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Groundwater dynamics along a hillslope: A test of the steady state hypothesis

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[1] Appropriate conceptual simplifications and assumptions are a central issue for hydrological modeling, especially when those models serve as the foundation for more complex hydrochemical or ecological models. A common and often unexamined assumption in conceptual modeling is that the relation between groundwater levels and runoff can be described as a succession of steady state conditions. This results in a single-valued, monotonic function between the groundwater levels and runoff. Consequently, the simulated rise and fall in groundwater levels always follow the dynamics of runoff. We tested this assumption with an analysis of detailed groundwater level data along two opposing hillslopes along a stream reach in a Swedish till catchment at Svartberget. Groundwater levels in areas close to the stream followed the dynamics of the runoff. The correlation between groundwater level and runoff decreased markedly for wells farther than approximately 40 m from the stream. The levels were often independent of streamflow: Upslope area groundwater could be rising when riparian groundwater and runoff were falling, and vice versa. There was a high degree of correlation between groundwater levels at similar distances from the stream. The median Spearman rank correlation between wells within 35 m from the stream was 0.86 and for wells located more than 60 m from the stream was 0.96. This indicated that there is a common hydrological pattern even in the upslope area that can be identified and modeled. Despite the widespread acceptance of the steady state assumption previously in this and other study catchments, our study shows that it is not valid for the investigated hillslope site. If the divergence from steady state, with potential ramifications for other processes such as runoff chemistry, is common, then it will be worthwhile to reconsider the appropriate range of applicability for the steady state hypothesis, and the alternatives to that hypothesis. *INDEX TERMS:* 1829 Hydrology: Groundwater hydrology; 1860 Hydrology: Runoff and streamflow; 1866 Hydrology: Soil moisture; *KEYWORDS:* groundwater, runoff, steady state, watershed

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1. Introduction

[2] The balance between practical simplifications and justifiable model complexity is unresolved in hydrological modeling [*Beven*, 2001a, 2001b]. In most cases the available data motivates the use of simple, conceptual model approaches rather than the use of a fully distributed, physically model with a large number of model parameters. The steady state assumption is the hallmark of most conceptual runoff models, where a single valued, monotonic function between the groundwater storage and runoff is the basic underlying structure. The conceptual hydrologic model typically depicts a catchment using a number of storages. One (or more) of them usually represent(s) groundwater storage that can be related to actual groundwater levels. Consequently, the dynamics of the simulated outflow from the groundwater zone always follows the simulated rise and fall in groundwater levels. TOPMODEL [*Beven et al.*, 1995] is an example of such a conceptual model. While TOPMODEL simulates spatially distributed groundwater levels using a topographic index, these groundwater levels always go up and down in parallel. The simulated runoff from the groundwater zone follows the same dynamic. Thus it is assumed implicitly that the groundwater storage and runoff can be described as a succession of steady state flow conditions.

[3] Despite almost ubiquitous use, surprisingly few studies have sought to test the validity of the steady state assumption. One notable exception is that of *Moore and Thompson* [1996] who examined whether groundwater table variations were consistent with the steady state assumption. They analyzed groundwater levels in a research catchment in British Columbia, Canada. While their results supported the steady state assumption, this might be explained by the location of the wells and by the measurement techniques used in their study. Their wells were located mainly in convergent zones, most sites were located close to the stream, and all of their groundwater

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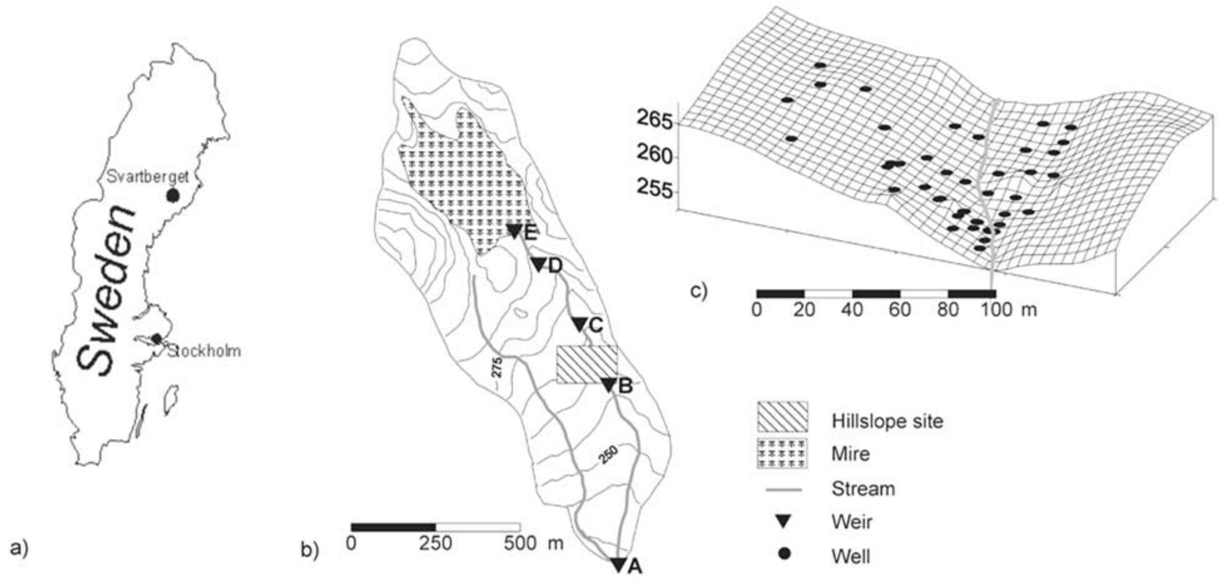

