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Controls and characteristics of variability in soil moisture and groundwater in a headwater catchment

H. K. McMillan and M. S. Srinivasan

National Institute of Water and Atmospheric Research, P.O. Box 8602, Christchurch, New Zealand

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Correspondence to: H. K. McMillan (h.mcmillan@niwa.co.nz)

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Abstract

This paper presents experimental results from a new headwater research catchment in New Zealand. We made distributed measurements of streamflow, soil moisture and groundwater levels, sampling across a range of aspects, hillslope positions, distances from stream and depths. Our aim was to assess the controls, types and implications of spatial and temporal variability in surface and groundwaters.

We found that temporal variability is strongly controlled by the seasonal cycle, for both soil moisture and water table, and for both the mean and extremes of the distributions. The standard deviation of both soil moisture and groundwater values calculated per timestep is larger in winter than in summer, and standard deviations typically peak during rainfall events due to partial saturation of the catchment. Controls on the spatial variability differed between the water stores. Aspect had a strong control on groundwater but not on soil moisture, distance from stream controlled both soil moisture and groundwater. The depth of the soil moisture sensor had little impact in terms of mean water content, but a strong impact on the extreme values, i.e. saturation. Co-measurement of soil moisture and water table level variability allowed us to identify variability components that differed between these water stores e.g. patterns of strong response in soil water content were not the same for groundwater level, and those that were consistent e.g. vertical infiltration of summer rainfall through upper and lower soil depths, or rising near-stream water tables through shallow wells to lower soil depths.

Signatures of variability were observed in the streamflow series, showing that understanding variability is important for hydrological prediction. Total catchment variability is composed of multiple variability sources. The dominant variability type changes with catchment wetness conditions according to which water stores are active, and in particular those which are close to a threshold such as field capacity or saturation. Our results suggest that the integrative processes that create emergent catchment behaviour should be understood as the sum of these multiple, time varying components.

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1 Introduction

Hydrological processes, including runoff generation, depend on the distribution of water in a catchment, in space and time. Understanding the distribution and its effects on dominant processes is a prerequisite for identifying organising hydrological principles (Troch et al., 2008) and building hydrological models that produce “the right answers for the right reasons” (Kirchner, 2006). However, water stores and fluxes are typically characterised by high complexity and variability at all scales (e.g. Grayson et al., 2002; Zimmer et al., 2012).

The high variability of soil moisture and groundwater has far reaching implications for hydrological measurement, prediction and modelling. Most measurements of soil moisture or groundwater are made at the point scale, and so high variability makes it difficult and costly to estimate spatial average values. However, studies into controls on variability can give insights into the best monitoring locations and strategies to estimate spatial averages (e.g. Teuling et al., 2006 for soil moisture), and may allow us to identify sites likely to mirror the mean wetness conditions of the catchment (Grayson and Western, 1998).

Hydrological models simulate water fluxes integrated over some “model element” scale; so where variability exists below that scale, model fluxes will differ from point-scale measurements (Blöschl and Sivapalan, 1995; Western et al., 2002). This makes it difficult to compare model simulations against measured data. The same scale sensitivity affects climate models, which use land surface water content as a boundary condition (Seneviratne et al., 2010). In addition, the prevalence of high nonlinearity and thresholds in hydrological responses means that simple averaging of water content is not sufficient. For example, integrated drainage fluxes derived from soil moisture patterns with realistic variability and spatial organisation exceed those estimated from uniform soil moisture fields (Bronstert and Bardossy, 1999; Grayson and Bloschl, 2000). Model descriptions of relationships between mean soil moisture and drainage must therefore be altered to take account of soil moisture variability (e.g. Moore, 2007;

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Wood et al., 1992) and organisation (Lehmann et al., 2007), and may need to change seasonally as soil moisture variability changes (McMillan, 2012). Threshold relationships between water content and runoff generation, which have been widely observed at the point scale, may need to be smoothed at the model element scale to reflect spatial variability (Kavetski et al., 2006). The critical point here is that multiple sources and characteristics of variability may exist in any catchment. To understand and model the emergent, catchment-scale processes they create, we must understand how the individual components of variability interact and change with time.

A well-established strategy to improve our understanding of hydrological variability and processes is through the development of densely instrumented research catchments (Tetzlaff et al., 2008; Sidle, 2006; Warmerdam and Stricker, 2009). Such sites expose interrelations and patterns in hydrological variables, and allow us to test hypotheses on catchment function. In recent years, improved sensor and communication technologies have increased our ability to capture space and time hydrological variability (Soulsby et al., 2008). While acknowledging the importance of breadth, as well as depth in hydrological analysis (Gupta et al., 2014), intensively-studied catchments remain a critical part of hydrological research.

In New Zealand, experiments in research catchments have uncovered the importance of vertical flow and the displacement mechanism for streamflow generation, using applied tracers (Woods et al., 2001; Mahurangi catchment) and isotope measurements (McGlynn et al., 2002; Maimai catchment). The subsequent incorporation of our revised process understanding into conceptual models of the catchments has emphasised the need to measure variability and dynamic response in groundwater as well as soil moisture (e.g. Graham and McDonnell, 2010; Fenicia et al., 2010). Groundwater dynamics and subsurface flow pathways are a key control on runoff generation and flow dynamics in a variety of different catchments (Onda et al., 2001; Soulsby et al., 2007), with strong evidence coming from hydrochemical analysis of streamwater. The hydrology of the riparian zone may be particularly sensitive to groundwater connections (Vidon and Hill, 2004). While previous NZ catchment studies have measured

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groundwater response in a limited number of locations (Bidwell et al., 2008) or without simultaneous surface water measurements (Gabrielli et al., 2012), a joint data set of spatio-temporal surface and groundwater measurements did not previously exist in New Zealand.

