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Multiple runoff processes and multiple thresholds control agricultural runoff generation

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Abstract. Hydrologic connectivity associated with runoff processes is a critical concept for understanding catchment hydrologic response at the event timescale. However, to date, most attention has focused on single runoff response types in individual research catchments. Here we examine how runoff response and the catchment threshold response to rainfall affect a suite of runoff generation mechanisms in a small agricultural catchment. A 1.37 ha hillslope in the Lang Lang River catchment, Victoria, Australia was instrumented and hourly data of rainfall, runoff, shallow groundwater level and isotope water samples were collected. We analyse 60 rainfall events that produced 38 runoff events over two runoff seasons. Our results show that the catchment hydrologic response was typically controlled by the antecedent soil moisture condition and rainfall characteristics. There was a strong seasonal effect in the antecedent moisture conditions that led to marked seasonal scale changes in runoff response. Analysis of shallow well data revealed that streamflows early in the runoff season were dominated primarily by saturation excess overland flow from the riparian area. As the runoff season progressed, the catchment soil water storage increased and the hillslope connected to the riparian area. The hillslope transferred a significant amount of water to the riparian zone during and following events. Then, during a particularly wet period, this connectivity to the riparian zone, and ultimately to the stream, persisted between events for a period of one month. These findings are supported by isotope results which showed the dominance of pre-event water, and increased contributions of new water early (rising limb and peak) in the event hydrograph for wetter conditions. We conclude that event runoff at this site is a combination of subsurface event flow and saturation excess overland flow. However, during high intensity rainfall events, flashy hillslope flow was observed even though the soil moisture threshold for activation of subsurface flow was not exceeded. We hypothesize that this was due to the activation of infiltration excess overland flow and/or fast lateral flow through preferential pathways on the hillslope and saturation overland flow from the riparian zone.

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1 Introduction

Thresholds have been an integral part of overland flow theory since the early infiltration excess work of Horton (1933) and saturation excess studies of Dunne and Black (1970a, b). Thresholds in runoff response have also been observed in subsurface stormflow dominated systems (Hewlett and Hibbert, 1967). More recent work has shown these to be a function of catchment wetness status for saturation excess overland flow (Western and Grayson, 1998;Western et al., 2005) and subsurface stormflow (Freer et al., 2002;Tromp-van Meerveld et al., 2007). Hydrological connectivity is now a useful generic concept that links reservoirs to their downstream conduits (Tetzlaff et al., 2010) and a connectivity framework can provide a powerful explanator of catchment flow and transport response (Ali et al., 2013;Detty and McGuire, 2010;Lehmann et al., 2007;McGuire and McDonnell, 2010;Western et al., 1998, 2001). Connectivity and thresholds are intimately related; typically a threshold in some catchment state controls the transition between connected and disconnected states; for example, the observation that subsurface flow becomes connected above some soil water storage and rainfall threshold (Detty and McGuire, 2010;Tromp-van Meerveld and McDonnell, 2006a).

Despite significant progress in understanding the non-linear behaviour of catchments related to soil moisture thresholds, watertable dynamics, connectivity of surface and subsurface pathways and their influence on runoff generation mechanisms, it is not explicitly understood how the non-linear properties of catchments (connectivity and thresholds) work to convert rainfall to runoff nor how such behaviours vary between different types of catchments. It has been argued that interactions between the various processes and thresholds leads to complex non-linear rainfall-runoff behaviour in catchments (Hopp and McDonnell, 2009;Kirchner, 2006;Tetzlaff et al., 2010;Uchida et al., 2005) including: thresholds for initiation of hillslope-to-stream connectivity (Ali et al., 2013;Detty and McGuire, 2010;Fujimoto et al., 2008;Lehmann et al., 2007;McGuire and McDonnell, 2010;Tromp van Meerveld and McDonnell, 2005;Tromp-van Meerveld and McDonnell, 2006a); variable flow hysteresis patterns depending on rainfall amount and antecedent soil moisture conditions (Bowes et al., 2009;Holz, 2010;McGuire and McDonnell, 2010); and flushing of nutrients in agricultural catchments (Bracken and Croke, 2007;Ocampo et al., 2006;Tockner et al., 1999;Withers and Lord, 2002).

While the concept of connectivity has been useful in many of these studies, the studies have concentrated on individual mechanisms. It is less clear how catchments behave when subject to a mixture of runoff mechanisms including infiltration excess and saturation excess overland flow, and subsurface stormflow. Few studies have tried to tease apart the influence of multiple processes in catchments where infiltration excess, saturation excess and subsurface stormflow are all important. Here we do that for an agricultural catchment in south-eastern Australia and show the shifting importance of different processes over time associated with changes in catchment wetness and rainfall intensity. Prior to this, we consider the role of multiple thresholds in catchment states and fluxes as well as the role of thresholds in certain timescales in controlling different modes of hydrologic connectivity and associated rainfall-runoff response.

Figure 1 summarizes the status quo in terms of the combined effects of thresholds and connectivity. It shows the importance of various timescales, fluxes and states, and how these relate to variation in rainfall-runoff processes over time (and between

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Hydrology and Earth System Sciences Discussions

catchments). Of course, questions of instantaneous flux and also of the relative timescales of various processes are often important in determining the existance of connectivity (Tromp van Meerveld and McDonnell, 2005;Western et al., 2005). It would be attractive to think of the problem of runoff response purely in terms of timescales of competing processes following Oldham et al. (2013); however, both flux and time thresholds are important. This arises because there is finite capacity for flow in various parts of the catchment system.

Figure 1 is divided into three areas, the lefthand area (climate and landscape characteristics) provides a series of catchment thresholds that determine runoff processes and connectivity, depending on whether they are exceeded or not. The middle area points to the outcome in terms of runoff generation processes and the righthand area provides example catchments from the literature that exhibit those processes. Some of the thresholds are posed in terms of flux rate compared with a flow capacity (e.g. box 2) and some in terms of a state threshold (box 5). The flux and state thresholds are considered in the context of a process timescale. This is because the threshold needs to be exceeded for a sufficient time for the action of the process to lead to a significant impact.

Consider box 1. Rainfall rates vary across a very wide range to timescales. If the rainfall (or throughfall) intensity exceeds the infiltration threshold for only a very short time, the water that ponds on the surface will continue to infiltrate as it flows toward the stream (runon infiltration) when the intensity reduces and very little or no runoff will result (surface connectivity didn’t become established). However if average intensities exceed the infiltration capacity for long enough for ponded water to flow to the catchment outlet, the hillslope will connect to the catchment outlet via surface pathways and produce runoff. The remaining boxes consider thresholds in the context of subsurface flow times. Box 3 considers situations where subsurface saturation exists, allowing lateral subsurface flow paths to be activated. If any of deep infiltration through the impeding layer (Jackson et al., 2014), unfilled bedrock storage (Janzen and McDonnell, 2015) or evaptranspiration cause the saturation and/or lateral flow to disipate before water can move a significant distance downstream, the water will not be effectively redistributed downslope and subsurface connection wont be established (this is Grayson et al.’s (1997) local control). If the saturation persists for long enough lateral subsurface flow will connect to the stream. At the other extreme (box 7), if lateral flow is persistently exceeding the hillslope subsurface flow capacity, surface saturation will exist leading to saturation excess runoff.

Figure 1 goes about here

While Figure 1 suggests catchments are dominated by certain processes it needs to be recognised that many catchment conditions vary over time. For example summer rainfall is often more intense than winter rainfall. Soil water conditions vary seasonally in response to both rainfall and potential evapotranspiration, sometimes leading to switching between characteristic spatial patterns and prevailing responses to rainfall (Grayson et al., 1997;Western et al., 1999). Topographic, soil and vegetation conditions can also vary across a catchment. This all suggests that catchments could exhibit a mix of processes.

Here we use the above framework to understand the behaviour of a catchment that does indeed exhibit a mix of runoff processes. We examine how soil water storage and shallow water table response influence subsurface connectivity and rainfall-runoff response at seasonal and event based time scales. We also examine the relative role of saturation excess and subsurface flow in generating peak runoff rates and event volumes. Finally we examine circumstances under which rainfall intensity plays a role in runoff generation responses. The field site is a small agricultural catchment in the Lang Lang River catchment, Victoria, Australia, which we examine through the lens of hydrometric and isotope and geochmistry measurements. These results are used to propose a conceptual model of the processes and pathways that contribute event runoff as catchment wetness and rainfall intensity vary.

2 Methods

2.1 Study location

The study site is a 1.37 ha hillslope (RBF) located on a dairy farm at Poowong East, in the Lang Lang River Catchment, Victoria, Australia, 130 km south-east of Melbourne (Figure 2). A general description of the study catchment can be found in Adams et al. (2014). The study period was between September 2009 and December 2011. Elevation ranges from 160 to 210 mAHD and the slope varies from 2% to 50%. Based on field observations and the hydrologic behaviour, the hillslope was divided into four different zones: 1) the riparian area located on the relatively flat convergent lower part of the hillslope (outlined in black on Figure 2) included sites 16, 1, 2, 32 and 3; 2) the lower slope (low slope) area; 3) the mid slope area with sites 4, 5, 6 and 7 ; and 4) the upper slope (upslope) area with sites 10, 11 and 15 (Figure 2).

