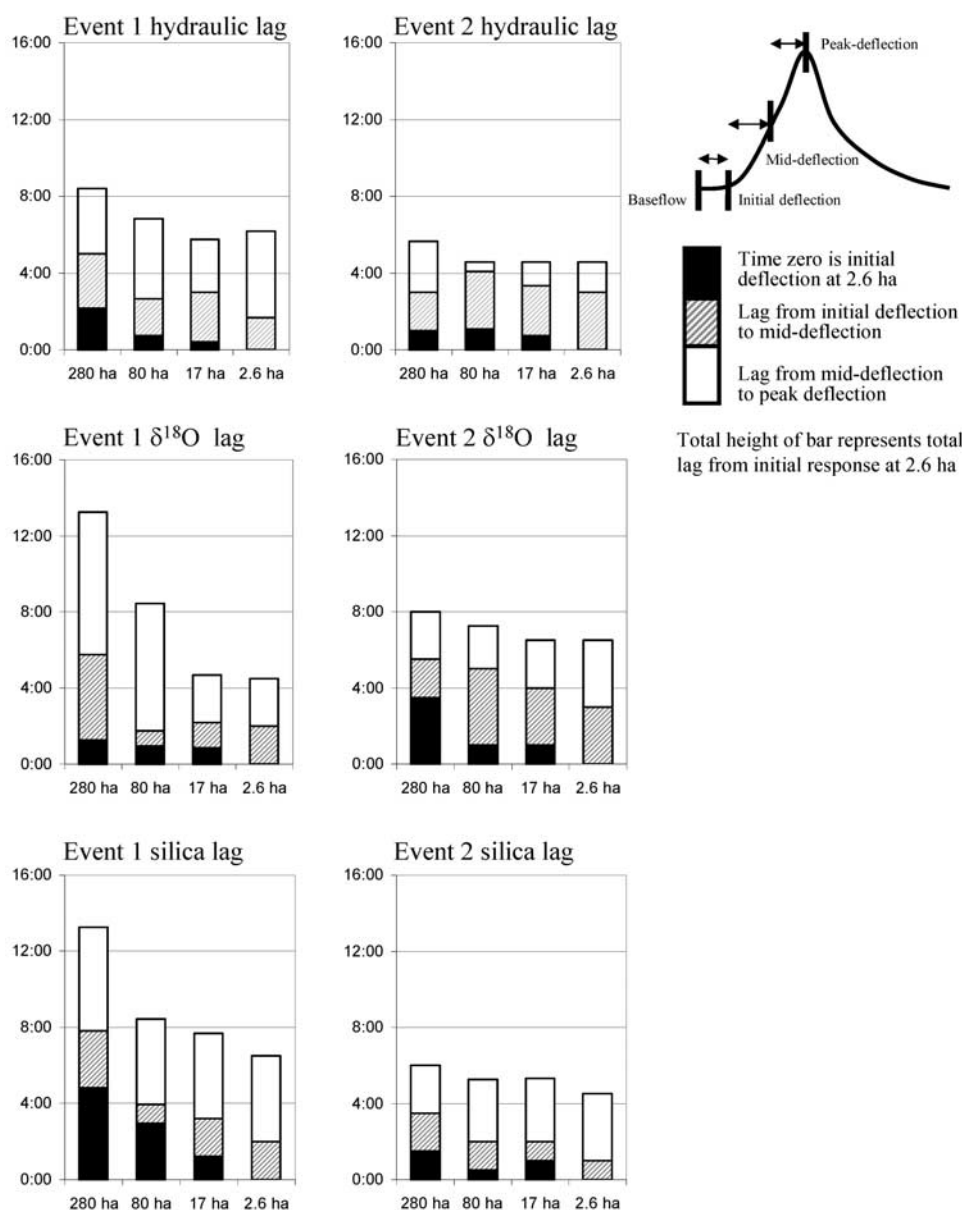


Figure 8. Natural tracer (^{18}O and silica) transport and time of concentration lags. Progressive lags with increasing scale in (left) event 1. Less increase was observed in tracer lags with increasing scale in (right) event 2. The graduated bar graphs are a distillation of data provided in Figure 7 and show the tracer response lag at the outlet of each catchment scale for base flow to initial deflection, initial deflection to peak deflection, and middeflection to peak deflection.

