Assessing Water Storage and Discharge Dynamics at the Catchment Scale under Complex Wetting and Drying Conditions

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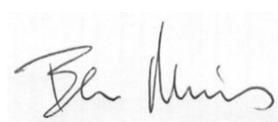
Approved: 
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ABSTRACT

Hysteresis in the soil water storage / discharge relationship is an important but poorly understood aspect of catchment response to rainfall, particularly in regards to spatial and temporal variations. In this study, a physics-based hydrologic response model was used to examine differences in hysteresis at the catchment and point scale for rainfall events with different durations and initial conditions. Additionally, the annual water balance of the catchment was analyzed to explore the factors that influence runoff and to identify possible predictors of runoff generation. Differences in topography that result from position within the catchment (hillslope vs. hollow) act as a major control on the timing and magnitude of discharge within the catchment and can influence the amount of hysteresis observed in the soil water content/discharge relationship. The results show that the direction of hysteresis across the catchment was unpredictable and did not correspond to either storm duration or initial conditions, which is an indicator of the complex spatial dynamics in response to rainfall. A soil moisture threshold for discharge was observed at 0.48 but was less likely to be observed for storms with short duration or dry initial conditions. Areas of average topography (CASMM sites) can be used to represent the average hydrologic state of the catchment, which has important implications for the role of topography and means identifying these locations could be useful for future research. The use of hydrologic response models and representative locations allows for high spatial and temporal resolution studies with lower costs and fewer measurement errors, making them valuable methods for studying catchment hydrologic properties.

INTRODUCTION

Understanding the relationship between soil water storage and discharge is essential for predicting runoff and catchment hydrologic response. However, many complexities make this relationship difficult to measure and predict using theoretical means. A threshold relationship between the average soil water content of a catchment and stream flow at the catchment outlet has been observed in many experimental settings (Tromp van Meerveld et al., 2006; Graham et al., 2010; Detty and McGuire, 2010), which causes difficulties when trying to predict runoff values during a storm event based on rainfall data alone. Furthermore, hysteretic behavior in the soil moisture / discharge relationship has been observed to vary with different antecedent moisture conditions (Penna et al., 2011), which further complicates the use of simple soil-moisture metrics for predicting runoff. Although topography acts as a major control on runoff during wet periods, slope can have a more random influence on soil moisture patterns during dry seasons (Duffy, 1996; Western and Grayson 1998).

Previous researchers have proposed the concept of selecting a few catchment average soil moisture monitoring (CASMM) sites (Grayson and Western 1998), which consistently exhibit the average or representative hydrologic state of the catchment. Potential locations for CASMM sites are typically areas of average topography where the slope of the land represents a medium gradient between that of the catchment’s level and steeper terrain. The significance of these areas of average topography suggests that catchment response varies with spatial location and that any differences in signal between the hollows and hillslopes may be lost when considering soil moisture as an average across the catchment. Although the importance of topographic position within the catchment (Western and Grayson, 1998) and also antecedent moisture conditions (Zehe and Bloschl, 2004) have been well documented, the nuances of how these factors influence storage-discharge relations remains poorly understood. More comprehensive analysis of stream flow at the catchment outlet and soil moisture at potential CASMM sites under different initial moisture conditions may help inform the development of simpler models for runoff predictions at the hillslope and catchment scales.

Soil moisture and stream discharge are challenging and expensive to measure, whereas physics-based hydrologic response simulation can be used to examine the relationship between discharge and soil water content at greater resolution than is possible with direct field measurements (Loague et al., 2006). Current measurements aimed at understanding soil moisture-discharge dynamics have revealed many complexities in this relationship, but field campaigns are often limited to monitoring of hydrologic response during a single storm event or a fairly short series of events within a given year. Long-term monitoring at experimental catchments is prohibitively expensive and thus relatively rare. Detailed simulations with sophisticated physics-based models can help address these measurement deficiencies and allow for longer duration catchment monitoring at high spatial and temporal resolution, without the measurement gaps and expenses usually associated with field work (Mirus et al., 2009).

In order to simplify the soil water content/discharge relationship and assess how this relationship varies for different events, this study will focus on changes in the magnitude and directionality of hysteresis. Hysteresis, which is defined as the reliance of a variable on the past state of the system, will be used in this paper to refer to the differences between wetting and drying signals in the storage/ discharge relationship (Camporese, 2014). Storage refers to the amount of water in the unsaturated zone and can be represented using the percent of an area at saturation (at the catchment scale) or soil water content (at the point scale). The magnitude of hysteresis measures the extent to which wetting and drying signals differ, while direction of hysteresis describes the order in which saturation and discharge increase and subside on a discharge/storage plot.

The objective of this study is to systematically investigate the influence of topography, seasonality, and climate on the variable relationship between soil moisture and discharge. The study relies on results from physics-based hydrologic response simulation for a simple catchment to examine how spatial location, initial conditions, and storm properties influence these relationships. The study also examines how annual changes in the net balance of discharge, storage, and evapotranspiration relate to soil-moisture at representative locations throughout the catchment. By analyzing these changes the study seeks to address the following questions:

1. What can we learn from physics-based hydrologic response simulations about the storage-discharge relationship?
2. What can the annual water balance of the catchment teach us about the controls on the timing and magnitude of discharge?
3. How does the soil water content-discharge relationship vary in space? and
4. How does the soil water content-discharge relationship vary for events with different initial conditions and storm characteristics?