Figure 2 goes about here

The study area has a humid climate and rainfall is reasonably uniformly distributed across the year with an annual mean (1961-1990) of 1100 mm (Bureau of Meteorology, 2009). Annual areal potential evapotranspiration is 1040mm (Bureau of Meteorology, 2005). The catchment geology comprises of sandstones and mudstones of the Cretaceous Strezlecki Group (VRO, 2013). Outcrops on the lower stream banks of the catchment (just downstream of the monitored hillsope) show weathered sandstone and mudstone bedrock. Hand augering revealed a soil depth of <= 1.5-1.6 m, and the lower parts of the profile included mottled clay and weathered bedrock particles. The soils are acidic and mesotrophic brown dermosols (Isbell, 2002). Soil profile depth decreases moving downslope. These soils typically have a moderate hydraulic conductivity surface horizon (0-40 cm, $K_s \approx 5*10^{-6}$ m s^{-1}, about 20 mm hr^{-1}). The dominant land use is grazing by dairy cows.

2.2 Site instrumentation and hydrometric data monitoring

Rainfall data were recorded using a 0.2 mm tipping-bucket raingauge at an automatic weather station which was installed in 2010 at the top of RBF. A rainfall sampler (Kennedy et al., 1979) collected up to ten sequential rainfall samples, each being equivalent to 6.6 mm of rainfall. The sampler was initially installed close to the AWS, however, due to instances of damage by animals, it was relocated near to the flume in August 2010 until the end of the study period. A trapezoidal flume was installed at the riparian zone outlet and an Odyssey (Dataflow Systems inc. Christchurch, NZ) pressure transducer (PT) recorded water levels every 10 minutes, which were used to compute instantaneous flow rates. After August 2011, the PT was replaced with an ISCO (Teledyne ISCO , Lincoln,NE,USA), model 730 bubbler.

An auto sampler (Teledyne ISCO 6712) was installed at the outlet of RBF and was triggered based on the rising stage and programmed to collect up to 24 samples at hourly intervals. Samples were collected from the auto sampler within 48 hours. To reduce the laboratory analysis workload, the flow hydrograph was graphed in the field prior to event sample collection. All samples during the rising limb and the peak were collected and samples were typically selected at an interval of 4 hours during the falling limb. Routine grab sampling was undertaken at weekly intervals during the main runoff season when water was flowing through the RBF flume. This was supplemented by additional grab sampling during visits to collect event samples from the auto sampler.

Weather variables (temperature, humidity, wind, rainfall, global radiation) were measured by the automatic weather station. Areal potential evapotranspiration (APET) was also computed using the Morton (1983) wet environment method on a daily basis. APET was strongly seasonal resulting in strongly seasonal soil moisture contents and intermittent streamflow at RBF. Hourly volumetric water content (VWC) was measured at 0-30 cm and 30-60 cm depths using vertically installed 30 cm long Campbell Scientific CS625 probes (Campbell Scientific, 2006) situated close to the AWS. The soil moisture sensor data were corrected for soil temperature which was also measured close to the AWS.

To capture the nature of hydrologic connectivity, runoff mechanisms and flow pathways, shallow (1.5-1.6 m) groundwater wells were installed across the RBF hillslope using 40 mm PVC pipes and backfilled with sand, bentonite, the topsoil and grass. Figure 2 shows these sites of which 1, 2, 3, 16 and 32 were in the riparian zone; 4, 5, 6 and 7 were on the mid slope; and 10, 11 and 15 were on the upper slope. Sites 4, 5 and 6 were equipped with water level loggers from July 2010, and sites 3, 7, 16 and 32 were logged from winter 2011. Water levels were logged using Odyssey PT loggers.

2.3 Water sample analysis

Sub-samples were taken of stream water from both manual and auto sampler samples, and from all full rainfall sample bottles; these were collected in glass bottles for isotope analysis. Bottles were completely filled. The samples were refrigerated (+ 4°C) until analysis for $\delta^{18}O$ and $\delta^{2}H$, either by the Monash University Earth Sciences laboratory or by Professor Russell Drysdale's isotope laboratory at the University of Melbourne, where a Picarro L2120i cavity ring-down isotope analyser was used to determine isotope ratios. The uncertainty in results was $\delta^{18}O$=0.1‰ and $\delta^{2}H$ =0.4‰. Sub-samples were also taken from each water sample for selected major ion (Na^{+}, K^{+}, Ca^{2+}, Mg^{2+} and Cl^{-}) analyses, which were analysed in the NATA-certified, analytical chemistry laboratory of the Water Studies Centre at Monash University using standard methods.

2.4 Rainfall and runoff events

In order to analyse event behaviour, it was necessary to identify rainfall and runoff events. Based on an examination of the time series of hourly rainfall in the catchment, rain events were defined as having >= 5 mm total rainfall, and peak hourly rainfall intensity, I_{peak}>= 1.5 mm hr^{-1}. Distinct events were separated by > 12 hours without rainfall.

The runoff hydrograph was also divided into events. Runoff events began when the hydrograph started to rise from its initial low flow value or moved above a threshold of 0.05 mm hr^{-1} following the commencement of a rainfall event. Events ended either when: 1) the flow returned to its initial value; 2) a new rainfall event started; or, 3) 96 hours after the end of the rainfall event in unusually wet situations where elevated flow continued. For each event, a number of characteristics were determined as shown in Tables 1 and 2.

The antecedent soil moisture condition (ASI) was represented using the soil water storage in the top 60 cm of the profile at the AWS at the start of each rainfall event. Saturated area extent was estimated based on manual measurements of the upstream extent of the saturated area (see Figure 2 for the maximum boundary location at site 3) in the field between events, combined with GIS information. The saturated area is topographically constrained in the lateral direction. The proportion of saturated area was estimated using these data and then used to estimate saturation excess runoff generation for the different events. In this study we separate return flow and flow resulting from direct precipitation on the saturated area and use Saturation excess Overland Flow (SOF) to refer to the latter. The event runoff depth (mm) and event runoff coefficient (RC %) were calculated by separating the event hydrograph using the method of (Hewlett and Hibbert, 1967), which has been widely applied (Buttle et al., 2004;Fujimoto et al., 2008;McGuire and McDonnell, 2010). The method assumes that baseflow increases at the rate of 0.55 l s^{-1}km^{2}h^{-1} (0.002 mm hr^{-1}) from the start of the rising limb.

3 Results

The following results first provide an overview of the seasonal behaviour and rainfall-runoff events. They then examine whether thresholds in the antecedent conditions and/or event rainfalls exist. Next, links between the hillslope condition and the event runoff are examined using the piezometer and soil moisture data. After that, the recession behaviour of events is examined and linked to hillslope wetness conditions. Finally isotope and major ion data are presented for selected events.

3.1Overview of runoff behaviour and rainfall-runoff event characteristics

Figure 3 shows time series of weekly rainfall, APET, soil water storage and runoff. The rainfall, although variable from week-to-week, exhibited little seasonality, while there was strong seasonality in PET. This drove a strong seasonality in soil water storage. An examination of the weekly runoff data shows that there was generally no flow from about October to May due to the seasonal nature of this catchment; however, an exception was that persistent low flow occurred from 26 November 2011 to the end of the event on 10 December 2011. During this period ASI was often relatively low but there was frequent and substantial rainfall (>200mm in 30 days). While a strong link between runoff and soil water storage is evident in Figure

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3, there are exceptions. For example in February 2011, there was a runoff response despite the catchment being near to the lowest soil water storage for the study period.

Figure 3 goes about here

Moving to the event timescale, Table 1 summarises 38 rainfall-runoff events and Table 2 shows a summary of 22 rainfall events that did not produce a runoff response. A further 16 rainfall events occurred over the study period which are not included in the analysis due to missing runoff data. For the 38 runoff events, total event rainfall varied from 7 to 72 mm, I_{peak} ranged from 2 to 31 mm hr^{-1}, ASI ranged from 130 to 286 mm and total event runoff varied between 0.23 and 41 mm. For the no-flow events (Table 2), total rainfall varied from 5 to 28 mm, I_{peak} ranged from 2 to 10 mm hr^{-1}and ASI ranged from 146 to 238 mm. Figure 4 shows rainfall-runoff responses for selected events at RBF. These graphs are ordered from lowest (27/11/2010) to highest ASI (7/6/2011) for the selected events. Most of the events presented in Figure 4 had zero or very low initial flow.

Table 1 goes about here

Table 2 goes about here

Figure 4 goes about here

In Figure 4 most events showed rapid response to rainfall, except for the event on 12/11/2010 which did not produce any runoff and the event on 7/6/2011. The events on 27/11/2010 and 10/12/2011 in particular showed a very flashy response. These events had the highest peak hourly rainfall intensity during the study period and they occurred at the end of the flow season with low ASI (for the characteristics of these events see Table 1). The highest peak runoff rates for the study period were for the events on 27/11/2010 and 10/12/2011, which were 2.4 and 5.6 mm hr^{-1}, respectively. In contrast to most events, the runoff response for the event on 27/11/2010 was transient with very rapid recession. For the event on 10/12/2011, a second peak of moderate rainfall intensity (about 10 mm hr^{-1}) produced a second runoff peak and there was a more significant recession flow following the rainfall bursts. This was also true for the other events shown in Figure 4, which were typical of responses to lower intensity rainfall during wetter (in terms of soil water) periods.

