## *Authors' response to Anonymous Referee #1 on "Multiple runoff processes and multiple thresholds control agricultural runoff generation" by S. Saffarpour et al.*

We appreciate the reviewer's comments and suggestions, which we found very useful. We have addressed each reviewer comment separately. In the following document the blue font indicates the reviewer's comment and the black font shows our reply.

## General comment

1. **This is a very interesting work that focuses on the analysis of runoff processes and the controls exerted by different thresholds on the hydrological mechanisms related to runoff generation in an agricultural Australian catchment. The research aims to understand how subsurface connectivity, saturation excess and rainfall intensity play a role in rainfall-runoff response at the seasonal and event time scale. The manuscript is well written, logically organized and with overall clear graphical presentations. Results are generally well supported by data and interpretation are overall sound. I particularly like the conceptual summary of hydrological processes and thresholds reported in Fig 1, and how this figure was referred to in the Introduction and in the discussion. However, I think that there are some confused points that deserve to be clarified and better explained. I have some comments and suggestions that can hopefully help this paper to have a greater impact on the hydrological community.**

Thank you for these positive comments.

## Specific comments

2. **5, 24-26. As far as I understand, two different isotope laser analysers have been employed for the analysis of stable isotopes of water. This is a methodologically critical point: based on my experience, two different laser machines, even of the same model and calibrated using the same set of reference standards, could return quite different values of isotopic composition. Using a different sets of standards in different laboratories, as it seems that was the case here, could lead to differences that have the potentials to impact the resulting analysis of hydrograph separation. I think it is important for the paper to run some tests and report some comparison metrics between the measurements performed by the two machines in order to assess, and in case correct, potential deviations.**

We have added the following to the methods (p8, l3) section to clarify this issue.

Stable isotope ratios were measured either at Monash University using a Finnigan MAT 252 and ThermoFinnigan Delta Advantage Plus mass spectrometers (2010 samples) or at the University of Melbourne, where a Picarro L2120i cavity ring-down isotope analyser was used to determine isotope ratios (2011 samples). The instrumental precision was δ18O = ±0.15‰ and δ2H = ±1‰ for the isotope samples analysed at the Monash University and it was δ18O=0.1‰ and δ2H =0.4‰ for samples analysed at the Melbourne University. The results from the two laser analysers were checked for systematic differences, by analyzing duplicate samples in both laboratories. We developed and applied a correction between the two laboratories based on these samples. With the exception of determining pre-event end member uncertainty (described later) the analyses presented here only use samples analysed at the Monash laboratory and hence this difference between laboratories only affects our hydrograph separation uncertainty estimations.

3. **6, 10-12. It is not clear how the soil water storage has been computed starting from ASI. A specification, perhaps including equations, would be really useful here. This is important because the soil water storage is addressed several times in the rest of the manuscript.**

The following explanation was added at p6, l26.

Soil moisture storage was calculated from the volumetric water content which was measured for the 0-30 cm and 30-60 cm layers and recorded hourly by the automatic weather station (AWS) logger using two vertically installed 30 cm long Campbell Scientific (CS625) soil moisture probes (Campbell Scientific, 2006).. The 0-30cm probe was inserted from the surface. To install the 30-60cm probe, a 30cm deep hole was dug, with the excavated soil set aside. The probe was inserted vertically and then the excavated soil was repacked so that the soil was replaced at a similar depth to that from which had been removed.

The CS625 produces a pulse signal and the pulse period was temperature corrected using measured soil temperature and the manufacturers recommended temperature correction, as follows (Campbell Scientific, 2006).

$$\tau_{corrected}(T_{soil}) = \tau_{uncorrected} + (20 - T_{soil}) * (0.526 - 0.052 * \tau_{uncorrected} + 0.00136 * \tau_{uncorrected}{}^{2}) \quad (1)$$

where $\tau_{uncorrectd}$ is the probe output period, $T_{soil}$ is the soil temperature and $\tau_{corrected}$ is the corrected probe output. The *VWC* was then computed from $\tau_{corrected}$ using (Campbell Scientific, 2006):

$$VWC = -0.0663 - 0.0063 * period + 0.0007 * period^{2} \quad (2)$$

Soil water storage over the top 60 cm soil depth was computed by adding the VWC from the 0-30 cm and 30-60 cm layers and then multiplying by the 300 mm soil depth. We use this soil water storage at the start of each rainfall event as an index of antecedent soil water (ASI) and assume it represents the catchment wetness condition.

4. **Moreover, it's not clear how manual measurements of the saturated are have been carried out. Please explain.**

Measurement of the saturated area is now explained in section 2.4 (p9, L12) as follows.

The topography of the catchment was surveyed using a differential Global Positioning System (dGPS) and a 1 m horizontal resolution DEM (digital elevation model) was developed by interpolation methods. Instrument and well locations were also determined using dGPS. Then this data was used to produce maps of the study area and including sampling sites using Arc GIS. The lateral boundary of the saturated area was topographically constrained and field observations suggested it was stable over time, while the upstream boundary moved up and down the riparian zone. The saturated area was estimated by locating the upper boundary through field inspection and then measuring the distance from either well 2 or 3 (The saturated area extended towards site 3 during very wet conditions). Figure 2 demonstrates the approximate maximum boundary location of the saturated area at site 3 and the main stream located close to the outlet of the catchment. The saturated area was then estimated from this information combined with the mapping of the riparian zone boundary in Arc GIS.

5. **8, 2. The statement that 'any rainfall depth could produce a response' seems to contradict what reported elsewhere in the manuscript (eg, 7, 4-5; 8, 14; 8, 26) about some rainfalls that did not produce runoff. This is confusing and should be clarified. 8, 6-16.**

We have removed this sentence.

6. **Fig. 5b seems to be dense and informative. However, I think that is not straightforward to understand it. The different symbols are hard to distinguish and the scale of runoff coefficients is not very useful to understand their values. I suggest considering to replace it by another graphical way (eg, cumulative distribution + bar plot or multiple panel boxplot). Moreover, I don't understand why ASI and ASI+rain have been plotted against rainfall intensity: the relation is obviously scattered (and so the sentence at 8, 12 is obvious too since rainfall is a stochastic process) because no relation is expected between these two variables and intensity of rainfall events. But if the authors used this representation to show how the different events plot in reference to these variable this should be clearly stated.**

Figures 5a-d are used to examine various influences and thresholds leading to different rainfall-runoff behaviors. The reason for plotting ASI + rain against rainfall intensity is that runoff shows threshold behavior with respect to these two variables, not because we expect a relationship between the two variables. We have added the thresholds in both catchment wetness and rainfall intensity to these figures to make the interpretation clearer. We have also edited section 3.2 to more carefully guide the reader through the interpretation of these figures. A revised version of Figure 5 is below. A joint threshold involving intensity and water storage that correctly separates nearly all events into those that produce runoff and those that do not is also shown. This is discussed in the first paragraph of section 3.3 where we mention interaction between intensity and wetness.

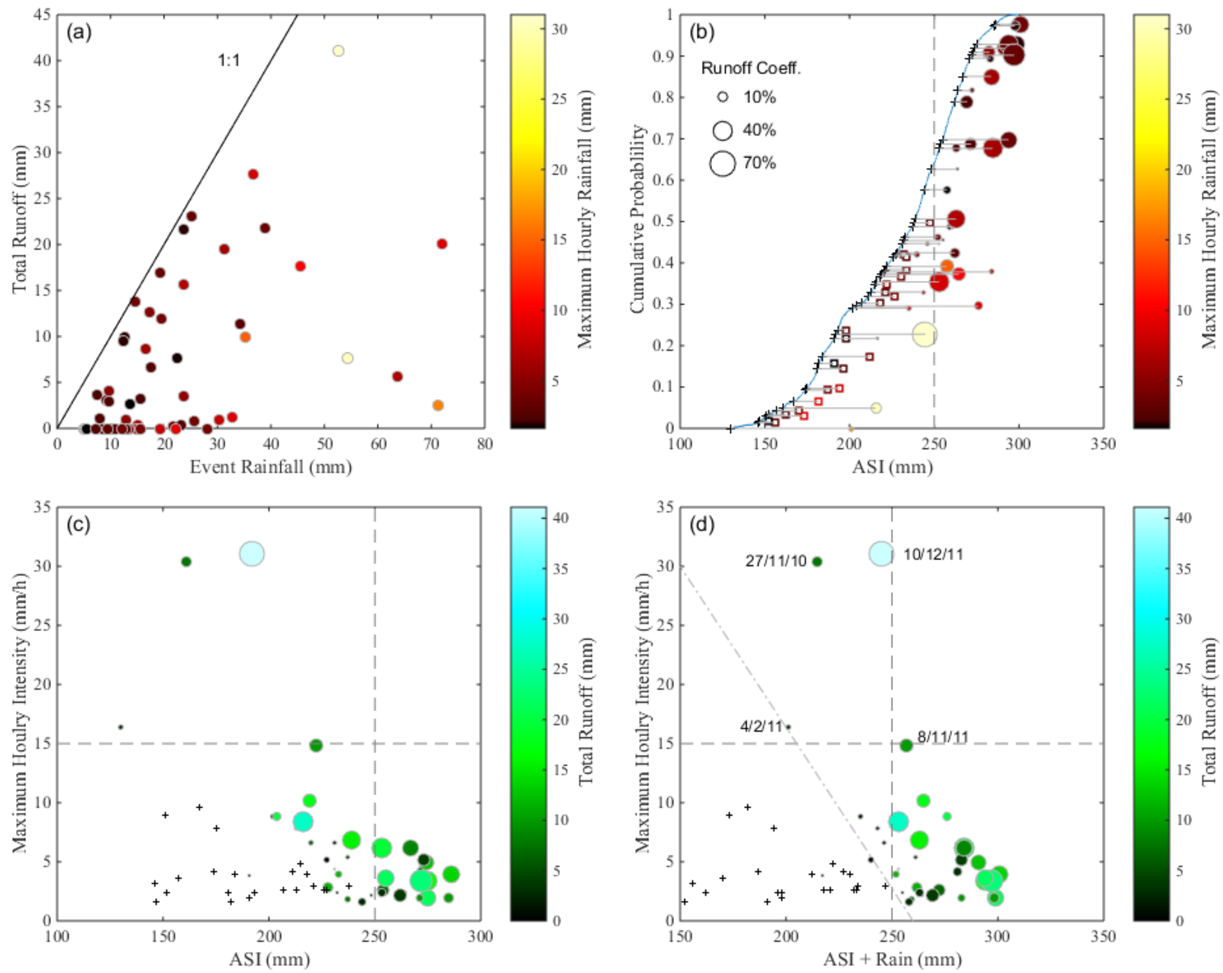



**Figure 5. Thresholds of runoff mechanisms at RBF, a) event rainfall versus total event runoff, colours indicate the highest hourly rainfall intensity, b) the impact of five factors together including: cumulative curve of the distribution of soil water storage as observed through the study period, ASI, 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. The dashed lines in b), c) and d) show thresholds at ASI and ASI+rain = 250mm and $I_{peak}$ = 15mm/h. The dot-dashed line in d) shows a threshold of 260 – 3/11*$I_{peal}$.**

7. **10, 25-26. Here a two-component mixing model is mentioned but no details are given in the Materials and Method section. I'm not suggesting to report the well-known equations (a simple citation to the suggested references 5 and 6 below is enough) but some methodological/conceptual information are needed, eg: which sample(s) has been considered as pre-event for the application of the hydrograph separation technique? Why only deuterium data have been used since both 18-oxygen and deuterium data have been measured? How many samples for isotopes have been collected and which ones were used? How many events have been sampled? More importantly: why has the separation been carried out only for the 12 August event showed in Fig. 9? Or was it also performed for other events? In this case,**

**what are the results? Are they similar so that they corroborate the proposed conceptualization? Or did they provide much different estimates? Can the author report the results of all sampled events in a Table? This would be useful. All this information should be reported and these points well addressed in the revised version of the manuscript.**

**Another major point related to this is the lack of uncertainty analysis of the estimated fractions of pre-event water and event water (I prefer these terms instead of old and new water) in streamflow. This is particularly critical since these estimates have been used to build some conceptualization (eg, 17% of event water corresponding to 5% of rainfall amount..but what is the uncertainty of that 17%?). And is the result about 5% of rainfall based only on the 12 August event? In that case this is not robust. The traditional method of uncertainty estimation proposed in reference 2 below is suggested.**

We have added uncertainty analysis, analysed by the 2H and 18O results and provided more detail on the methodology. The following was added to the hydrograph separation section (p9, L32):

Isotope samples are used here for hydrograph separation into pre-event and event contributions. We applied the well- known one tracer, two component model of hydrograph separation approach (Pinder and Jones, 1969; Sklash and Farvolden, 1979). We determined uncertainties following Genereux (1998). We undertook the analysis using both the 2H O18 data. We used the mean of the rainfall samples during the event to estimate the event water end member and low flow samples from the few days to the event for the pre-event end member. In the uncertainty analysis, the standard deviations of the event rainfall samples and of all the low flow samples across the study period were used. Half the analytic uncertainty was used to represent the standard deviation of the streamflow sample.

We added the number of isotope samples to page 8 line 5:

For isotope analysis, in total we collected 115 samples of rainfall, 28 samples during low flows and multiple stream water samples of isotopes from five events.

We have provided our reasons for presenting only one event (it was the only one for which we could obtain reliable results) and amended the presentation of results in section Isotope and major ion results (p16, L5)

Of the five events sampled, two events were missing rainfall samples, which prevented their analysis. For another two events the rainfall isotope signature was quite close to the typical low flow signature. Uncertainty estimates showed standard deviations for pre-event and event fractions being over 50% for these two events, therefore these events were also excluded. For the event on 12 August 2010, the standard deviations were approximately 12% and 9% for 18O and 2H respectively, which we judged to be acceptable.

We have also significantly edited the relevant results paragraph (p16, L11) to:

Figure 9 shows the 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.

We used a pre-event low-flow sample from ~2days before the analysed event as the pre-event end member. We estimated the contribution at the time of each stream flow sample. Over the study period $\delta^2H$ ($\delta^{18}O$) for rainfall varied between -7‰ and -83‰ (-1.4‰ and 12.6‰) and isotopic concentrations for low flows were highly damped. Low flow samples from the RBF flume before and after the event showed a $\delta^2H$ ($\delta^{18}O$) of -27‰ (-4.1‰) and rainfall for this event was strongly depleted (3 samples prior to and during the event $\delta^2H$ = -42, -67 and -57‰, $\delta^{18}O$ = -6.5, -9.8 and -8.2‰), compared with low flow. The runoff samples showed a very different isotopic concentration during the rising limb and the peak of the hydrograph ($\delta^2H$ =-43‰, $\delta^{18}O$ = -6.8‰) in comparison to antecedent low flow. This shows that the isotopic concentration moves significantly towards the rainfall sample concentrations. To estimate the overall event water contribution we first separated the hydrograph at each sampling time and then interpolated the fraction of event water between stream water sampling times and combined this with the flow hydrograph to calculate the overall volume of event water. This analysis suggests that the percentage of rain becoming runoff based on $\delta^2H$ and $\delta^{18}O$ is 4.4% (3.4-5.4%) and 3.6% (3.0-4.2%), respectively. The figures in the brackets are 95% confidence intervals for uncertainty based on the hydrograph separation uncertainty only. These results suggest that precipitation on the saturated area generates direct runoff in amounts that are close to what would be expected (i.e. 100% runoff) given that the saturated area is around 5-6% of the catchment area.

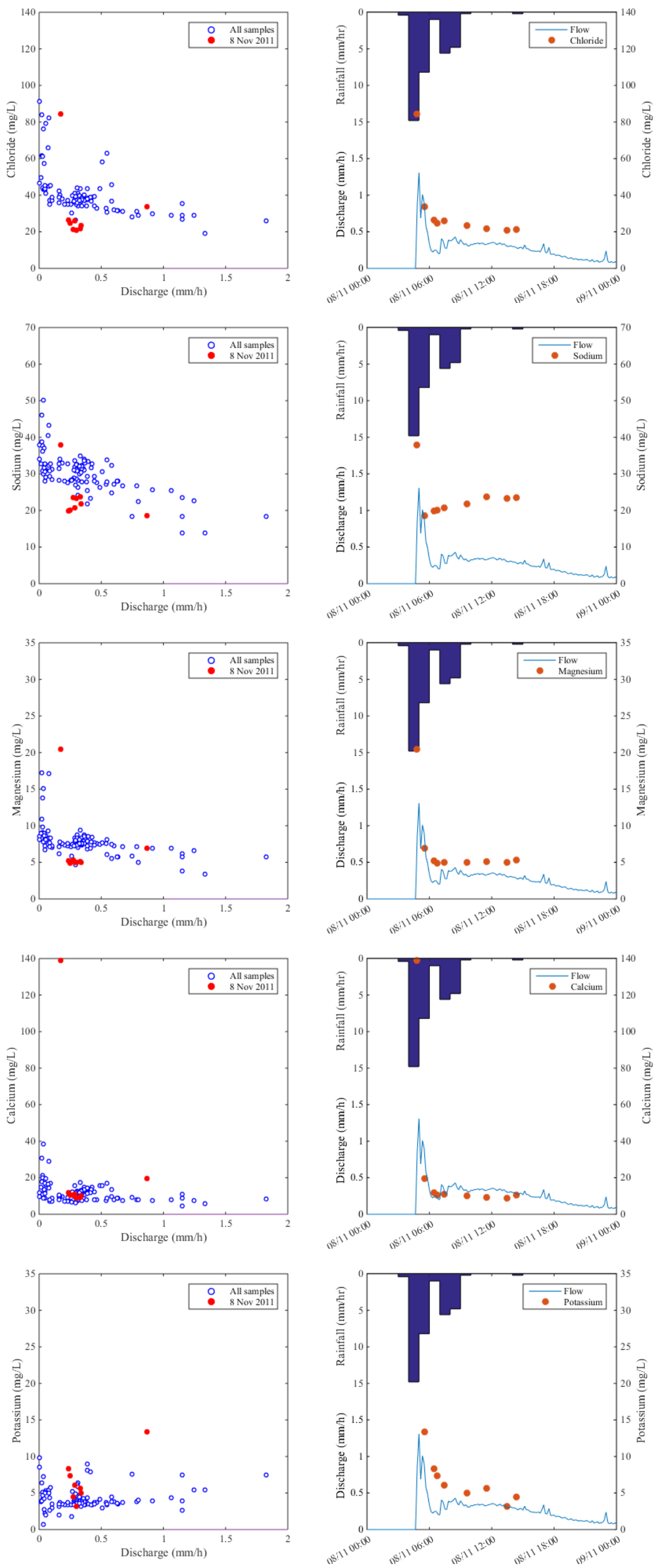
8. **11, 1-11. It is mentioned that the concentration of major ions is available for the 8 November event but only chloride has been selected and showed (Fig. 10). What is the reason behind this choice? Moreover, where does the estimate of 5% of the rainfall come from, that agrees surprisingly well with the estimate of the 12 August event (10, 26)? From a two-component hydrograph separation based on chloride? On isotopes? Please, explain in detail.**

We have also examined the behavior of Calcium, Magnesium, Sodium and Potassium and now provide these plots in a supplement. The reason for choosing Chloride was that we expect less complication due to any ion exchange processes. We have amended the discussion of the chemistry by adding the following to p16 L33.