METHODS

This study uses the Synthetic Rangeland-1 (SR-1) dataset (Mirus *et al.*, 2011), which was generated using the physics-based Integrated Hydrology Model (InHM) (VanderKwaak and Loague, 2001). The SR-1 dataset includes 11 years of continuous climatic forcing and synthetic hydrologic response data based on field observations from the 10.5 hectare Tarrawarra catchment in southeastern Australia (Western and Grayson, 1998; Mirus et al., 2009). The SR-1 dataset consists of both instantaneous snapshots and continuous time series of state variables, including surface water depth, pressure head, volumetric water content, surface water and groundwater velocity vectors, and flux measurements for the surface-subsurface boundary, as well as discharge hydrographs from the catchment outlet. This includes 11 years of continuous time-series data sampled using vertical profiles for 0.0, 0.02, 0.1, 0.5 and 1.0 m depths at 11 stations distributed throughout the catchment (Figure 1). The SR-1 dataset also includes regular snapshots of all state variables and fluxes sampled at high temporal resolution throughout the entire catchment for 11 selected storm events.

To address the question of how soil moisture fluctuations during storm events may vary spatially, the soil moisture discharge relationship was examined at different points throughout the catchment. To gauge the influence of topography and slope position within the catchment this study included points from topographical end members on the hillslope near the catchment boundary (point 11) and within the main hollow (Point 5) (see Figure 1). Point 11 corresponds to one of the possible CASMM locations identified by Grayson and Western (1998), so this location is expected to be representative of the average hydrologic response and state of the catchment as a whole. The soil moisture at each point was sampled from the dataset at a depth of 0.02 m which showed a slightly dampened signal from that on the surface, but was consistently above the shallow water table fluctuations.

The storm events selected to analyze temporal differences in the soil moisture discharge relationship include the storms on 04/04/1996, 06/23/1996, 02/28/1999, 11/13/2004, 09/12/2005, and 09/29/2005. These storms span a wide range of time and were selected to help isolate the effects of differing antecedent moisture conditions and storm duration. Storms 06/23/1996 and 11/13/2004 represent the differences between events that took place with wet and dry initial conditions, respectively. These storms were selected because they had a similar maximum discharge despite different rainfall durations. The time to maximum intensity for each storm was also similar enough to support a comparison. Storms 09/12/2005 and 02/28/1999 were selected to represent the differences between short and long duration storms, each with different time to peak rainfall intensity and total discharge. The intensity of storms was also analyzed by reconsidering storm 02/28/1999 and comparing to storm 09/29/2005 and 04/04/1996. Characteristics of the selected storms are summarized in ***Table 1***.

To analyze the wetting and drying of the catchment as a whole the discharge during each storm event was compared to the percent of the catchment area at saturation. This reveals seasonal changes in catchment response as well as different responses that result from different rainfall characteristics. To examine the different responses at topographical end members, discharge was also plotted against soil moisture at the two selected points.

The differences between wet years, with high cumulative rainfall, and dry years are often overlooked when considering individual storm events. Therefore the cumulative precipitation, discharge, and potential evapotranspiration were examined on an annual timescale. Annual plots of these processes highlight the impact of precipitation on antecedent moisture conditions, which not only vary seasonally, but also from wet to dry years. Comparison of the cumulative fluxes with time-series of soil-water content at the CASMM location on the hillslope facilitates a more detailed evaluation of the annual storage and discharge relations. To examine how these relations may differ with topography soil-water content at a location in the hollows (Point 5) was also considered.

RESULTS

Figures 2 and 3 shows annual plots of soil water content at the CASMM site, as well as cumulative precipitation (PPT), potential evapotranspiration (PET), surface runoff (Q_{s}), and groundwater discharge (Q_{pm}) for the catchment. Figure 3 also includes soil water content at the hollows location. Examination of Figure 2 reveals the seasonal and annual variability of discharge and soil moisture storage dynamics. Comparing the magnitude of soil moisture and cumulative variable fluxes reveals potential links between catchment response to variations in rainfall and soil moisture thresholds for runoff generation.

Precipitation varied considerably for each of the observed years, from a maximum annual cumulative of 0.947 m during the wettest year (1996) to a minimum of 0.465 m during the driest year (1997). Groundwater discharge from the catchment is consistently negligible compared to the other cumulative fluxes, but considerable differences in surface runoff were observed for each year. Visible increases in discharge occur only during years where cumulative precipitation exceeds 0.5 m, so we classify years based on total precipitation as being wet (> 0.5 m) or dry (< 0.5 m). While cumulative precipitation levels are a reasonable indicator of the occurrence of surface discharge for any given year, the amount of discharge varies with the temporal distribution of precipitation events. For example, 1998 and 2003 experienced approximately the same cumulative annual precipitation but significantly different total surface discharge due to the timing of rainfall both at the event scale and seasonally.

Figure 2 also demonstrates seasonal and annual differences in PET. Precipitation exceeds PET only in the wettest year when PET is low and PPT is unusually high. For the remaining years PET remains well above cumulative precipitation throughout the year, particularly in dry years. For wet years in which PET exceeds rainfall, surface discharge begins to increase in winter months when the growth in cumulative PET slows. Even though summer storms may lead to large increases in PPT early in the year, runoff does not noticeably increase in months where the slope of PET is steep.