For events with I_{peak} < 10 mm hr^{-1} there was a general increase in response as the ASI increased. The event on 12/11/2010 had 184 mm ASI and total rainfall was 28 mm and it did not produce any runoff. This was a typical example of no flow events. Coming into the runoff season, as ASI increased (e.g. 220 mm on 11/5/2011), RBF started to respond gradually, producing small amounts of runoff (e.g. for events on 11/5/2011 and 14/5/2011). When the ASI was > 250 mm for the event on 7/6/2011, it can be clearly seen that RBF responded to this low intensity, small size rainfall event with a delayed and smooth flow hydrograph with continued flow following the event. This also occurred for the next event on 1/8/2010.

3.2Runoff thresholds

In Figure 1 we set out a number of thresholds that are important in runoff production mechanisms. We now explore the event data from the perspective of thresholds, concentrating on two key ones: catchment wetness and rainfall intensity. Figure 5 builds on approaches by Detty and McGuire (2010) and Janzen and McDonnell (2015). Figure 5a shows event runoff as a function of event rainfall, with the highest hourly rainfall intensity indicated by colour. Acknowledging that we have excluded rainfall events below 5 mm total rainfall, essentially any rainfall depth could produce a response at the catchment outlet, but there was a wide variation in runoff coefficients (indicated by the scatter). It is also clear that the events with high peak hourly intensity also had relatively large total rainfall accumulations.

Figure 5 goes about here

Figure 5b shows the impact of five factors together. The cumulative curve shows the distribution of soil water storage as observed through the study period. Specific events are shown with the ASI identified (left hand end of the grey lines) and the ASI plus rainfall depth (filled markers at the right end of the grey lines). The length of the lines is the rainfall depth. The colour shows the peak hourly rainfall intensity (I_{peak}) and the size of the bubbles shows the quick flow runoff coefficient. Squares indicate events that did not produce any runoff or where the peak runoff rate was less than 0.05 mm hr^{-1}. There are several trends that can be discerned from Figure 5b. Rainfall events occurred across the full range of catchment wetness and were relatively evenly spread. The larger rainfall events generally occurred when ASI<250 mm and a mix of low and high intensity events occurred for these conditions. All the events on a wet catchment (ASI>250 mm) had low I_{peak} (≤6.2 mm hr^{-1}). Events where the ASI plus rainfall was less than 250mm usually did not generate any runoff, although there were some high intensity exceptions and a small number of events with very low runoff coefficients (1-4%) where the ASI plus rainfall was generally between 240 and 250mm. These low runoff coefficient events were at the end of the runoff season.

Figures 5c and 5d look at the role of catchment wetness at the start (5c) and end (5d) of the event, combined with rainfall intensity, I_{peak}. The bubble size shows the quick flow runoff coefficient, as before, and crosses indicate rainfall events that did not produce runoff. Colour indicates the runoff volume. The runoff behaviour is separated into groups more clearly in Figure 5d than in 5c. There are essentially three different groups including: 1) events without runoff where ASI+Rain<250mm and I_{peak}<10 mm hr^{-1}; 2) events that produce runoff when ASI+Rain > 250 mm; and 3) events with ASI+Rain<250 mm and I_{peak}>15 mmhr^{-1} that did produce runoff (Tables 1 and 2). Where the ASI plus event rainfall exceeded 250 mm (group 2), some runoff was always produced.

Both of the first and third groups had ASI plus event rainfall less than 250 mm but they behaved differently in that some produced runoff and others did not. In the first group low intensity rainfalls mostly happened in drier periods when ASI varied between 146 and 227 mm. These rainfall events completely infiltrated into the soil and they did not produce runoff (see Table 2 for event characteristics).

The third group, including events on 27/11/2010, 4/2/2011 and 10/12/2011, occurred during dry periods at the end of the flow season when the ASI was < 200 mm. These events were distinguished by having maximum hourly rainfall intensities above ~15 mm hr^{-1} and they did produce runoff. In particular, two of these events on 27/11/2010 and 10/12/2011 had the highest rainfall intensities observed (I_{peak}> 30 mm hr^{-1}) and they produced the highest peak runoff rates (8.1 mm hr^{-1}and 9.1 mm hr^{-1}) and hourly runoff totals (2.4 and 5.6 mm) observed during the study period (Figure 3). These runoff peaks were synchronised with the highest rainfall intensities. Antecedent flow for the events on the 27/11/2010 and 4/2/2011 was zero and the hydrograph rose and recessed quickly. For the event on the 10/12/2011, the ASI was 192 mm, the total rainfall was

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Hydrology and Earth System Sciences Discussions

53 mm, with an initial flow of 0.13 mm hr^{-1} (Table 1). It produced the highest observed peak hourly runoff of 5.6 mm, the runoff duration was 32 hours and total runoff was 41 mm. The highest intensity was observed in the first two hours of the event and 18% of the rainfall had become runoff by the end of those 2 hours. This compared to a maximum surface saturated extent of about 6% of the catchment area. The event on 10/12/2011 marked the end of a particularly rainy period, with more than 200 mm over 30 days. Note that due to equipment being removed after this event, this event was the last recorded flow event at RBF.

3.3 Evidence for runoff processes and thresholds

The above presentation of results from Figure 5d identifies a threshold catchment wetness expressed as antecedent soil water storage plus event rainfall depth of 250 mm above which runoff always occurred and another threshold of hourly rainfall depth exceeding 15 mm which also led to runoff production. Looking at events in the lower right quarter of Figure 5d also shows that the event runoff coefficient tends to increase as either catchment wetness or peak hourly intensity increases. These results suggest that there are both a wetness dependent and an intensity dependent runoff production mechanisms operating. This section examines the evidence for different runoff mechanisms contributing to event runoff.

3.3.1 Hillslope wetness-flow response relationships

Figure 6 shows the runoff time series together with water level time series at several shallow piezometers; sites 4, 5, 3, 32, 2 and 1 (Figure 2). All sites except 4 were located in drainage lines. The sites are organized by elevation from highest to lowest in the catchment. Manually read sites are shown with dashed lines. Figure 6 clearly shows that the duration of saturation increased downslope. Comparing the runoff time series with the piezometer record for sites 1, 2 and 32, it is clear that the water table rose to the surface in the upper parts of the riparian zone during runoff events. Furthermore, the lower half of the riparian zone remained saturated to the surface for long periods during the runoff season. The record for site 3 indicates that the water table at this site did not rise to the surface, even during events.

Figure 6 goes about here

Looking at the flow record, there were periods where significant baseflow persisted between events. These correspond to periods where the water table at site 5 was above about 120 cm and at site 4 was above about 140 cm. Flow became more strongly persistent between rainfall events as the water table at sites 4 and 5 rose further. The water table recessions at sites 4 and 5 correspond with flow recessions when the water table was above 120 cm and 140 cm at sites 4 and 5, respectively. Figure 7 shows the relationship between water table levels on the hillslope (sites 4 and 5) and soil water storage at the weather station. Site 5 in particular shows a strong change in behaviour for soil water storage above 250 mm. Above this threshold much higher water tables were typically observed and those water tables showed relatively rapid recession when shallower than 120 cm. Similar observations were seen at site 4 but the threshold depth was 140 cm. Figure 7 thus explains the linkage between the 250mm ASI plus event rainfall threshold and runoff. When soil water contents exceeded this level, water tables rose into a more permeable zone and lateral subsurface drainage occurred, as evidenced by the recessions. That

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Hydrology and Earth System Sciences
Open Access
Discussions

is, the hillslope was becoming connected to the catchment outlet via subsurface flow. There were a few occasions where the water table responded strongly for soil water storage less than 250 mm. As indicated by the red colour, these corresponded to high intensity rainfall events. It is not clear exactly how the water moved rapidly into the wells in these cases but it could be due to preferential flow through macropores.

Figure 7 goes about here

Flow recessions provide information on the drainage characteristics of catchments. Figure 6 shows that the hillslope flow usually ceased between events during the wet period, with no flow during dry periods. However, in August and early September 2010, continuous hillslope flow endured for a month (Figure 6). There was also a marked variation in the recession behaviour during August/September 2010. To explore this, we calculated the recession constant, *K* (as in $Q = Q_0 e^{-kt}$), and plotted it against soil water storage at the start of the recession for individual events within this period (Figure 8). *K* decreased as soil water storage increased. Considering this and the transient nature of flow during dry periods, it is clear that the wetter the catchment is, the slower the recessions are. By inference, this implies greater (perhaps more spatially extensive) subsurface connectivity is providing flows from the hillslope and maintaining catchment discharge during wetter conditions.

Figure 8 goes about here

3.3.2 Isotope and major ion results

Clearly, subsurface flow is often important in this catchment, suggesting that the event outflow would be dominated by "old" water; however, the saturated area in the lowest parts of the catchment would also be expected to produce direct flows of "new" water. Figure 9 shows an event from 12 August 2010 during the wettest part of the study period. The antecedent soil water storage at the beginning of this event was 274 mm and total rainfall was 17 mm. Stable isotope data was available for the event and is shown on Figure 9. Over the study period δ^2H for rainfall varied between -7‰ and -83‰ and δ^2H for low flows was highly damped. Low flow samples from the RBF flume before and after the event showed a δ^2H of -27‰ and rainfall for this event was strongly depleted (3 samples prior to and during the event δ^2H = -42, -67 and -57‰), compared with low flow. The runoff samples showed a very different signature in the rising limb and the peak of the hydrograph (-43‰) in comparison to antecedent low flow (-27‰). Using a two-component mixing model, we estimate that the peak contribution of new water was about 50%, and the new water contribution to the event volume was 17%, corresponding to 5% of the rainfall depth. The timing of the new water contribution matched the main rainfall burst well with relatively rapid return to the typical old water isotopic signature following the cessation of rainfall. These results suggest that precipitation on the saturated area generates direct runoff in amounts that would be expected given that the saturated area is around 5-6% of the catchment area.