Similar plots are shown for Sodium, Magnesium, Calcium and Potassium in the supplementary material Figure S1. Sodium and Magnesium show similar behavior to Chloride. Potassium also shows somewhat anomalous behaviour but with anomalously high concentrations. The relationship between flow and K+ is also different to Cl-, Na+ and Mg2+ in that concentrations increase slightly as flow increase above about 0.2mm/mm, rather than a decline. Calcium does not show anomalous behavior.

We have also explained how we obtained the 5% proportion for the first peak on p17, L7.

Up until the end of the first flow peak (i.e. 0600), there had been 23.4mm of rainfall and 1.0mm of runoff. This runoff volume is 4.3% of the rainfall volume, which is similar to the proportion of event water that became runoff for the 12 August 2010 event discussed above.


Chloride (mg/L)
Discharge (mm/h)
All samples
8 Nov 2011
Rainfall (mm/hr)
Discharge (mm/h)
Flow
Chloride
Chloride (mg/L)
08/11 00:00
08/11 06:00
08/11 12:00
08/11 18:00
09/11 00:00
Sodium (mg/L)
Discharge (mm/h)
All samples
8 Nov 2011
Rainfall (mm/hr)
Discharge (mm/h)
Flow
Sodium
Sodium (mg/L)
08/11 00:00
08/11 06:00
08/11 12:00
08/11 18:00
09/11 00:00
Magnesium (mg/L)
Discharge (mm/h)
All samples
8 Nov 2011
Rainfall (mm/hr)
Discharge (mm/h)
Flow
Magnesium
Magnesium (mg/L)
08/11 00:00
08/11 06:00
08/11 12:00
08/11 18:00
09/11 00:00
Calcium (mg/L)
Discharge (mm/h)
All samples
8 Nov 2011
Rainfall (mm/hr)
Discharge (mm/h)
Flow
Calcium
Calcium (mg/L)
08/11 00:00
08/11 06:00
08/11 12:00
08/11 18:00
09/11 00:00
Potassium (mg/L)
Discharge (mm/h)
All samples
8 Nov 2011
Rainfall (mm/hr)
Discharge (mm/h)
Flow
Potassium
Potassium (mg/L)
08/11 00:00
08/11 06:00
08/11 12:00
08/11 18:00
09/11 00:00

9. **11, 19. The saturation amount at the 5% of the catchment area is not shown and clearly presented, yet it is one of the most interesting results in terms of process interpretation. Please, provide a sound explanation.**

The estimation of the saturated area is explained in response to comment 4 above.

10. **12, 29. I do not see such a clear threshold at 250 mm of ASI + rain. . .please, explain better, also in the results, where it derives from.**

As explained in our response to comment 6, we have shown the thresholds on Figure 5 and tried to explain these more clearly.

11. **Some relevant studies that I'm aware of and that are strictly linked to this research have not been cited. I think they should incorporated in the paper, particularly in the Discussion section (except the ones referring to methods, such as 2, 5 and 6):**

    **1. Fu C, Cheng J, Jiang H, Dong L. 2013. Threshold behavior in a fissured granitic catchment in southern China: (1) analysis of field monitoring results. Water Resources Research 49: 1–17. DOI: 10.1002/wrcr.20191**

Added to P 2 L 15 and the reference list

**2. Genereux D. 1998. Quantifying uncertainty in tracer-based hydrograph separations. Water Resources Research 34(4): 915–919. DOI: 10.1029/98WR00010**

Added to P10 L1 and the reference list

**3. Penna, D., van Meerveld, H.J., Oliviero, O., Zuecco, G., Assendelft, R.S., Dalla Fontana, G., Borga, M., 2015. Seasonal changes in runoff generation in a small forested mountain catchment. Hydrological Processes 29, 2027–2042. doi:10.1002/hyp.10347**

Added to P 2 L 15 and the reference list

**4. Penna, D., van Meerveld, H.J., Zuecco, G., Dalla Fontana, G., Borga, M., 2016. Hydrological response of an Alpine catchment to rainfall and snowmelt events. Journal of Hydrology 537, 382–397. doi:10.1016/j.jhydrol.2016.03.040**

Added to P 17 L 27 and the reference list

**5. Pinder, G.F., Jones, J.F., 1969. Determination of ground-water com-ponent of peak discharge from chemistry of total runoff. Water Resour. Res. 5 (2), 438–445. http://dx.doi.org/10.1029/WR005i002p00438.**

Added to P9 L32 and the reference list

6. **Sklash MG, Farvolden RN. 1979. Role of groundwater in storm runoff. Journal of Hydrology 43(1–4): 45–65. DOI: 10.1016/0022-1694(79)90164-1**

Added to P9 L 32 and the reference list

## Minor comments and technical corrections

12. **1, 10. The reference to individual research catchments makes the reader think that this paper focuses on the analysis of several catchments but this is not the case. I suggest to remove or reformulate.**

We have re-written this as "However, to date, most attention has focused on single runoff response types"

13. **2, 12. Here the suggested references 1 and 3 could be added.**

Added

14. **3, 3-4. This sentence is not totally clear. Please, explain.**

We have expanded this explanation (now at P3 L28) as follows.

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), who used a generalise Damköhler to represent the competing effects of transport and reaction timescales on the loss of material along a flow path. When the reaction timescale is small compared with the transport timescale, the reactant is consumed before reaching the exit of the flow path it is moving along. A complication here is that, both flux and time thresholds are important. This arises because there is finite capacity for flow in various parts of the catchment system.

15. **3, 22. Typo.**

Fixed

16. **3, 27. 'certain processes': too vague. Reformulate.**

Reformulated to: "While Figure 1 suggests catchment rainfall-runoff response is dominated by speicific processes (e.g. saturation excess runoff) it needs to be recognised that many catchment conditions vary over time and space."

17. **3, 30. Here the suggested references 1 and 4 could be added.**

Added.

18. **4, 9. It is a bit surprising to know that the study area is a hillslope after reading the Introduction that focuses almost exclusively on processes at the catchment scale!**

It is really a small catchment. We have changed our terminology throughout the paper.

19. **4, 17. ‘reasonably’ is too vague. Specify.**

The sentence has been revised to (p5 l30):

The study area has a humid climate and rainfall is uniformly distributed across the year.

20. **5, 26. This can be misunderstood as the uncertainty in the presented results of hydrograph separation. I think it’s clearer to use the term ‘instrumental precision’.**

This has been revised to: “The instrumental precision was ….”

21. **6, 15. Do the authors mean ‘conceptually separate’ here, ie they are considering these processes, and not physically computing the fractions of return flow and SOF in stream- flow? Please, reformulate for clarity.**

Done

22. **7, 6. Better to use ‘stream’ or ‘streamflow’ here instead of ‘runoff’.**

Done

23. **7, 23. For the sake of clarity, indicate which events/panels.**

Done

24. **8, 9. How was the quick flow runoff coefficient computed? In section 2.4 it was not defined. . .unless it’s, as I think, the same than ‘event runoff coefficient’. In the latter case, please be terminologically consistent.**

We will edit the paper so that we use event runoff coefficient consistently.

25. **8, 28-9, 4. This part could be condensed by pointing out at the Tables.**

Done

26. **10, 10. Although known and intuitive, the symbols of this equation should be explained. Moreover, it should be stated that the events falling into this period are 10 (as inferred from Fig. 8).**

We have revised this to (p15 L16):

To explore this, we calculated the recession constant, $k$ (as in $Q_t = Q_0 e^{-kt}$ , where $Q_t$ is flow at time $t$ during the recession period, $Q_0$ is the flow at the beginning of the recession and $k$ is the recession constant), and plotted it against soil water storage at the start of the recession for individual events within this period (Figure 8). This period contained 10 events. $K$ decreased as ….

27. **10, 17. 'Clearly'. I think it would be more cautious to start this sentence stating the results and/or the figures that point at this.**

We have amended this to begin as follows (p16 L2):

"The hydrometric results presented in Figures 6, 7 and 8 suggest that subsurface flow is important in this catchment. Given this, we would expect the hydrograph to be dominated by "old" or pre-event water; however, the saturated area….."

28. **10, 24. 'different signature': ok, but the trend is similar and should be remarked.**

We have reworded this to (p16 L17):

"The runoff samples showed a very different isotopic concentration during the rising limb and the peak of the hydrograph (δ2H =-43‰, δ18O = -6.8‰) in comparison to antecedent low flow. This shows that the isotopic concentration moves significantly towards the rainfall sample concentrations."

29. **10, 25. Here the suggested references 5 and 6 could be added.**

The Hydrograph separation is now explained in the methods and these references are cited.

30. **11, 20. Please, explain what the 'field observations' are.**

This has been explained as follows (p17 l19):

Field observations of surface saturation extending to the flume and well hydrograph measurements of the water table at the surface showed that the saturated area was highly connected to the catchment outlet and suggest that it would be expected to produce saturation excess runoff.

31. **11, 24. Here the suggested reference 4 could be added.**

Done

32. **13, 7-13. This part is not very relevant to the observed results and could be skipped, in my opinion.**

We will delete this paragraph.

33. **Tables and Figures Table 1. Remove the first column, it's not useful. Don't use abbreviations in the column name.**

Column 1 is needed in Table 1 as it distinguishes between group 2 and group 3 events. We have removed the abreviations

34. **Fig. 1. The first 'Yes' on the top horizontal arrows should be moved more to the right close to the dashed arrow, in my opinion. And perhaps the second 'Yes' can be removed.**

We have amended the figure as suggested

35. **Fig. 2. I suggest the terms lower, mid and upper hillslope (or slope) instead. Remove the notation and the arrow pointing to the wells and put them in a legend. Why has the DEM been cut before the stream. . .cannot be extended to it?**

We will amend the figure as suggested

36. **Fig. 4. Replace 'overview' with 'example'. I also suggest to include a no-flow event.**

Done. A zero flow event has been included.

37. **Fig. 5. Please, see my comment above. Moreover, the difference between 'Soil Moisture Index' of panel b) and 'ASI' of panel c) is not clear and should be explained (or fixed if they are the same thing).**

    **(I think 'soil moisture index' and 'ASI' are the same thing so we should change the title of X axis in panel b to 'ASI'.)**

Yes the soil moisture index in Figure 5 and ASI are the same thing. We have edited the figure so we use consistent labelling and checked that we are also consistent throughout the text.

38. **Fig. 6. Why are there values above zero? Explain or fix.**

The soils are highly pugged in this area and water pooled on the surface in places leading to slightly positive water levels being recorded at site 2. We have explained this in the figure caption as follows.

Figure 6. Time series of discharge (grey lines) and groundwater levels at sites 4, 5, 3, 32, 2 and 1, manually read sites are shown with dashed lines. Levels above zero at sites 1 and 2 occur as the soils are highly pugged in the riparian zone and water pooled on the surface in places leading to slightly positive water levels being measured at site 2 in particular.

39. **Fig. 7. Why have only these sites been shown and not also water table at the other locations? This should be explained in the text. Additionally, 'high intensity' is too vague and should quantified, possibly using thresholds presented in Fig. 5.**

We have explained on p14 l30 that these sites were chosen because they show significant dynamics and we had logged records available. Other sites with loggers had limited dynamics or short records.

We define high intensity in the caption (>15mm/h) and have amended the figure so this definition is consistent with the threshold in Figure 5.

40. **Fig. 8. Add a mention to the period when these events have been selected. It would be interesting to see these results also for other events.**

The following sentence is added to the caption of the Figure 8:

These events happened in the very wet period during August/September 2010. We will consider adding other events.

41. **Fig. 9. The symbol '‰should be put in parenthesis. ´**

Done

42. **Fig. 10. Please be consistent with the use of terms such as 'discharge' (as here) or 'flow' (as in Fig. 9).**

We have edited the figures as suggested. We use discharge where instantaneous measurements are plotted and runoff where total volumes over some period are plotted. We have edited the paper for consistency.

## *Authors' response to Anonymous Referee #2 on "Multiple runoff processes and multiple thresholds control agricultural runoff generation" by S. Saffarpour et al.*

We appreciate these useful reviewer comments and suggestions. We have addressed each comment separately. The following document has been structured as 1) the blue font indicates the reviewer's comment and 2) the black font shows the authors' reply.

**General Comments:** **The content of the article is relevant to the hydrological community and meets the focus of the selected journal. It investigates functional relationships between antecedent wetness and rainfall characteristics and the streamflow response of a small agricultural catchment in Australia. In doing so the authors aim at identifying multiple co-existing runoff processes and potential threshold behavior between catchment-states and streamflow response. The dataset, comprising of hydrometric and hydrochemical parameters has potential but needs more quantitative analysis in order to address the outlined themes.**

We thank the reviewer for outlining our research and highlighting its importance for the hydrological community.

**My main suggestions to improve the manuscript are the following:**

43. **I acknowledge the idea to use a decision scheme based on properties and mechanisms to structure runoff processes such as in Figure1. However, such a scheme is designed to result in one dominant runoff process and not in multiple ones such as outlined in the title. (We all know, that processes co-exist in different degrees of intensity). Original versions of such decision schemes are designed for the point or plot scale. While I acknowledge the authors idea to extend it with the concept of connectivity and time scales, I think that this causes a mismatch of scales. At least the authors need to define very clearly what spatial and temporal scale they are considering (and stick to their definition) and what the landscape units are, between which they consider connectivity. I suggest to come up with a separate Figure for connectivity**

This figure is intended to address hillslope scale processes and phenomena (i.e. connection to the stream) at the event timescale. We have edited the discussion of the figure to reflect this. We have changed figure 1 to indicate when surface and subsurface connectivity exists (indicated by red arrows).

44. **The method section needs to provide more quantitative information. (e.g. soil profile, total number of Q, GW, NS, monitoring sites, procedure of manual sampling, delineation of the saturated area, lab-analysis devices used. (Using two different devices for analyzing isotopes can cause considerable difficulties in comparing or pooling data).**

We have add these details to the methods section. As discussed in our response to reviewer 1, the two isotope analyzers were compared. Differences were controlled for and have limited impact here as the final analysis only used samples analysed by a single machine, with the exception of the uncertainty analysis.

45. **The result section is descriptive and lacks statistical/data analysis to quantify the authors' statements and derive generally applicable results. Some results are based on one or a few selected events only, which is not representative to draw conclusions. I suggest to exploit the entire dataset the authors have at hand and calculate statistics over all events.**

We have exploited the full data set already in terms of the hydrometric analysis. The ion and isotopic analysis addresses issues for specific types of events and we use all available data that can be analysed with reasonable uncertainty, as discussed in our various responses to reviewer 1. We have clarified this in the revised paper. We will provide some further statistical summaries of the various categories of events including statistical summaries of the rainfall characteristics and runoff responses.

46. **Some parts of the result section are the authors' interpretation and better fit in to the discussion section. Terms are either not defined in the text (e.g., in the method section) or not used consistently and the term "threshold" is used in circumstances where "exponential relation" is more appropriate.**

We have defined and clarified terms in response to specific comments from this reviewer. We disagree with the suggestion that "exponential relation" is more appropriate. Runoff responses below the identified thresholds are zero, not just small as would be the case with an exponential relationship. Our use of the term threshold is also consistent with the literature.

47. **The conclusions are drawn from one or two individual rainfall events and not logically derived from or supported by the results of this study. I would encourage the authors to refine and strengthen their analysis based on their dataset. I think it is good to discuss the findings in the light of Fig1. but as it is originally developed for point- or plot scale assessments it misses out the spatial (and temporal) heterogeneity across a catchment. – a fundamental aspect when analyzing thresholds and connectivity – and something that I think the authors try to address. For my detailed comments please see the provided pdf documents and summary of comments.**

We disagree with the reviewers contention that we base our conclusions on single events. The hydrometric results consider 60 rainfall events and 38 runoff events. We acknowledge that some of our later exploration of specific phenomena is based on single events but we have analysed all the suitable data available to us and those results are providing additional lines of evidence in support of the hydrometric analysis. Figure 1 is derived with the hillslope scale in mind. We have edited our presentation to make this clearer and to capture the issues of heterogeneity mentioned.

48. **In general, I think this manuscript has potential to be an interesting contribution to the hydrological society why I encourage the authors to work on a revised version.**

**Page:1**

**Number: 1 Strikeout “increased”**

Done

**Number: 2 Insert text increased**

Done

**Number: 3 Maybe this become clear in the text but how did you distinguish between these runoff source areas/mechanisms?**

We clarify this as follows:

Based on a combination of various hydrometric analyses and some isotope and major ion data, we conclude that event runoff at this site is typically a combination of subsurface event flow and saturation excess overland flow.

**Page:2**

**Number: 1**

**General Comment on Introduction:**

**The introduction is a lot about Fig., and less describes what others have found about thresholds and runoff mechanisms (only mentioned in a few sentences and (good list of references).**

**I also think, that not all studies only concluded that one runoff mechanism is dominating in their catchment. So some pervious work has also concluded, that there are multiple processes happening at the same time or vary seasonally**

We agree with the reviewer comment. We have revised this sentence to (P3, L1):

“While the concept of connectivity has been useful in many of these studies, some studies have concentrated on individual mechanisms. It is less clear how catchments behave when ….”

**I also think, that it needs to be clearly stated that Fig. 1 (at least I think) is describing dominant processes at the point or plot-scale.**

We have clarified our intention as follows (P3 L14).

To aid systematic consideration of the variation in runoff processes between catchments and over time, we develop a summary of the status quo in terms of the combined effects of thresholds and connectivity on runoff processes at the hillslope to zero-order catchment scale (Figure 1). Often we think of dominant runoff processes and as Figure 1 is easiest to interpret in that context the following discussion takes that view initially. However, there is often a mix of runoff processes either spatially due to heterogeneity or for different events and Figure 1 can also be used to interpret such a mixture, which we will return to later. This paper aims to tease the influence of different processes apart by considering 60 rainfall events (resulting in 38 runoff events) in a small agricultural catchment. We then investigate runoff processes in an agricultural catchment in south-eastern Australia in detail and show the shifting importance of different processes over time associated with changes in catchment wetness and rainfall intensity and apply the runoff process framework. We consider the role of thresholds in different 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. The variety of potential thresholds leads to a variety of runoff processes, as illustrated in the following discussion.

**I like the idea of the authors to go beyond that and think about aspects that need to be considered in terms of connectivity between this points but they are not in the diagram (Fig.1). (see my comments for more detail). If talking about connectivity, this term needs to be diefined and also between what (e.g. hillslope stream).**

We have defined connectivity on p2, l10 as follows:

In this paper we are interested in connectivity in terms of the movement of water from hillslopes to streams and we say there is connectivity along a flow pathway when water is moving along that pathway and contributing to stream flow from the catchment.

**Time scale: I also like the idea to pay more attention to time-scales but it needs to be defined what the authors think of. I guess, in some circumstances they are not talking about time-scale but rather duration.**

Yes at times we mean duration. We have edited the discussion of Figure 1 to clarify this.

**The authors could be more clear what this work contributed to and say more about how their work is new!**

We have stated the contribution as we view it more explicitly at the end of the introduction as follows.

Thus the contributions of this paper revolve around the introduction of the framework in Figure 1 and demonstration of its application using a catchment where multiple runoff processes are important. The paper also contributes to further understanding of the role of thresholds and connectivity in determining flow pathways and runoff processes in agricultural catchments. Most connectivity studies in the past have focused on forested catchments.

**Number: 2**
**There also exists the concept of a continuous nature of connectivity but I agree, that most studies chose the threshold-type of concept. You could say, that you chose the latter concept which implies ...**
In this study the latter concept was used to examine runoff mechanisms in the study area. This concept enabled us to discuss how various runoff mechanisms produced and progressed during the runoff season.