Figure 1. Location of the Svartberget catchment (a) and the hillslope research area (b). (c) The hillslope research area. The black circles indicate the locations of the groundwater wells.

wells were located in the lower third of the hillslope (within 80 m from the stream). Furthermore, groundwater levels were measured only every second week. Between these observations only the maximum level for each well was recorded, but not the timing of this peak. *Moore and Thompson* [1996] were aware of the problem that upslope sites lacked representation in their data set and speculated that the upslope parts of their catchment might not follow the steady state assumption. For that case, they suggested an extension of the TOPMODEL concept using a two-zone catchment model.

[4] The presence of hydrological patterns within the catchment that do not follow the steady state assumption could be of great importance for the chemistry of stream water and its response to different influences. This is especially true if a lack of correlation between runoff and groundwater levels is not simply random divergence, but consistent response structures that influence mass fluxes within the catchment, as well as the chemical development of soils and the hillslope catena in a consistent way. If one were to fully examine well dynamics across a catchment to test the steady state hypothesis, then one would need a distributed network from stream to ridgetop. Indeed, differences between the hydrological regime of the near-stream riparian zone and the more distant upslope areas have been identified; often in relation to critical hydrogeochemical properties of the riparian zone that can differ from those of the upslope areas [*Bishop et al.*, 1990a, 1994, 1995; *Cirmo and McDonnell*, 1997]. In this study, we use detailed groundwater level data from two opposing hillslopes to investigate the validity of the steady state assumption with the aim of identifying zones where this approximation is or is not appropriate. We test the following null hypothesis: Groundwater levels rise and fall uniformly across the hillslope and in unison with the rise and fall of the outflow from the groundwater zone. We hope that this will provide an indication about the required model complexity for similar hillslopes and catchments.

2. Materials and Methods

2.1. Study Site

[5] The 0.50-km^2 Nyänget basin is located on the Svartberget Experimental Forest near Vindeln in the province of Västerbotten, Sweden, 60 km northwest of Umeå (64°14′N, 19°46′E, Figures 1a and 1b). This catchment (together with its climate) has been monitored since 1980, and investigated by *Rodhe* [1987], *Bishop et al.* [1990a], *Bishop et al.* [1995], *Sirin et al.* [1998], *Laudon et al.* [1999], and *Nyberg et al.* [2001], among others. The hydrology of this small basin is fairly typical for much of the interior of northern Sweden.

[6] Between 1980 and 1998, measured annual precipitation was 600 mm, with a mean annual runoff of 325 mm and a mean air temperature of +1°C. Half of the runoff occurs during the snow-free half of the year (June to November), and a third of the runoff occurs during 3–4 weeks of spring flood in April or May. Except for an 8-ha, headwater mire, the catchment is forested with mature Norway spruce (*Picea abies*) in low, wetter areas and Scots pine (*Pinus sylvestris*) on higher, better-drained areas.

[7] Podzol soils have developed on several meters of compact glacial till that have slopes with topographic gradients of between 5% and 10%. These podzols give way to riparian peat soils in a 5- to 15-m-wide band along the channels of the two tributaries. These riparian peats are 20 to 80 cm in depth and overlie a mineral soil enriched in organic carbon [*Bishop*, 1994]. The streams were deepened by hand to a depth of approximately 1 m during the 1920s in order to improve forest production. (This type of manipulation has been widely practiced on forested, headwater streams throughout Sweden.)

[8] The groundwater data used in this study were collected along two opposing hillslopes, each about 120 m

long with a maximum height difference of 8 m (Figure 1c) [*Bishop*, 1991]. A seismic refraction survey along these hillslopes located bedrock between 7 and 20 m beneath the soil surface [*Bishop*, 1991]. A boundary in the compaction of the till was noticeable in the seismic survey between 0.5 and 2 m depth. Excavation of pits across the catchment [*Ivarsson and Johnson*, 1988] showed the more compact, underlying till to be a sandy basal till. Well draw-down tests found the saturated hydraulic conduction in the basal till to be less than 10^{-6} m s^{-1} (H. Grip, personal communication, 1990). The less compact, overlying layer of till is an ablation till which had, on average, a sand content of roughly 50% and a silt/clay fraction of somewhat under 30% with gravel making up the remaining 20%. Given the low hydraulic conductivity of the basal till, the lateral water flux is confined to the upper 2 m of the soil profile where the less compact ablation till is found.

[9] The till soils and riparian peats at Svartberget have a high infiltration capacity which limits the frequency and extent of overland flow. Such high infiltration capacities are typical of many Swedish till catchments [*Rodhe*, 1987, 1989]. Field observations during runoff events gave no evidence of saturation overland flow as being an important runoff component in the investigated hillslopes [*Bishop*, 1991]. These findings were supported by isotope hydrograph separations, according to which pre-event water dominated the catchment runoff in all investigated rainfall generated runoff events, including those reported in this study [*Bishop*, 1991; *Rodhe*, 1987].