Figure 9 goes about here

Another interesting event is the higher intensity (I_{peak} = 15 mm hr^{-1}) event on 8/11/11. Major ion geochemistry data were available for this event. Figure 10a shows the typical relationship between flow and chloride concentration, with samples from this event identified by red. Figure 10b shows the time series of chloride concentration along with the hydrograph. The first and second chloride samples respectively plot above and within the typical scatter of data on Figure 10a, while the remaining samples plot well below the typical chloride concentration. Given the late spring timing of this event, the first sample probably reflects some evapoconcentration of solutes in the riparian area. The flow shows a rapid peak in response to the main rainfall burst followed by a sustained relatively low flow and a recession over the second half of the day suggestive of subsurface flow. The volume of the main peak corresponds to around 5% of the rainfall. The flow after the main peak had a surprisingly low concentration of chloride (the cluster of low concentration red points on Fig 10a), which may suggest that the higher intensity activated either overland or preferential flow paths, limiting soil contact time and leading to this low concentration.

Figure 10 goes about here

4 Discussion

4.1 Runoff mechanisms

The hydrometric data enables us to identify the important runoff mechanisms under different circumstances. The isotope and major ion geochemistry data provide further supporting evidence. The rainfall plus antecedent soil water storage threshold of 250 mm that needs to be exceeded for runoff in most circumstances shows that wetness dependent runoff processes are important, that is either saturation excess or subsurface stormflow. Shallow groundwater data combined with field mapping of surface saturated areas shows that complete profile saturation is limited to about 5% of the catchment area and this saturation is persistent over the winter-spring season. Field observations show this saturated area is highly connected to the catchment outlet and it would be expected to produce SOF. The isotope results for 12 August 2010 enabled the event runoff to be separated into new water and old water contributions. Five percent of the rainfall volume on the catchment appeared in the event runoff, which corresponds to the proportion of surface saturated area in the catchment, supporting the contention of significant saturation excess runoff from this part of the catchment, as observed elsewhere (McGlynn and McDonnell, 2003). While saturation excess runoff undoubtedly occurs, many of the event runoff coefficients were well in excess of 5% and they approach 1 under very wet conditions (Figure 5). The event on 12 August showed substantial old water contribution, logged shallow wells show that the water table did not reach the surface on the steeper hillslope areas, even within the convergent drainage lines under very wet conditions (e.g. sites 5, 7). The recession behaviour of wells on the hillslope suggests subsurface flow is moving from the hillslope under wet conditions and the recession constant analysis shows that this connection becomes stronger as the hillslope wets beyond 250 mm of stored water. This is all consistent with a substantial contribution of subsurface flow to event runoff once the hillslope is sufficiently wet to establish connection to the riparian area, as has been inferred in other studies (Buttle et al., 2004;Detty and McGuire, 2010;Hewlett and Hibbert, 1967;Jencso et al., 2009;Penna et al., 2011).

Perhaps more surprisingly, there was a group of events that produced runoff under conditions of relatively low soil water content (ASI + rainfall < 250 mm) but high rainfall intensity. This suggests an intensity dependent runoff process is being triggered when rainfall exceeds some threshold for sufficient time, in this case about 15 mm of rainfall in an hour. The runoff coefficients for the four events exceeding 15 mm hr^{-1} peak hourly intensity are 3, 12, 20 and 68% for peak hourly intensities of 16, 30, 15 and 31 mm hr^{-1} and event rainfall + ASI of 202, 215, 257 and 245 mm respectively. Note that one of these events exceeds both the wetness and intensity thresholds. It is tempting to assume that this evidence shows surface runoff due to infiltration excess runoff, but it is also possible that the high rainfall intensities are efficiently activating macropore networks (Beven and Germann, 1982) and that the flow could be following subsurface pathways.

The hydrograph from the event on 8/11/11 (the event that exceeded both thresholds, Figure 10) shows both a rapid runoff and a delayed runoff response. The concentration of chloride was unusually low during the delayed runoff component compared with all other events with major ion data. This may suggest limited contact with the catchment soils which could occur if macropore flow was important but it is not definitive. Of the two events with peak hourly intensities around 15 mm hr^{-1}, one also exceeded the wetness (rainfall + ASI) threshold of 250 mm and the other had a very low runoff coefficient (only 3%) and hence these two events are somewhat equivocal in terms of the importance of intensity. However, the two events with peak hourly rainfall intensities around 30 mm hr^{-1} both produced rapid runoff responses without a significant delayed component (Figure 4) and had runoff coefficients (12 and 68%) well in excess of the surface saturated area (5%) in the catchment, showing clear evidence of the role of an intensity of 30 mm hr^{-1}. Unfortunately isotope and major ion data were not available for those events to attempt to determine whether surface or subsurface pathways are important. Overall there is clear evidence for intensity dependent runoff mechanisms, especially for the largest 30 mm hr^{-1} events.

In summary, the process evidence suggests a catchment where subsurface flow leads to a seasonally saturated riparian area that produces saturation excess runoff. This saturation excess is augmented by subsurface stormflow when the catchment wetness (rainfall + ASI) exceeds a 250 mm threshold. This subsurface flow exfiltrates in the riparian area. When hourly rainfalls exceed a threshold of 15-30 mm hr^{-1}, an intensity dependent runoff process is activated that also contributes flow from the hillslope area outside the riparian zone. It is not clear whether this is a purely surface runoff process or not.

4.2 Thresholds and connectivity in runoff production

We identified two important thresholds in the catchment response. The first is a wetness threshold of event rainfall plus ASI exceeding 250 mm. Under these conditions the water table approaches the surface in the riparian area and water tables rise on the hillslope into what is inferred from relatively rapid hillslope water table recessions to be a more transmissive part of the soil profile (within ~120-140 cm of the surface). We infer that the hillslope becomes connected to the riparian zone under these conditions. Similar catchment wetness thresholds for connectivity and runoff generation have been reported elsewhere (Detty and McGuire, 2010;Penna et al., 2011;Tromp-van Meerveld and McDonnell, 2006b). These have been expressed either in terms of rainfall depth, antecedent soil water storage conditions, or a combination of these. Similar to our results, in a study of a forested subcatchment with highly permeable soils and a small riparian area (Detty and McGuire, 2010) found a very strong relationship between a threshold of 316 mm for ASI plus rain and the start of the event flow from the hillslope and demonstrated that the ASI+rainfall threshold corresponded with a water table height threshold. They also suggested that subsurface flow, transmissivity feedback and preferential flow can be used to explain runoff mechanisms. They did not observe either Hortonian overland flow or SOF even during the largest events.

In other studies, total rainfall has been found to be the main controller of threshold behaviour (Fujimoto et al., 2008;McGuire and McDonnell, 2010). Analysing 147 rain events in the Panola catchment, USA, Tromp-van Meerveld and McDonnell (2006b) defined an event precipitation depth threshold of 55 mm for initiation of connectivity and subsurface runoff. They (Tromp-van Meerveld and McDonnell, 2006a) proposed the "fill and spill" mechanism and suggested that subsurface connection happens through connectivity of transient bedrock perched areas when depression storage of bedrock fills and water spills over micro-topographic relief. Figure 5a shows that total rainfall is a poor predictor of runoff behaviour in our case.

A second threshold associated with high rainfall intensities was also evident. A similar role of intensity has also been observed by Janzen and McDonnell (2015) who found that the Panola hillslope can produce significant runoff from dry antecedent conditions when high intensity rainfall occurs. In general event runoff from Panola is controlled by catchment wetness, similar to our hillslope. These are the only two studies we know of that have reported intensity thresholds in catchments where runoff is normally dominated by wetness thresholds. This may be a consequence of such events being relatively rare in any given catchment (roughly 10% of runoff producing events in our case).

4.3 Runoff processes framework

We now consider the three runoff processes occurring in the catchment in relation to the framework proposed in Figure 1 and the various flux and timescale thresholds identified therein. Essentially Figure 1 is posing a series of questions that allow us to systematically think through the runoff processes. Above we have identified three groups of events – those that do not produce runoff, those that produce runoff by saturation excess and subsurface stormflow from a wet catchment and those that produce runoff from higher intensity events.

The rainfall events that do not produce runoff are not exceeding infiltration capacity for sufficient time for runoff to flow from the catchment (box 1, "No"). They may or may not produce significant percolation (box 2) but if any of these events do produce percolation to a perched water table, this only results in an ephemeral water table that dissipates before lateral flow can move water down the hillslope (box 3, "No") and they do not saturate the full profile (box 4, "No"). As a consequence no event runoff is produced. These conditions correspond to the local control state of Grayson et al. (1997).