**Number: 3**
**maybe add Penna et al., 2015**

Added.

**Number: 4**
**not 100% clear. You mean multiple threshold for different runoff generation mechanisms?**

We have clarified this as follows.

Prior to this, we consider the role of thresholds in different 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. The variety of potential thresholds leads to a variety of runoff processes, as illustrated in the following discussion

**Number: 5**
**state here that Fig1 is about dominant runoff mechanisms or that you consider them to co-exist in parallel.**

We have added the following to p3 L16

Often we think of dominant runoff processes and Figure 1 is easiest to interpret in that context; however, there is often a mix of runoff processes and this paper aims to tease those apart in a small agricultural catchment and Figure 1 can also be used to interpret such a mixture.

**Number: 6 Insert Text**
**on dominant runoff processes.**
**(see my comment at Fig1)**

We have inserted "on runoff processes" and added some further discussion of both using Figure 1 to interpret dominant runoff processes and also mixtures of runoff processes.

## Page:3

**Number: 1 Insert Text**
**with different physiographic characteristics**

Added

**Number: 2**
**2006?**

2005 is relevant but we have also added 2006b

**Number: 3**
**Do you mean the difference between the dominant runoff process concept and a concept of co-existing of these processes with different degree of importance. Can you rewrite?**

We have reworded the text here as follow, which hopefully make it clearer.

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), who used a generalise Damköhler to represent the competing effects of transport and reaction timescales on the loss of material along a flow path.  When the reaction timescale is small compared with the transport timescale, the reactant is consumed before reaching the exit of the flow path it is moving along. A complication here is that, both flux and time thresholds are important. This arises because there is finite capacity for flow in various parts of the catchment system.

**Number: 4 Strikeout**

Done

**Number: 5**
**parts?**

Added

**Number: 6**
**I am not sure if they tell directly about connectivity? Connectivity between what? Hillslope stream, neighbouring sites? maybe better "lateral flwo"?**

The sentence was amended to:

Figure 1 is divided into three parts, the lefthand area provides a series of catchment thresholds that depend on hydroclimatic and landscape characteristics and influence the type of runoff process and the connectivity between the hillslope and stream, depending on whether they are exceeded or not.

**Number: 7**
**that depend on climate and landscape characteristics and ...**

Numbers 4-7.  Amended to “Figure 1 is divided into three parts, the lefthand area provides a series of catchment thresholds that depend on hydroclimatic and landscape characteristics and influence the type of runoff process and the connectivity between the hillslope and stream, depending on whether they are exceeded or not”

**Number: 8 Insert text**
**Dominant**

Done

**Number: 9**
**I like this idea but I think you need to introduce the reader more to these time scales.**

Specific examples have been added to the following paragraph including:

P4 L26: Thus the duration of high intensity rainfall compared with the overland flow timescale (flow distance / wave celerity) is important.

P4 L33: Thus the ratio of the lateral flow timescale for the hillslope and the evaporative drying (or other loss) timescale is important here.

**Number: 10**
**I think these are not time scales but time durations or simple ".. over an event"**

We agree some are durations but the lateral flow process is characterized by a timescale determined by hillslope flow distance and wave celerity, which is clarified in the above response.

**Number: 11**
**I understand what you want to say but I think now you need to decide if you consider the diagram in Fig.1 to be on the point- scale (which I think the diagram is). If you want to consider processes such as run-on, than you need to redraw your diagram. Suggestion: try to come up with a similar diagram that considers connectivity between the hillslope and the stream and what processes can occur. For connectivity a few other criteria need to be fulfilled. Things you describe here fit well in this other context.**

We see figure 1 applying at the hillslope scale and we have explicitly included (surface and subsurface) lateral flow processes in the diagram. We are not sure what the reviewer thinks should be added.

**Number: 12**
**please define**

Reworded: "allowing water to flow along lateral subsurface flow paths"

**Number: 13**
**On an event-time-scale evapotranspiration might be a minor component. It more effects e.g. antecedent conditions.**

Agreed and we have expanded the following discussion to make that clearer.

**Number: 14**
**use different word**

Changed to "cease"

**Number: 15**
**it is not only about persistence (which implies time), it is about a continuous connection (hydraulically or hydrologically from point A to point B.**

**Please define at the beginning A and B.**

Amended to: If the saturation persists for long enough lateral subsurface flow to move down the hillslope and into the stream connectivity between the hillslope and the stream will develop.

**Number: 16**

**On a singe hillslope there can be patches of different processes. The question is: Do they for a continous path between A and B?**

We have added: Provided continuous saturation exists to the stream, this will lead to a surface flow path connecting the hillslope and stream.

**Number: 17 Insert Text**
**in our study catchment ...**

Added

**Number: 18 Insert Text**
**and space**

Added

**Number: 19**
**patterns of what (soil moisture?)**

Yes, clarified in the text

**Number: 20 Insert Text:**
**in Australia**

Added

## Page:4

**Number: 1**
**do you mean runoff generation response or dominant runoff mechanism?**
We have clarified this as follows: "These results are used to examine various runoff generation mechanisms and flow pathways that are important in the study catchment and to determine how they contribute to produce the catchment runoff as the catchment wetness and rainfall intensity vary.

**Number: 2**
**In general: the individual sections could improve from the order in which facts are stated. Please provide more quantitative information (e.g. soil profile), total number of Q, GW, NS, monitoring sites be more specific about which instruments have been used to analyze water samples. Where did you manually take samples, how often nad when> How did you determine the saturated area?**
We have heavily revised the methods section to address all these comments. The more substantive ones are addressed in detail below.

**Number: 3**
**Is this the catchment name? If so please write out the full name once and put the abbr. behind.**
Yes, the name of the catchment was rainbow flume (RBF). Added to the text.
**Number: 4**

**groundwater?**

Added.

**Number: 5**

**groundwater, streamflow?**

Amended to : “1) the riparian area located on the relatively flat convergent lower part of the catchment (outlined in red on Figure 2) included shallow groundwater sites 1, 2, 32”

**Number: 6**

**please describe the criteria you used to define these zones (range of slope values, TWI, etc.)**

The text is revised as follows (p6, L2):

Based on field observations, the topography, range of slopes and the groundwater behaviour, the catchment was divided into four different zones

**Number: 7**

**(1961 - 1990 ?)**

Yes that is right.

**Number: 8 Strikeout**

Done.

**Number: 9**

**... at all groundwater wells ?**

The sentence amended to: “Hand augering revealed a soil depth of between 1 and 1.6 m, and the lower parts of the profile included mottled clay and weathered bedrock particles.”

**Number: 10**

**please be clear if this is the average soil depth, the range ...**

**Number: 11**

**What about the other horizons. Is ther an impeding soil layer at what depth?**

**Number: 12**

**section needs better ordering. E,g, if you start with rainfall, than continue with all other meteo parameters. Consider to start with the parameters that are most relevant.**

Section 2.2 reordered.

**Number: 13 Strikeout**

Done.

**Number: 14**

**per event, day, season?**

Per event. This is clarified in the text.

**Number: 15**

**please provide full name!**

Full name was provided and the sentence was transferred to p7, L16.

**Number: 16**

**give site number**

The hillslope flume is now shown more clearly on see Figure 2.

## Page:5

**Number: 1**

**with what equation (give a citation)**

The following equation was used for calculation of $Q$ from RBF site. A reference to Clemens et al 1984 and rating equation are provided.

**Number: 2**

**sampling what (I guess streamflow)**

**So you had one site with water samples?**

Yes one site

**Number: 3**

**how did you know the hydrograph before the event? Unclear please rewrite.**

We plotted recorded water levels from the RBF flume in the field when the samples were removed from the auto sampler.

**Number: 4**

**interval for the sampling?**

Hourly for auto sampler and weekly for grab samples

**Number: 5**

**how did you measure the lower range when the probe is 30 cm? Pits? If so, describe their installation procedure**

A soil pit was dug in order to install the lower CS615 probe. Details are given in the paper.

**Number: 6**

**soil water content?**

Volumetric soil moisture which was converted to soil water. The method of calculation of soil water storage/content was completely described in the comment 6, 10-12 of reviewer#1.

**Number: 7**

**please state clearly how many Q, GW, SM sites you had.**

Done

**Number: 8**

**... until 20xx**

Done

**Number: 9**
**I think Odyssey are not pressure transducers!**

It is a NZ brand of pressure transducer. A www address was provided in the original paper.

**Number: 10**
**until 20xx (state the duration you were analysing!**
Done

**Number: 11**
**You need t say more about the manual sampling. Where, how often, at what times in streamflow, in gw?**
Done. The following sentence was added to p7, L28:

"Routine grab sampling was also undertaken at weekly intervals during the main runoff season when water was flowing through the RBF flume."

**Number: 12**
**Please state exactly which instruments you used (not the Professor).**
**If you used different machines but pooled the data for the analysis you have to somehow say something about potential differences (best you state which samples were analyezed where or at least sampels from 2010 ... and 2011 ...**
This point has been answered in our response to comment 2 from Reviewer #1.

**Number: 13**
**How is this determined?**
Sample isotopic analysis is now described in detail.

**Number: 14**
**which ones and which machines**
Sample chemical analysis is now described in detail.

**Page:6**
**Number: 1**
**state the duration of the study period**
This was mentioned in the section 2.1 study location. The study period was between September 2009 and December 2011.

**Number: 2**
**I think stating ASI needs also to state a duration over which ASI is calculated. If it is the VWC at the start of an event, than it is not typically called ASI. Please define!**
In this study ASI was the amount of soil water storage/content at the start of a rainfall event. The method of calculation of the soil water storage/content was described in response to comments from reviewer #1. We refer to it as an index because we are using a point to represent catchment conditions.

**Number: 3**

**not clear from Fig. 2. Also not clear, if you did this during each events. Was it based on mapping? Was it satturated area or the extent of the channel?**

This is described in detail in response to reviewer 1 comment4.

**Number: 4**

**by multiplying the area with ...**

We mean we conceptually separate, as described in response to Reviewer 1 comment 21.

**Number: 5**

**How can you do that unless you are mapping the catchment. Please describe very clearly.**

See reviewer 1 comment 4.

**Number: 6**

**I like the idear of giving definition. Please can you do that in the introduction and for all processes you are referring to!**

We have done this in our description of Figure 1 as follows (p4).

Figure 1 we define the specific runoff processes as follows.

- Infiltration excess runoff: runoff that occurs due to the rainfall (or throughfall) rate exceeding the infiltration capacity of the surface and that results in flows of water to the catchment outlet by surface flow pathways.
- Subsurface stormflow: runoff due to infiltration that generates rapid lateral subsurface flow (i.e. a quickflow response) that flows to the catchment outlet through subsurface flow paths for at least part the distance to the outlet. This water may exfiltrate in low convergent parts of the catchment or directly into the stream before reaching the catchment outlet. Often impeading layers and preferential flow paths are implicated.
- Saturation excess runoff: runoff due to rainfall on saturated areas that flows to the catchment outlet by surface flow pathways. The saturated area may be generated by either lateral flow in excess of the capacity of the hillslope to transmit the lateral flow, a drainage impediment at depth coupled with a sufficient excess of infiltration over evapotranspiration and drainage, or a combination of these.

**Number: 7**

**is this approach also applicable in your catchment?**

We acknowledge that the method is arbitrary, just like all hydrometrically based baseflow separation techniques. We did consider other methods such as digital filters but in our view that are just as arbitrary and more complex. Our results are insensitive to the exact rate of rise assumed. We have added a sentence acknowledging this at p9 l28 as follows.

While this method, like other hydrograph based baseflow separateion methods, is arbitrary, the results are insensitive to the assumed rate of rise.

**Number: 8**
**Summary of general comments:**

**Result section is very descriptive and lacks statistical/data analysis. Some results are based on one or a few selected events only. I suggest to exploit the nice dataset the authors have at ahdn and calcualted statistics over many events to derive generally applicable results.**
**Results (e.g. thesholds) are "read" form graphs and not calculated from the dataset.**
We feel most of the results are obvious from the figures, particularly figure 5d and that the pattern in these figures is the most important feature by which to compare groups. We feel that fitting the thresholds by eye is sufficient for the purposes of the paper. Nevertheless, we have added a table summarizing the average conditions for each runoff event group and a paragraph discussing that table and also undertaken statistical testing using the bootstrap technique to examine statistical differences. These are discussed at the end of section 3.2.

**Result section contains parts, that are better suited in the discussion section because they are subject to the authors interpretation and not based on data only.**
We acknowledge some small sections with results interpretation in section 3.3 where we are examining further evidence for runoff processes. These relate to individual aspects of the results, not interpretations of the results collectively. We wish to retain these where they are because we think they make the results easier to digest for the reader, rather than the reader having to retain all the detail in their memory for later interpretation.

**Terms are either not defined in the text (e.g., in the method section) or not used consistently.**
**The term "theshold" is used in circumstances where an exponential relation is more appropriate.**
**As the different runoff mechanisms are prominent in the title, they should be clearer addressed in the results**
We have edited the paper to define and clarify terms in response to specific comments from this reviewer. We disagree with the suggestion that “exponential relation” is more appropriate. Runoff responses below the identified thresholds are zero, not just small as would be the case with an exponential relationship. Our use of the term threshold is also consistent with the literature.
**Number: 9 Strikeout**

Done

**Number: 10**
**define ASI the first time you use it!**
We have defined this at p7 l8 as follows:

We use this soil water storage at the start of each rainfall event as an index of antecedent soil water (ASI) and assume it represents the catchment wetness condition.

**Number: 11**
**qunatify?**

Fixed

**Page:7**

**Number: 1**

**the overall seasonal pattern is the same but details not!**

We have clarified this as follows p10 l17:

While a strong link between runoff and soil water storage is evident at the seasonal scale in Figure 3, there are exceptions at the event scale

**Number: 2**

**which ones?**

Fixed (p10, L23).

**Number: 3**

**whcih ones! fable them with a,b,c, so you can refer to them**

We have labelled the subfigures and amended the text as follows (p10 L27):

All events (except events on 26/11/2011 and 10/12/2011(Figure 4c)) presented in Figure 4 had zero or very low initial flow. For the events on the 26/11/2011 and 10/12/2011, the initial discharge was 0.07 and 0.13 mm hr-1, respectively.

**Number: 4**

**give value in ()**

Done

**Number: 5**

**that does what?**

We have clarified what each of these past studies considered as follows:

Figure 5 builds on approaches by Detty and McGuire (2010), who considered thresholds in ASI and ASI+Rain (i.e. Figure 5c and d), and Janzen and McDonnell (2015), who considered the impact of event rainfall and rainfall intensity on event runoff (i.e. Figure 5a).

**Page:8**

**Number: 1**

**its not the RC but the Total Runoff**

We have removed this sentence

**Number: 2**

**Fig 5a could be described more. What about the relation with intensity?**

We have expanded our description of Figure 5a as follows (p11 l24):

Figure 5a shows event runoff as a function of event rainfall, with the highest hourly rainfall intensity ($I_{peak}$) indicated in colour. This illustrates that there is little relationship between event rainfall and runoff or between rainfall intensity and runoff. For some quite large events (up to ~25mm), zero runoff can occur. There was also 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. Overall, Figure 5a shows that event rainfall and intensity do not effectively differentiate rainfall-runoff behaviour when considered by themselves.

**Number: 3**
**Fig 5b. needs much better explanation (consider to reduce information to make more clear).**

Done

**Number: 4**
**I like the figure but it has (too) many information in one plot in order to deliver your message.**
**readability:**
**Where can I quantify what the length of the grey line is? Where is zero for each individual line?**

We have added further description of the figure which should help to make its interpretation clearer.

**Number: 5**
**but your legend suggest that the filled marker is RC?**

It is stated in the text that the bubble size is the runoff coefficient and the color is the total runoff

**Number: 6**
**use other expression**

This was amended to:

**“**There are several trends that can be discerned from Figure 5b. First the rainfall events analysed here occurred across the full range of catchment wetness and were relatively evenly spread, showing that the rainfall events occur over a representative range of catchment antecedent conditions. The larger rainfall events generally occurred in summer when *ASI*<250 mm and a mix of low and high intensity events occurred for these conditions, also in summer. All the events on a wet catchment (*ASI*>250 mm) had low $I_{peak}$ (≤6.2 mm hr$^{-1}$). Events where the *ASI*+Rain was less than 250mm usually did not generate any runoff, although there were some high intensity rainfall events that were exceptions and a small number of events with very low runoff coefficients (1-4%) where the *ASI*+Rain was generally between 230 and 250mm. These low runoff coefficient events were at the end of the runoff season”.

**Number: 7**
**How much of Fig. 5b is actually describing the general seasonal pattern in rainfall event types?**

**Number: 8 Insert Text**
**rainfall events that state**

Comments 3-8: We have edited the paragraph in response to all these comments.

**Number: 9**
**the role on what?**

Amended to: Figures 5c and 5d examine the impact of catchment wetness, quantified as ASI and ASI+Rain respectively, at the start (5c) and end (5d) of the event on event runoff response, combined with the impact of rainfall intensity, Ipeak. Catchment wetness is plotted on the x-axis and rainfall intensity on the y-axis. Values ASI=250mm (Fig 5c), ASI+Rain =250mm (Fig 5d) and Ipeak=15mm/h are shown by grey dashed lines.

**Number: 10**
**(quantified as ASI and ASI+ Rain)**

Amended to: Figures 5c and 5d examine the impact of catchment wetness, quantified as ASI and ASI+Rain respectively, at the start (5c) and end (5d) of the event on event runoff response, combined with the impact of rainfall intensity, Ipeak. Catchment wetness is plotted on the x-axis and rainfall intensity on the y-axis. Values ASI=250mm (Fig 5c), ASI+Rain =250mm (Fig 5d) and Ipeak=15mm/h are shown by grey dashed lines.

**Number: 11**
**(RC)**

Added.

**Number: 12**
**say also that the y-axis is Ipeak (Fig 5 c , d)**

Comments 9-13 have been addressed in specific edits.

**Number: 13**
**are these three groups statistically significant. It "looks" promising, they are!**

Yes they are different - see response to general comment on statistical analysis.

**Number: 14**
**why? Guide the reader to your thoughts.**

We have added the following guidance at p12 l21:

In Figure 5d, three different groups of events can be identified. Looking along the x-axis, there is a threshold at ASI+Rain=250mm that separates events with a significant runoff response from those without. Looking along the y-axis direction, it can be seen that the ASI+Rain threshold is not successful at distinguishing runoff when Ipeak is high and there is also a threshold in runoff response at Ipeak =15mm/h. Thus the three groups are

**Number: 15 Strikeout**

done

**Number: 16**
**what do you mean by synchronized (peak timing?)**
Yes. Reworded to:

These runoff peaks happened at the same time as the highest recorded rainfall intensities.

**Number: 17**
**steaflow?**

fixed

**Page:9**
**Number: 1**
**the RC calculated for the first 2 hours was 18% (is that what you wanted to say?)**
Yes correct. We have reworded to (p13 l9):

The highest intensity was observed in the first two hours of the event and the runoff coefficient calculated for the first 2 hours of the rainfall event was 18%. . The RC calculated for the duration this event was 68%.

**Number: 2**
**You could summarize all findings in one or two sentences at the end. (also applies to other result sections)**

Done

Overall these results demonstrate a range of different rainfall runoff responses. The responses depended on both the catchment wetness as quantified by ASI+Rain and on the peak hourly rainfall intensity, Ipeak , with thresholds of 250mm and 15mm/h being identified. Runoff was produced whenever thresholds in either of these were exceeded.