that a relatively small rain event with dry antecedent conditions resulted in more lagged and damped hydrographs with increasing catchment size (i.e., downstream). Most pronounced were the differences between the 80-ha and 280-ha catchments. Analysis of runoff and groundwater levels also gave indications of which parts of the landscape contributed to runoff. Groundwater level dynamics from riparian zones in the different catchments showed that only the wells in the riparian zones in the sub-80-ha catchments responded together with runoff. The wider valley bottom riparian zones along the main valley of the 280-ha catchment were unresponsive. The monitored hillslope segments were also unresponsive and did not contribute to catchment runoff in event 1 [McGlynn and McDonnell, 2003b]. Together this

indicated that runoff was generated mainly in the riparian zones and an expanding variable source area between the conservatively mapped riparian zone and the gauged hillslope in the smaller catchments [McGlynn and McDonnell, 2003b]. The damped and lagged runoff response as catchment size increased might therefore be caused by two related processes: (1) Runoff was generated predominantly in sub-80-ha riparian zones as indicated by water table dynamics and coincident catchment runoff, and (2) runoff was transferred downstream through the channel network to the 280-ha catchment outlet without significant runoff contributions from the wide valley bottom zone.

[25] In event 2, the combination of higher antecedent wetness conditions and larger rainfall amount caused rapid