Some high intensity rainfall events on a dryer catchment do exceed the infiltration capacity for sufficiently long periods of time (box 1, "Yes"; hourly intensity of 15-30 mm hr^{-1}) and these events produce runoff. The increase in runoff coefficient as intensity increases for a given ASI+rainfall in Figure 5 suggests that infiltration thresholds may also be playing a role for wetter conditions (i.e. box 1 "Yes) but that infiltrated water (the dashed link in Figure 1) also contributes through other mechanisms.

The final group of events are those that produce runoff from a wet catchment at low intensity rainfall. These follow the path box 1 "No", box 2 "Yes" and box 3 "Yes" in Figure 1. On the upper hillslope parts of the catchment the subsurface flow capacity is sufficient that the water table does not reach the surface and water drains either during or shortly after the storm (box 6, "Yes"). Subsurface connectivity develops during the event and subsurface flow dominates. In the riparian area in the lower part of the catchment there is a substantial reduction in lateral subsurface flow capacity due to much lower slopes (and probably lower hydraulic conductivity associated with poorly structured, poorly drained soils) and this area drains very slowly; taking longer than the typical time between events in the wet season (box 7, "Yes"), resulting in saturation excess runoff from the lower catchment. Hence under wet conditions this catchment produces a mix of saturation excess and subsurface storm flow, but from geographically distinct parts of the catchment.

The above illustrates how the framework in Figure1 can be used to understand the role of different thresholds regarding fluxes and timescales in determining runoff mechanisms. Such a framework is likely to be particularly valuable where there is a mix of runoff mechanisms operating for different events or in different parts of the catchment. Our study catchment nicely illustrates such a mixture.

5 Conclusion

This study has examined the role of intensity and wetness thresholds in determining runoff responses for an agricultural hillslope in the Lang Lang River catchment, Victoria, Australia. Both intensity dependent and wetness dependent thresholds were identified in the runoff response. During wet conditions, hydrological connectivity has a strong influence on water delivery to the riparian area. Saturation excess runoff from the riparian zone was also important. The results of this study demonstrated that:

1) Runoff generation in most events is dependent on the catchment connectivity and soil moisture conditions. When the sum of the antecedent soil water storage and event rainfall exceeded 250 mm, runoff was typically produced by a mix of saturation excess and subsurface storm flow. Under these conditions, a water table forms in the soil and a saturated area develops in the riparian zone. When the water level rises to within about 1 m of the surface at mid slope sites, rapid subsurface flow pathways are activated which connected the mid slope and riparian area, contributing event flow to the hillslope flume.

2) When the catchment became very wet, high water levels persisted at the mid slope sites which remained hydrologically connected to the riparian area and baseflow became persistent between events.

3) High rainfall intensity events produced runoff even when the soil water content plus event rainfall content was below the 250 mm threshold. This could be due to either Hortonian overland flow or fast subsurface preferential flow paths being activated.

We have also advanced a set of threshold conditions or questions (Figure 1) that allow a logical examination of which runoff mechanism are likely to be important in a catchment given, thresholds regarding fluxes and timescales. This framework provides a useful way of thinking through the controls on rainfall-runoff response as conditions change either between events or between different parts of the catchment. It is illustrated using the behaviour of this catchment. Our study catchment demonstrates a mix of intensity dependent and wetness dependent processes, something which has been rarely reported for humid catchments.

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Table 1. Rainfall-runoff events summary at RBF

Grp No.	Date	Rain dur'n (hr)	Total rainfall (mm)	Peak hourly rainfall intensity (mm/hr)	ASI (mm)	ASI+ rainfall (mm)	Runoff duration (hr)	Total runoff (mm)	Quick flow (mm)	RC (%)	Sat'd area (%)
2	25/06/2010	49	22.4	1.8	237	259	74	7.6	1	4	4.5
2	13/07/2010	33	23.8	5.4	237	261	41	3.5	0.54	2	
2	20/07/2010	15	9.2	4.2	272	281	32	3.1	0.8	9	5.3
2	1/08/2010	30	31.4	6.2	253	284	67	19.5	13.7	44	5.5
2	5/08/2010	52	23.6	2	275	299	96	21.6	7	30	5.5
2	12/08/2010	34	17.2	5	274	291	94	12.7	4.3	25	5.5
2	16/08/2010	50	19.2	3.4	275	294	73	16.9	7.7	40	5.5
2	18/08/2010	34	14.6	4	286	301	57	13.8	4.6	32	5.5
2	24/08/2010	4	9.6	5.2	273	283	24	4.1	1.6	17	5.5
2	25/08/2010	59	12.6	2	285	298	73	10	1.4	11	5.5
2	31/08/2010	22	12.4	2	271	283	80	9.5	0.8	6	5.5
2	5/09/2010	47	25.2	3.4	272	297	74	23.1	13.5	54	5.5
2	9/09/2010	17	8.0	2.4	264	272	16	1.1	0.2	3	5.3
2	6/10/2010	18	15.2	6.6	231	246	3	0.37	0.27	2	na
2	15/10/2010	59	34.2	2.8	228	262	86	11.3	3.9	11	na
2	23/10/2010	11	12.8	5.2	227	240	8	1	0.57	4	na
2	30/10/2010	29	32.8	8.8	202	235	16	1.2	0.83	3	na
3	27/11/2010	19	54.4	30.4	161	215	31	7.6	6.5	12	na
2	19/12/2010	49	25.6	3.8	191	217	10	0.83	0.18	1	na

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-288, 2016
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Hydrology and Earth System Sciences
Discussions
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Table 1. cont Rainfall-runoff events summary at RBF

Grp No.	Date	Rain dur'n (hr)	Total rainfall (mm)	Peak hourly rainfall intensity (mm/hr)	ASI (mm)	ASI+ rainfall (mm)	Runoff duration (hr)	Total runoff (mm)	Quick flow (mm)	RC (%)	Sat'd area (%)
3	4/02/2011	33	71.2	16.4	130	201	10	2.5	2	3	na
2	11/05/2011	122	63.6	6.6	220	284	47	5.6	2.2	3	na
2	22/05/2011	50	21.6	4.4	231	253	3	0.23	0.1	0.46	na
2	26/05/2011	37	13.6	1.6	244	258	33	2.66	1	7	na
2	7/06/2011	25	17.6	2.6	254	272	43	6.7	2.9	16	Na
2	17/06/2011	31	15.6	2.2	248	264	45	3.2	0.2	1	4.6
2	21/06/2011	61	38.8	3.6	255	294	80	21.8	12.1	31	4.6
2	5/07/2011	10	9.8	2.4	253	263	26	2.9	0.8	8	4.7
2	6/07/2011	12	16.6	6.2	267	284	29	8.7	4.8	29	4.7
2	10/07/2011	20	7.4	2.2	262	269	27	3.7	1.4	19	4.7
2	28/09/2011	74	72.0	8.8	204	276	96	20.1	6.1	8	5.4
2	9/10/2011	54	23.2	2.4	232	255	5	0.35	0.14	1	na
2	28/10/2011	19	30.2	7.8	213	243	6	0.92	0.6	2	na
3	8/11/2011	12	35.2	14.8	222	257	31	10	7.1	20	5.2
2	9/11/2011	14	23.8	6.8	239	263	44	15.7	8.9	37	5.2
2	18/11/2011	30	45.5	10.2	219	265	82	17.7	8.9	20	5.5
2	26/11/2011	29	36.8	8.4	216	253	85	27.6	16.3	44	5.5
2	29/11/2011	47	19.4	4	233	252	70	11.9	0.9	5	5.5
3	10/12/2011	16	52.6	31	192	245	32	41.1	35.6	68	5.5

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Table 2. Rainfall events summary at RBF-no flow events

Grp No.	Date	Rain dur'n (hr)	Total rainfall (mm)	Peak hourly rainfall intensity (mm/hr)	ASI (mm)	ASI+ rainfall (mm)	Runoff duration (hr)	Total runoff (mm)
1	12/10/10	5	5	3	227	232	0	0
1	12/10/2010	5	5	2.6	227	232	0	0
1	12/11/2010	32	28.2	4.0	184	212	0	0
1	25/11/2010	17	13	3.6	157	170	0	0
1	2/12/2010	8	7.2	2.0	191	198	0	0
1	8/12/2010	11	19.2	7.8	175	194	0	0
1	9/12/2010	6	5.2	2.4	193	198	0	0
1	17/12/2010	21	15	2.4	181	196	0	0
1	10/01/2011	18	10	3.2	146	156	0	0
1	11/01/2011	26	10.4	2.4	152	162	0	0
1	13/01/2011	26	22.2	9.0	151	173	0	0
1	25/01/2011	9	5.4	1.6	147	152	0	0
1	5/02/2011	12	8.6	1.6	182	191	0	0
1	16/02/2011	20	14.8	9.6	167	182	0	0
1	26/02/2011	13	13.4	4.2	174	187	0	0
1	21/04/2011	28	8.4	2.6	213	221	0	0
1	1/05/2011	8	10.8	2.6	207	218	0	0
1	8/05/2011	14	7.2	4.8	215	222	0	0
1	5/06/2011	18	9.4	3.0	238	247	0	0
1	9/09/2011	22	12.8	3.0	221	234	0	0
1	19/09/2011	18	12.2	4.0	218	230	0	0
1	24/10/2011	12	15.6	4.2	211	227	0	0