**Number: 3 Strikeout**

Done

**Number: 4**
**You need to calculate the actual value. In the discussion it is OK to round it to a meanungfull value.**

The paragraph amended to:

**"**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. It should be noted that there is some uncertainty in the $I_{peak}$ threshold as the most intense event (for *ASI*+Rain<250mm) that failed to produce runoff was 10mm/h, while the least intense event that did produce runoff was 14.8mm/h. 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. In fact, runoff and non-runoff producing events are very well separated by the relationship $I_{peak}$ = 3/11*(*ASI*-260). These results suggest that there are both wetness dependent and intensity dependent runoff production mechanisms operating. This section examines the evidence for different runoff mechanisms contributing to event runoff."

**Number: 5**

**This is based on 4 datapoints and you have a gap in data between ca. 10 and 15 mm total rainfall. I think it is valid to state the 15 mm threshold but you need to be critical about it in the text.**

We have added this caveat:

It should be noted that there is some uncertainty in the Ipeak threshold as the most intense event (for *ASI*+Rain<250mm) that failed to produce runoff was 10mm/h, while the least intense event that did produce runoff was 14.8mm/h.

**Number: 6**

**you need to do a statistical test to prove this (e.g., rank correlation).**

We have shown a new threshold dependent on both intensity and wetness that demonstrates this.

**Number: 7**

**what do you mean? Where they aligned along transects?**

We have clarified as follows (p14 l10):

In figure 6, the sites are ordered by elevation from highest to lowest in the catchment.

**Number: 8**

**please help the reader to better understand this. Saturation would mean to me, that the entire soil profile is saturated and the groundwater level at the soil surface. That's, only the case for well 1 and 2 (maybe for 32).**

We have reworded this to (p14 l12):

Figure 6 clearly shows that the water table became shallower and that the occurrence of profile saturation (water table at the surface) was restricted to the riparian zone. Within the riparian zone, sites 1, 2 were saturated much of the time and site 32 quickly became saturated during events. The water table remained below the surface at sites 3 (at the upstream end of the riparian area), 4 and 5 (in Mid slope positions).

**Number: 9**

**What do you mean. Manually read groundwater levels? If so please state this in the method section. It seemed, you were using Odyssey loggers for all wells.**

**If you used irregular intervals, please use a line type that has a dot at each time you were manually taking a reading.**

Yes manually read sites are already indicated by a dashed line with markers for measurement points. This is explained in the caption of Figure 6.

**Number: 10**

**I think it is hard to say something about recession details then plotting 1.5 years of data (x-axis). If you want to say something about the relationship between certain groundwater levels and streamflow, you should either show selected events or even better use statistical tests that show, that streamflow is statistically higher, when certain gw-levels (e.g., in well 4 and 5) are above a theshold of XY cm. That would nicely fit your topic.**

We have added a second panel to Figure 6 so that this is clearer.

**Number: 11**

**Why do you use soil water storage (or are you actually using soil moisture (VWC)?**
**You compare groundwater on the hillslope with soil moisture in the riparian zone?**
**Why not plotting streamflow as a function of depth to groundwater or streamflow as a function of soil water storage?**

We have provided additional context at p14 l25 to explain this as follows.

So far we have examined thresholds in catchment wetness (ASI+Rain) associated with a change in runoff behaviour and the linkage between shallow water tables and catchment response. It is probably that the linkage between catchment wetness and runoff is through the intermediary of shallow subsurface flow controlled by the existence of saturated conditions within a permeable part of the soil horizon.

**Number: 12**

**Can you remind the reader that site 4 and 5 are on the hillslope**

Done -> The water table remained below the surface at sites 3 (at the upstream end of the riparian area), 4 and 5 (in Mid slope positions).

**Number: 13**

**It looks lie an exponential relation rather than a threshold.**

We have reworded this as follows (p14 L31):

Site 5 in particular shows a rapid change in behaviour for soil water storage around 250 mm, which corresponds with the *ASI*+Rain threshold identified above. As soil water storage moves above this level, much higher water tables develop and those water tables showed relatively rapid recession when shallower than 120 cm. Similar observations were seen at site 4 but the corresponding depth was 140 cm.

**Number: 14**

**This is descriptive. Please can you quantify this using statistics using all you events.**

Amended to (p14, L20):

Looking at the discharge record in Figure 6a, 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 deep. 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 6b).

So far we have examined thresholds in catchment wetness (*ASI*+Rain) associated with a change in runoff behaviour and the linkage between shallow water tables and catchment response. It is probably that the linkage between catchment wetness and runoff is through the intermediary of shallow subsurface flow controlled by the existence of saturated conditions within a permeable part of the soil horizon. Figure 7 shows the relationship between water table levels in the catchment (sites 4 and 5) and soil water storage at the weather station. These sites represent planar and convergent mid slope positions respectively. These sites were chosen because they show significant dynamics and we had logged records available. Other sites with loggers had limited dynamics or short records. Site 5 in particular shows a rapid change in behaviour for soil water storage around 250 mm, which corresponds with the *ASI*+Rain threshold identified above. As soil water storage moves above this level, much higher water tables develop and those water tables showed relatively rapid recession when shallower than 120 cm. Similar observations were seen at site 4 but the corresponding depth was 140 cm. Figure 7 thus explains the linkage between the 250mm *ASI*+Rain threshold and runoff. When soil water storage exceeded this level, water tables rose and lateral subsurface drainage occurred, as evidenced by the recessions. The recessions in particular suggest that the water table moved into a more permeable zone on these occasions. This is consistent with soil profiles being characterised by mottled clay at depth which is likely to have lower hydraulic conductivity. This behaviour at these two wells in combination with the soil water and flow data, indicate that the hillslopes were becoming connected to the catchment outlet via subsurface flow from the hillslope to the riparian zone. Our analysis of isotope data below will add to the evidence for this. There were a few occasions where the water table responded strongly for soil water storage less than 250 mm (Figure 7). As indicated by the red colour, these corresponded to high intensity ($I_{peak}$>15mm/h) rainfall events.

**Number: 15**
**you only gave one Ksat, So you do you know that the lower soil horizon is less permeable (That is a reasonable assumption you could use in the discussion but not in the results section).**

We have provided qualitative evidence for this as follows (p15 l3):

The recessions in particular suggest that the water table moved into a more permeable zone on these occasions. This is consistent with soil profiles being characterised by mottled clay at depth which is likely to have lower hydraulic conductivity.

**Number: 16**
**subsurface drainage form the hillslopes to the stream?**

**Number: 17**

**You base your conclusion on data of two wells?**

16 and 17 were clarified as follows (p15, l5):

This behaviour at these two wells in combination with the soil water and flow data, indicate that the hillslopes were becoming connected to the catchment outlet via subsurface flow from the hillslope to the riparian zone

**Page:10**

**Number: 1**

**Can you use your isotope data to prove this?**

We refer the reader forward to our isotope analysis: Our analysis of isotope data below will add to the evidence for this.

**Number: 2**

**... in Fig.xy**

Done

**Number: 3**

**Please move this to the discussion section. There it is possible to speculate about potential causes.**

Done.

**Number: 4**

**you only measure groundwater levels and not flow.**

We measured groundwater levels and also water level at the catchment flume.

**Number: 5**

**unless you have a trench, you cannot say anything about hillslope flow.**

We measured groundwater levels and also water level at the catchment flume.

**Number: 6**

**... of streamflow (or of the groundwater levels?)**

**Q would indicate streamflow so you where plotting k of stremaflow as a function of volumetic water content (which is also measured near the outlet of the catchment. What do we learn form this in terms of connectivity between hillslope and streams (see title)?**

We have changed this from “hillslope flow” to “catchment flow” for clarity.

Yes we plot k for streamflow against soil storage but the reviewer is incorrect is saying that it is near the outlet, the soil water storage is measured at the top of the hillslope as shown in Figure 2.

**Number: 7**
**Please quantify!**

We added the following to p15 l27:

*k* decreased as soil water storage increased at a rate of about $0.1d^{-1}$ for each 10mm increase in soil water storage.

**Number: 8 replace**
**Suggests**
Done.

**Number: 9**
**It is OK to show only one event in the paper but for deriving conclusions you need to analyse many events and give the statistic. You have a good data set, so please use it!**

We explain the limitations of the data for reviewer 1 comment 7.

**Number: 10**
**in what amounts (please check sentence to be complete)**

Amended to:

These results suggest that precipitation on the saturated area generates direct runoff in amounts that are close to what would be expected (i.e. 100% runoff) given that the saturated area is around 5-6% of the catchment area.

**Number: 11**
**This result is different to what you concluded from the hydrometric data.**

We don't see the result as being different to the hydrometric data results. We do not understant the detail of what the reviewer means or why s/he sees it as different.

**Page:11**
**Number: 1**
**Also here: I tis OK to show one example but you need to analyse all your events and present statistics of the general behaviour. You have a good dataset!**

There were only four high intensity events and one with major ion data.

**Number: 2**
**What is a typical Chloride concentration (define!)**

Reworded to (p16 L31):

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 variation in chloride concentration with flow (Figure 10a).

**Number: 3**
**Please put your interpretation in the discussion section and present only results.**

done

**Number: 4**
**The conclusions are drawn from one or two individual rainfall events and not logically derived from the results of this study but more based on general hydrological conceptualization.**
**The discussion is short and could better tie in the results of this study and critically discuss them.**
**I think it is good to discuss the findings in the light of Fig1. But Figure 1 is for poin- or plot scale assessments and misses out spatial (and temporal) heterogeneity across a catchment.**
**Fig. 1, in my opinion, also misses out connectivity and interactions between sites (e.g., run-on form uphill sites). Your idea to bring that in is good but I think it needs a separate scheme to do this because of different scales of consideration.**

As noted earlier, we disagree with the reviewers contention that we base our conclusions on single events. The hydrometric results consider 60 rainfall events and 38 runoff events. We acknowledge that some of our later exploration of specific phenomena is based on single events but we have analysed all the suitable data available to us and those results are providing additional lines of evidence in support of the hydrometric analysis. Figure 1 is derived with the hillslope scale in mind. We have edited our presentation to make this clearer and to capture the issues of heterogeneity mentioned.

**Number: 5**
**not so clear form the results**

It is as clear as we can make it with the data available.

**Number: 6**
**I think your conclusions from the isotope data are showing a contrast rather support the hydrometric data (see also your title).**

It is not clear what the reviewer means by this comment

**Number: 7**
**Isn't it varying between events and seasons?**
We have clarified the reduction in saturated area during the dry season as follows (p17 l16):

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 with only a small variation (see table 1) over the winter-spring season but reduces over the dry summer-autumn period.

**Number: 8**
**Please give evidence rather than your subjective field impression.**

We have added a reference to Table 1 which has the detailed evidence.

**Number: 9**
**one event is not enough to draw conclusions from it!**

Agreed more events would be better but we only have one and in the original text we only have one and only claim support not confirmation of the hypothesis.

**Number: 10**
**This is rather general, please discuss, what you study contributed on new insights on multiple runoff processes occurring in parallel.**

That is covered in subsequent paragraphs.

**Page:12**
**Number: 1**
**Please discuss in more detail, what your study and other studies found.**

We have added clearer statements of contributions.

**Number: 2**
**unfortunately only 4 events**

We analysed all available data.

**Number: 3**
**You used hourly data but a different temporal resolution would lead you to a different threshold. Please, discuss this issue!**

Good point. We have added the following paragraph.

It is worth noting that the 15mm/h threshold will be dependent on the timestep used in calculating the intensity. The choice of timestep needs to consider the travel time from hillslope to stream as runon infiltration processes occurring on the catchment surface will impact on the connectivity to the stream. Thus the most appropriate time to use for averaging intensity would be the average travel time to the stream because it is this time period which is available to infiltrate rainfall that has become runoff at the point scale. Here the choice of hourly rainfall was pragmatic that was the recording timestep of the AWS.

**Number: 4**

**better move to results**

Done

**Number: 5**
**Please use evidence form your result section to better corroborate this.**

Done

**Number: 6**
**You cannot conclude this from one event, only.**

The sentence is clearly discussing multiple events.

**Number: 7**
**is it intensity or storage capacity?**

We have expanded this paragraph so it reads as follows (p18)

In summary, the process evidence relating runoff behaviour with catchment wetness thresholds, together with the data from shallow wells suggests a catchment where subsurface flow leads to a seasonally saturated riparian area that produces saturation excess runoff in immediate response to rainfall. This saturation excess is augmented by subsurface stormflow when the catchment wetness (*ASI*+Rain) exceeds a 250 mm threshold. This subsurface flow exfiltrates in the riparian area. Volume considerations provide evidence that, for many of the monitored events, water must be coming from outside area. This area is only about 5% of the catchment but quickflow runoff coefficients very regularly exceed this, often (about 1/3 of runoff events) exceeded 20%, and on occasion exceeded 50%. The role of both saturation excess runoff and subsurface stormflow is corroborated to some extend by isotopic data from one event where the hydrograph separation shows a volume of event water similar to the volume of rainfall on the saturated area and by the highly damped isotopic signal in the stream in general. 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. One of the key contributions of this work is clear field evidence of the interplay of both wetness and intensity dependent runoff processes in the one catchment.

**Number: 8**
**A saturated area would immediately produce saturation excess overland flow if hit by a rainfall.**

Agreed. Noted in the above paragraph

**Number: 9**
**You assume, that "old water" is from the hillslope but you need to sample water there in order to prove this. In regards to your chosen title, I think this would be something I had expected.**

Volume considerations really mean it can’t come from elsewere, as explained above.

**Number: 10**
**I doubt if one threshold (250 mm) is very informative for two very contrasting landscape units (riparian zone and hillslope). I would assume that they have different threshold or 250 mm are more related to the hillslope.**

The riparian zone saturated area is dependent on lateral flows of water from the hillslope. Given the two areas are linked through this process they share a common threshold.

**Number: 11**
**Please give soil properties for this soil horizon in the method section.**

Done

**Number: 12**
**please use your data to give evidence**

We have added (p19 l20)

Based on the volume of event runoff (Table 1), the lack of surface saturation on the hillslope and the behaviour of shllow wells (Figure 6), we infer that the hillslope becomes connected to the riparian zone under these conditions. The existence of a large volume of pre-event water in the event on 12 August 2010 (Figure 8) adds further corroboration to this.

**Number: 13**
**I am not sure, if you analyzed wetness thresholds of connectivity. Please refer to your data to do so. I think it is rather an assumption, that if we see runoff response (of "old water") in the stream we think it is from the hillslope.**

See above response – we haven't claimed to measure – we claim to "infer"

**Page:13**
**Number: 1 Strikeout**

Done

**Number: 2**
**NO! Figure 3 in Detty & McGuire plots streamflow on the y-axis! So they do not say anything about the hillslope contribution but about the entire watersehd runoff.**

We have edited this to make our comparison clearer. Like us they measure streamflow but use other evidence to make inferences about hillslope contributions.

**Number: 3**
**Please be more speciffic about what they found for what landscape position**

Clarified as follows.

Detty and McGuire (2010) found a relationship between a threshold of 316 mm for *ASI*+Rain and the start of the event streamflow response. They showed that the *ASI*+Rain threshold corresponded with a water table height threshold. Based on this, they suggested that subsurface flow, transmissivity feedback and preferential flow from hillslope to stream could be used to explain runoff mechanisms in their catchment. They did not observe either Hortonian overland flow or SOF even during the largest events.

**Number: 4 insert text**
**in their catchment**

Done

**Number: 5**
**threshold behaviour of what (streamflow, groundwater, soil moisture)?**
Event runoff response – we have clarified in the text.

**Number: 6**
**What about other studies?**

It is not clear what the reviewer means by this comment.

**Number: 7**
**threshold to initiate what? Streamflow, groundwater response?**

Event streamflow response – we clarified in the text.

**Number: 8**
**Please be more clear in the section before what your three runoff processes are and why?**

Done at the end of 4.1

**Number: 9**
**I think it is good to discuss your findings in the light of Fig1. But you miss out a spatial difference in runoff generation mechanisms across the catchment and treat all as one! I think this is not insightful enough! The scheme in Figure 1 should be applied to different landscape units in your catchment and could so reveal a mosaic of processes. Next step would be to discuss connectivity between thse mosaic parts. That's something different!**

As discussed above we intent Figure 1 to apply at the hillslope to catchment scale and we have amended our introductory discussion of the figure to try to make that clearer.

**Page:14**

**Number: 1**
**give evidence why you assume this?**

We have reworded this paragraph as follows (p20, l26)

The shallow well data (Figure 6, wells 1 and 2, to some extent 32) shows that the riparian area in the lower part of the catchment drains very slowly. There is a substantial reduction in slopes (and probably lower hydraulic conductivity associated with poorly structured, poorly drained soils) that suggests a substantial reduction in lateral subsurface flow capacity. The surface topography also suggests subsurface flow would converge in this area. From the perspective of Figure 1, this leads to a situation where water is taking longer than the typical time between events in the wet season to drain (box 7, "Yes"), resulting in persistent surface saturation and saturation excess runoff generation from the lower catchment

**Number: 2**
**I am not is sure if it is only one process over the entire event**

We believe the results show it is, especially the well data.

**Number: 3**
**I am not so sure: I think Fig 1 is for hte point-or plot-scale and needs an additional step (assessing connectivity) be be meaningful on the catchment scale.**

As noted earlier we have amended our introduction of Figure 1 to address this.

**Number: 4**
**General Comment:**

**The conclusions are drawn from one or two individual rainfall events and not logically derived or supported from the results of this study. I would encourage the authors to refine and strengthen their analysis based on more of their dataset. I think it is good to discuss the findings in the light of Fig1. but as it is originally developed for point- or plot scale assessments it misses out the spatial (and temporal) heterogeneity across a catchment. – a fundamental aspect when analyzing thresholds and connectivity.atial variability within the catchment.**

Most of our conclusioins are drawn from the hydrometric data from 60 rainfall events and 38 runoff events. This is complemented by other data. We have used all the available pertinent data here.

**Number: 5**
**Soil moisture is measured at one site in the catchment?**
Yes, it was measured at one site.

**Number: 6**
**I think you are limited in how much you can say about connectivity**

**Number: 7**
**This is your assumption not clear from data**

**Number: 8**

**I think flow and connectivity cannot be derived form your data. You assume, that this happens.**

6-9: We stand by our conclusions and they they are logical inferences from the data. A combination of data (field measurements of flow, depth and chemistry) have been combined with observations to test hypotheses of flow and connectivity.

**Number: 9**
**What is the hillslope flume? It appears here for the first time do you men the streamflow flume at the catchmetn outlet?!**
Yes clarified.

**Page:15**
**Number:1**
**I think Fig1 is a point or plot scale**

As noted above we present this at hillslope scale

**No comment**

**No comment**

**No comment**

**Page:19**
**Number: 1**
**Typo**

Fixed.

**Number: 2**
**define in caption!**
Done.

**Number: 3**
**typo!**

Fixed.

**Number: 4**
**Group number ? define?!**
Done.

**Number: 5**
**NA? define**
All the above have been addressed for Table 1 and 2.

**No comment**

**No comment**

**Page:22**
**Number 1:**
We have addressed points 1-3 below in our revised description of Figure 1 in the text.

**1) I agree with your decision tree but in fact it results in one dominant runoff mechanisms and your paper shows that these processes co-exist in parallel in different**

**2) This view neglects the contributions form upslope or neighboring sites.**

**3) it is also not clear if you consider the hillslope-scale or the point-scale. Typically these schemes are used to characterize the point- or plot-scale.**

**4) in box #3: do you mean surface topography? Bedrock topography might be quite important (i.e. large storage to prevent still)**
We mean bedrock topography and in the text we reference Janzen and McDonnell who examined connectivity impacts of bedrock depressions.

