Response to review of: "McMillan, H.K. and Srinivasan, M.S., Controls and characteristics of variability in soil moisture and groundwater in a headwater catchment" by Reviewer 1.

We very much appreciate the positive and constructive reviews by both referees, and their helpful suggestions on improvement of our manuscript. In our response below, we address individually each comment from Reviewer 1. For each comment we 1. Quote the comment (black font), 2. Give our response (blue font), 3. Showed the modified text (blue font, italic).

General Comments:
This paper investigates variability in soil moisture and groundwater tables in a small catchment in New Zealand. The authors observe temporally and spatially changing variabilities and aim to explain what controls them. In order to do this they look at seasonal cycles as well as individual precipitation events and also at some physical catchment characteristics. The approach of looking at the whole catchment system instead of just observing individual hydrologic processes to explain catchment response is interesting and deserves attention. Therefore, I think that this manuscript is well suited for publication in the HESS journal.
Thank you for this positive assessment of our paper.

Still, there are some problems concerning the structure of the manuscript that should be addressed. The authors should provide a better sequence of arguments, one building on the other. For example, in the results section the authors often already interpret the results instead of just reporting what they have observed. Afterwards the summary/ discussion section reads like a collection of individual observations that sometimes lack connection since the authors jump from one topic to the next without describing the links sufficiently (if you read the manuscript and some of its sections a couple of times then the connections become clear but it would be much easier for the reader to get some more help when reading it for the first time). So the discussion section where the main findings are summarized and presented could use some restructuring: maybe start by explaining the observed temporal differences in soil moisture before looking at the groundwater table differences. Then continue by explaining the reasons for the temporal changes in variability of both soil moisture and water tables. Then turn to the spatial differences. Also, it is mentioned that there are many types of variability occurring in the catchment. A brief overview (systematic description) of these types would be helpful.
Thank you to the reviewer for this major suggestion on how to improve the readability and flow of the summary and discussion section, and strengthen the description of our findings. In response to this comment we have completely restructured the summary section according to the order suggested. We summarise the temporal variability in soil moisture and groundwater, followed by spatial variability in soil moisture and groundwater, then connections between them, i.e. temporal changes in spatial variability. Subheadings in bold are also used to guide the reader. We have also added an overview figure, shown below. Please see the revised paper as the new section is not reproduced here. We also rewrote the conclusion section to follow the same ordering of results.

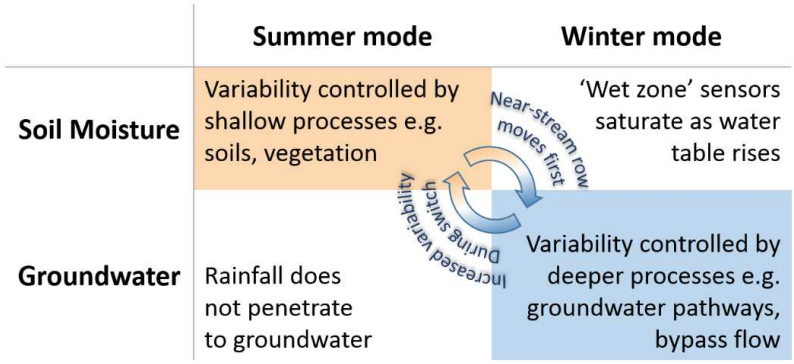

Figure 13: Summary of changes in variability of soil moisture and groundwater as the catchment cycles between summer and winter modes

The paper is well-written in terms of spelling and grammar. What the authors could still improve is the structure, especially by untangling some of the nested sentences that are quite frequent.
See previous comment regarding the structure. In our rewriting, we have split sentences to shorten them where possible.

Specific Comments:

Title: 'Characteristics and controls. . .' is the more natural order for this title. Also, it flows better. But that is a matter of taste, I guess...

Changed as suggested – new title is:

Characteristics and controls of variability in soil moisture and groundwater in a headwater catchment

p. 9476, l. 2: Do you need to classify the catchment as 'new'. It doesn't really mean anything.

Changed as suggested

"This paper presents experimental results from a headwater research catchment in New Zealand."

p. 9476, l. 7: Which 'seasonal cycle' are you referring to exactly? The seasonal cycle of precipitation? Evaporation? Climate in general?