Soil water content increases rapidly in response to large cumulative rainfall input and gradual drying occurs during prolonged periods of no precipitation. For all years, surface discharge occurs only when soil water content at the CASMM site increases past a threshold of 0.48. This relationship is likely visible as result of the moderate topography at the CASMM site that allows it to retain some soil moisture without emptying immediately or remaining at saturation for long periods after the event. The same relationship is not visible at other points in the catchment, such as the hollows (see Figure 3), where once the soil wets up it retains moisture for much longer due to lateral drainage and topographic convergence.

Figure 4 shows a hydrograph as well as plots of the saturation/discharge relationship at the catchment scale and at the selected monitoring locations. The selected events in Figure 4 include wet and dry initial moisture conditions with short and long duration rainfall. High and low intensity storms are also represented. In Figure 4 storm events are separated into two groups of those that show significant hysteresis at the catchment scale and those that do not. Comparing the storm hydrographs in Figure 4 reveals the catchment responds very differently to different rainfall intensities and durations (note the difference in scale on the discharge and rainfall axes). Storms with wet initial conditions have higher peak discharge values compared to those with dry, regardless of the length of the storm or distribution of rainfall. This difference is likely the result of differences in the timing of overland flow response for storms with different initial conditions. When the catchment is already wetted, soils reach saturation more quickly leading to earlier initiation of saturation excess/Dunne overland flow and greater runoff.

For each event hydrograph, Figure 4 also illustrates the temporal changes in the storage-discharge relations at the catchment scale as well as the spatial variations in soil moisture storage dynamics. The discharge-saturation plots show the catchment wetting up, as the amount of water in storage increases, and the resulting increase in runoff from saturation excess overland flow as the soil storage capacity is exceeded, followed by the draining of the soils through subsurface lateral flow. The remaining plots for the hillslope and hollow show the soil water content discharge relationship for each event at the selected points in the hollows and on the upper hillslope (Figure 1). Similar to the plots of saturated area vs. discharge, they show how the soil moisture discharge relationship varies for each event, but instead of averaging over the catchment they show the smaller scale, spatial differences that result at different topographic positions.

Hysteretic relationships are observed at the catchment scale because water is more evenly distributed across the catchment at the beginning of an event but becomes more focused in the topographic lows by the end, after some drainage occurs. Because topography plays such an important role in the flow of water through the catchment, hysteretic behavior may be more or less prominent depending on spatial location or when averaging over the catchment. Because hysteresis is the difference in wetting and drying signals it can be seen in curves that display two different saturation states for the same discharge, or two different discharges for the same saturated area. These differences can be read from the shape of the saturated-discharge curve at the separate scales. For example, in Figure 4 the largest hysteresis is seen in the SW storm which exhibits the circular shape indicative of hysteresis at both the catchment and point scale. Straight lines that closely overlap each other instead of forming a circle, like the ones at the hollow for the LW storm, indicate that the soil moisture discharge relationship is not changing between wetting and drying which means little hysteresis is occurring.

In Figure 4, more significant hysteresis at the catchment scale occurs for rainfall events with short durations (storms SW and SDs, Table 1) regardless of discharge magnitude or differences in the initial conditions. This relationship was true for both the saturated area of the catchment as a whole and the soil water content in the hillslope, whereas the soil moisture discharge relationship in the hollow generally showed very little hysteretic behavior. Unlike the saturated area of the catchment, the soil moisture discharge relationships at the hillslope and hollow are influenced by a soil water content threshold that must be reached before much discharge can occur. The threshold soil moisture value is approximately 0.48 and is most apparent at the hollow locations and for storms with short duration and/or wet initial conditions. As a property of the soil, the location of the threshold is consistent for all storms and spatial points, however the hillslope locations, particularly during storms with dry initial conditions, show more deviation from the threshold relationship. The hillslope point also shows greater hysteresis than does the dampened signal from the hollows location, although not as much hysteresis as is seen for the catchment as a whole.

The impact of the initial moisture conditions on the amount of hysteresis was less obvious than storm duration. At the catchment scale, for events with the same duration, wetter initial conditions tended to exhibit runoff events with more hysteresis than those with dryer initial conditions. However, the opposite was true at the point scale where the most obvious hysteretic loops at point 11 occurred for storm SD (with short duration and dry initial conditions).

In addition to differences in shape, hysteric loops can also differ from each other by their directionality, which can be read by following the color sequence of the curve during a single wetting and drying event to determine if the overall relationship is clockwise (CW) or counterclockwise (CCW). The hysteretic loops of discharge and soil moisture are not consistently CW or CCW across the catchment for the storm events, which is indicative of the complex wetting and drying dynamics present across the hillslope and hollows. While no direction of hysteretic loops was found to be dominant for all storms, storms with short durations (SW and SDs) were more likely to have similar directionality (CW for storm SW and CCW for storms SD) in the hysteretic loops of the saturated area and soil water content plots. In contrast, the directions of hysteretic loops for longer storms (LW and LD) were more difficult to judge, due to a lack of readable directionality at the point scale. The long duration and wet initial conditions event (LW) showed CCW hysteresis in the saturated area discharge relationship but no hysteresis in the soil water content discharge relationship at the individual points. Event LD (with long duration and dry initial conditions), on the other hand showed less hysteresis in general and directionality, where it could be read, appeared CW at both scales.

DISCUSSION

The differences in the amount of runoff between years with similar precipitation totals (Figure 2) show that the timing and intensity of rainfall events has an important impact on the amount of surface runoff during that year. While total precipitation can be used as an indicator of whether discharge will occur in a given year the influence of seasonal changes in PET means it cannot predict the occurrence of discharge for an event. The limitations of using precipitation as a means of predicting discharge helps illustrate the importance of the soil moisture discharge relationship, which provides a method by which to judge if and when individual events will initiate discharge. The presence of a soil moisture threshold at the CASMM site makes this relationship a more effective predictor of runoff on an event scale.