**5) box #5 has no "NO" option!**

We have added a no option leading to “No runoff”

**Page:23**
**Number: 1**
**Can you destinguish the groundwater, streamflow, soil moisture, etc. sites with different symbols!**
A revised version of Figure 2 and its caption is provided.

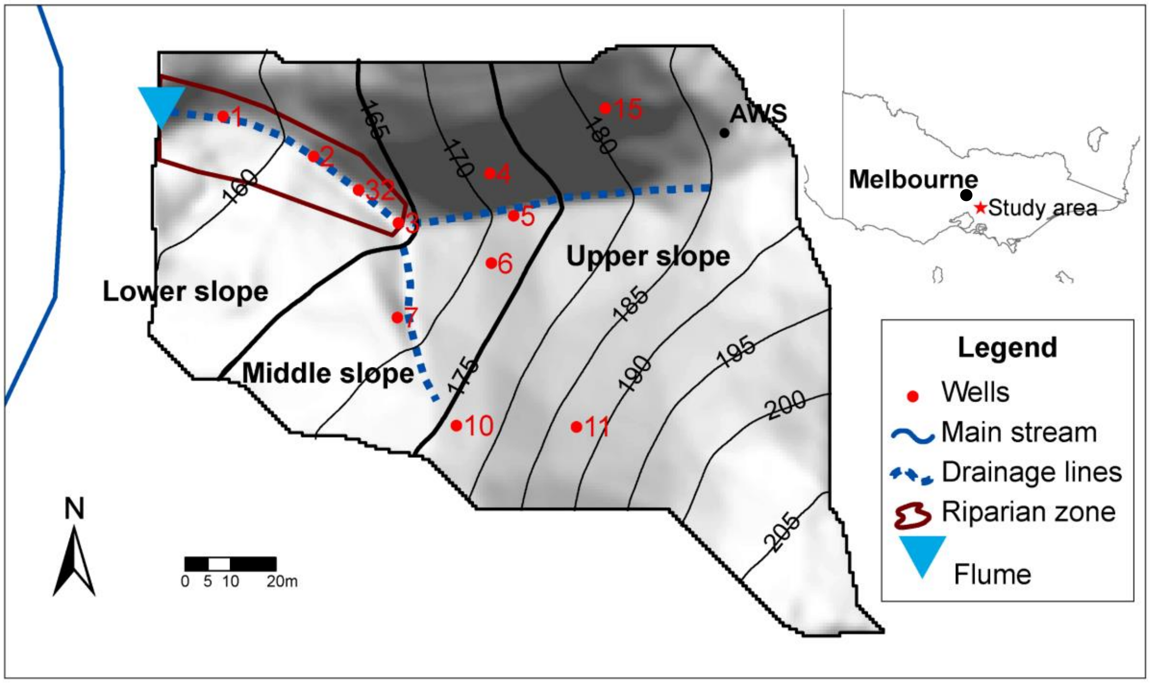



**Figure 2. The study site location within Australia and a hillshaded DEM, topography and sampling site locations at RBF. In this figure the black circles show shallow groundwater sites, the red circle shows soil moisture site and the blue triangle demonstrates the hillslope flume.**

**Page:24**

**Number: 1**

**important: Is this one site, n average over how many sites?**

Clarified that it is one site in the caption.

**Number: 2**

**please give full names in captions so that they can stand alone. This applies to all figures and tabes!**

The caption of Figure 3 is revised as:

Figure 3. (A) Weekly rainfall and APET (areal potential evapotranspiration) time series (data from automatic weather station (AWS), (B) soil water storage in top 60 cm of the soil profile and weekly runoff time series at RBF. The vertical bars show the timing of events in Figure 4.

**Page:25**

**Number: 1**

**why green?**

Now blue

**Number: 2**
**can you mark these events in Fig.3B!**
**and maybe make the rows of these events bold in table 1 and 2**

Done

**Number: 3**
**include info on the streamflow as well**

?It is graphed

**Number: 4**
**8 selected rainfall events (sorted by their Antecedent Soil moisture Index (ASI), riainfall shown in blue ...**

Figure 4 caption is now:

Figure 4. Characteristics of 8 selected rainfall-runoff events sorted by their antecedent soil moisture index (ASI). Rainfall is shown in blue. It should be noted that the axis scales vary between events. All events (except those on 26/11/2011 and 10/12/2011) had zero or very low initial discharge. For the events on 26/11/2011 and 10/12/2011, the initial discharges were 0.07 and 0.13 mm $hr^{-1}$, respectively. .

**Number: 5**
**make the reader aware, tha the y-axis scale differ between events.**

Done

**Page:26**
**Number: 1**
**is this cumulative ASI? (be specific)**

ASI is now clearly defined in the methods and in the caption

**Number: 2**
**please put (a) in to the upper left corner**

done

**Number: 3**
**Rainfall Intensity (I guess)?**

Yes, clarified in caption

**Number: 4**
**You are actually not showing thresholds in these figures**

Now shown

**Page:27**
**Number: 1**
**groundwater level ...**

Done

**Number: 2**
**... runoff (grey line) ...**

Done

**Page:28**
**Number: 1**
**You need to define "typical" and "high intensity" in the method section and in the captions**

Done (Ipeak>115mm/h)

**Number: 2**
**How did you calculate soil water storage? Average across the catchment? Please state int he method section.**
Now explained in detail in the methods and noted in the caption. It is storage in top 60cm at the AWS.

**Number: 3**
**Please be consistent with using your terms. I guess soil water storage is volumetric water content of the upper 60 cm of the soil profile), or can you define soil water storage in the method section.**
Now explained in methods

**Page:29**
**Number: 1**
**Important: Which events did you chose? Why not all events? Please give objective reasosn how you selected these events.**
This is now explained in the discussion of this figure.

# Multiple runoff processes and multiple thresholds control agricultural runoff generation

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**Abstract.** Thresholds and hydrologic connectivity associated with runoff processes is a critical concept for understanding catchment hydrologic response at the event timescale. To date, most attention has focused on single runoff response types and the role of multiple thresholds and flow path connectivities has not been made explicitly. Here we first summarise existing knowledge on the interplay between thresholds, connectivity and runoff processes at the hillslope-small catchment scale into a single figure and use it in examining 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 catchment 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. The rainfall, runoff and antecedent soil moisture data together with water levels at several shallow piezometers are used to identify runoff processes in the study site. We use isotope and major ion results to further support the findings of the hydrometric data. 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 index 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 hillslopes connected to the riparian area. The hillslopes 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, together with significant contributions of event water early (rising limb and peak) in the event hydrograph. Based on a combination of various hydrometric analyses and some isotope and major ion data, we conclude that event runoff at this site is typically a combination of subsurface event flow and saturation excess overland flow. However, during high intensity rainfall events, flashy catchment 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.

## 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).

In this paper we are interested in connectivity in terms of the movement of water from hillslopes to streams at the timescale of events and longer. We say there is connectivity along a flow pathway when water is moving along that pathway and contributing to stream flow from the catchment. 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;Fu et al., 2013;Penna et al., 2015). In this study we use the threshold concept to examine runoff generation mechanisms and to discuss how various mechanisms produce runoff and change in importance during the runoff season.

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). Moreover, the explicit linkage of runoff mechanisms and flow pathways has received less attention in agricultural landscapes compared with forested basins. An exception is the study of Ocampo et al. (2006). Ocampo et al. (2006) investigated hydrologic connectivity, the threshold dependency of connectivity and its influence on seasonal and event based runoff mechanisms in an agricultural catchment in Western Australia.

While the concept of connectivity has been useful in many of these studies, most 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. Only a small number studies have tried to tease apart the influence of multiple processes in catchments where infiltration excess runoff, saturation excess runoff and subsurface stormflow are all important (e,g, Lana-Renault et al., 2007;Lana-Renault et al., 2014;Latron and Gallart, 2008). These catchments are in Mediterranean environments and have typically been studied by field inspection of the catchment surface to identify infiltration excess runoff generation areas, field inspection of saturated areas to identify saturation excess source areas and also by examination of hydrographs in combination with groundwater wells. These studies associate certain controls with specific processes, such as past cultivation being associated with infiltration excess runoff (Lana-Renault et al., 2014). These studies have generally not considered rainfall intensity information at scales finer than daily. Despite the considerable improvement in our understanding of basic catchment functional mechanisms, today it is still challenging to apply our understanding of these specific case studies to other areas due to the problems of catchment heterogeneity, complexity, non-linearity of behaviour, scale, etc. (Beven, 2002).

To aid systematic consideration of the variation in runoff processes between catchments and over time, we develop a summary of the status quo in terms of the combined effects of thresholds and connectivity on runoff processes at the hillslope to zero-order catchment scale (Figure 1). Often we think of dominant runoff processes and, as Figure 1 is easiest to interpret in that context, the following discussion takes that view initially. However, there is often a mix of runoff processes either spatially due to heterogeneity or for different events and Figure 1 can also be used to interpret such a mixture, which we will return to later. This paper aims to tease apart the influence of different processes by considering 60 rainfall events (resulting in 38 runoff events) in a small agricultural catchment. We show the shifting importance of different processes over time associated with changes in catchment wetness and rainfall intensity and apply the runoff process framework. We consider the role of thresholds in different 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. The variety of potential thresholds leads to a variety of runoff processes, as illustrated in the following discussion.

Figure 1 shows the importance of various timescales, durations, fluxes and states, and how these relate to variation in rainfall-runoff processes over time (and between catchments with different physiographic characteristics). 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, 2006b;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), who used a generalised Damköhler number to represent the competing effects of transport and reaction timescales on the loss of material along a flow path. When the reaction timescale is small compared with the transport timescale, the reactant is consumed before reaching the exit of the flow path it is moving along. A complication here is that, 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 parts, the lefthand area provides a series of catchment thresholds that depend on hydroclimatic and landscape characteristics and influence the type of runoff process and the connectivity between the hillslope and stream, depending on whether they are exceeded or not. The middle area points to the outcome in terms of dominant runoff generation processes and the righthand area provides example catchments from the literature that exhibit those processes. In Figure 1 we define the specific runoff processes as follows.

- Infiltration excess runoff: runoff that occurs due to the rainfall (or throughfall) rate exceeding the infiltration capacity of the surface and that results in flows of water to the catchment outlet by surface flow pathways.
- Subsurface stormflow: runoff due to infiltration that generates rapid lateral subsurface flow (i.e. a quickflow response) that flows to the catchment outlet through subsurface flow paths for at least part the distance to the outlet. This water may exfiltrate in low convergent parts of the catchment or directly into the stream before reaching the catchment outlet. Often impeading layers and preferential flow paths are implicated.
- Saturation excess runoff: runoff due to rainfall on saturated areas that flows to the catchment outlet by surface flow pathways. The saturated area may be generated by either lateral flow in excess of the capacity of the hillslope to transmit the lateral flow, a drainage impediment at depth coupled with a sufficient excess of infiltration over evapotranspiration and drainage, or a combination of these.

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 process timescales and durations. 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. That impact typically involves lateral flow either on the surface or through the subsurface and hence also interactions up and downslope. Specific examples are given below.

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 down the hillslope toward the stream (runon infiltration) after the intensity reduces and very little or no runoff will reach the stream (surface connectivity did not 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. Thus the duration of high intensity rainfall compared with the overland flow timescale (flow distance divided by wave celerity) is important. The remaining boxes consider thresholds in the context of subsurface flow times. Box 3 considers situations where subsurface saturation exists, allowing water to flow along lateral subsurface flow paths. If any of deep infiltration through the impeding layer (Jackson et al., 2014), unfilled bedrock storage (Janzen and McDonnell, 2015) or evaptranspiration (including between events) causes the saturation and/or lateral flow to cease before water can move a significant distance downstream, the water will not be effectively redistributed downslope, subsurface connection will not be established. If the saturation persists for long enough for lateral subsurface flow to move down the hillslope and into the stream, connectivity between the hillslope and the stream will develop. Thus the ratio of the lateral flow timescale for the hillslope and the evaporative drying (or other loss) timescale is important here. At the other extreme (box 7), if lateral flow is persistently exceeding the subsurface flow capacity, surface saturation will exist leading to saturation excess runoff because saturated areas will exist antecedent to the event in this case. Provided continuous saturation exists to the sream, this will lead to a surface flow path connecting the hillslope and stream. In this case the lateral flow timescale is long enough to lead to memory in the spatial patterns between events (non-local control of Grayson et al (1997)).

Figure 1 goes about here

While Figure 1 suggests catchment rainfall-runoff response is dominated by specific processes (e.g. saturation excess runoff) it needs to be recognised that many catchment conditions vary over time and space. For example in our study catchment summer rainfall is often more intense than winter rainfall and this can lead to differences in runoff processes between events. Soil water conditions vary seasonally in response to both rainfall and potential evapotranspiration, sometimes leading to switching between characteristic spatial patterns of soil moisture 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.

Having introduced the framework above, we use it to understand the behaviour of a catchment in Australia that does indeed exhibit a mix of runoff processes. We examine how soil water storage and shallow water table response influence surface and 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. In the context of Figure 1, these results are used to examine various runoff generation mechanisms and flow pathways that are important in the study catchment and to determine how they contribute to produce the catchment runoff as the catchment wetness and rainfall intensity vary. Thus the contributions of this paper revolve around the introduction of the framework in Figure 1 and demonstration of its application using a catchment where multiple runoff processes are important. The paper also contributes to further understanding of the role of thresholds and connectivity in determining flow pathways and runoff processes in agricultural catchments. Most connectivity studies in the past have focussed on forested catchments.

## 2 Methods

### 2.1 Study location

The study site is a 1.37 ha catchment (named 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). The study area has a humid climate and rainfall is uniformly distributed across the year with an annual mean (1961-1990) of 1100 mm (Bureau of Meteorology, 2009). Annual areal potential evapotranspiration (1961-1990) is 1040mm (Bureau of Meteorology, 2005).

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, the topography, range of slopes and the groundwater behaviour, the catchment was divided into four different zones: 1) the riparian area located on the relatively flat convergent lower part of the catchment (outlined in red on Figure 2) included sites 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 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 between 1 and 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) that grade from a fine sandy clay loam to a medium clay with mottles and weathered bedrock. 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

Stream discharge was measured at the catchment outlet (Figure 2) using an RBC flume (Clemens et al., 1984) and an Odyssey (Dataflow Systems inc. Christchurch, NZ) pressure transducer (PT) recorded stream water levels every 10 minutes, which were used to compute instantaneous discharge rates. After August 2011, the PT was replaced with an ISCO (Teledyne ISCO , Lincoln,NE,USA), model 730 bubbler. The following rating curve was used to calculate $Q$ from water level:

$$Q = 0.001H^2 + 0.0168H \quad (3)$$

where $Q$ is stream flow discharge and $H$ is water head.

Rainfall data were recorded using a tipping-bucket raingauge at an automatic weather station (AWS) which was installed in 2010 on the upper boundary of RBF. Weather variables (temperature, humidity, wind, rainfall, global radiation) were measured by the AWS. 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. Soil moisture storage was calculated from the volumetric soil water content which was measured for the 0-30 cm and 30-60 cm layers and recorded hourly by the AWS logger using two vertically installed 30 cm long Campbell Scientific (CS625) soil moisture probes (Campbell Scientific, 2006). The 0-30cm probe was inserted from the surface. To install the 30-60cm probe, a 30cm deep hole was dug, with the excavated soil set aside. The probe was inserted vertically and then the excavated soil was repacked so that the soil was replaced at a similar depth to that from which it had been removed.

The CS625 produces a pulse signal and the pulse period was temperature corrected using measured soil temperature and the manufacturers recommended temperature correction, as follows (Campbell Scientific, 2006).

$$\tau_{corrected}(T_{soil}) = \tau_{uncorrected} + (20 - T_{soil}) * (0.526 - 0.052 * \tau_{uncorrected} + 0.00136 * \tau_{uncorrected}{}^{2}) \quad (1)$$

where $\tau_{uncorrectd}$ is the probe output period, $T_{soil}$ is the soil temperature and $\tau_{corrected}$ is the corrected probe output. The *VWC* was then computed from $\tau_{corrected}$ using (Campbell Scientific, 2006):

$$VWC = -0.0663 - 0.0063 * period + 0.0007 * period^{2} \quad (2)$$

Soil water storage over the top 60 cm soil depth was computed by adding the VWC from the 0-30 cm and 30-60 cm layers and then multiplying by the 300 mm soil depth. We use this soil water storage at the start of each rainfall event as an index of antecedent soil water (ASI) and assume it represents the catchment wetness condition.

To capture the nature of hydrologic connectivity, runoff mechanisms and flow pathways, shallow (1.5-1.6 m) groundwater wells were installed at 12 sites across the RBF catchment 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 until the end of study period in December 2011. Sites 3, 7, 16 and 32 were logged from winter 2011 until the end of study period in December 2011. Water level loggers were not installed at sites 1 and 2 since they were nearly always saturated. At sites 1 and 2 groundwater levels were measured manually. Water levels were logged using Odyssey PT loggers.

### 2.3 Water sampling and analysis

A rainfall sampler (Kennedy et al., 1979) collected up to ten sequential rainfall samples per event, 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 (December 2011).

An auto sampler (Teledyne ISCO 6712) was installed at the flume and streamflow sampling was triggered based on the rising stage. Following triggering, the sampler was programmed to collect up to 24 samples of streamflow at hourly intervals. Samples were removed from the auto sampler within 48 hours. To reduce the laboratory analysis workload, we plotted recorded water levels from the RBF catchment in the field prior to removing the event sample from the auto sampler and selected certain samples for analysis. All samples during the rising limb and the peak were selected 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. Routine grab sampling was also undertaken at weekly intervals during the main runoff season when water was flowing through the RBF flume.

Sub-samples for isotopic analysis 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$^{o}$C) until analysis for $\delta^{18}$O and $\delta^{2}$H. Stable isotope ratios were measured either at Monash University using a Finnigan MAT 252 and ThermoFinnigan Delta Advantage Plus mass spectrometers (2010 samples) or at the University of Melbourne, where a Picarro L2120i cavity ring-down isotope analyser was used to determine isotope ratios (2011 samples). The instrumental precision was δ18O = ±0.15‰ and δ2H = ±1‰ for the isotope samples analysed at the Monash University and it was $\delta^{18}$O=0.1‰ and $\delta^{2}$H =0.4‰ for samples analysed at the Melbourne University. The results from the isotope analysers were checked for systematic differences, by analysing duplicate samples in both laboratories. We developed and applied a correction between the two laboratories based on these samples. With the exception of determining pre-event end member uncertainty (described later), the analyses presented here only use samples analysed at the Monash laboratory and hence this difference between laboratories only affects our hydrograph separation uncertainty estimates. For isotope analysis, in total we collected 115 samples of rainfall, 28 samples during low flows and multiple stream water samples of isotopes from five events.