Changed to "climatic seasonal cycle"

"temporal variability is strongly controlled by the climatic seasonal cycle"

p. 9476, l. 10: Does this already refer to spatial variability? It is a bit confusing whether you talk about temporal or spatial variabilities when you mention partial saturation. Also, what does 'calculated per time step' mean? Do you use a moving window to capture the variability of different precipitation events?

Yes, we were referring to spatial variability. We calculated the spatial standard deviation at each data time step (i.e. 15 min) and plotted these as a time series. Graphs of these time series (for soil moisture and groundwater) showed that spatial standard deviation was greater in winter than in summer. The sentences have been reworded for clarity, also note that more detail is given in the main text of the paper.

"The spatial standard deviation of both soil moisture and groundwater is larger in winter than in summer. It peaks during rainfall events due to partial saturation of the catchment, and also rises in spring as different locations dry out at different rates."

p. 9476, l. 16-20: This is a sentence that should be divided into smaller sentences, it is hard to read.

The sentence has been broken into three, and reworded for clarity:

"Co-measurement of soil moisture and water table level allowed us to identify interrelationships between the two. Locations where water tables peaked closest to the surface had consistently wetter soils and higher water tables. These wetter sites were the same across seasons. However, temporary patterns of strong soil moisture response to summer storms did not correspond to the wetter sites."

p. 9476, l. 23-25: This sentence is unclear, maybe better write: 'The dominant variability type changes with catchment wetness conditions according to which water stores are active. In particular, the variability type is sensitive to those stores that are close to a threshold.'

Changed as suggested

p. 9479, l. 5: 'experimental data' is, in my opinion, data that was collected during an experiment (i.e. while someone was controlling and/or modifying the boundary conditions of a catchment. You did not perform experiments.

Changed to remove the word "experimental".

"The results presented in this paper…"

p. 9480, l. 2: What do you mean by 'significant variation was found'? Maybe that 'significant differences in variation were found'? Please be more specific.

We meant that they were significant differences in water table depth estimated by different tensiometers. The sentence has been reworded as follows:

"At Maimai catchment in Westland, nested arrays of tensiometers were used to estimate variability in the depth to water table. High variability was found within nests (plot scale) and between nests (hillslope scale) (McDonnell, 1990; Freer et al., 2004)."

p. 9480, l. 22: Better not say 'ASPECTS of land use. . .'. This could cause confusion.

Thanks-changed to 'descriptors'

"descriptors of land use and topography"

p. 9480, l. 23: Concerning the structure of this section I would recommend to start with controls of soil moisture before continuing to controls of soil moisture variability.
The order of these two paragraphs has been reversed in the text.

p. 9480, l. 23 – p. 9481, l. 2: It would be useful (if not necessary) to add to this summary how the controls influence soil moisture. You write that upslope area was identified as a control – but does an increasing upslope area cause higher or lower mean values?
Thanks for the suggestion. The information in this paragraph has been moved to Table 1, which now allows room to describe how the controls influence soil moisture as suggested.

p. 9481, l. 10-19: Again in this summary I would like to read more about the actual results of these studies (so what is this relationship between topography and subsurface flow dynamics?). The way it is presented now is not very informative for the reader.
The paragraph has been extended to provide more details on each reviewed study, as follows:
"Studies of variability in groundwater dynamics are less common, reflecting the greater difficulty and expense in measuring groundwater levels, but a wide range of controls on groundwater levels have been identified. Detty and McGuire (2010a) considered surface topography controls, by dividing the landscape into landform units, e.g. footslopes, planar backslopes, or convex shoulders. They found statistical differences in metrics of water table hydrograph shape between different landform units. The hydrographs increased in duration and magnitude from shoulders to foot slopes, but were most sustained on backslopes. The responses also differed between the growing and dormant seasons. Anderson and Burt (1978) showed that topography can control matric potential and downslope flow: at their field site, hillslope 'hollows' had specific discharge an order of magnitude higher than hillslope spurs. Fujimoto et al. (2008) found that topography interacts with storm size to control subsurface processes. For small storms, a concave hillslope stored more water than a planar slope and produced less runoff; whereas for larger storms, transient groundwater in the concave slope caused greater expansion of the saturated area than in the planar slope, and correspondingly greater runoff. Bachmair et al. (2012) drilled 9 transects, each of 10 shallow wells (< 2 m deep) to study the effect of land use and landscape position on variability in groundwater dynamics. They found that patterns of groundwater response in winter reflected expansion of saturated areas at the base of the hillslope, whereas in summer groundwater response was controlled by transient preferential flow networks and was highly spatially variable. The wells with the strongest response also varied between events."