[10] Several methods in the field and laboratory were used to determine the saturated hydraulic conductivity profiles along the hillslopes. The results showed an exponential decrease with depth from approximately 10^{-4} m s^{-1} at 10 cm depth to approximately 10^{-6} m s^{-1} at 1 m depth, but with a large (± one order of magnitude variation) between the methods, and individual samples [*Bishop*, 1991]. Detailed analysis of the soil physical properties, groundwater/runoff dynamics and stable isotope tracers have found that a well-defined band of transiently saturated, subsurface flowpaths can account for the runoff generation on these hillslopes [*Bishop et al.*, 1990a, 1990b].

[11] Since hardly any overland flow is observed on the studied hillslopes, the outflow from the groundwater zone can be assumed to equal the measured runoff from the hillslopes. This runoff was computed as the difference in discharge between weirs above and below the hillslope site (reach area = 5 ha). Groundwater and stream water levels were measured manually one to seven times a day, with the more intense measurements (time step 2–4 hours) during runoff events. The groundwater-level measurements were reproducible to within 0.2 cm. Runoff was calculated from manual measurements at V notch weirs along the stream at the same time as groundwater observations were made, along with continuous measurement at the catchment outlet. Groundwater levels were measured on 160 occasions covering a period of 19 weeks altogether during the summer months of 1986 to 1988.

2.2. Correlation Analysis

[12] Plotting runoff against groundwater levels often reveals a strong correlation, but usually the relation is far from linear (Figure 2). The functional expression, which describes the relationship best, may vary for different locations, which makes comparison between locations difficult. Non-parametric statistics can be used to overcome these difficulties. In this study the correlation between the dynamics of runoff and the groundwater levels at different locations on the slope was quantified by the Spearman rank correlation coefficient. When calculating this correlation coefficient, the value of each x_i is replaced by the value of its rank among all other x in the sample. The Spearman rank correlation coefficient, r_s,

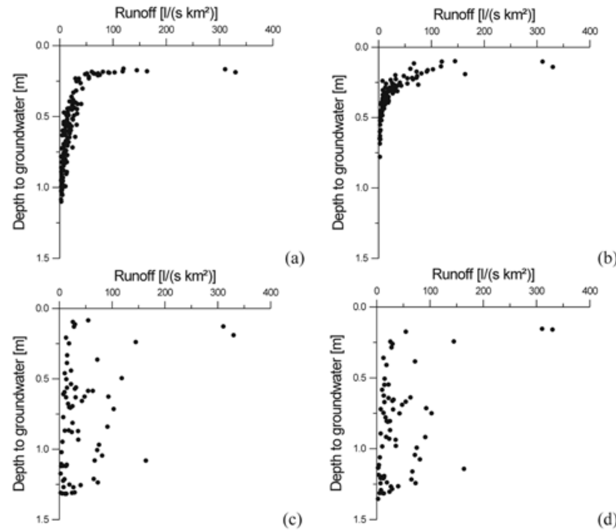

Figure 2. Relation between runoff and depth to groundwater for four different locations, (a) well J3G1, 14 m from stream, (b) well TG3, 26 m from stream, (c) well WG4, 78 m from stream, (d) well J6G1, 103 m from stream.

$$r_s = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \tag{1}$$

is then computed based on the number of observations, n, and the differences between the ranks of the paired observations, d_i (equation (1)). In our case, the paired observations were runoff and groundwater level at a certain point in time and the ranks were computed from the respective time series.

[13] Similar to the usual correlation coefficient, the values for r_s vary between -1 and $+1$, with values close to zero indicating a lack of correlation and values close to 1 or -1 indicating a strong correlation. By using the nonparametric rank correlation, no specific function had to be assumed for the relationship between groundwater levels and runoff in order to evaluate the degree to which a higher groundwater level corresponded to a larger runoff. We also studied the correlation of groundwater levels at pairs of wells. Here we used rank correlation as well.

2.3. General Linear Model

[14] To assess how well a steady state model could predict spatially distributed hillslope groundwater levels, a reformulation of TOPMODEL was used. Following TOPMODEL [*Beven and Kirkby*, 1979], the depth to the groundwater table at location i and time t, $z_{i,t}$, is a function of the mean depth in

the catchment, $\bar{z}_t$, a parameter governing the rate of decrease of the saturated hydraulic conductivity with depth, f, a local soil-topographic index, I_i, and its average over the entire catchment area, $\bar{I}$ (equation (2)):

$$z_{i,t} = \bar{z}_t - \frac{1}{f}\left(I_i - \bar{I}\right) \tag{2}$$

Equation (2) can be rearranged and formulated more generally [*Moore and Thompson*, 1996]:

$$z_{i,t} = \frac{\bar{I}}{f} - \frac{I_i}{f} + \bar{z}_t \tag{3}$$

$$z_{i,t} = a_0 + b_i + c_t + \varepsilon \tag{4}$$

In equation (4), a_0 is a constant, b_i represents the location effect, c_t represents the time effect, and ε is the random error.

[15] According to equation (4), each groundwater level observation can be described by three components: (1) a constant (for a given catchment), (2) a location effect (which is used for one location at all points in time), and (3) a time effect (which is used for all locations at a certain point in time). The first component depends on the average depth to the groundwater table. The second component is a result of the topographic position and other characteristics of the individual location such as transmissivity. The third component reflects the hydrologic conditions at the observation occasion. A least squares approach was used to fit equation (4) to the observed groundwater-level data. There were significantly more wells installed in the lower part of the hillslopes and, thus, there were more observations close to the stream than further away. This would introduce a bias in the analysis because the time effect, c_t, would largely follow the conditions in the lower part of the hillslopes. Therefore, the observations at wells further away from the stream were weighed higher so that the (weighted) number of observations per unit length (from stream) was about uniform. If the steady state assumption, on which equation (2) is based, were fully valid, it would be possible to fit equation (4) perfectly with the observed data. Thus, the better the model represented by equation (4) can simulate the observed depths to the groundwater table, the more valid is the steady state assumption.