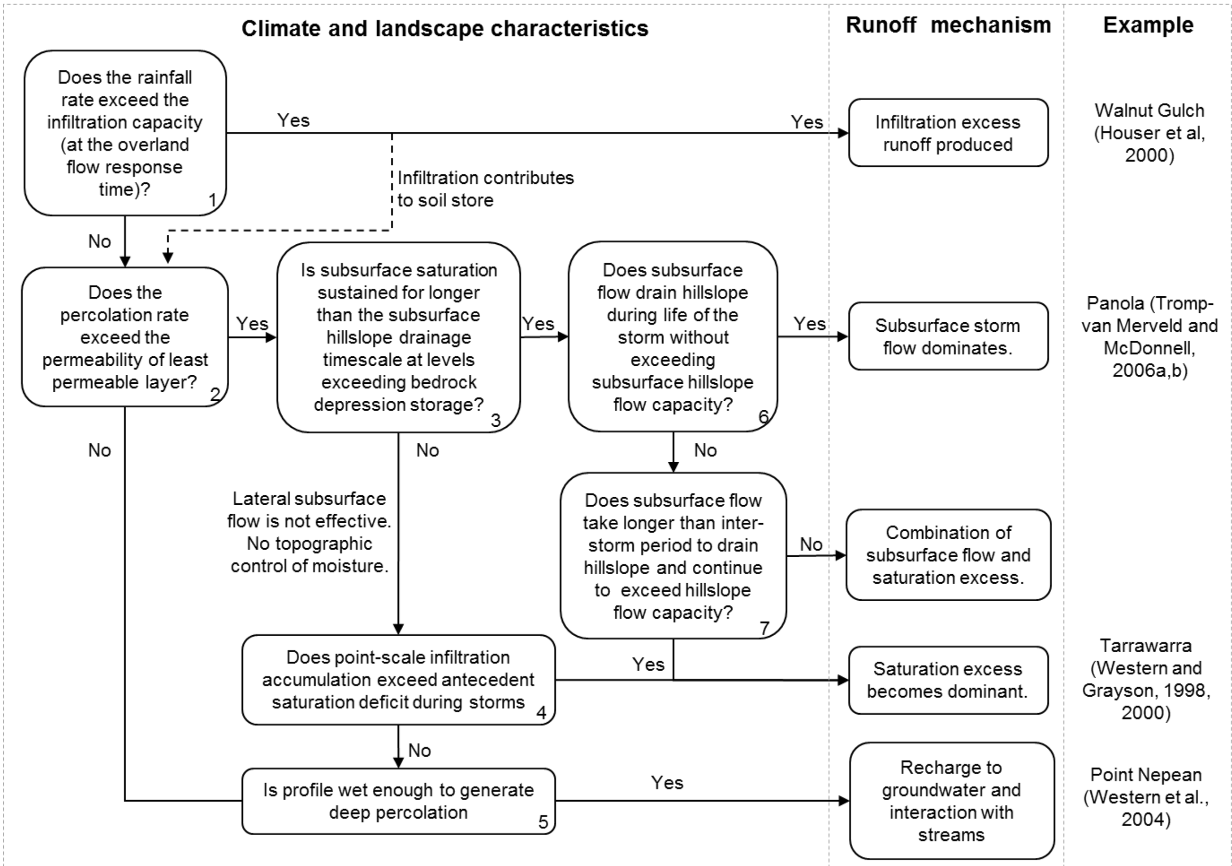

Figure 1: The role of flux and timescale thresholds in determining runoff processes.

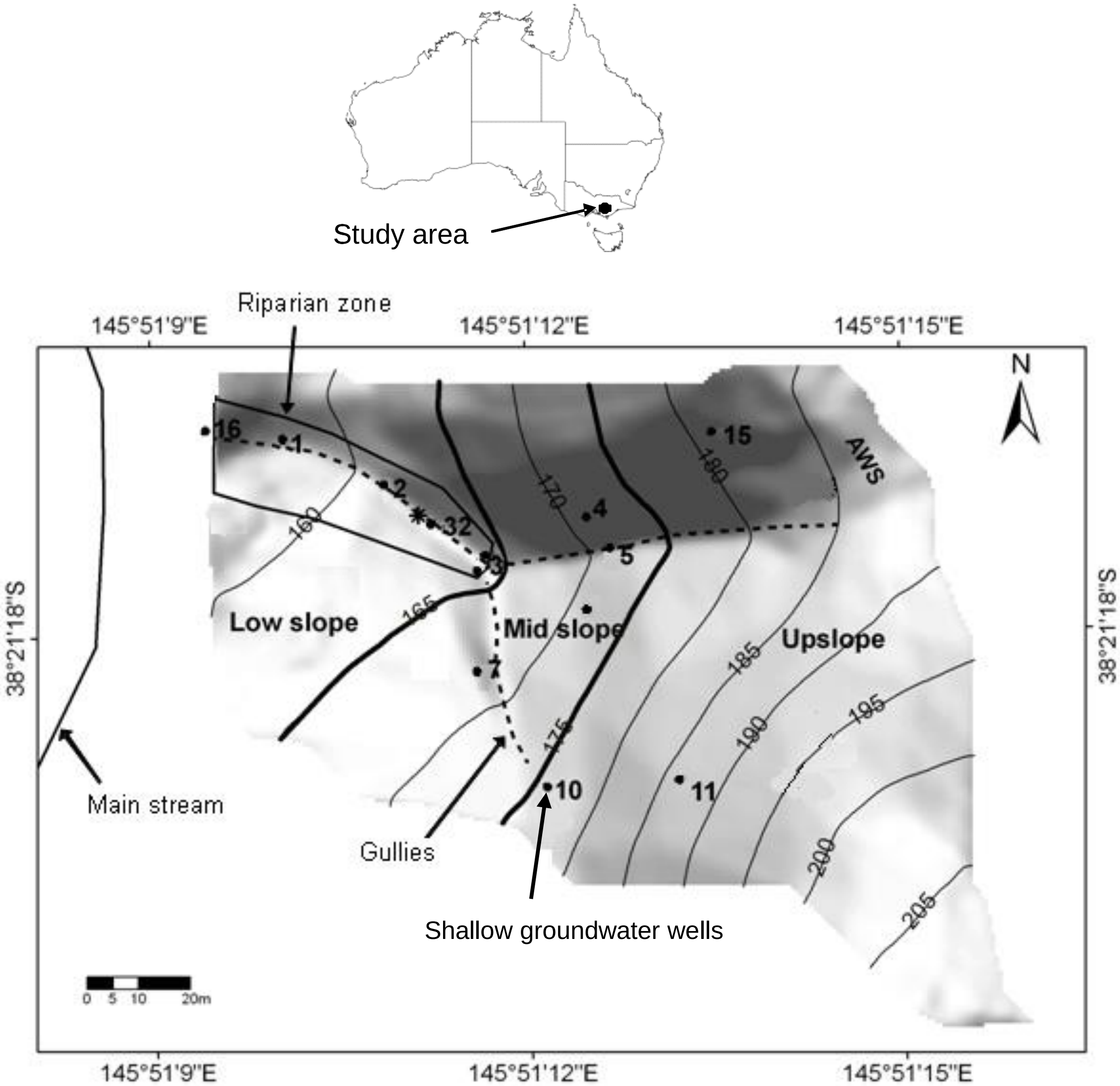

Figure 2. The study site location within Australia and a hillshaded DEM, topography and sampling site locations at RBF.