That the soil moisture threshold was visible at the CASMM sites and obscured at other locations (Figure 3) demonstrates the importance of position in the selection of a representative site and the importance of using such representative sites for predicting runoff. The relationship between the soil saturation and discharge is most apparent in areas of average relief, like the CASMM site, whereas soil moisture near the outlet may reach the threshold before discharge begins and points in areas of high relief may never reach saturation. CASMM sites can be of use for predicting not only when discharge will begin, but also how long it will continue. Identifying CASMM locations in other catchments may prove to be a cost-effective method of monitoring catchment average soil moisture dynamics and predicting which years will experience discharge.

In Figure 3, the observed differences in the soil moisture discharge curves for the selected storms illustrate the impact that both initial conditions and storm duration have on the soil moisture-discharge dynamics of the catchment. Changes in the shape and direction of hysteresis between the plots demonstrate the timing of runoff and the dominant flow path. The CCW hysteretic loops in the soil water content dynamics observed at multiple scales for storm SD indicates that catchment wetting is occurring before discharge begins, and drying before discharge ends, which is evidence of the importance of subsurface lateral flow within the catchment. The opposite behavior is evident for storms dominated by CW hysteretic loops (storm SW).

The differences between the soil-moisture discharge relationship shown at the catchment scale and the selected points show that the behavior of the soil in response to wetting is very dependent on initial conditions, in addition to spatial location. The soil moisture threshold for discharge, was most prominent at the hollows locations because these areas reach saturation more quickly than the hillslopes, which laterally transfer water downslope and therefore may not reach saturation until after discharge has already begun. The threshold relationship was also more prominent for certain events, like those with long duration and dry initial conditions, for which catchment response in the hollows and hillslopes differs. For example, dry and short events do not have sufficient time or the aid of residual soil moisture to establish an equilibrium between the hollows and hillslopes, meaning that discharge may be initiated due to saturation in the hollows, which saturate more quickly than or instead of the hillslopes.

Storm duration was also found to have an important impact on the hysteresis in the soil-moisture discharge relationship. Catchment scale hysteresis reflected the differences between the response of the hillslope and hollow locations and the magnitude of hysteresis was greatest for storms with short duration where the storage-discharge relationship at the selected points was more likely to differ. This occurs as a result of the underlying mechanism of hysteresis which relies on the differences in travel times between water moving toward the outlet from different locations in the catchment. For long duration storms, drainage from the hollows to the hillslopes has time to establish and maintain connectivity so the difference between these locations is only visible at the onset, whereas short duration storms lead to different moisture levels in the hillslopes and hollows since they may establish subsurface lateral flow but do not have enough time to saturate the hillslopes and establish a large saturated contributing area for Dunne overland flow.

SUMMARY AND CONCLUSIONS

Previous studies have analyzed hysteresis in soil-moisture discharge relations by averaging soil moisture across the catchment (e.g., Detty and McGuire, 2010). In this study hysteresis in the soil-moisture discharge relationship at the Tarrawarra catchment was analyzed using a synthetic data set of simulated hydrologic response spanning 11 years at high temporal and spatial resolution (Mirus et al., 2011). To examine how changes in the hysteretic relationship may vary across the catchment due to topography, catchment discharge and soil moisture were observed at selected points. Variability in storm characteristics and catchment initial moisture conditions were also considered by selecting several storms with different lengths that occurred during different seasons. Counterclockwise hysteretic loops were observed for several rainfall events in the catchment, which suggests the importance of subsurface lateral flow. Short duration storms showed more significant hysteresis and a greater difference in the soil-moisture discharge relationship at the selected points. Storms with long duration and dry initial conditions showed discharge initiating more quickly in the hollows causing deviations from the predicted threshold relationship.

Previous studies have also suggested the existence of areas of average topography with the potential to be used as monitoring locations (CASMM) because they are representative of the average catchment characteristics (Grayson and Western, 1998). Using soil-moisture discharge plots at a representative site as well as the annual water balance of the catchment for each year, this study examined the utility of these CASMM sites to represent the hydrologic behavior of the catchment. A soil moisture threshold of 0.48 was found throughout the catchment but was most prominent at the CASMM site suggesting it could be a reliable method of monitoring when discharge is expected to occur at multiple temporal scales. However, because this study relied on a simulation that represents soil as homogenous unit and does not represent the influence of aspect on ET, the reliability of the CASMM site may have been overstated relative to selection of a representative site in the field.

This study has examined the importance of topographic location within the catchment when considering hysteresis in the soil-moisture discharge relationship, as well as the importance of storm duration and initial condition. The potential of using CASMM sites as representative locations for catchment monitoring was also supported. Finally, the use of a physics-based hydrologic response simulation for this study further supports the use of synthetic data sets and virtual experiments to reduce field research costs and to increase spatial and temporal resolution.

Overall, this study was successfully able to use a physics-based hydrologic response simulation to not only model the storage-discharge relationship but also to show how that relationship is expected to differ spatially and temporally. The annual water balance of the catchment was used to examine several variables in relation to the timing and magnitude of surface water runoff and the significance of using a CASMM site to predict when discharge will occur. Differences in the magnitude and direction of the hysteresis in the soil water content discharge relationship were observed between the catchment point scales and for events with different initial conditions. The effect of the discharge threshold also varied between the hollows and hillslopes and for different events, which reflects the underlying mechanisms of hysteresis.