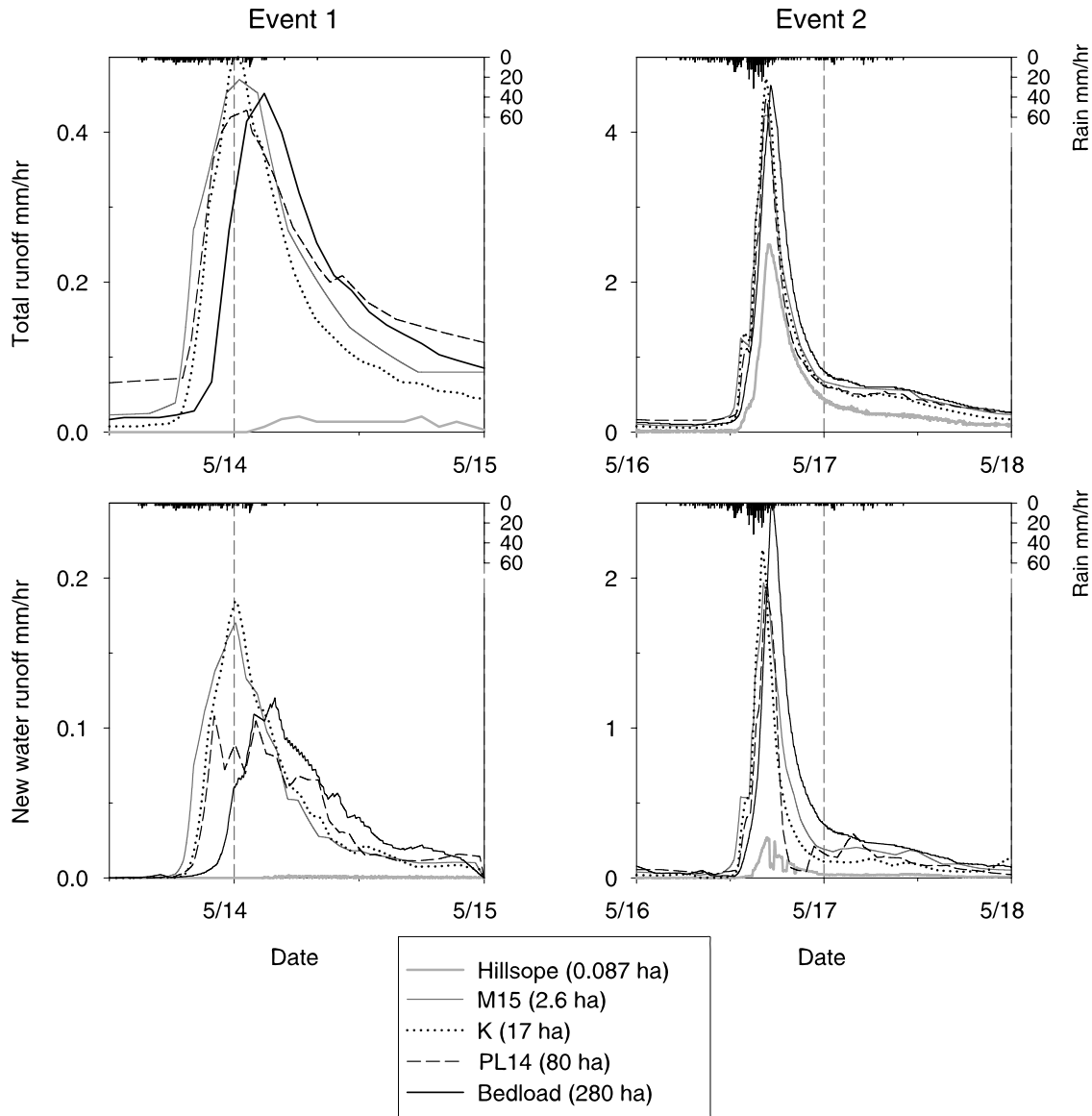


Figure 9. (top) Total runoff from each gauged scale for (left) event 1 and (right) event 2. (bottom) New water runoff from each gauged scale for (left) event 1 and (right) event 2. Note there is an order of magnitude difference in Y axis scales between event 1 and event 2 for both total runoff and new water runoff.

water table responses across the sub-80-ha riparian zones. Water tables rose to the ground surface in the wide 280-ha riparian zones, albeit delayed and strongly hysteretic with catchment discharge. At the hillslope site, runoff was observed midway through the rising limb of the catchment hydrograph in the second event. These observations suggest that runoff production was more widespread across the landscape in the second event. This also suggests that runoff dynamics were more coincident between the catchments in the second event.

[26] The runoff ratios for each scale and each event (Table 2) imply that for catchments between ~ 2.6 and 280 ha, there is no clear relationship between catchment size and yield. Our gauged hillslope runoff ratios imply that the smallest catchments runoff ratios range from zero to approaching the ratios of larger catchments if antecedent conditions are wet enough and the storm is large enough.

Similarity in runoff ratios across scale is likely due to the dominance of headwater catchments in the landscape and their control on yield. *McGlynn and Seibert* [2003] quantified the landscape (subcatchment) organization at Maimai and reported that 35% of the 280 ha catchment area originates in subcatchments smaller than 1 ha, 60% in <4 ha subcatchments, and 85% in <20 ha subcatchments [*McGlynn and Seibert*, 2003; *McGlynn et al.*, 2003].

5.2. Reconciling Hydrological and Tracer Responses Across Scale

[27] Natural tracers furnished further insight into catchment runoff response across a range of catchment sizes by providing another measure of catchment runoff response to precipitation. Deflection of $\delta^{18}\text{O}$ from its base flow value was caused by rainwater dilution. The lag from initial deflection to peak deflection increased strongly with

increasing catchment scale, supporting the hydrometric evidence of upstream generation of runoff primarily in headwater riparian zones and little runoff generation along the riparian floodplain of the 280-ha catchment main channel. Differences between the tracer lags to peak and hydraulic lag to peak for the 280-ha catchment were more than four times greater than those differences for the 2.6-ha catchment. Despite nearly synchronous runoff peaks, $\delta^{18}\text{O}$ lags increased with catchment scale in the sub-80-ha catchments. This means that the catchment hydrological response became temporally disconnected from the catchment tracer response. This disconnection becomes more pronounced from the headwaters to larger catchment scales, despite similar initial runoff generation and tracer response mechanisms. This suggests that as catchment size increases, tracer concentrations and temporal runoff dynamics collected at the catchment outlet provide poor representation of upstream runoff generation processes unless tracer travel times and source areas are quantified. Internal catchment measures and a nested observation design are needed to constrain conclusions based on catchment outlet observations.