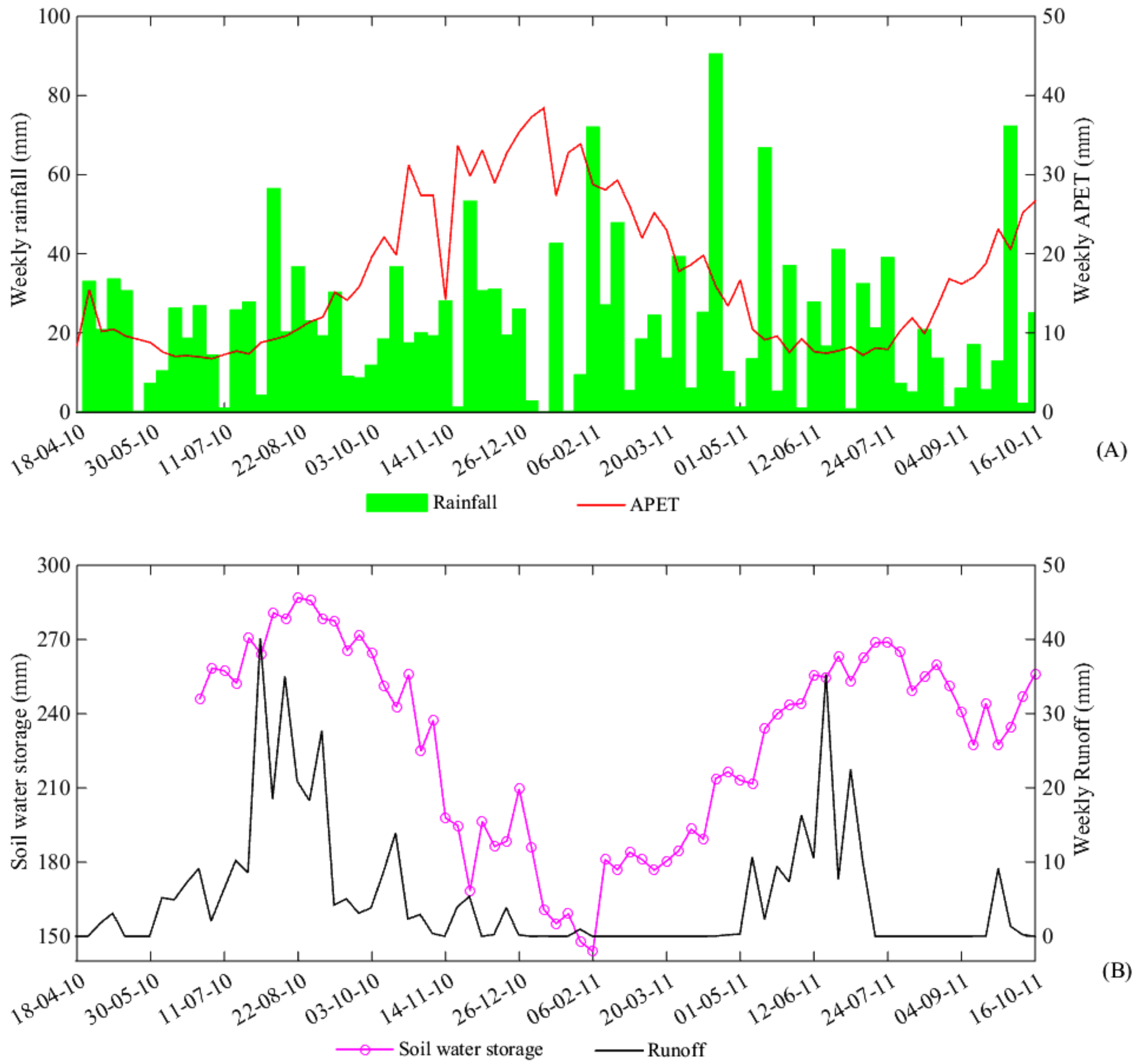

Figure 3. (A) Weekly rainfall and APET time series (data from AWS), (B) soil water storage in top 60 cm of the soil profile and weekly runoff time series at RBF.

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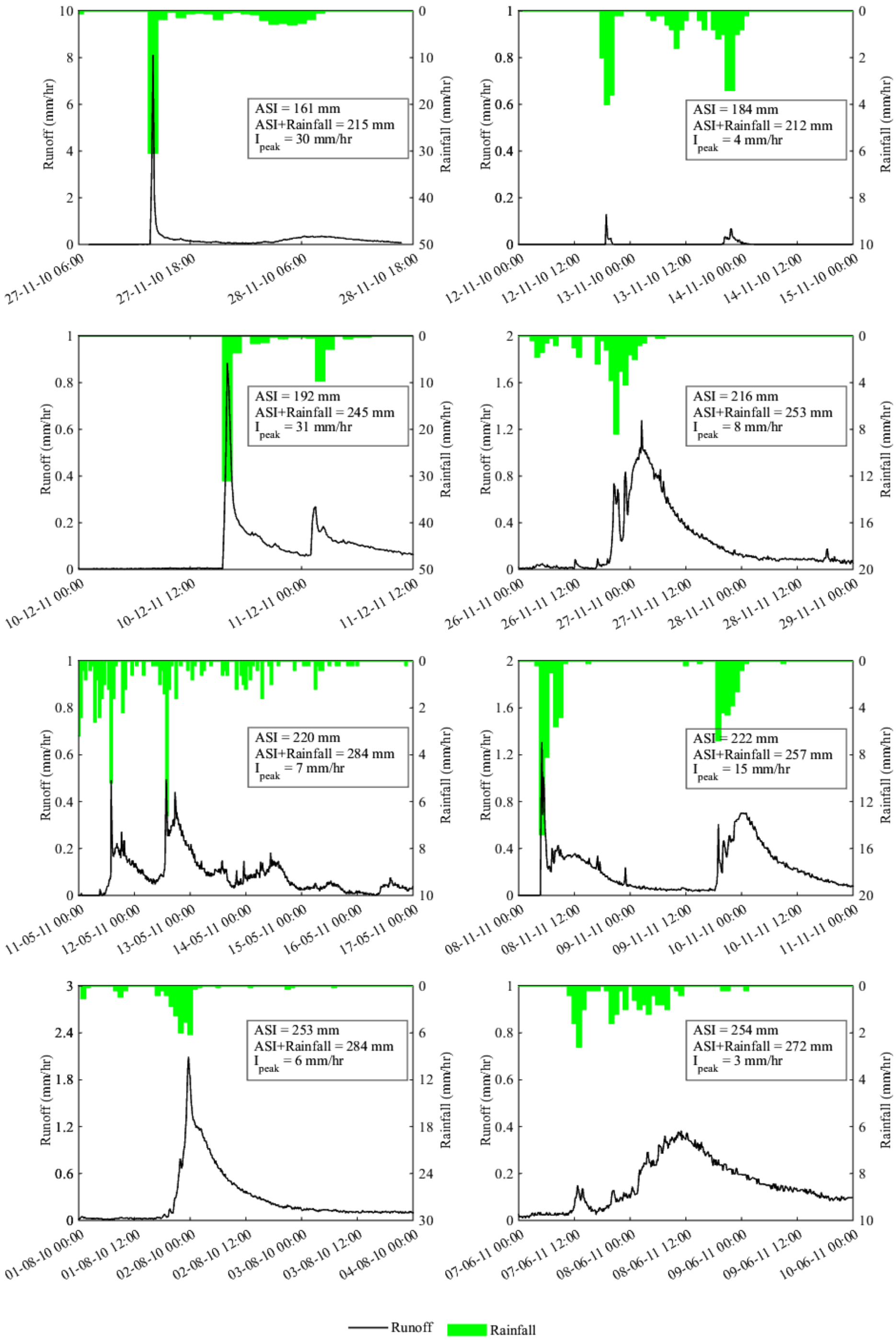

Figure 4. Overview of rainfall-runoff event characteristics and runoff behaviour at RBF

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-288, 2016
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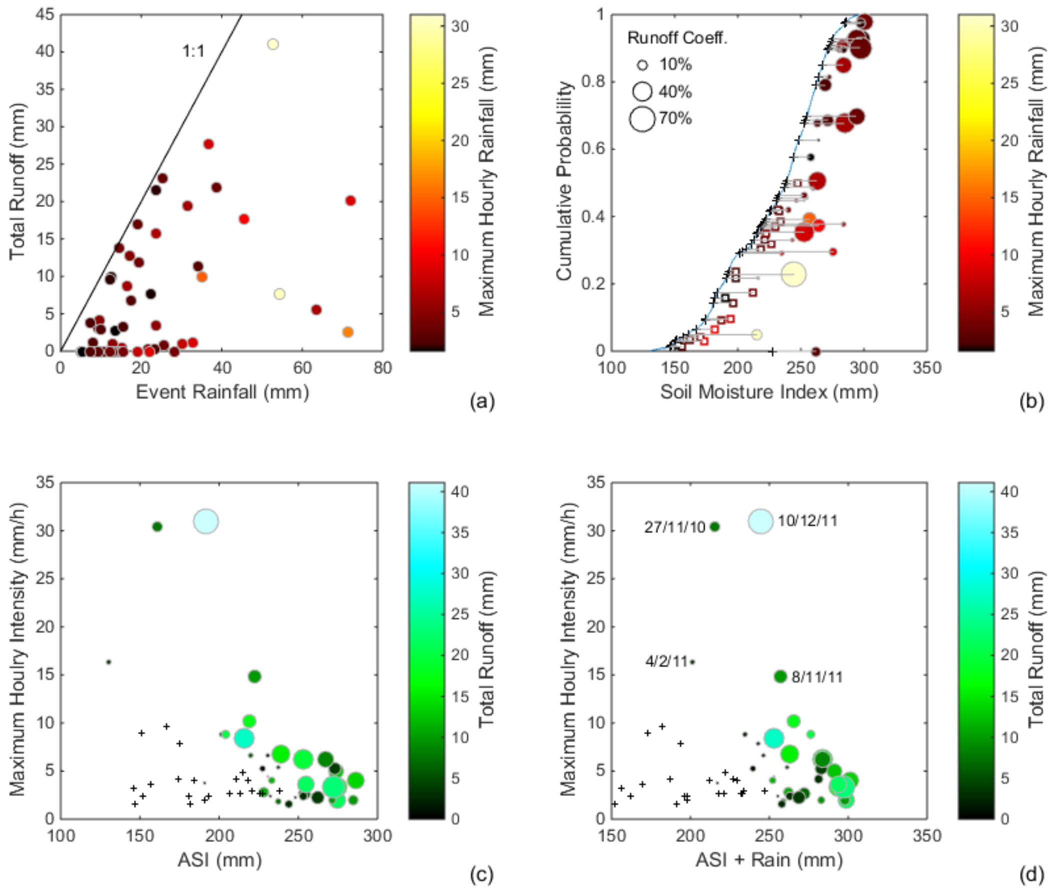

Figure 5. Thresholds of runoff mechanisms at RBF, a) event rainfall versus total event runoff, colours indicate the highest hourly rainfall intensity, b) the impact of five factors together including: cumulative curve of the distribution of soil water storage as observed through the study period, ASI, ASI+rain, colour shows the peak hourly rainfall intensity (I_{peak}) and the size of the bubbles shows the quick flow runoff coefficient, c) ASI versus the peak hourly rainfall intensity (I_{peak}) and the size of the bubbles shows the quick flow runoff coefficient and colour shows event total runoff, and d) ASI+rain versus the peak hourly rainfall intensity (I_{peak}) and the size of the bubbles shows the quick flow runoff coefficient and colour shows event total runoff.