REFERENCES

Camporese, M., D. Penna, M. Borga, and C. Paniconi, 2014. A field and modeling study of nonlinear storage-discharge dynamics for an Alpine headwater catchment, *Water Resources Research* **50***:* 806–822, DOI:10.1002/2013WR013604.

Detty, J. M. and McGuire, K. J., 2010. Threshold changes in storm runoff generation at a till-mantled headwater catchment, *Water Resources Research* **46**: W07525, DOI:10.1029/2009WR008102, 2010b.

Duffy, C. J., 1996. A Two-State Integral-Balance Model for Soil Moisture and Groundwater Dynamics in Complex Terrain, Water Resources Research **32***(*8*):* 2421–2434, DOI:10.1029/96WR01049.

Graham, C. B., R. A. Woods, and J. J. McDonnell, 2010. Hillslope threshold response to rainfall: 1. A field based forensic approach, *Journal of Hydrology*, **393**: 1–2, 65–76.

Grayson, RB, AW Western, 1998. Towards areal estimation of soil water content from point measurements: time and space stability of mean response. *Journal of Hydrology*, **207**: 68-82.

Loague, K., CS Heppner, BB Mirus, BA Ebel, Q Ran, AE Carr, SH BeVille, JE VanderKwaaK 2006. Physics-based hydrologic-response simulation: Foundation for hydroecology and hydrogeomorphology. *Hydrological Processes* **20**: 1231-1237.

Mirus BB, K Loague, JE VanderKwaak, S Kampf, SJ Burges. 2009. A Hypothetical Reality of Tarrawarra-Like Hydrologic Response. *Hydrological Processes* **23**:1093-1103.

Mirus BB, K Loague, NC Cristea, SJ Burges. SK Kampf. 2011. A synthetic hydrologic-response dataset. Hydrol. Process., **25**: 3688–3692. doi: 10.1002/hyp.8185Penna et al. 2011

Tromp-van Meerveld, H. J., and J. J. McDonnell (2006), Threshold relations in subsurface stormflow: 1. A 147-storm analysis of the Panola hillslope, *Water Resources Research* **42**: W02410, DOI:10.1029/2004WR003778.

VanderKwaak, JE, K Loague. 2001. Hydrologic-response simulations for the R-5 catchment with a comprehensive physics-based model. *Water Resources Research* **37**: 999-1013.

Western, AW, RB Grayson. 1998. The Tarrawarra dataset: Soil moisture patterns, soil characteristics and hydrological flux measurements. *Water Resources Research* **34**: 2765-2768.

Zehe, E, G Bloschl. 2004. Predictability of hydrologic response at the plot and catchment scales: Role of initial conditions. *Water Resources Research* **40**:W10202, DOI:10.1029/2003WR002869.

Table 1. Characteristics of selected storm events

Storm name	Start date (mm/dd/yyyy)	start time (h)	end time (h)	Storm duration (h)	Total depth (mm)	Max intensity (mm/h)	Time to max intensity (h)
SW	6/23/1996	4152	4224	48	49	13	34
SD	9/29/2005			52	22	21	7
SD	9/12/2005	6048	6273	185	60	8	140
LDH	2/28/1999	0	1478	62	48	27	49
LD	4/4/1996			444	135	12	179
LW	11/13/2004	6672	7638	64	53	9	33