[28] Runoff peak lags in event 1 were greater than ^{18}O peak lags in the 2.6 and 16.9-ha catchments (Figure 8) because a higher proportion of new water contributed to runoff on the rising limb of the hydrograph [McGlynn and McDonnell, 2003b]. In the headwaters, local runoff along the channel caused more deflection in the stream water signal because of the higher ratios of local runoff to total runoff. In the first event, local contributions to runoff seemed to be minor along the main valley of the larger catchments. Therefore routing of the tracer signals generated in the headwaters caused delayed $\delta^{18}\text{O}$ deflection peak arrival relative to the faster hydraulic response. The hydraulic response was slower than the tracer response in the headwaters because riparian new water runoff arrived at the catchment outlet more quickly than the slower subsurface old water runoff. For the larger catchments, however, deflection signals generated in the headwaters had longer travel times to the outlets and the faster flood wave propagation compared to particle travel times became significant. In addition, longer channel travel distances increase opportunity for transient storage exchange and delayed tracer response. To summarize, in the smaller headwater catchments, riparian runoff processes mediated tracer arrival at the catchment outlet whereas at the larger catchment scales, tracer arrival at the catchment outlet was mediated by in-channel transport.

5.3. On the Relative Role of Hillslopes, Riparian Zones, and Channel Networks

[29] In our study we evaluated the relative roles of riparian and hillslope runoff processes and channel network structure on catchment runoff across a range of catchment sizes from the largest to smallest monitored catchments. These data illustrate a shift from a channel-mediated runoff response to a riparian/hillslope mediated runoff response. Our observations correspond to the recent theoretical approach of Robinson *et al.* [1995], who described the relative roles of hillslope processes, channel routing, and channel network geomorphology in the hydrologic response of catchments. They demonstrated through numerical modeling that catchment response is governed primarily by

hillslope processes in small catchments whereas it is governed primarily by network structure and geomorphology in larger catchments. The conclusions of Robinson *et al.* [1995] reinforce the numerical modeling conclusions of Surkan [1969], Kirkby [1976], Mesa and Mifflin [1986], and Beven and Wood [1993], who each report on the relative importance of hillslope, channel routing, and network geometry in controlling the shape of the storm hydrograph and how this might change with increasing catchment scale.

[30] We found that spatially localized runoff generation in headwater catchments resulted in a riparian zone mediated catchment response in the headwater catchments and channel network mediated response at the 280-ha catchment scale. Under higher antecedent moisture conditions and a larger 70 mm rain event, we observed a shift at the 280-ha catchment scale from a channel mediated catchment response to a near stream mediated catchment response. As a result, greater synchronicity across catchment scale was observed. These results demonstrate a shift from riparian and hillslope controlled runoff and tracer response to a channel network mediated response from the headwaters to the 280-ha scale. The scale at which this occurs appears to shift from smaller to larger catchment sizes as a function of antecedent moisture conditions and storm event characteristics.

5.4. Where Water Comes From and How This Varies Across Scale

[31] Only a few published studies have made reference to event based new water/old water separations with varying basin scale. Pearce [1990] examined δD , Cl, and pH data at Maimai and found qualitative evidence for increasing new water contributions with basin scale. McDonnell *et al.* [1999], utilizing the water age spectra model of Stewart and Rowe [1994], also found some evidence for increasing new water contributions with increasing scale. Both studies at Maimai attributed the increase of new water to an increase in valley bottom and saturation excess overland flow pathways. However, each study relied on only three subcatchments and did not include concurrent internal sampling of soil water and groundwater concentrations.