3. Results

3.1. Correlation Between Groundwater Levels and Runoff

[16] Groundwater levels close to the stream had temporal dynamics similar to runoff and were strongly correlated with runoff volume and timing (Figures 2a, 2b, and 3). This strong relationship between runoff and groundwater, with an exponential increase in runoff as groundwater rises and superficial, highly conductive layers become saturated is a characteristic feature of the transmissivity feedback runoff generation mechanism at this site [*Bishop*, 1991; *Bishop et al.*, 1998]. On the other hand, groundwater levels farther from the stream showed little correlation with the runoff (Figures 2c and 2d) although the general pattern of the groundwater dynamics showed some similarity with that of

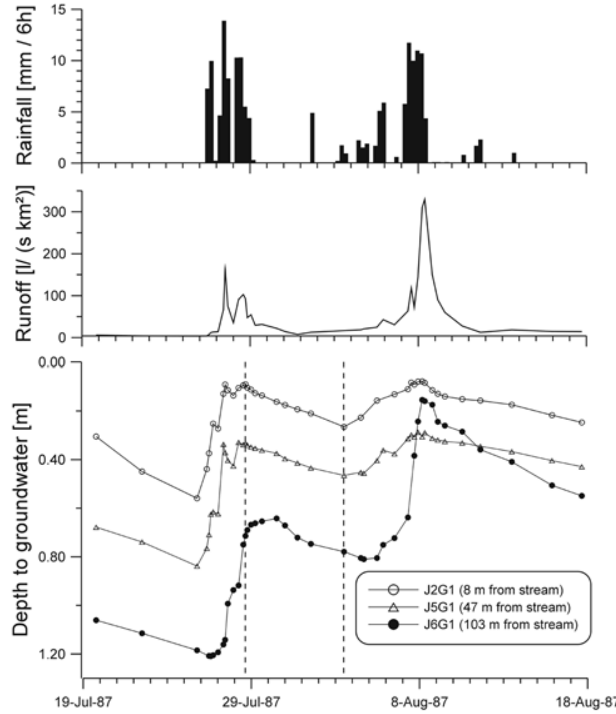

Figure 3. Time series of rainfall and hillslope runoff as well as groundwater levels measured at different locations.

the runoff (Figure 3). Looking more closely at Figure 3, it is seen that early in a runoff event, while runoff and riparian groundwater levels are rising, the upslope groundwater may still be slowly falling as part of the recession from a rain event several days before (Figure 3, vertical line down from start of second episode). Similarly, the groundwater level could still be rising upslope a day after rainfall had stopped, when both the runoff and the downslope groundwater levels had peaked and were declining (Figure 3, vertical line down from second hump of first episode).

[17] These qualitative relations in Figures 2 and 3 point to rejection of the steady state hypothesis for this site. To quantify this further, the differences in the timing of hydrological response in upslope groundwater were compared to the stream and riparian groundwater response using the Spearman rank correlation. Note that there is hardly any overland flow observed at the study site and, thus, the runoff from the hillslopes can be assumed to equal the outflow from he groundwater zone. As expected from Figure 2, the correlation between the groundwater level in individual wells and runoff was high near the stream and low at more distant locations (Figure 4). The correlation coefficient dropped abruptly at about 35–60 m from the stream, from values around 0.9 to about 0.3.

[18] As commented above on Figure 3, the different dynamics for the near stream and upslope groundwater levels are partly an effect of a slower response of the groundwater level to rainfall in the upslope positions. In order to investigate this delay quantitatively, the correlation coefficients between groundwater levels and runoff were also calculated with the groundwater-level time series shifted by different time steps compared to the runoff. Since the observations were not equidistant in time (observation interval varying

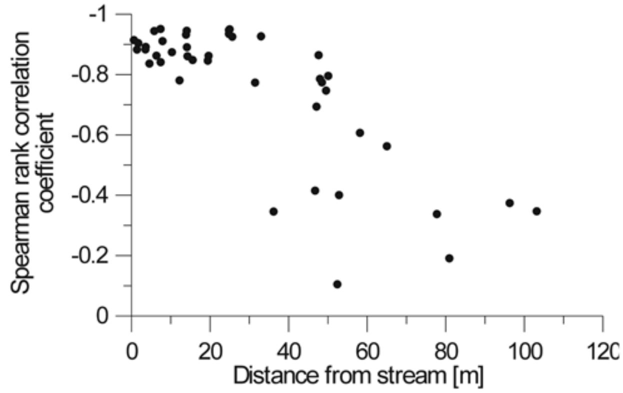

Figure 4. Rank correlation between groundwater levels and hillslope runoff versus distance from the stream.

from less than 2 hours to a few days, with the most frequent observations during high flows), time series with a time step of 2 hours were computed using linear interpolation. These series were then used to determine the time shift needed to obtain the strongest rank correlation between groundwater levels and runoff. Although there were exceptions, the correlation between runoff and groundwater level in the upslope positions could be considerably improved with time shifts of about 50–70 hours, indicating a delay in upslope groundwater level responses of 2 to 3 days compared to runoff (Figure 5).