For the measurement of major ions, subsamples of grab and event streamflow samples were collected using 50 ml plastic bottles. 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 the Monash University using standard methods. Major ions were determined in non-filtered samples as follows (Cm is ion concentration):

- $Mg^{2+}$ was determined by atomic absorption spectrometry (APHA, 2005). The issue of interference with Si, Al, and P was solved using a combination of Lanthanum and Caesium. The determined uncertainty for $Mg^{2+}$ was Cm* 0.0596, with 95% confidence interval (CI).
- $Ca^{2+}$ was analysed using atomic absorption spectrometry utilising an air/acetylene flame based on the American Public Health Association procedure (APHA, 2005). The issue of interferences with Si, Al, and P was solved using Lanthanum releasing agents. The determined uncertainty for $Ca^{2+}$ was Cm* 0.0386 (95% CI).
- Following APHA (2005) approach, "flame atomic absorption spectrometry" was used to determine $K^{+}$ concentration and Caesium was used to solve the issue of ionization. Uncertainty for $K^{+}$ was Cm* 0.0372 (95% CI).
- $Na^{+}$ which is "ionized in the air/acetylene flame" was analysed by adding Caesium to overcome this problem following the APHA (2005) method. Uncertainty in $Na^{+}$ results was Cm * 0.0432 (95% CI).
- $Cl^{-}$ was analysed by colourimetrically method "using flow injection analysis (FIA)" (APHA, 2005). Uncertainty in $Cl^{-}$ analysis laboratory results was Cm * 0.05 (95% CI).

### 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 (in the study period which was between April 2010 and December 2011), 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 stream discharge 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 discharge 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 index (*ASI*) was represented as the amount of the soil water storage in the top 60 cm of the profile at the AWS at the start of each rainfall event. The topography of the catchment was surveyed using a differential Global Positioning System (dGPS) and a 1 m horizontal resolution DEM (digital elevation model) was developed by interpolation methods. Instrument and well locations were also determined using dGPS. Then these data were used to produce maps of the study area and including sampling sites using Arc GIS. The lateral boundary of the saturated area was topographically constrained and field inspections suggested it was stable over time, while the upstream boundary moved up and down the riparian zone. The saturated area was estimated by locating the upper boundary through field inspection and then measuring the distance from either well 2 or 3 (The saturated area extended towards site 3 during very wet conditions). Figure 2 demonstrates the approximate maximum boundary location of the saturated area at site 3 and the main stream located close to the outlet of the catchment. The saturated area was then estimated from this information combined with the mapping of the riparian zone boundary in ArcGIS. These measurements were made between events. The proportion of saturated area was estimated using these data and then used to estimate saturation excess runoff generation for the different events. Consistent with our definitions in Figure 1, here we conceptually separate return flow and flow resulting from direct precipitation on the saturated area and use Saturation Excess Runoff 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. While this method, like other hydrograph based baseflow separateion methods, is arbitrary, the results are insensitive to the assumed rate of rise.

### 2.5 Isotopic Hydrograph Separation

Isotope samples are used for hydrograph separation into pre-event and event contributions. We applied the well- known one tracer, two component model of hydrograph separation approach (Pinder and Jones, 1969; Sklash and Farvolden, 1979). We determined uncertainties following Genereux (1998). We undertook the analysis using both the $^2H$ and $^{18}O$ data. We used the mean of the rainfall samples during the event to estimate the event water end member and low flow samples from the few days to the event for the pre-event end member. In the uncertainty analysis, the standard deviations of the event rainfall samples and of all the low flow samples across the study period were used. Half the analytic uncertainty was used to represent the standard deviation of the streamflow sample.

## 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 catchment 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 catchment 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 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 at the seasonal scale in Figure 3, there are exceptions at the event scale. For example in February 2011, there was 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 stream discharge 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. All events (except events on 26/11/2011 and 10/12/2011(Figure 4c)) presented in Figure 4 had zero or very low initial flow. For the events on the 26/11/2011 and 10/12/2011, the initial discharge was 0.07 and 0.13 mm hr$^{-1}$, respectively.

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 8/12/2010 (Figure 4b), which did not produce any significant 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 (30.4mm/ and 31mm/h respectively) during the study period and they occurred at the end of the flow season with low *ASI* (*ASI* was 161 and 192 mm respectively). 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 (26/11/11, 11/5/11, 8/11/11, 1/8/10, 7/6/11) 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 discharge hydrograph with continued flow following the event. This also occurred for the next event on 1/8/2010.

### 3.2 Runoff 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), who considered thresholds in *ASI* and *ASI*+Rain (i.e. Figure 5c and d), and Janzen and McDonnell (2015), who considered the impact of event rainfall and rainfall intensity on event runoff (i.e. Figure 5a). As we move from Figure 5a to 5d, the various influences on rainfall-runoff behaviour and thresholds become clearer. Figure 5a shows event runoff as a function of event rainfall, with the highest hourly rainfall intensity ($I_{peak}$) indicated in colour. This illustrates that there is little relationship between event rainfall and runoff or between rainfall intensity and runoff. For some quite large events (up to ~25mm), zero runoff can occur. There was also 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. Overall, Figure 5a shows that event rainfall and intensity do not effectively differentiate rainfall-runoff behaviour when considered by themselves.

Figure 5 goes about here

Figure 5b begins to separate out different effects by showing the impact of five factors together. The cumulative curve shows the distribution of soil water storage as observed throughout the study period. Specific events are shown with the *ASI* identified (left hand end of the grey lines) and the *ASI*+Rain depth (filled markers at the right end of the horizontal grey lines). The length of the lines is the rainfall depth for the event. The colour of each bubble shows the peak hourly rainfall intensity ($I_{peak}$) and the size of the bubbles shows the event runoff coefficient. Squares indicate events that did not produce any runoff or where the peak runoff rate was less than 0.05 mm hr$^{-1}$. The vertical grey dashed line shows *ASI* (left hand end of horizontal grey line) or *ASI*+Rain=250mm (right hand end of horizontal grey line).

There are several trends that can be discerned from Figure 5b. First the rainfall events analysed here occurred across the full range of catchment wetness and were relatively evenly spread, showing that the rainfall events occur over a representative range of catchment antecedent conditions. The larger rainfall events generally occurred in summer when *ASI*<250 mm and a mix of low and high intensity events occurred for these conditions, also in summer. All the events on a wet catchment (*ASI*>250 mm) had low $I_{peak}$ (≤6.2 mm hr$^{-1}$). Events where the *ASI*+Rain was less than 250mm usually did not generate any runoff, although there were some high intensity rainfall events that were exceptions and a small number of events with very low runoff coefficients (1-4%) where the *ASI*+Rain was generally between 230 and 250mm. These low runoff coefficient events were at the end of the runoff season.

Figures 5c and 5d examine the impact of catchment wetness, quantified as *ASI* and *ASI*+Rain respectively, at the start (5c) and end (5d) of the event on event runoff response, combined with the impact of rainfall intensity, $I_{peak}$. Catchment wetness is plotted on the x-axis and rainfall intensity on the y-axis. Values *ASI*=250mm (Fig 5c), *ASI*+Rain =250mm (Fig 5d) and $I_{peak}$=15mm/h are shown by grey dashed lines. The bubble size shows the event runoff coefficient, as before, and crosses indicate rainfall events that did not generate any runoff. Colour indicates the runoff volume. The runoff coefficient behaviour is separated into groups more clearly in Figure 5d than in 5c. In Figure 5d, three different groups of events can be identified. Looking along the x-axis, there is a threshold at *ASI*+Rain=250mm that separates most events with a significant runoff response from those without. Looking along the y-axis direction, it can be seen that the *ASI*+Rain threshold is not successful at distinguishing runoff when $I_{peak}$ is high and there is also a threshold in runoff response at $I_{peak}$ =15mm/h. Thus the three groups are: 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 *ASI*+Rain exceeded 250 mm (group 2), some runoff was always produced.

Both of the first and third groups had *ASI*+Rain 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. It is assumed that rainfall completely infiltrated into the soil and these events did not produce runoff (see Table 2 for event characteristics).

The third group (Table 1) occurred during dry periods at the end of the flow season when the *ASI* was < 200 mm. The runoff coefficients for the four events with peak hourly intensity of 15 mm hr$^{-1}$ and higher are 3, 12, 20 and 68% for peak hourly intensities of 16, 30, 15 and 31 mm hr$^{-1}$ and *ASI*+Rain of 202, 215, 257 and 245 mm respectively. Note that one of these events exceeds both the wetness and intensity thresholds. 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 happened at the same time as the highest recorded rainfall intensities. Antecedent stream discharge 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 53 mm, with an initial discharge 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 the runoff coefficient calculated for the first 2 hours of the rainfall event was 18%. . The RC calculated for the duration this event was 68%. These are large compared with the maximum surface saturated extent throughout the study period of about 6% of the catchment area, indicating processes other than saturation excess runoff are important. 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 flow measurement equipment being removed after this event, it was the last recorded at RBF.

Table 3 provides a summary of the average conditions for each group of events. In terms of rainfall characteristics, the events that produced runoff (groups 2 and 3) tended to have higher total rainfall, with the highest intensity events also having the largest total rainfall. Of course the grouping criteria means larger groups are more likely to fall into group 2 compared with group 1. Peak rainfall intensities were both low and almost identical for groups 1 and 2. The runoff behaviour is quite different with almost no flow and very low runoff coefficients on average for group 1 and average runoff coefficients of 17.9 and 25.8 for groups 2 and 3 respectively. These runoff coefficients are clearly much higher than the observed maximum saturated area proportion (6%).

We also undertook a bootstrap analysis to test for differences between the group means. This showed that groups 2 and 3 are statistically different from group 1 at the 1% significant level for total event runoff, quick flow and the quickflow runoff coefficient. Groups 1 and 2 (which are distinguished by *ASI*+Rain) are statistically similar in terms of $I_{peak}$, suggesting rainfall intensity does not explain the runoff response differences between these two groups. Groups 1 and 3 (which are distinguished by $I_{peak}$) are statistically similar in terms of *ASI*+Rain, suggesting that catchment wetness does not explain the runoff response differences between these two groups.

Overall these results demonstrate a range of different rainfall runoff responses. The responses depended on both the catchment wetness as quantified by *ASI*+Rain and on the peak hourly rainfall intensity, $I_{peak}$ , with thresholds of 250mm and 15mm/h being identified. Runoff was produced whenever thresholds in either of these were exceeded.

### 3.3 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. It should be noted that there is some uncertainty in the $I_{peak}$ threshold as the most intense event (for *ASI*+Rain<250mm) that failed to produce runoff was 10mm/h, while the least intense event that did produce runoff was 14.8mm/h. 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. In fact, runoff and non-runoff producing events are very well separated by the relationship $I_{peak}$ = 3/11*(*ASI*-260). These results suggest that there are both wetness dependent and intensity dependent runoff production mechanisms operating. This section examines the evidence for different runoff mechanisms contributing to event runoff.

### 3.3.1 Catchment wetness-flow response relationhips

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. In Figure 6, the sites are ordered by elevation from highest to lowest in the catchment. Manually read sites are shown with dashed lines. Figure 6 clearly shows that the water table became shallower and that the occurrence of profile saturation (water table at the surface) was restricted to the riparian zone. Within the riparian zone, sites 1, 2 were saturated much of the time and site 32 quickly became saturated during events. The water table remained below the surface at sites 3 (at the upstream end of the riparian area), 4 and 5 (in Mid slope positions). 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 data recorded at 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 discharge record in Figure 6a, 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 deep. 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 6b).

So far we have examined thresholds in catchment wetness (*ASI*+Rain) associated with a change in runoff behaviour and the linkage between shallow water tables and catchment response. It is probable that the linkage between catchment wetness and runoff is through the intermediary of shallow subsurface flow controlled by the existence of saturated conditions within a permeable part of the soil horizon. Figure 7 shows the relationship between water table levels in the catchment (sites 4 and 5) and soil water storage at the weather station. These sites represent planar and convergent mid slope positions respectively. These sites were chosen because they show significant dynamics and we had logged records available. Other sites with loggers had limited dynamics or short records. Site 5 in particular shows a rapid change in behaviour for soil water storage around 250 mm, which corresponds with the *ASI*+Rain threshold identified above. As soil water storage moves above this level, much higher water tables develop and those water tables showed relatively rapid recession when shallower than 120 cm. Similar observations were seen at site 4 but the corresponding depth was 140 cm. Figure 7 thus explains the linkage between the 250mm *ASI*+Rain threshold and runoff. When soil water storage exceeded this level, water tables rose and lateral subsurface drainage occurred, as evidenced by the recessions. The recessions in particular suggest that the water table moved into a more permeable zone on these occasions. This is consistent with soil profiles being characterised by mottled clay at depth which is likely to have lower hydraulic conductivity. This behaviour at these two wells in combination with the soil water and flow data, indicate that the hillslopes were becoming connected to the catchment outlet via subsurface flow from the hillslope to the riparian zone. Our analysis of isotope data below will add to the evidence for this. There were a few occasions where the water table responded strongly for soil water storage less than 250 mm (Figure 7). As indicated by the red colour, these corresponded to high intensity ($I_{peak}$>15mm/h) rainfall events.

Figure 7 goes about here

Flow recessions provide information on the drainage characteristics of catchments. Figure 6 shows that the catchment flow usually ceased between events during the wet period, with no flow during dry periods. However, in August and early September 2010, continuous catchment flow endured for a month (Figure 6). There was also a marked variation in the recession behaviour during August/September 2010 and at other times during the study period. To explore this, we calculated the recession constant, $k$ (as in $Q = Q_0 e^{-kt}$ , where $Q_t$ is discharge at time $t$ during the recession period, $Q_0$ is the discharge at the beginning of the recession and $k$ is the recession constant). In fitting recessions, we target the period after the recession of the event flow, which typically ceased around 24 hours after the end of the rainfall event. This was judged visually by a marked change in slope of the recession hydrograph plotted in semi-log space. Recessions were only fitted where a long enough period of reliable flow data (>=24 hours) were available. Data availability was sometimes limited by the commencement of another event or flow falling to very low (<0.05mm/h). $k$ is plotted against soil water storage at the start of the catchment flow recession for individual events (Figure 8). In total we could estimate values of $k$ for 20 events. The three events in Figure 8 coloured blue were from November 2011 from a relatively dry period in late spring when there was a drying trend but where flow from the riparian area was just persisting. These were excluded from the fitting because, in our judgement, they appear to represent different behaviour. $k$ for each event and the soil water storage at the start of the recession limb of was negatively correlated ($R^2$=0.64) (Figure 8). $k$ decreased as soil water storage increased at a rate of about 0.1$d^{-1}$ for each 10mm increase in soil water storage. 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 suggests greater (perhaps more spatially extensive) subsurface connectivity is providing flows from the hillslope and maintaining catchment flow during wetter conditions.

Figure 8 goes about here

3.3.2 Isotope and major ion results

The hydrometric results presented in Figures 6, 7 and 8 suggest that subsurface flow is important in this catchment. Given this, we would expect the hydrograph to be dominated by "old" or pre-event water; however, the saturated area in the lowest parts of the catchment would also be expected to produce direct flows of "new" or event water. This is addressed here using isotope data. We faced some constraints in obtaining meaningful hydrograph separation results. Of the five events sampled, two events were missing rainfall samples, which prevented their analysis. For another two events the rainfall isotope signature was quite close to the typical low flow signature. Uncertainty estimates showed standard deviations for pre-event and event fractions being over 50% for these two events, therefore these events were also excluded. For the event on 12 August 2010, the standard deviations were approximately 12% and 9% for $^{18}$O and $^{2}$H respectively, which we judged to be acceptable.

Figure 9 shows the 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. We used a pre-event low-flow sample from ~2days before the analysed event as the pre-event end member. We estimated the contribution at the time of each stream water sample. Over the study period $\delta^{2}$H ($\delta^{18}$O) for rainfall varied between -7‰ and -83‰ (-1.4‰ and 12.6‰) and isotopic concentrations for low flows were highly damped. Low flow samples from the RBF flume before and after the event showed a $\delta^{2}$H ($\delta^{18}$O) of -27‰ (-4.1‰) and rainfall for this event was strongly depleted (3 samples prior to and during the event $\delta^{2}$H = -42, -67 and -57‰, $\delta^{18}$O = -6.5, -9.8 and -8.2‰), compared with low flow. The runoff samples showed a very different isotopic concentration during the rising limb and the peak of the hydrograph ($\delta^{2}$H =-43‰, $\delta^{18}$O = -6.8‰) in comparison to antecedent low flow. This shows that the isotopic concentration moves significantly towards the rainfall sample concentrations. To estimate the overall event water contribution we first separated the hydrograph at each sampling time and then interpolated the fraction of event water between stream water sampling times and combined this with the discharge hydrograph to calculate the overall volume of event water. This analysis suggests that the percentage of rain becoming runoff based on $\delta^{2}$H and $\delta^{18}$O is 4.4% (3.4-5.4%) and 3.6% (3.0-4.2%), respectively. The figures in the brackets are 95% confidence intervals for uncertainty based on the hydrograph separation uncertainty only. These results suggest that precipitation on the saturated area generates direct runoff in amounts that are close to what would be expected (i.e. 100% runoff) 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 discharge 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 variation in chloride concentration with flow (Figure 10a). Similar plots are shown for Sodium, Magnesium, Calcium and Potassium in the supplementary material Figure S1. Sodium and Magnesium show similar behaviour to Chloride. Potassium also shows somewhat anomalous behaviour but with anomalously high concentrations. The relationship between discharge and $K^+$ is also different to $Cl^-$, $Na^+$ and $Mg^{2+}$ in that concentrations increase slightly as discharge increase above about 0.2mm/mm, rather than a decline. Calcium does not show anomalous behaviour.

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. Up until the end of the first flow peak (i.e. 0600), there had been 23.4mm of rainfall and 1 mm of runoff. This runoff volume is 4.3% of the rainfall volume, which is similar to the proportion of event water that became runoff for the 12 August 2010 event discussed above.

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 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 with only a small variation (see table 1) over the winter-spring season but reduces over the dry summer-autumn period. The extent of the saturated area at the riparian zone varied seasonally and between events. Field observations of surface saturation extending to the flume and well hydrograph measurements of the water table at the surface showed that the saturated area was highly connected to the catchment outlet and suggest that it would be expected to produce saturation excess runoff. This surface connection disappeared during the dry summer season when the water level in all wells fell below the surface (see Figure 6), so that the saturated area in the riparian zone disappeared. The isotope results for 12 August 2010 enabled the event runoff to be separated into event water and pre-event water contributions. Four to five percent of the rainfall volume on the catchment appeared in the event runoff, which corresponds well to the proportion of surface saturated area in the catchment (5.5%, Table 1), supporting the identification of significant saturation excess runoff from this part of the catchment, as observed elsewhere (McGlynn and McDonnell, 2003;Penna et al., 2016).

While saturation excess runoff undoubtedly occurs, many of the event runoff coefficients were well in excess of 5% and they approach 100% under very wet conditions (Figure 5). The event on 12 August showed a substantial pre-event water contribution; logged shallow wells show that the water table did not reach the surface in the steeper areas of the catchment, even within the convergent drainage lines under very wet conditions (e.g. sites 5, 7). The recession behaviour of wells in the catchment suggests subsurface flow moves down the catchment under wet conditions and the recession constant analysis shows that this connection becomes stronger as the catchment wets beyond 250 mm of stored water. This is all consistent with a substantial contribution of subsurface flow to event runoff once the catchment is sufficiently wet to establish subsurface connection with 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 storage (*ASI*+Rain < 250 mm) but high rainfall intensity. This suggests that 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. It is worth noting that the 15mm/h threshold will be dependent on the time step used in calculating the intensity. The choice of time step needs to consider the travel time from hillslope to stream as runon infiltration processes occurring on the catchment surface will impact on the connectivity to the stream. Thus the most appropriate time to use for averaging intensity would be the average travel time to the stream because it is this time period which is available to infiltrate rainfall that has become runoff at the point scale. Here the choice of hourly rainfall was pragmatic as that was the recording time step of the AWS but it is also likely that it reasonably approximates the flow times.