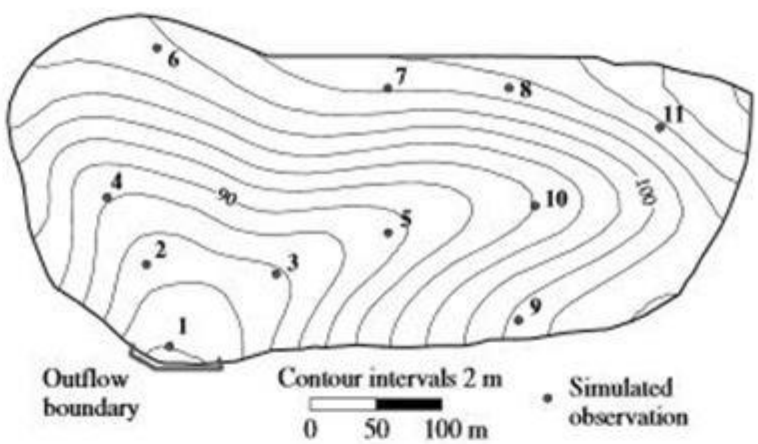

Figure 1. Topography and station locations of the SR-1 dataset

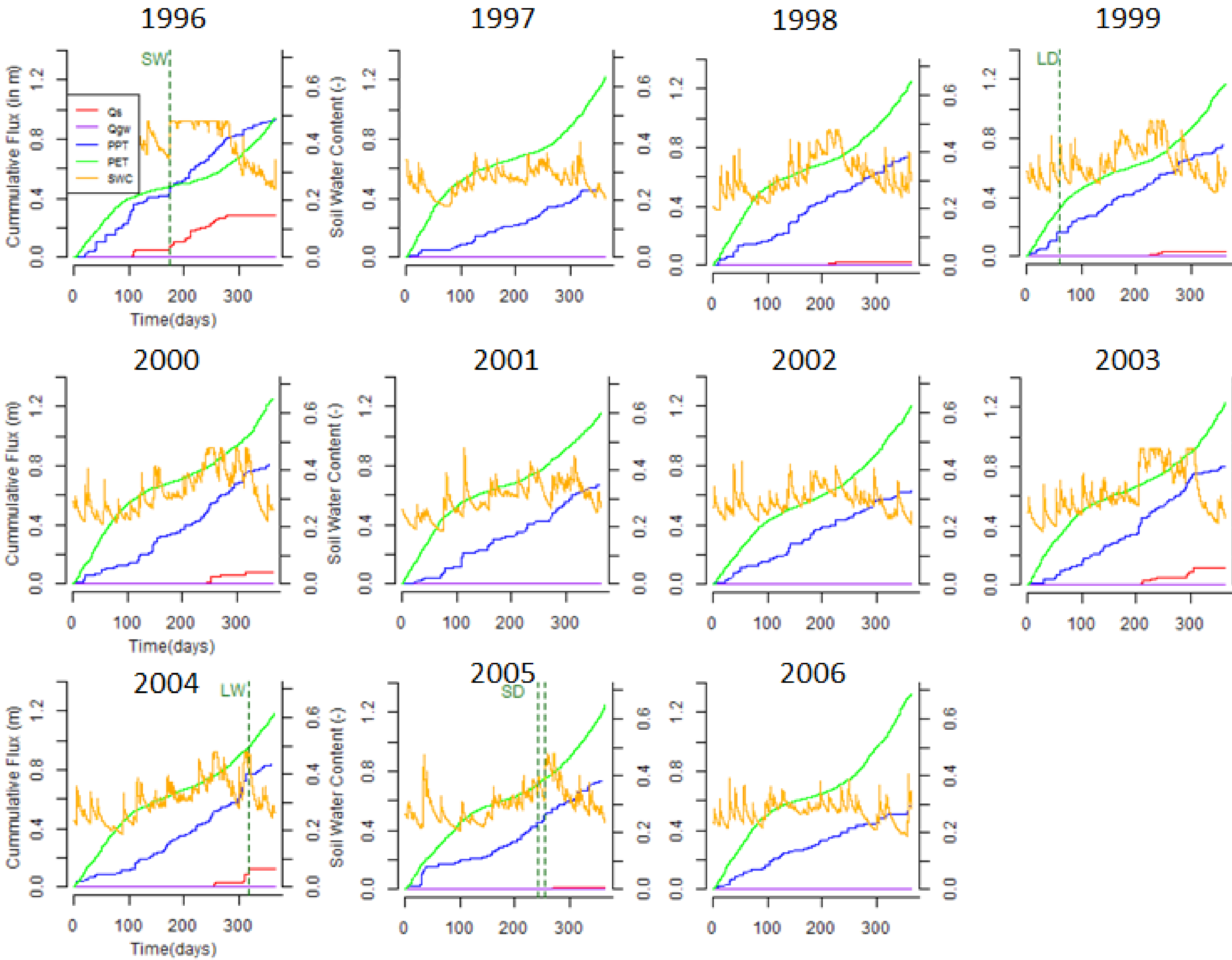

Figure 2. 11 years of annual cumulative totals throughout the catchment of surface discharge (Qs) in red, discharge in the porous media (Qgw) in purple, precipitation (PPT) in blue, and potential evapotranspiration (PPT) in green. All cumulative totals are measured in meters and plotted against the left hand y axis. Time in days is shown on the x axis. Soil water content at point 11 (potential CASMM site) at a depth of 0.1 m is also shown (gold) plotted against the right hand y axis. Figures correspond to years 1996 through 2006 moving across the rows.