3.2. Correlation Between Groundwater Levels

[19] The high rank correlation between groundwater levels near the stream and runoff implies that the riparian groundwater levels also were highly correlated internally. One might suspect that the groundwater levels further from the stream were less correlated internally, since their correlation with the runoff were very variable. In order to investigate the internal structure of the groundwater dynamics in more detail, rank correlation coefficients between groundwater levels in pairs of wells were calculated, for all wells and for three subsets: wells less than 35 m from the stream, wells from the transition zone between riparian and hillslope (35–60 m), and wells more than 60 m from the stream. There were much less pairs of wells with both wells located more than 60 m from the stream. These pairs, however, indicated that the groundwater levels in the upslope wells were also highly correlated internally, even though they were only weakly correlated with runoff (Figure 6).

[20] The above analysis shows that in these hillslopes, two distinct zones can be identified with regard to groundwater dynamics: a riparian zone (<35 m from the stream) in which there is a close relationship between groundwater level and runoff and an upslope zone (>60 m from the stream) in which groundwater dynamics are internally similar but different from that of the runoff.

[21] Table 1 reports the summary statistics of groundwater observations in the two zones. Clearly, there are differences between well response near the stream and farther away from the stream channel. For instance, groundwater in wells near the stream remained closer to the surface and had an absolute range of fluctuation that was much narrower than their upslope counterparts. There are at least two reasons for these differences. The volume of water that has to be discharged through the soil profile increases downhill, forcing the thickness of the groundwater zone to increase and the groundwater level to come close to the ground surface. Since the saturated hydraulic conductivity in these soils increases rapidly with height in the superficial soil layers, comparatively small groundwater level variations in these layers are sufficient to account for the flow changes imposed by the water budget variations for a certain segment of the riparian zone during events. The decline of the groundwater table between events is also comparatively small in the riparian zone due to the continuous supply of water draining the upslope areas. These two effects give shallow groundwater levels with moderate variations in the riparian zone.

3.3. General Linear Model

[22] Our final test of the steady state hypothesis at the Svartberget hillslope site was the application of the general linear model derived from TOPMODEL (equation (4)) to the groundwater level data. We fitted the general linear model (equation (4)) to all of the available groundwater data. Both location and time had a significant ($p = 0.001$) effect on the groundwater level at a certain well i observed at time $t, z_{i,t}$. The linear model explained 87% of the variance of the groundwater levels overall, and the mean squared error was 0.022 m^2 (Table 2). This corresponds to an average error of 15 cm in the predicted groundwater levels (Figure 7).

4. Discussion

4.1. On the Differences Between Riparian and Hillslope Zones

[23] The analysis of the groundwater dynamics using Spearman rank correlation coefficients yielded two statistically and conceptually distinct hydrological zones on the hillslope site. Groundwater dynamics and runoff dynamics were similar for wells close to the stream (<35 m). In areas farther from the stream (>60 m) groundwater dynamics

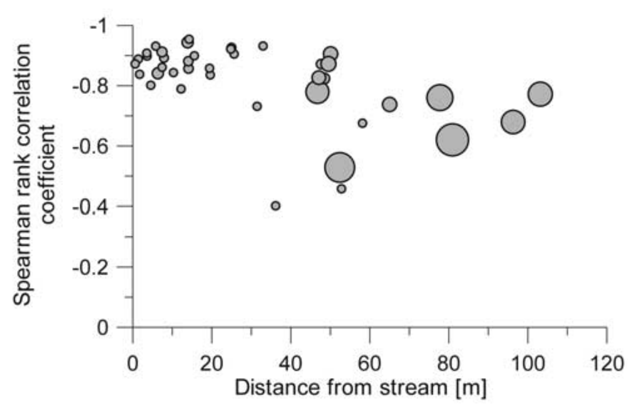

Figure 5. Strongest rank correlation between groundwater levels and runoff versus distance from the stream when shifting the groundwater-level time series in time. The area of the bubbles is proportional to the time shift needed to obtain the strongest correlation varying from 0 (smallest bubbles) to 80 hours.

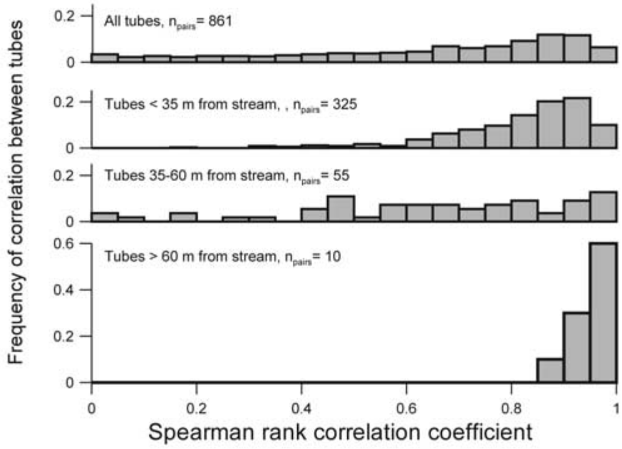

Figure 6. Frequency distribution for the rank correlation coefficients for all pairs of wells and all pairs of wells that are located less than 35 m, between 35 and 60 m, and more than 60 m from the stream.

differed from runoff dynamics, but still agreed between the different wells in that zone. The weaker correlation with runoff for the upslope wells reflects the fact that for several events, the direction of change in groundwater levels upslope differed from the direction in the riparian zone (and runoff), i.e., levels rose in the upslope zone and fell in the riparian zone at the same time (e.g., on 28 July 1987, Figure 3). This weaker correlation for the upslope locations can to some extent be attributed to a simple time shift with the groundwater levels lagging 2 to 3 days behind the runoff (and groundwater levels in the riparian zone). This delay was fairly similar for all upslope locations.