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2016-288, 2016
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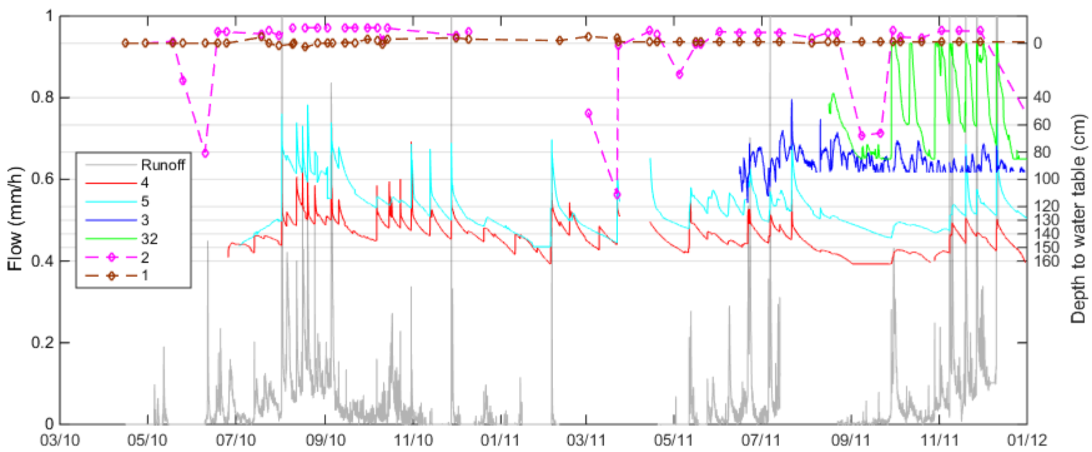

Figure 6. Time series of runoff and water levels at sites 4, 5, 3, 32, 2 and 1, manually read sites are shown with dashed lines.

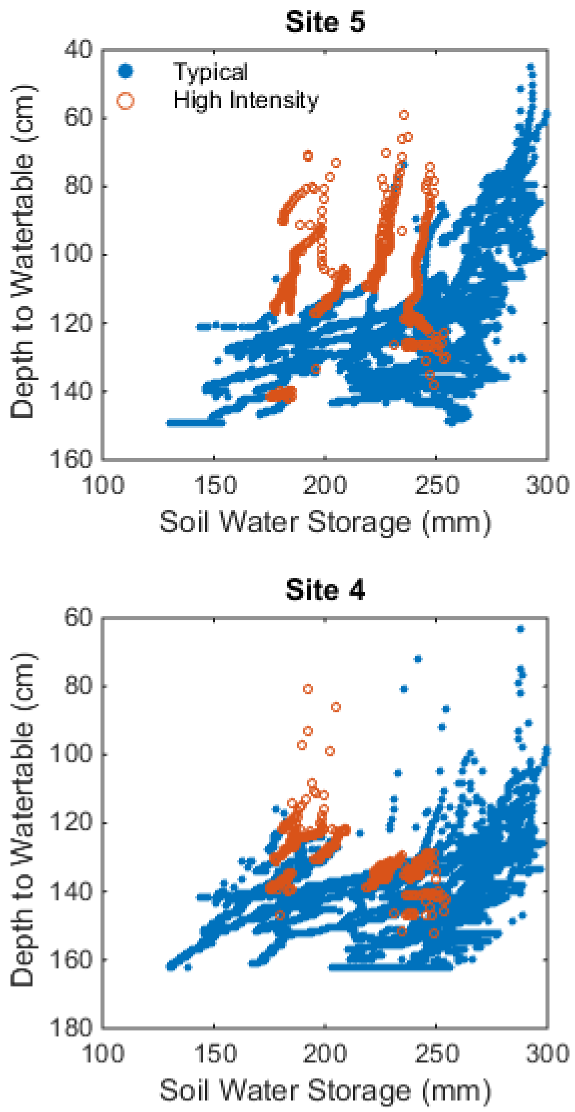

Figure 7. Soil water storage versus water table level at sites 4 and 5. Colours distinguish hourly rainfall intensity.

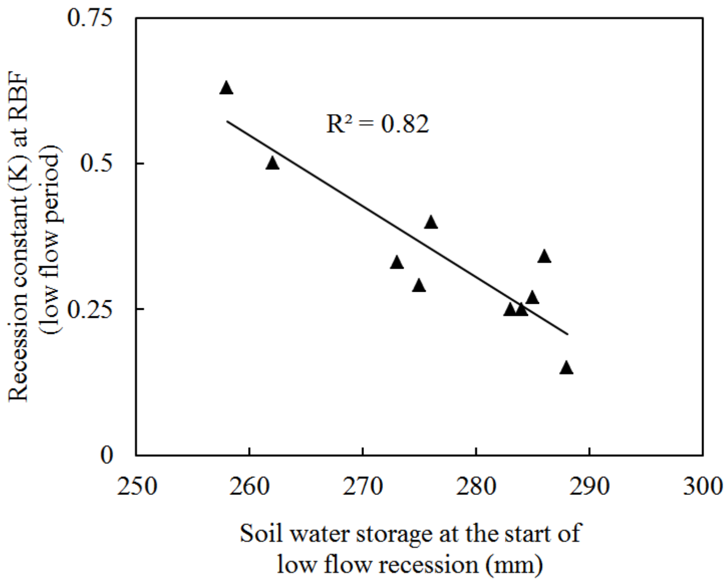

Figure 8. Recession constant (*K*) and soil water storage the start of the recession for individual events

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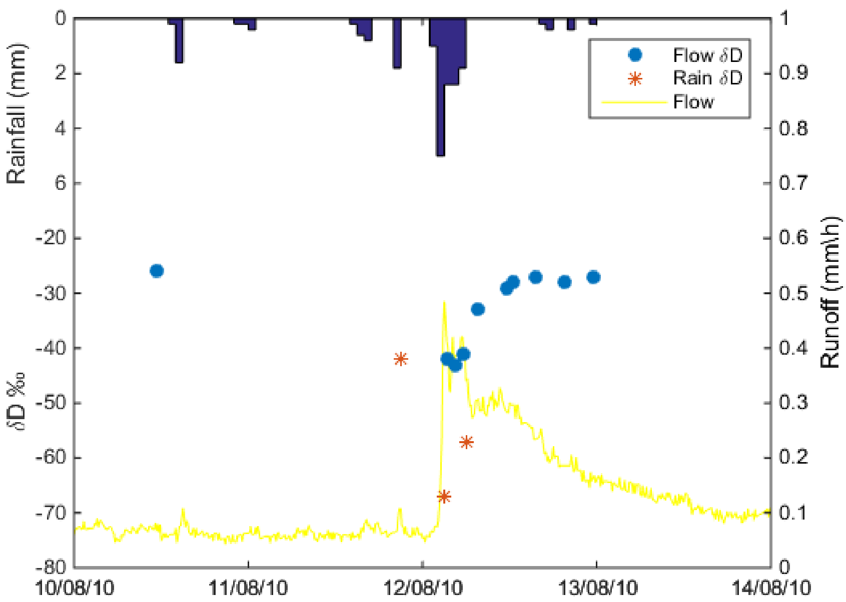

Figure 9. Time series of total rainfall and runoff, ^{2}H of rainfall and runoff for the event on 12/8/10

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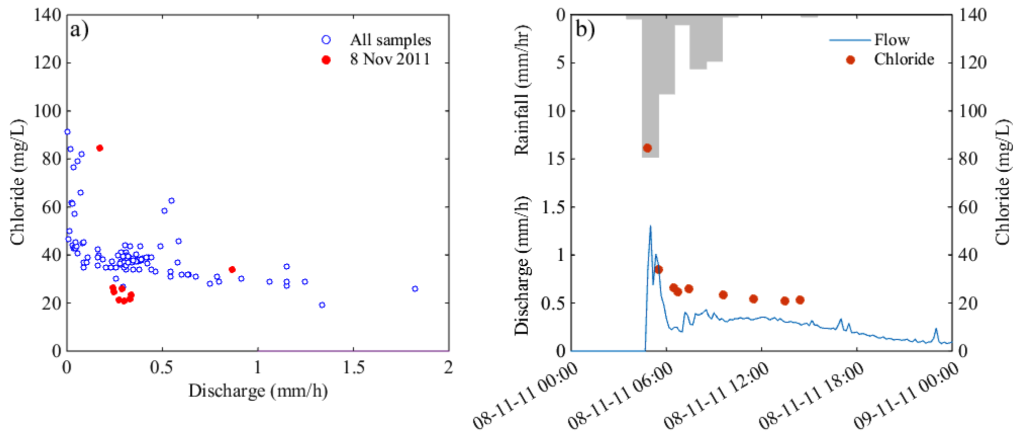

Figure 10. a) Runoff versus Cl^- concentration for all events. The red colour identifies samples from event on 8/11/11, and b) Time series of rainfall, runoff and Cl^- concentration for the event on 8/11/11