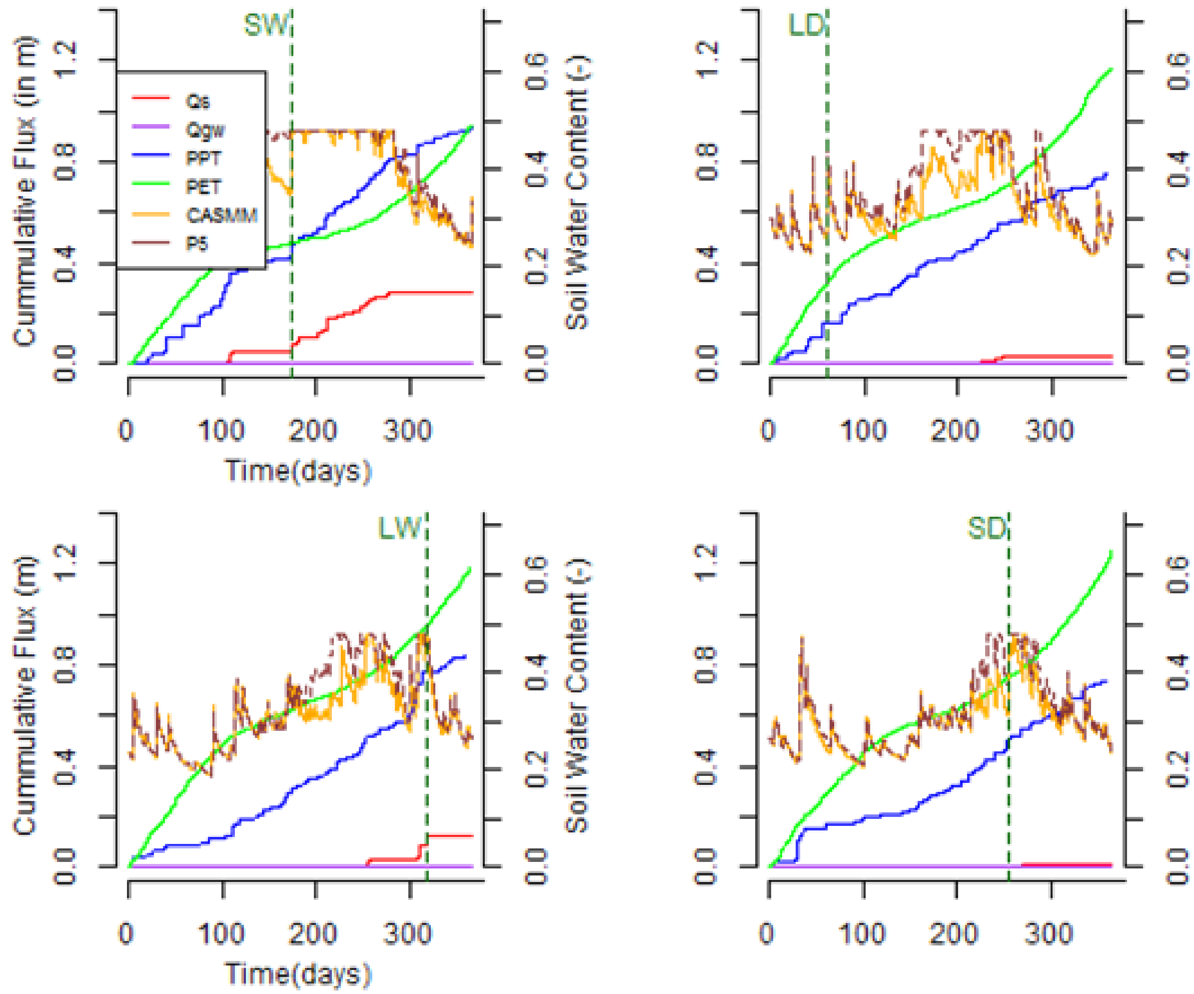

Figure 3: Cumulative discharges for years that include selected storms (1996, 1999, 2004, and 2005). Cumulative variables are the same as Figure 2 but soil moisture is shown at both the CASMM location (gold) and point 5 in the hollows (brown).