[32] Brown *et al.* [1999] found that new water proportions decreased with increasing catchment size for seven nested catchments in the Neversink watershed in New York. They concluded from two and three component hydrograph separations that shallow through flow dominated runoff production. They hypothesized that longer flow paths at larger catchment scales resulted in decreasing new water with catchment size. Shanley *et al.* [2002], for three nested catchments in Vermont, found that new water proportions in storm flow increased with increasing basin scale for one year of monitored spring snowmelt and one summer storm. However, a second year of spring melt monitoring and subsequent hydrograph separations showed no discernible scaling of new water proportions with increasing catchment size. Several explanations were presented to account for the variability in new water scaling between monitored events. Variability in overland flow pathways and extent due to ground frost and differences in saturated hydraulic conductivity between the basins were postulated as possible explanations. Despite the qualitative findings of Pearce *et al.* [1986] and Brown *et al.* [1999], the equivocal findings of Shanley *et al.* [2002], and the

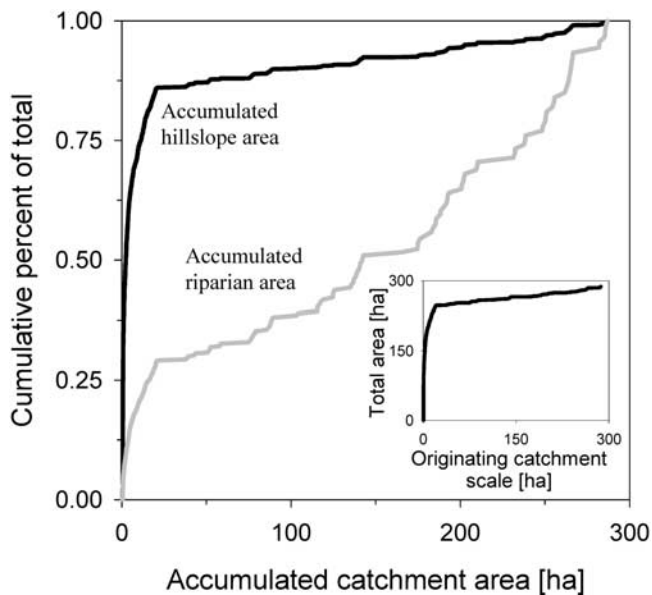


Figure 10. Area accumulation as a function of source catchment size for hillslope area and riparian area. The hillslope area CDF is steepest in the headwater portions of each sub-catchment. Along the main valley axis (catchment scales greater than 15-ha), the hillslope area CDF slope is flattest, signifying small hillslope inputs to the main stem of the stream network and numerous focused hillslope inputs via defined tributaries. Thirty percent of riparian areas are accumulated in sub-10-ha catchments. Riparian area is accumulated in headwater catchments because they are numerous in the landscape; however, riparian widths increase with catchment scale, and therefore total riparian area continues to increase with catchment scale [McGlynn *et al.*, 2003]. The inset plot is the total area CDF.

preliminary findings of McDonnell *et al.* [1999], the controls on new water fractions in a single catchment and the relationship between catchment scale and new/old water ratios in storm flow have not been elucidated. There does not appear to be a general relationship between basin size and new water runoff.

[33] Our results indicate that hydrograph separations reported as total new water runoff or peak new water runoff rates enable only equivocal conclusions. On the other hand, the lag times for the new water contributions in this study were strongly correlated to catchment size and confirmed our preliminary conclusions about the disconnection/connection of runoff producing zones across the landscape. The first appearance of new water runoff was progressively more delayed with increasing catchment size for event 1. Peak new water runoff rates were comparable for 2.6-ha and 16.9-ha catchments, but for the 80-ha and 280-ha catchments new water peaks were smaller and were both damped and lagged. The ^{18}O response the timing of new water delivery to each catchment outlet was directly related to the spatial sources of runoff within each catchment and integration of travel times associated with upstream runoff. The delay associated with both the first appearance of detectable new water and the timing of new water peaks increased with catchment size. In addition, new water runoff hydrographs

at the 80-ha and 280-ha catchment scales were more damped compared to the 2.6 and 16.9-ha catchment new water runoff hydrographs.