p. 9482, l. 3: What evidence? Same problem here. You do not need to explain the whole paper but if you cite, you should provide the essentials.
We extended the explanation as follows:
"In Plynlimon catchment in Wales, Haria and Shand (2004) found that groundwaters at 1.5 m, 10 m and 30 m depth were not hydraulically connected, and were chemically stratified, with distinct Ph, electrical conductivity and redox characteristics. Different groundwater pathways to the stream could therefore be identified, including discharge from fractured bedrock, and upwelling into the soil zone causing rapid lateral flow."

p. 9482, l. 23-27: Make this data a table, it would be much clearer.
Done

p. 9483, l. 11: What measurements were more detailed in the one slope and how were they more detailed? You were talking about aerial photographs and GPS mapping.
This is now explained more clearly:
"Aerial photos were only taken on the slope above the north-facing sites, and GPS point spacing was also closer in this area."

p. 9487, l. 1: Maybe better 'we average by location' instead of 'we summarize'.
Changed as suggested

p. 9487, l. 19: What does 'induce water tables' mean?
The wording has been improved:
"In winter, the large events cause saturation at many of the soil moisture sensors, and water tables rise in many of the wells, including some in the upper row where the water table was previously lower than the well."

p. 9488, l. 7-12: A table would be easier to follow.
The data has been moved into a table

p. 9490, l. 2: What kind of 'seasonal cycle' are you referring to? Please be more precise.
Reworded as:
"there is a strong seasonal differentiation in runoff coefficients"

p. 9490, l. 5: Which typical event did you select?
Event details are now provided:
"We selected the following events: dry-period variability: 17-27 March 2013, 15.9 mm rainfall; wet-period variability: 5-25 October 2012, 164.9 mm rainfall; winter wet-up: 15-30 April 2013, 80.0 mm rainfall; recession period: 7 September – 5 October 2012."

p. 9492, l. 19-22: Unclear sentence, please rephrase.
Rephrased as:
"Locations where the water table was detected in the upper row of sensors were classified as slow groundwater responses (i.e. a later and prolonged peak), but they peak slightly before the downslope slow-response sites, which could indicate a delayed groundwater flow path from upslope."

p. 9494, l. 6-9: This is just one of quite a few sentences that could be phrased much clearer for the reader if it wasn't so nested and sloppily formulated (commas in the right locations would already help a bit). You write: 'During the year, the catchment experiences a shift between variability in summer controlled by shallow processes e.g. soils and vegetation, and in winter controlled by deeper processes e.g. groundwater pathways and bypass flow.' Actually, what you mean is that the controls of variability shift from summer to winter (which also eventually affects the catchment response).
This whole section has now been rewritten (see the major comment at the start of the review), including shortening & clarifying sentences.

p. 9494, l. 10-12: You better call it 'variable groundwater storage' since you don't know the total groundwater storage.
Changed as suggested

p. 9494, l. 12-20: There is an interesting study by Bachmair et al. (2012) that deals with water table fluctuations in different hillslope positions. You should have a look and compare your results on the different winter/summer dynamics.
Thanks for suggesting this paper. We now discuss their results in the literature review section (1.2):
"Bachmair et al. (2012) drilled 9 transects, each of 10 shallow wells (< 2 m deep) to study the effect of land use and landscape position on variability in groundwater dynamics. They found that patterns of groundwater response in winter reflected expansion of saturated areas at the base of the hillslope, whereas in summer groundwater response was controlled by transient preferential flow networks and was highly spatially variable. The wells with the strongest response also varied between events."

and in the summary section (5):
"However, the summer and winter modes in Langs Gully differ from those found by Bachmair et al. (2012), where intense summer storms onto dry soil caused preferential flow and fast, strong, spatially variable water table responses throughout the hillslope. In their catchment, winter storms led to slower water table responses that were strongest at near-stream locations."

p. 9494, l. 24: This is a result and should not be reported in the summary section for the first time.
This result is now first reported in Section 4.2 where the data are presented.