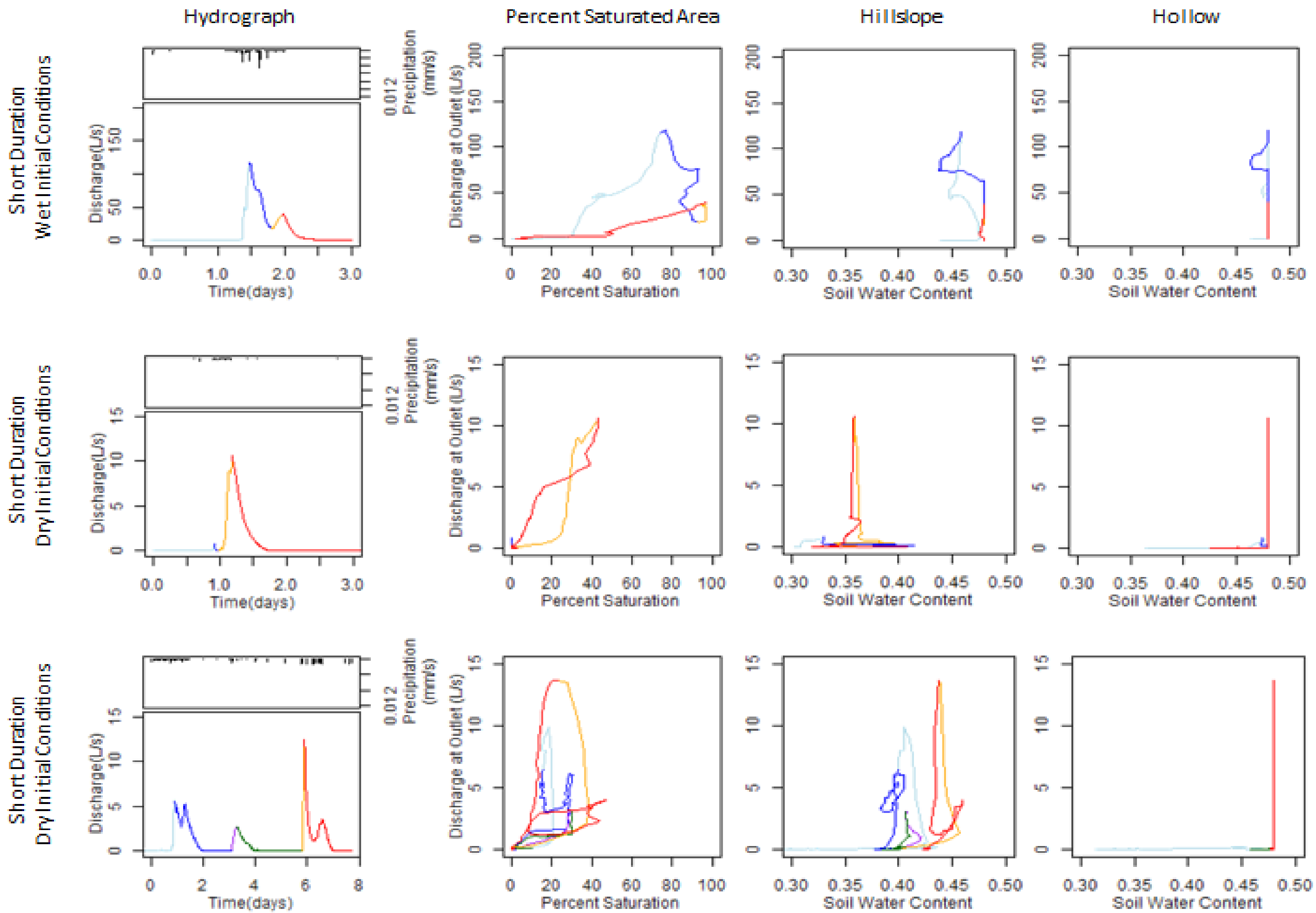

Figure 4. Storm hydrographs and soil moisture-discharge relationships for different storm events and spatial points. Rows represent selected storm events 06/23/1996, 9/29/2005, and 09/12/2005 with notable hysteresis. First column contains storm hydrographs with time (days) on the x axis, discharge at the catchment outlet (in L/s) on the left y axis, and precipitation shown above with rate (in mm/s) on the right y axis increasing downwards. Second column shows discharge (in L/s) vs. percent of catchment area at saturation during the event. Third column shows discharge (in L/s) vs. soil water content (theta) at point 11 (hillslope, potential CASMM site) at a depth of 0.02m. Fourth column shows discharge vs. theta at point 5 (hollow) at 0.02m. Colors (light blue, blue, purple, yellow, orange and red) were assigned to segments of the storm hydrograph and represent the corresponding times in the plots of moisture conditions during that event.

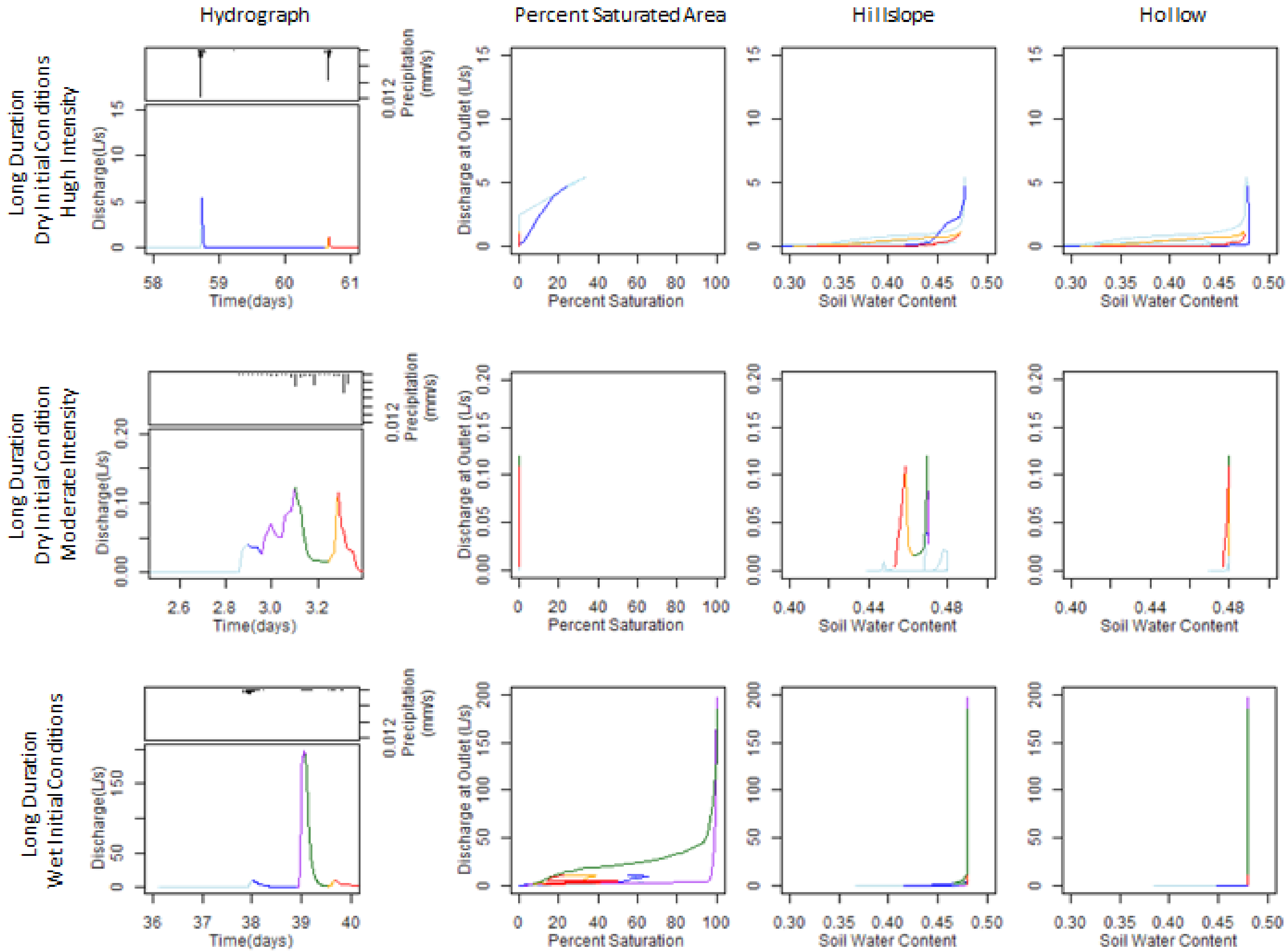

Figure 4 cont. Storm events without notable hysteresis 2/28/1999, 4/4/1996, and 11/13/2004.