[34] In event 1, the two smaller catchments (2.6 and 16.9-ha) showed peak new water contributions to runoff 20% greater than the two larger catchments (80 and 290-ha), whereas total new water runoff was more similar, although slightly higher in the smaller catchments. On the basis of observations that runoff was generated primarily in the headwater riparian areas and transferred to the larger catchments downstream via the channel network, comparable total new water/old water ratios are not surprising. 35% of the Bedload catchment (280 ha) area originates in subcatchments smaller than 1 ha, 60% originates in <4-ha subcatchments, and 85% originates in <20-ha subcatchments [McGlynn and Seibert, 2003]. We highlight the risk of analyzing new water contribution at peak flow alone for inferring runoff processes and highlight the impact of landscape organization on the distribution of runoff source areas across catchment scale.

[35] Results presented here and those reported by McGlynn and McDonnell [2003b] demonstrate the advantages of landscape discretization and monitoring of characteristic responses on dominant portions of the landscape such as riparian zones and hillslopes (Figure 10). These studies demonstrate that hillslopes are not a significant source of new water, even during large events under wet antecedent conditions. Riparian zones and the expansion of variable source areas into zones intermediate between the gauged hillslope and the mapped riparian zone control the portioning of new/old water. Analysis of characteristic hydrologic and tracer response in key landscape units coupled with understanding of the areal extent of each unit and landscape organization (topology) provides insight into where the classical runoff mechanisms occur, the relative magnitude within different parts of the catchment, and the degree of connectedness to the catchment outlet (Figure 10). Our results indicate that where the various runoff generation mechanisms occur and their relative magnitude across the landscape are critical to guiding model development and understanding the link between plot-scale runoff process observations and dynamics witnessed at the catchment outlet.

6. Concluding Remarks

[36] Consideration of landscape organization provided a contextual framework for concurrent analysis of hydrological and tracer dynamics in runoff. Discretization of catchments into their component landscape elements “hillslope zones” and “riparian zones” and monitoring hydrological response in both elements and in catchments of varying size provided insight into the spatial sources of runoff otherwise hidden in the lumped runoff signal monitored at the catchment outlet. Analysis of long-term hydrological response from each landscape unit in addition to event dynamics under varying antecedent conditions and storm sizes provided additional insight into the first-order controls on hydrological and tracer response monitored at the outlet of each gauged catchment. In this study, we found the following results.

[37] 1. Headwater riparian areas were consistently active during runoff events, whereas valley bottoms further down-

stream were not. The connection/disconnection of riparian areas to local hillslope inputs appeared to control the riparian water table–catchment runoff relationship. The tight relationship between riparian water table and catchment runoff in the headwater catchments suggested that runoff was typically generated in headwater riparian zones. The poor relationship for riparian wells and runoff further downstream suggested a disconnection from local hillslope drainage.

[38] 2. During the smaller event (event 1), runoff was generated primarily in headwater riparian zones. Response lags increased in a downstream direction as catchment scale increased. In the large event (event 2), runoff was generated more uniformly (including hillslopes and valley bottom floodplains) and lag times were more consistent across scale.

[39] 3. The runoff data at the 280-ha catchment scale, combined with data from the nested catchments and distributed water table observations, demonstrated a shift from network dominated catchment response to riparian–hillslope dominated catchment response. We found this shift to be a function of antecedent wetness, event size, and resulting hydrologic connectedness. Sub-17-ha catchments were primarily riparian–hillslope response dominated catchments through both monitored events.

[40] We suggest that landscape-scale hydrological monitoring together with internal observation and assessment of the hydrological dynamics of dominant landscape units and the distributions of these landscape units provides a fundamental structure for understanding runoff production and solute transport, especially as catchment scale increases from headwaters to the mesoscale. In addition, this improved understanding provides a basis for the further development of hydrological catchment models.

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