[24] In both zones, individual levels were highly correlated with the respective mean level for that zone, with a rank correlation coefficient, r_s, on average 0.91 and 0.95 for the riparian and upslope areas, respectively. The correlations within each subset were also much larger than the average correlation between all wells. When looking at all pairs of wells, the rank-correlation coefficient, between wells averaged 0.62 (median 0.72). The correlation was much stronger when only looking at pairs of wells, which were both located in the same zone (r_s on average 0.83 (median 0.86) within the riparian zone, and 0.95 (median 0.96) within the upslope zone).

[25] These findings indicate that there are two different groundwater dynamics and thus provide an objective physical justification for distinguishing the upslope and riparian zones when modeling the hydrology of this catchment. A model with a single-valued storage-runoff relation (i.e., using the steady state assumption) would not reproduce this behavior. A two-box model approach, with one upslope and one riparian box, would be needed to capture the differences between the riparian and the upslope zone and lay the foundation for a more realistic process representation. One such model approach has recently been suggested [*Seibert et al.*, 2002]. The findings in this paper provide a more detailed example of the distinct riparian-hillslope functionality that we have seen in other catchment studies at Maimai [*McDonnell*, 1990], Sleepers River [*Kendall et al.*, 1999; *McGlynn et al.*, 1999], Panola [*Hooper et al.*, 1998; *Burns et al.*, 2001], and Archer Creek [*McHale et al.*, 2002]. Thus, we argue that the distinction between riparian and upslope groundwater dynamics, which we observed at Svartberget, could possibly be found across a wide spectrum of catchment types.

Table 1. Statistical Description of the Groundwater Levels in the Riparian and Upslope Zones[a]

Variable	Riparian	Upslope
Mean	0.34 (0.17)	0.95 (0.19)
Median	0.32 (0.18)	0.96 (0.22)
Percentile, 10% (P_{10})	0.20 (0.18)	0.49 (0.35)
Percentile, 90% (P_{90})	0.52 (0.21)	1.34 (0.06)
Range (P_{90}–P_{10})	0.32 (0.17)	0.85 (0.32)

[a] Levels in meters below ground surface. Riparian zone, <35 m from stream; upslope zone, >60 m from stream. Mean values are of all respective wells; standard deviations are in parentheses.

Table 2. Analysis of Variance for the Model $z_{i,t} = a_0 + b_i + c_t + \varepsilon$[a]

Source	Degrees of Freedom	Sum of Square	Mean Square	F Ratio	p
Intercept, a	1	875	875	39,548	<0.001
Location, b	42	1,379	32.8	1,484	<0.001
Time, c	172	306	1.78	80	<0.001
Error, ε	11,104	246	0.022		

[a] $z_{i,t}$ values in m below ground surface. F-ratio = treatment mean square/error mean square; p is the significance level.

[26] It is not surprising that the near stream zone (and thus the stream) reacted more rapidly to rainfall. In the lower part of the hillslope, accumulating lateral flow inputs sustains an elevated groundwater level. The unsaturated zone water content is also elevated and closer to saturation relative to upslope conditions. This results in little possibility for water storage in the riparian unsaturated zone and a more rapid rise of the groundwater table during events. The deeper upslope groundwater table results in a drier unsaturated zone and longer vertical distances for the flow impulse generated by the rainfall on the ground surface to propagate to the water table. This would result in longer lag times for upslope wells and shorter lag times for riparian wells. These commonsense deductions are consistent with our data.

4.2. Why Has This Nonsteady State Response Not Been Previously Recognized in Runoff Modeling?

[27] The steady state assumption is widespread in conceptual hydrological modeling, although there have been a few attempts to relax this assumption [e.g., *Barling et al.*, 1994; *Beven and Freer*, 2001; *Watson et al.*, 2001]. Our findings clearly challenge the steady state assumption, at least for the Svartberget catchment. Nonsteady state response has been previously reported. *Kirkby and Chorley* [1967, p. 20] concluded based on theoretical calculations that "throughflow rarely achieves a steady state during a rainstorm." *Hinton et al.* [1993] found that groundwater levels in the lower part of a Canadian till catchment responded rapidly to rainfall, whereas the response of the groundwater level further upslope was comparatively slow. However, only few field studies have explicitly tested the steady

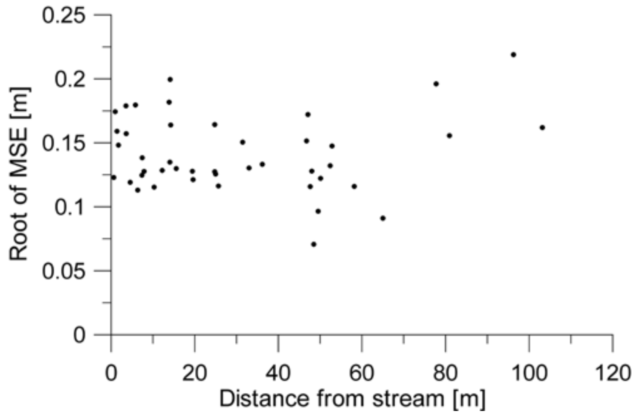

Figure 7. Root of mean squared error of the model $z_{i,t} = a_0 + b_i + c_t + \varepsilon$ against distance from the stream for each well.