It is tempting to assume that this evidence suggested surface runoff occurred 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. For these events there were also rapid responses in water levels in wells on the hillslope and 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. Furthermore for the high intensity event on 8 November 2011, 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.

The hydrograph from the event on 8/11/11 (the event that exceeded both thresholds, Figure 10) shows both a rapid 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 available). This may suggest limited contact with the catchment soils which could occur if macropore flow was important but this explanation is not definitive. Of the two events with peak hourly intensities around 15 mm $hr^{-1}$, one also exceeded the wetness (*ASI*+Rain) 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 rainfall 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 relating runoff behaviour with catchment wetness thresholds, together with the data from shallow wells suggests a catchment where subsurface flow leads to a seasonally saturated riparian area that produces saturation excess runoff in immediate response to rainfall. This saturation excess is augmented by subsurface stormflow when the catchment wetness (*ASI*+Rain) exceeds a 250 mm threshold. This subsurface flow exfiltrates in the riparian area. Volume considerations provide evidence that, for many of the monitored events, water must be coming from outside the riparian area. This area is only about 5% of the catchment but quickflow runoff coefficients very regularly exceed this, often (about 1/3 of runoff events) exceeded 20%, and on occasion exceeded 50%. The role of both saturation excess runoff and subsurface stormflow is corroborated to some extend by isotopic data from one event where the hydrograph separation shows a volume of event water similar to the volume of rainfall on the saturated area and by the highly damped isotopic signal in the stream in general. 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. One of the key contributions of this work is clear hydrometric evidence of the interplay of both wetness and intensity dependent runoff processes in the one catchment. These responses include two wetness dependent processes: saturation excess runoff and subsurface stormflow, and an intensity dependent processes for which we can't distinguish between surface and subsurface flow pathways with our data.

**4.2 Thresholds and connectivity in runoff production**

We identified two important thresholds in the catchment response. The first is a wetness threshold of *ASI*+Rain 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). Based on the volume of event runoff (Table 1), the lack of surface saturation on the hillslope and the behaviour of shallow wells (Figure 6), we infer that the hillslope becomes connected to the riparian zone under these conditions. The existence of a large volume of pre-event water in the event on 12 August 2010 (Figure 8) adds further corroboration to this. 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 relationship between a threshold of 316 mm for *ASI*+Rain and the start of the event streamflow response. They showed that the *ASI*+Rain threshold corresponded with a water table height threshold. Based on this, they suggested that subsurface flow, transmissivity feedback and preferential flow from hillslope to stream could be used to explain runoff mechanisms in their catchment. They did not observe either Hortonian overland flow or SOF even during the largest events.

A second threshold to initiate event streamflow response 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 catchment. Mixed wetness and intensity dependent runoff processes have also been reported in Mediterranean catchments (e.g. Lana-Renault et. al 2014). Nevertheless there are only a few 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 rainfall 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*+Rain 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 segments of the catchment, the subsurface flow capacity is sufficient so 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. The shallow well data (Figure 6, wells 1 and 2, to some extent 32) shows that the riparian area in the lower part of the catchment drains very slowly. There is a substantial reduction in slopes (and probably lower hydraulic conductivity associated with poorly structured, poorly drained soils) that suggests a substantial reduction in lateral subsurface flow capacity. The surface topography also suggests subsurface flow would converge in this area. From the perspective of Figure 1, this leads to a situation where water is taking longer than the typical time between events in the wet season to drain (box 7, “Yes”), resulting in persistent surface saturation and saturation excess runoff generation 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 catchment 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 flume at the catchment outlet.

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 antecedent soil water storage (ASI) plus event rainfall depth 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. *ASI* is the Antecedent Soil moisture Index. RC is the quickflow runoff coefficient. Runoff event grouping is discussed in section 3.2.**

| Group No. | Date | Rain duration (hr) | Total rainfall depth (mm) | Peak hourly rainfall intensity (mm/hr) | *ASI* (mm) | *ASI*+ rainfall depth (mm) | Runoff duration (hr) | Total runoff depth (mm) | Event runoff depth (mm) | RC (%) | Saturated 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 |

Group 2 has *ASI*+Rain>250mm, Group 3 has $I_{peak}$>15mm/h. "na" stands for "not available".

**Table 1. cont Rainfall-runoff events summary at RBF. ASI is the Antecedent Soil moisture Index. RC is the quickflow runoff coefficient. Runoff event grouping is discussed in section 3.2.**

| Group No. | Date | Rain duration (hr) | Total rainfall depth (mm) | Peak hourly rainfall intensity | *ASI* (mm) | *ASI*+ rainfall depth (mm) | Runoff duration (hr) | Total runoff depth (mm) | Event runoff depth (mm) | Runoff Coefficient (%) | Saturated 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** |

Group 2 has *ASI*+Rain>250mm, Group 3 has $I_{peak}$>15mm/h. "na" stands for "not available".

**Table 2. Rainfall events summary at RBF with no runoff (Group 1 events).** ***ASI* is the Antecedent Soil moisture Index.**

| Date | Rain duration (hr) | Total rainfall depth (mm) | Peak hourly rainfall intensity (mm/hr) | *ASI* (mm) | *ASI*+ rainfall depth (mm) | Runoff duration (hr) | Total runoff depth (mm) |
|---|---|---|---|---|---|---|---|
| 12/10/10 | 5 | 5 | 3 | 227 | 232 | 0 | 0 |
| 12/10/2010 | 5 | 5 | 2.6 | 227 | 232 | 0 | 0 |
| 12/11/2010 | 32 | 28.2 | 4.0 | 184 | 212 | 0 | 0 |
| 25/11/2010 | 17 | 13 | 3.6 | 157 | 170 | 0 | 0 |
| 2/12/2010 | 8 | 7.2 | 2.0 | 191 | 198 | 0 | 0 |
| **8/12/2010** | **11** | **19.2** | **7.8** | **175** | **194** | **0** | **0** |
| 9/12/2010 | 6 | 5.2 | 2.4 | 193 | 198 | 0 | 0 |
| 17/12/2010 | 21 | 15 | 2.4 | 181 | 196 | 0 | 0 |
| 10/01/2011 | 18 | 10 | 3.2 | 146 | 156 | 0 | 0 |
| 11/01/2011 | 26 | 10.4 | 2.4 | 152 | 162 | 0 | 0 |
| 13/01/2011 | 26 | 22.2 | 9.0 | 151 | 173 | 0 | 0 |
| 25/01/2011 | 9 | 5.4 | 1.6 | 147 | 152 | 0 | 0 |
| 5/02/2011 | 12 | 8.6 | 1.6 | 182 | 191 | 0 | 0 |
| 16/02/2011 | 20 | 14.8 | 9.6 | 167 | 182 | 0 | 0 |
| 26/02/2011 | 13 | 13.4 | 4.2 | 174 | 187 | 0 | 0 |
| 21/04/2011 | 28 | 8.4 | 2.6 | 213 | 221 | 0 | 0 |
| 1/05/2011 | 8 | 10.8 | 2.6 | 207 | 218 | 0 | 0 |
| 8/05/2011 | 14 | 7.2 | 4.8 | 215 | 222 | 0 | 0 |
| 5/06/2011 | 18 | 9.4 | 3.0 | 238 | 247 | 0 | 0 |
| 9/09/2011 | 22 | 12.8 | 3.0 | 221 | 234 | 0 | 0 |
| 19/09/2011 | 18 | 12.2 | 4.0 | 218 | 230 | 0 | 0 |
| 24/10/2011 | 12 | 15.6 | 4.2 | 211 | 227 | 0 | 0 |

**Table 2. Average characteristics for each event group. *ASI* is Antecedent Soil moisture Index.**

| Group and Criteria | Event rainfall (mm) | $I_{peak}$ (mm/h) | *ASI* (mm) | *ASI*+Rain (mm) | Total runoff (mm) | Quickflow (mm) | Quickflow Runoff Coefficient (%) |
|---|---|---|---|---|---|---|---|
| 1: ASI+Rain<=250 and $I_{peak}$<15 | 14.0 | 4.3 | 194.1 | 208.0 | 0.2 | 0.1 | 0.4 |
| 2: ASI+Rain>250 | 24.1 | 4.6 | 250.0 | 274.2 | 10.6 | 4.5 | 17.9 |
| 3: $I_{peak}$>=15 | 53.4 | 23.2 | 176.3 | 229.5 | 15.3 | 12.8 | 25.8 |

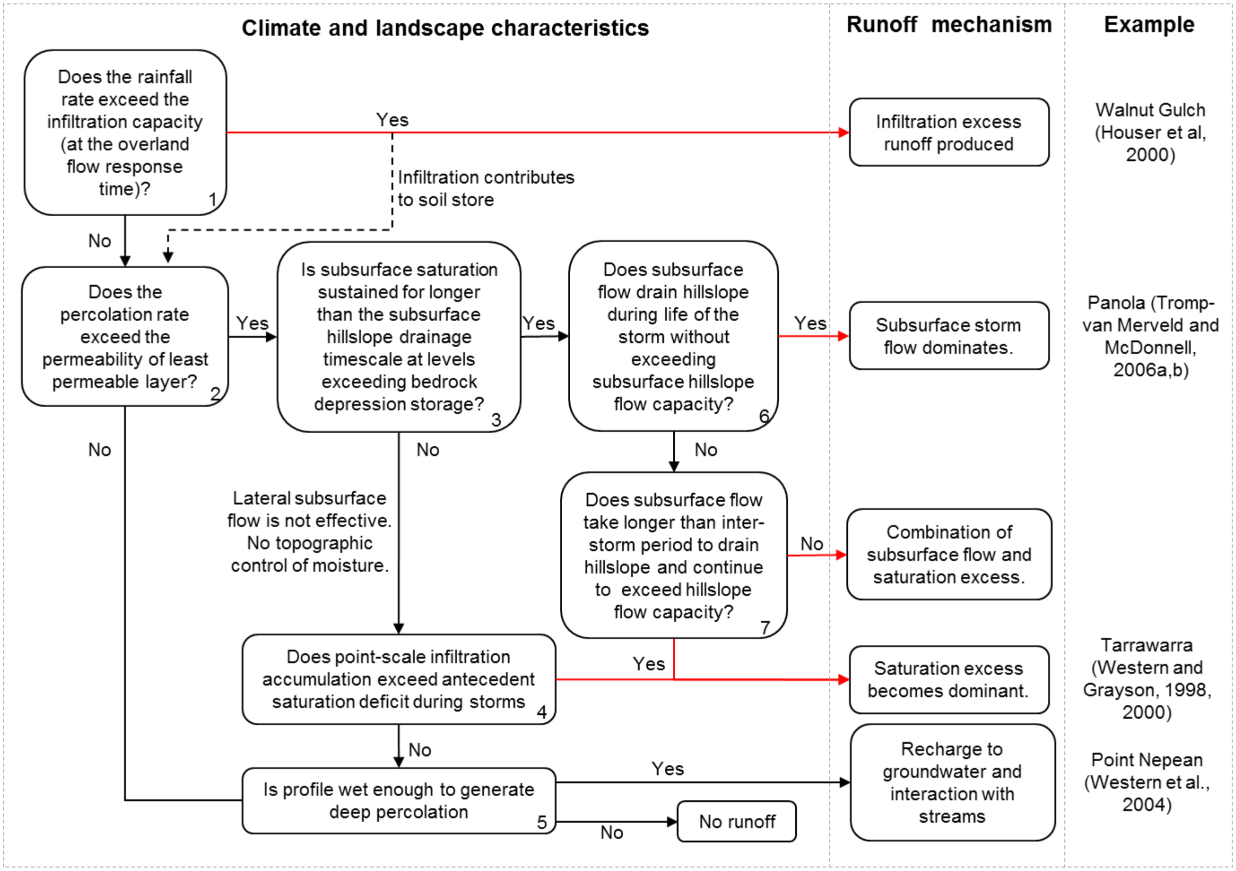


**Figure 1: The role of flux and timescale thresholds in determining runoff processes**. **The red lines indicate cases where there is surface or subsurface hillslope connectivity to the stream.**

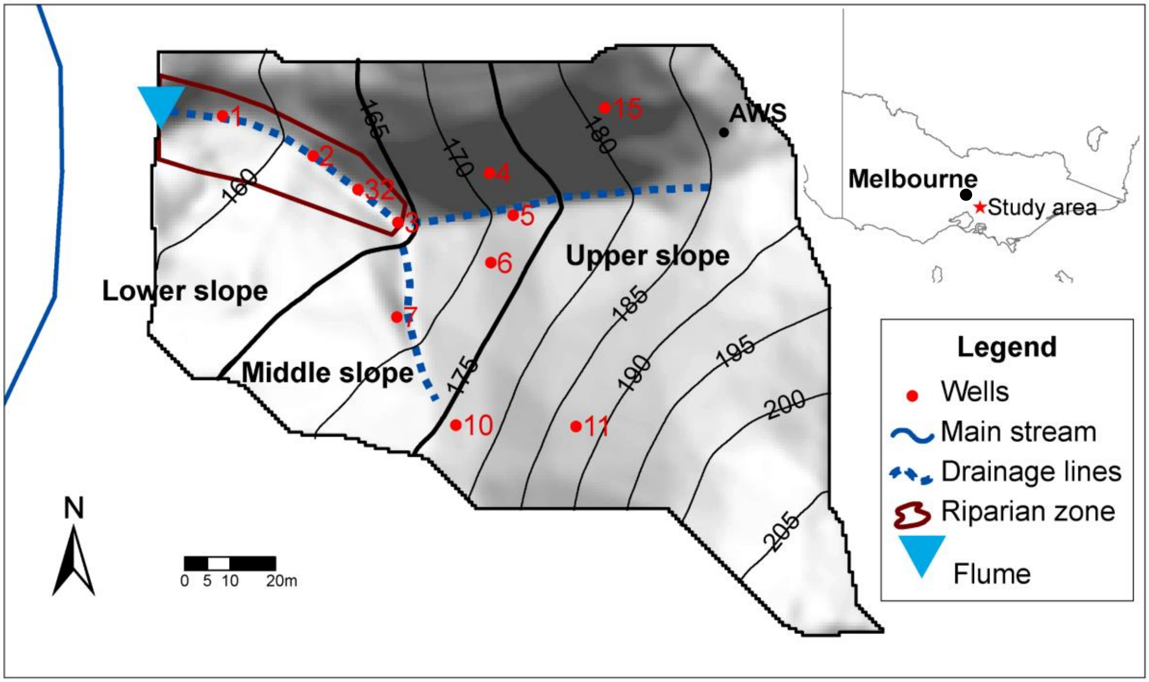


**Figure 2. The study site location within Australia and a hill shaded DEM, topography and sampling site locations at RBF. In this figure the black circles show shallow groundwater sites, the red circle shows soil moisture site and the blue triangle demonstrates the catchment flume.**

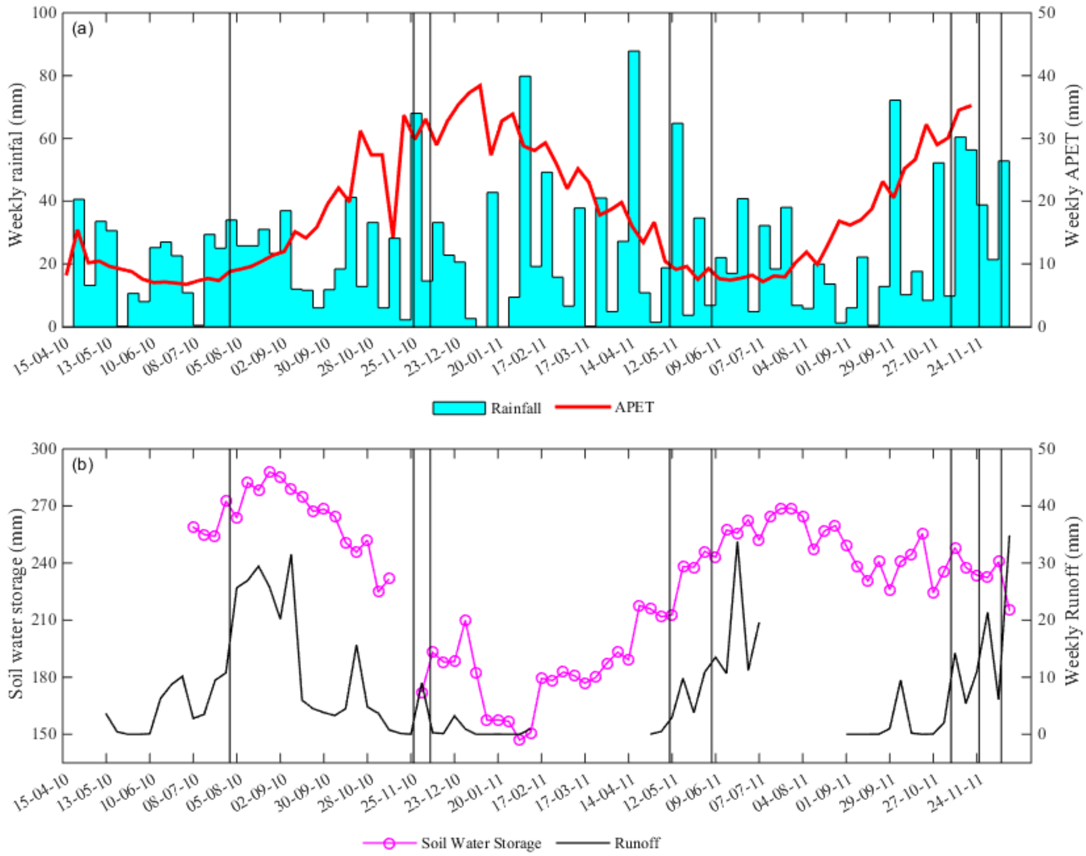


**Figure 3. (a) Weekly rainfall and APET (areal potential evapotranspiration) time series, (b) soil water storage in top 60 cm of the soil profile and weekly runoff time series for the flume at the catchment outlet. The rainfall, areal potential evapotranspiration and volumetric soil moisture, used to calculate soil moisture storage were all recorded at the AWS (automatic weather station) (Figure 1). The vertical bars show the timing of events in Figure 4.**