p. 9494, l. 5 – p. 9496, l. 13: In general, this section needs better connections and synthesis between the single sentences. It reads like a list of unconnected statements.
This whole section has now been rewritten (see the major comment at the start of the review).

p. 9495, l. 7: Unclear, please rephrase. Which relationship between which seasonal cycle and controls on variability?
This whole section has now been rewritten (see the major comment at the start of the review).

p. 9496, l. 7-11: Variability also controls how fast water flows through a catchment. For a recent paper on variable transit time controls please refer to Heidbüchel et al. (2013). They also describe how changing storage states cause different predominant flow paths with different characteristic transit times.
Thanks for this paper suggestion. We cited it as follows:
"Similarly, variability controls how quickly water flows through a catchment, as the different response modes direct water into flow paths with different transit times (Heidbuechel et al., 2013)."

p. 9497, l. 8-15: Please insert some more hard facts into the conclusions. For example, you state that 'catchment variability (what is that?) is composed of multiple variability types (which ones?) and is dominated by different stores (which stores?) according to catchment wetness condition'
We rewrote the conclusion section to follow the same ordering of results as the summary section (see the major comment at the start of the review). At the same time, we inserted more factual information:

"We made distributed measurements of flow, soil moisture and depth to groundwater in a New Zealand headwater catchment, to characterise controls on variability. The data showed that temporal variability was dominated by a strong climatic seasonal cycle, with event dynamics superimposed. The volume of stored water in the catchment had a corresponding seasonal cycle, mostly due to increased groundwater in winter. Spatial variability is controlled most strongly by aspect and distance from stream: South-facing and near-stream sites are typically wetter, and in particular have more and larger wetting events. The relative wetness of different locations was stable: high water table locations were consistent across seasons, and sites where water tables peaked above 30 cm depth had consistently wetter soils. Temporal dynamics vary spatially, including timing of winter wet up (faster on South-facing slopes), different speeds of groundwater response (slow at far-stream sites) and different recession shapes (no clear spatial pattern).

We examined soil moisture and groundwater responses to rainfall, for dry vs. wet antecedent conditions, and found significant differences in the patterns of response. This led us to classify catchment variability as being in 'summer mode' or 'winter mode'. In summer mode, variability is controlled by shallow processes e.g. soils and vegetation, and sites where soil moisture reacts strongly to a rainfall event may not correspond with the usual wetter locations. In winter mode, variability is controlled by deeper processes e.g. groundwater pathways and bypass flow. In both cases, variability is strongest for stores where typical water content is close to a threshold such as saturation. Because spatial variability changes with season, we suggest that methods to predict emergent catchment behaviour arising from small-scale variability may also need to change with season."

Figures & Tables:

Figure 4 & 5: It would be nice to combine these two figures into one.
We have done this

Figure 7 & 8: It would be nice to combine these two figures into one.
We have done this

Figure 10: It would be helpful to have a precipitation time series at the top. And where are the depicted depth to water table sensors located?
We added a precipitation time series and also changed the line colouring to show water table sensors on North and South facing slopes

Figure 11: Again, it would be helpful to add a precipitation time series at the top.
We added a precipitation time series and also changed the line colouring to distinguish between sensor that saturate or do not saturate (as shown in panel B)

Technical Corrections:

p. 9482, l. 1: ‘Even in [] headwater catchments. . .’ Done

p. 9482, l. 6: ‘. . .catchment is LOCATED in the. . .’ Done

p. 9482, l. 7: A river that ‘rises’? Changed to ‘*has its source*’

p. 9482, l. 13: Just writing ‘mean 943 mm’ sounds lazy. Changed to ‘*with a mean of 943 mm’*

p. 9482, l. 17: ‘. . .gravelLy. . .’. Done

p. 9482, l. 19: Fig. 2 is mentioned before Fig. 1 is mentioned for the first time. Figure 1 now referenced at the beginning of the section.

References:

Bachmair, S., M. Weiler, and P. A. Troch (2012), Intercomparing hillslope hydrological dynamics: Spatio-temporal variability and vegetation cover effects, Water Resour. Res., 48, W05537, doi:10.1029/2011WR011196.

Heidbüchel, I., P.A. Troch, S.W. Lyon (2013), Separating physical and meteorological controls of variable transit times in zero-order catchments, Water Resources Research, 49, 7644-7657, doi:10.1002/2012WR013149.