state assumption. The one study that we have found that did test this explicitly in a headwater catchment [*Moore and Thompson*, 1996] did not look on groundwater dynamics in areas more distant to the stream and did not monitor throughout the course of specific runoff episodes. Based on our data and comparison with their findings, we would argue that their conclusion that the steady state assumption holds for their catchment was caused by the fact that there were no observations in the more upslope catchment positions (i.e., like those in our study beyond 50 m) where nonsteady behavior can be found. Second, the temporal resolution of their measurements was too coarse to have detected the delay in water table response seen in our study. We would therefore emphasize their reservation [*Moore and Thompson*, 1996, p. 668] that the steady state assumption might only apply to the lower-slope convergence zones and not for the entire catchment. Continuous monitoring showed very similar responses of the groundwater levels in the four wells reported by *Myrabø* [1997] in the Sæternbekken Minifelt till catchment in Norway, supporting the steady state assumption, but also here the wells were all located in the lower or convergent parts of the hillslopes.

[28] While the general linear model (equation (4)) in our study yielded a fairly good representation of the data overall (lending support to a steady state conceptualization), the standard error of 15 cm was significant, especially when considering the observed variation of groundwater levels (Table 1). Compared to the results of *Moore and Thompson* [1996], the error was about three times larger in our study. This again indicates that the steady state assumption becomes less appropriate when areas further upslope are considered.

4.3. Do Our Data Lend Credence to the "Average Soil Monitoring Site" Hypothesis?

[29] *Grayson and Western* [1998] suggested that one way to deal with spatial variations of hydrological variables is to identify catchment average monitoring sites. These are sites that consistently show mean catchment behavior independent of the actual wetness conditions. Obviously, the existence of such a monitoring site would be extremely valuable for various hydrological studies. *Grayson and Western* [1998] used spatially distributed soil moisture observations to calculate, for observations at different points in time, the relative deviations of soil moisture at individual locations from the catchment average moisture. For a suitable monitoring site, the mean of these relative deviations over time should be close to zero, and the variability should be small.

[30] A similar analysis of the groundwater-level data from the Svartberget hillslope indicated that there might not be one single "average well." Mean relative deviations close to zero can obviously be found in the transition zone between the riparian and upslope zones, but these sites typically showed a high variation of the relative deviations over time. Since the variation of the relative deviations was not related to distance from the stream (Figure 8), the selection of a suitable average monitoring site appears to be precluded, even if one relaxes the zero-mean condition (i.e., allowing for a systematic, but time-stable deviation). This again supports the need to distinguish different hydrological zones (sometimes called hydrotopes or hydrologically similar units) in conceptualizing a catchment in order to capture the nonsteady state relationships between the landscape elements. For the Svartberget subcatchment two such zones are needed: a riparian zone and an upslope zone. This is similar to the data of *Grayson and Western* [2001] who advocate the consideration of two separate zones (hillslope and gully areas) with regard to soil moisture variations. For other hillslope reaches and catchments, where topographic convergence is much higher, it may be necessary to differentiate between upslope areas, hollows and riparian zones. This is a topic of much active research [*Seibert and McDonnell*, 2002; *McGlynn et al.*, 2002].

[31] This study presents only one example of nonsteady state behavior, and does not purport to assess the extent to which this is true more generally. It is worth noting though, that there does not appear to be one single "average soil monitoring site" on the hillslope. The main message here is that there may be a number of dynamic behavior patterns in any catchment, which can be captured by a few key landscape elements. This is in agreement with the idea to delineate differently reacting regions in a catchment based on topographical indices [e.g., *Ostendorf and Manders-*

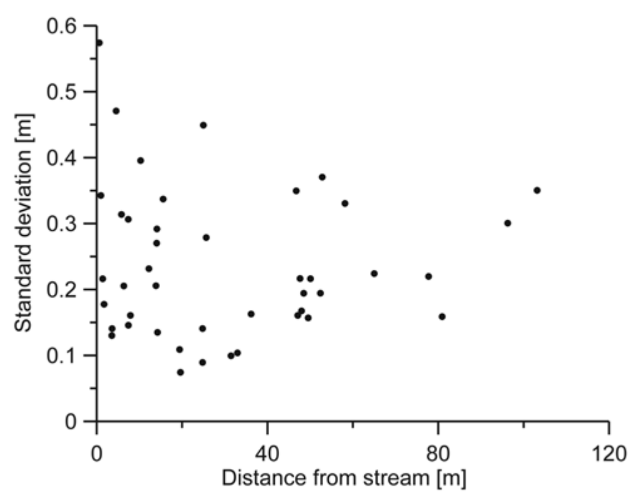

Figure 8. Standard deviation of the relative differences between local groundwater levels and the hillslope average level (for different points in time) versus distance of the well from the stream.

cheid, 1997] or with the hydrogeomorphic concept proposed by *Sidle et al.* [2000], in which different components of a catchment are supposed to exhibit unique hydrologic behaviors. We propose that while the steady state assumption for entire hillslopes or catchments may be inappropriate, this does not rule out the value of applying this assumption to individual zones within a catchment. Indeed, this is the theoretical basis of the new Dynamic TOPMODEL [*Beven and Freer*, 2001] and other recent modeling approaches [e.g., *Seibert et al.*, 2002]. The key advance that we put forward in this paper is the notion that the steady state assumption might not be valid for all zones of a catchment, and that one can objectively characterize these zones with hydrometric measurements.