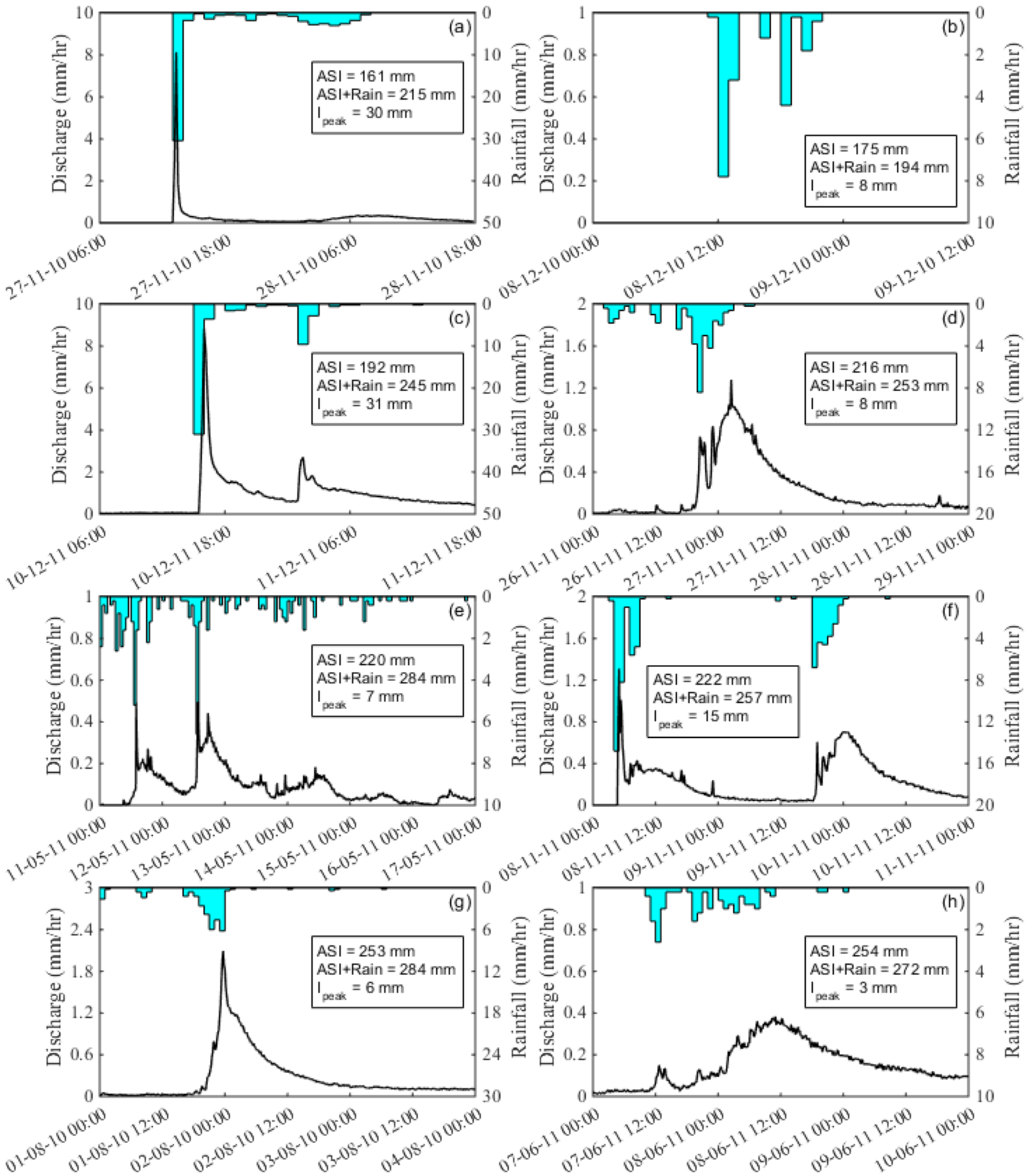


**Figure 4.** Characteristics of 8 selected rainfall-runoff events sorted by their antecedent soil moisture index (*ASI*). Rainfall is shown in blue. It should be noted that the axis scales vary between events. All events (except those on 26/11/2011 and 10/12/2011) had zero or very low initial discharge. For the events on 26/11/2011 and 10/12/2011, the initial discharges were 0.07 and 0.13 mm $hr^{-1}$, respectively. Note that the axes vary between events.

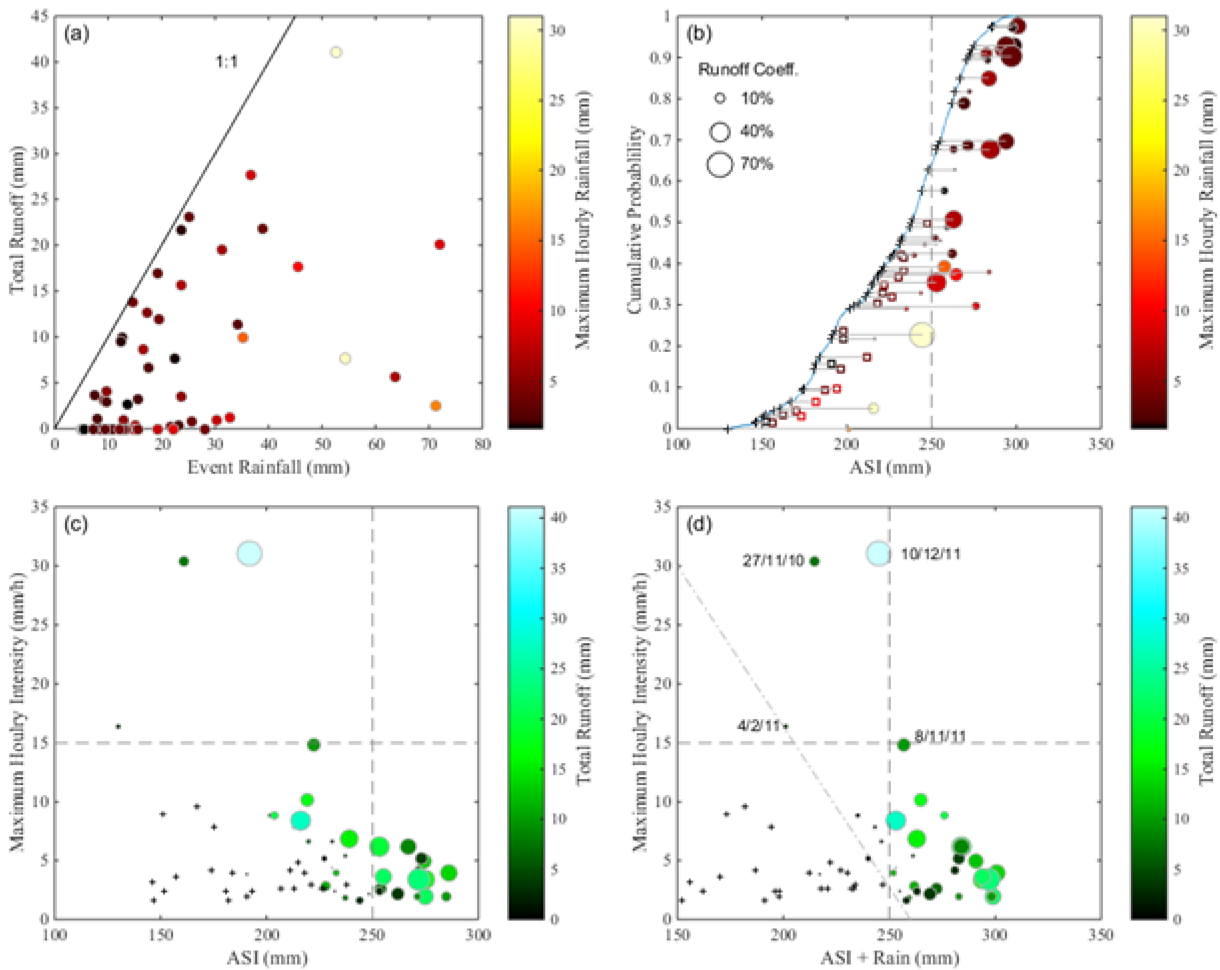


**Figure 5. Thresholds of runoff mechanisms at RBF, a) event rainfall versus total event runoff, colours indicate the highest hourly rainfall intensity, b) the impact of five factors together including: cumulative curve of the distribution of soil water storage as observed through the study period, *ASI*, *ASI*+Rain, colour shows the peak hourly rainfall intensity ($I_{peak}$) and the size of the bubbles shows the event runoff coefficient, c) *ASI* versus the peak hourly rainfall intensity ($I_{peak}$) and the size of the bubbles shows the event 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 event runoff coefficient and colour shows event total runoff. Note *ASI* is the antecedent soil water storage (mm) in top 60cm of soil at the AWS at the beginning of the event.**

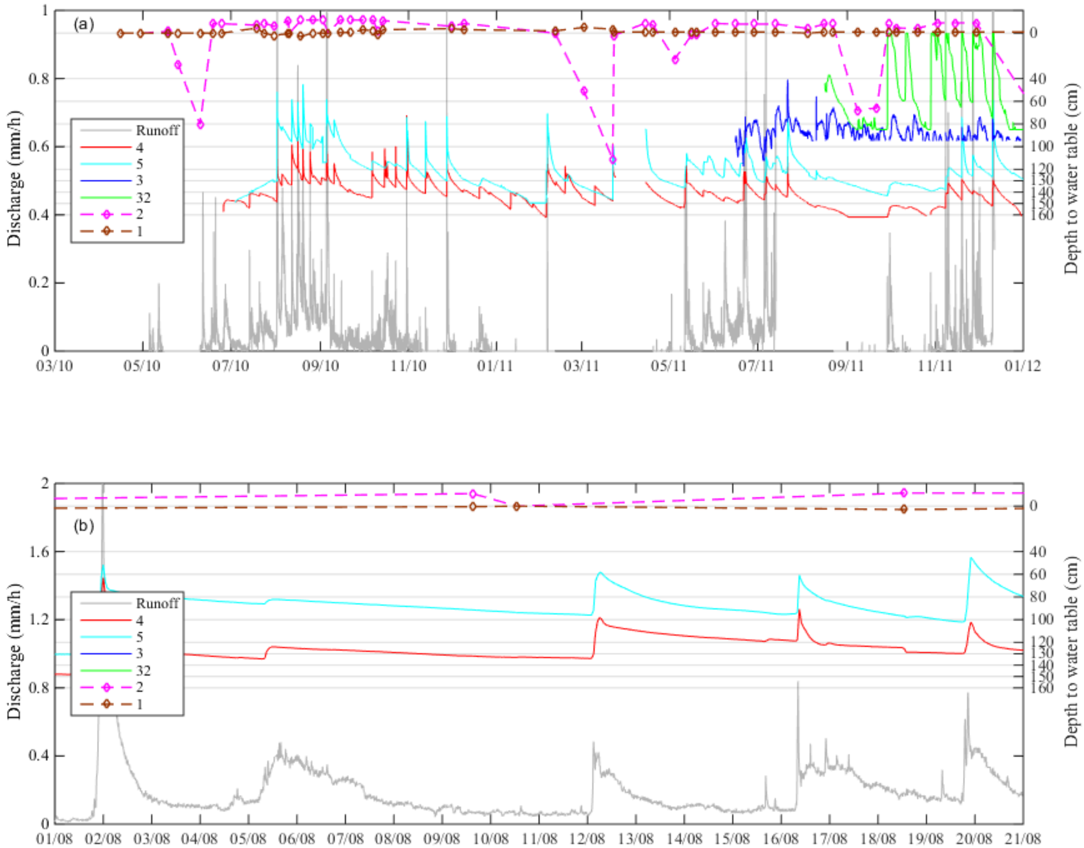


**Figure 6. Time series of discharge (grey lines) and groundwater levels at sites 4, 5, 3, 32, 2 and 1, manually read sites are shown with dashed lines and diamonds at measurement points. Levels above zero at sites 1 and 2 occur as the soils are highly pugged in the riparian zone and water pooled on the surface in places leading to slightly positive water levels being measured, at site 2 in particular.**

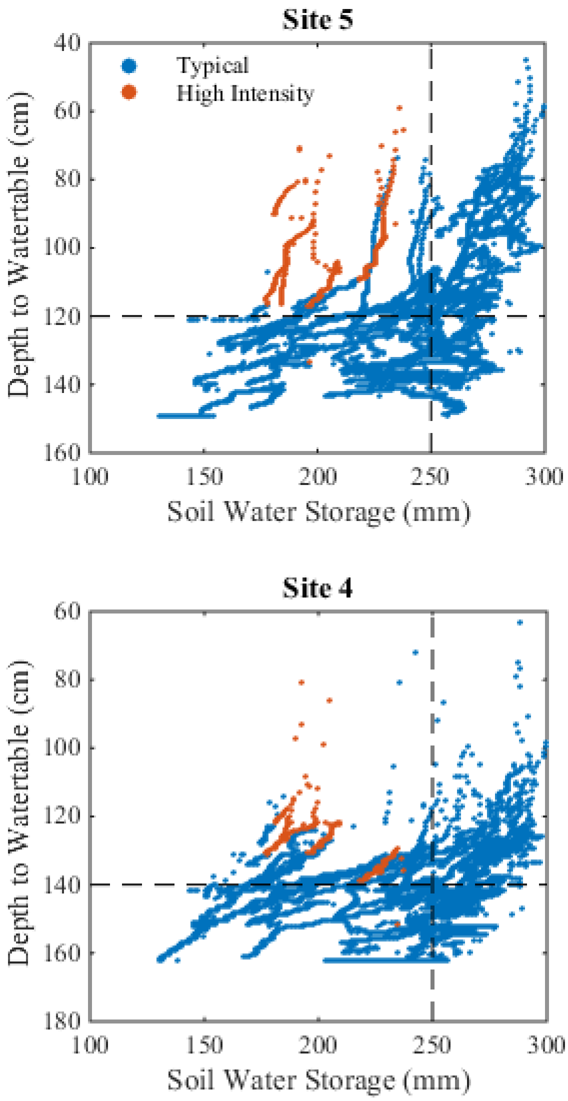


**Figure 7. Soil water storage versus water table level at sites 4 and 5. The red colour distinguishes events with high hourly rainfall intensity, defined as $I_{peak}$>15mm, consistent with Figure 5. The dashed black lines correspond to values of water level and soil water storage discussed in the text. Soil water storage is measured for the top 60cm at the Automatic Weather Station.**

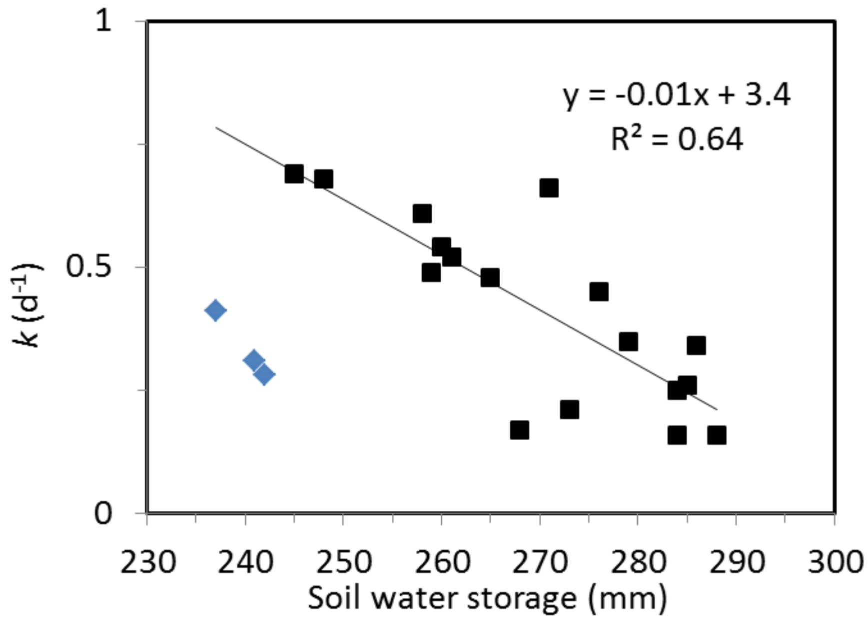


**Figure 8. Recession constant (*k*) and soil water storage the start of the recession for individual events. The choice of events is explained in the text, as are the three blue points.**

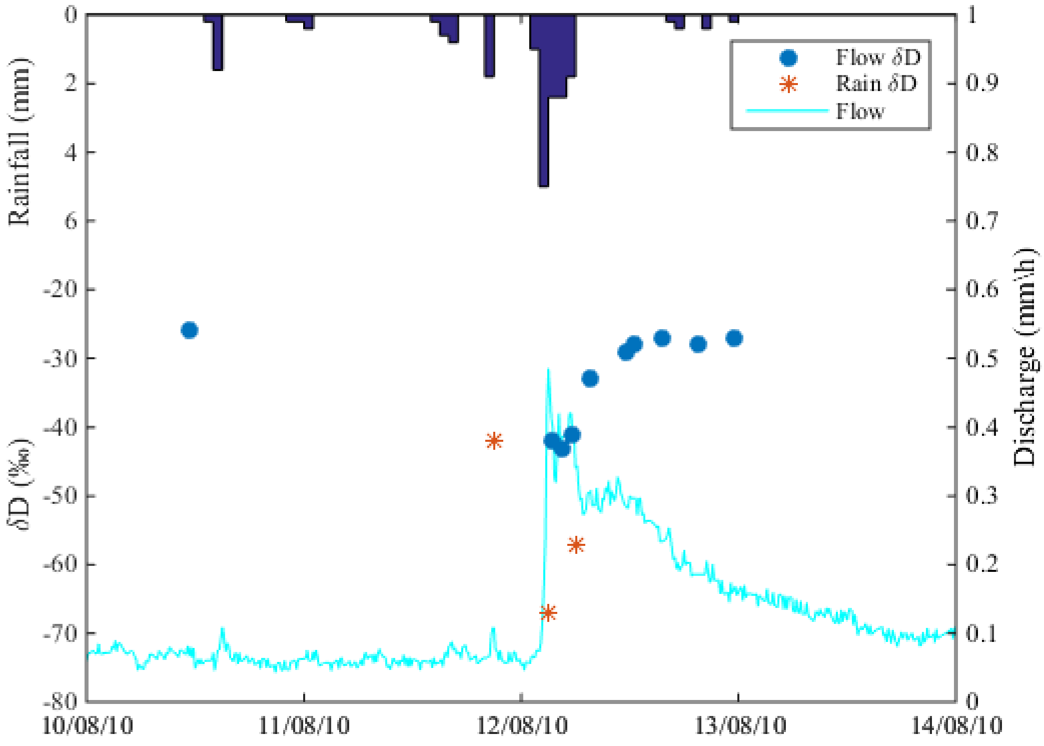


**Figure 9. Time series of total rainfall and discharge, $^{2}$H of rainfall and runoff for the event on 12/8/10**

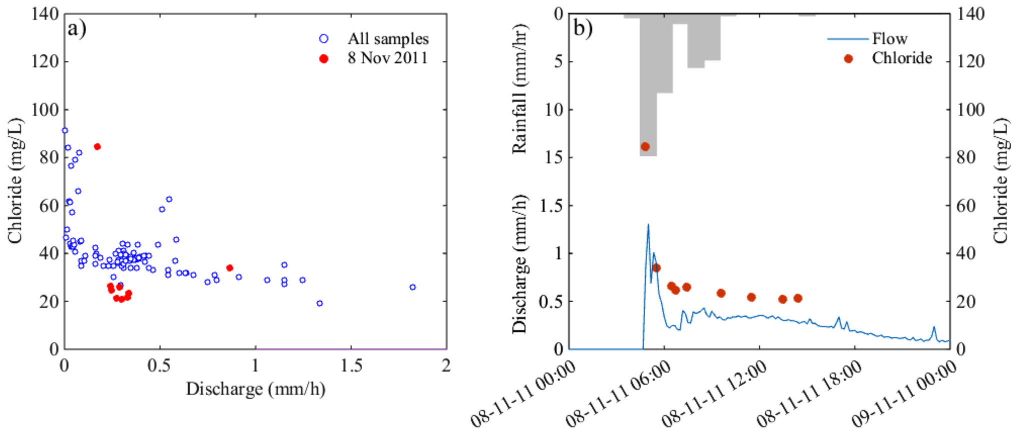


**Figure 10. a) Discharge versus Cl$^-$ concentration for all events. The red colour identifies samples from event on 8/11/11, and b) Time series of rainfall, runoff and Cl$^-$ concentration for the event on 8/11/11**