4.4. The Way Forward

[32] Even if a divergence from steady state proves to be a common observation in catchments, an evaluation must be made of the importance of complicating a catchment model by giving up the steady state assumption. For instance, if one is interested in just the short-term runoff chemistry of episodes that prove to be dominated by the chemistry of the riparian zone, then a steady state formulation of the hydrology may be adequate. One may also be satisfied by the fit of the general linear model (equation (4)). A standard error of 15 cm, which, as pointed out by *Moore and Thompson* [1996], can be attributed to nonlinear or nonunit slope relations between pairs of wells and the nonsteady state conditions, might well be acceptable in a variety of applications. On the other hand, for the riparian zone in this study, where the groundwater levels usually varied by less than 30–40 cm over time, the error might be unacceptable large.

[33] On the Svartberget hillslopes, the riparian and the upslope zone were distinguished based on hydrometric evidence. Others are working to do this for soil solution and groundwater chemistry [e.g., *Hooper et al.*, 1998]. Earlier work on the hillslopes in this study and another hillslope on a different tributary of the Svartberget catchment also has identified the riparian zone as having a decisive effect on runoff chemistry that is distinct from the soil solution chemistry of the upslope zone [*Bishop et al.*, 1990a, 1990b, 1994, 1995]. Thus hydrochemistry also indicates that a distinction between upslope and riparian zones is important. Even soil freezing has been shown to have distinct upslope and riparian dynamics in this catchment [*Nyberg et al.*, 2001; *Stähli et al.*, 2001].

[34] It remains to be seen if the hydrological upslope/riparian boundary suggested by limits of the steady state assumption will coincide with the boundary suggested by hydrochemical data. Work on other transects in the Svartberget catchment have found that the 10- to 20-m-wide band of riparian peat delineates this boundary. The recognition of the riparian/upslope boundary raises the issue of how to reconcile these boundaries in hydrochemical modeling, and a consideration of the hydrochemical significance of this boundary.

[35] The hydrochemical importance of the riparian zone at Svartberget stems from the fact that it is the last soil/zone experienced by subsurface flow before reaching the stream, and from the very different chemistry of that organic zone relative to the upslope soils. This distinctive chemistry is a result of wetter and often anoxic conditions over the long-term development of the soil. The difference in timing of groundwater rise and fall identified in this study is therefore not the reason for the riparian zones' significance for runoff chemistry. The steady state TOPMODEL can distinguish wet riparian conditions from those upslope. The importance of distinguishing riparian groundwater dynamics from upslope dynamics in a hydrological model would lie on a different plane, such as determining source areas during an episode when large volumes of runoff occur during periods when upslope flow paths may not have even started to respond to rainfall or snowmelt [*Bishop et al.*, 2000], or establishing the zone of hydrological connectivity during an episode [*Creed and Band*, 1998; *McGlynn et al.*, 2002]. On a longer time-scale the more attenuated upslope hydrological response may be associated with the wetter hydrological conditions that contribute to the development of the hillslope soil catena and the features of riparian soil chemistry that differ from upslope soils.

5. Concluding Remarks

[36] The results of this study showed that a steady state assumption for the entire catchment is not supported by the data collected at the Svartberget hillslope site. While the steady state assumption may be appropriate for the riparian zones within the catchment, groundwater well information showed that this is inappropriate for the upslope zone. Groundwater levels closest to the stream were in phase with runoff, while areas further away lagged behind the streamflow, and often moved in directions opposite to that in the stream and riparian groundwater. Thus a steady state approach to modeling these hydrological dynamics, using TOPMODEL or some other conceptual modeling approach, would necessarily miss a fundamental feature of the hydrological response within the Svartberget catchment: namely that riparian zones and upslope zones show distinctly different groundwater level-runoff relationships. Although we believe that the results in general are valid for other catchments, it has to be emphasized that results might vary for other hillslopes and catchments. The studied hillslope in the Svartberget catchment is rather straight without significant convex or concave forms and there is no significant topographic flow concentration on the slope itself. In situations with a more complicated topography, more than two different dynamics might be distinguished.

[37] Comparing the simulations of a conceptual model with observed data for more variables other than simply runoff is crucial to ensure internal model consistency and is also valuable for model development. The additional information from using groundwater-level data at different locations along a hillslope depends on the correlation between these levels and runoff. Groundwater levels from wells with a response different from that of runoff provide more new information than well levels with dynamics similar to runoff. If different dynamics between groundwater levels and runoff are a feature of a catchment, a model can, of course, use that spatially distributed information only if the model allows for these spatially differentiated dynamics (i.e., moving beyond the simple steady state assumption!). For modeling, the subdivision into two different zones is reasonable with respect to both hydrometric (this study) and hydrochemical [*Hooper et al.*, 1998] evidence. To fully quantify the relative importance for such

models, though, will require further field efforts to determine the extent and significance of divergence from the steady state assumptions, as well as a consideration of how to reconcile hydrological and hydrochemical information about where the conceptual riparian/upslope boundary should be drawn.

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