The experimental results presented in this paper, from a new research catchment in the headwaters of Waipara catchment, provide researchers with data to characterise and test hypotheses on variability and model representation of integrated surface water-groundwater physical systems. Such models are in high demand for management applications, as local governments must set allocation limits and manage supply under increasing demands for water. Although surface water and ground water systems have, historically, often been managed independently, there is now recognition that extractive use from either source impacts on the whole system (Lowry et al., 2003).

The aims of this paper are therefore to: (1) present initial experimental data of surface and ground water responses from a new research catchment in the alpine foothills of New Zealand (2) assess the types of spatial and temporal variability in soil moisture and groundwater in this headwater catchment, the factors that control the variability, and the implications for modelling.

1.1 Soil moisture variability

New Zealand has some well-known experimental catchments, which offer information into causes and effects of hydrological variability, focused on the soil zone. In the Mahurangi catchment in Northland, Wilson et al. (2004) compared the variability of gridded soil moisture measurements in time vs. in space. They found that temporal variability was approximately 5 times greater than spatial variability. Temporal variability was highly predictable, and explained by seasonality; whereas spatial variability was less easily predictable, only partly explained by terrain indices. In the same catchment, Wilson et al. (2003) compared variability of soil moisture at 0–6 cm depth vs. 30 cm depth, and found differences in distribution and low correlations between the two

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depths. At Maimai catchment in Westland, nested arrays of tensiometers were used to estimate variation in the depth to water table. Significant variation was found at scales from plot scale to hillslope scale (McDonnell, 1990; Freer et al., 2004).

Some characteristics of the New Zealand climate and landscape may result in locally important controls on variability. Aspect is important in New Zealand hill country, due to high radiation and prevailing wind direction. Typical Penman PET is 35–50 % greater on Northern than Southern facing slopes (Jackson, 1967; Bretherton et al., 2010), or more for sites exposed to the prevailing WNW wind (Lambert and Roberts, 1976). At one site, these differences translated into mean soil moisture differences of 10 % (Bretherton et al., 2010). In a similar environment to the catchment described in this paper (i.e. Eastern foothills of the Southern Alps, greywacke geology), aspect-induced microclimate differences were found to promote physical and chemical soil differences, with stronger leaching and weathering on South facing slopes (Eger and Hewitt, 2008).

High variability in soil moisture has many implications for hydrological process understanding and modelling. There is a large body of work investigating causes of low vs. high variability, without attempting to predict exact spatial or temporal patterns, often using geostatistical methods to quantify the magnitude and the scales of variation (e.g. Western et al., 1998; Brocca et al., 2007). Causes of high variability have been found to be: dry conditions (Brocca et al., 2007), mid-wetness conditions (Ryu and Famiglietti, 2005), wet or dry conditions conditional on climate, soil and vegetation types (Teuling and Troch, 2005; Teuling et al., 2007), increasing scale (Famiglietti et al., 2008; Entin et al., 2000), or aspects of land use and topography (Qiu et al., 2001).

Controls on soil moisture itself are equally varied, and authors study these in terms of soil moisture mean (in either space or time), distribution (Teuling et al., 2005) and dynamics such as recession, stability or recharge rate (Kim et al., 2007). Controls identified include: upslope area (Brocca et al., 2007), land use and topography descriptors including slope, aspect and elevation (Qiu et al., 2001), topographic position (Kim et al., 2007), slope and topographic index (Penna et al., 2009), depth and topographic index (Nyberg, 1996), and height above the nearest drainage (Crave and GascuelOdoux,

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1997). Controls on soil moisture may interact, such as soil type and topography (Crave and GascuelOdoux, 1997). Even though new technologies are becoming available to measure soil moisture and its variation on larger scales, including remote microwave sensing (Njoku et al., 2002) and electrical resistivity tomography (Michot et al., 2003), there is still no accurate way of predicting soil moisture patterns, with studies typically predicting less than 50 % of the spatial variation.

1.2 Groundwater variability

Studies of variability in groundwater dynamics are less common, reflecting the greater difficulty and expense in measuring groundwater levels. Hydrologists have found a wide range of controls on groundwater levels. Detty and McGuire (2010b) considered surface topography controls, by dividing the landscape into landform units, e.g. foot slopes, planar back slopes, or convex shoulders. They found statistical differences in the shallow groundwater response between different landform units. The response also differed between the growing and dormant seasons. Topography can control matric potential and downslope flow (Anderson and Burt, 1978), and subsurface saturated areas (Fujimoto et al., 2008). The relationship between topography and subsurface flow dynamics has been demonstrated theoretically (Harman and Sivapalan, 2009), although bedrock topography may be more important than surface topography (Freer et al., 2002; Graham et al., 2010; Tromp-van Meerveld and McDonnell, 2006a, b).

In areas with shallow slopes, other controls dominate, such as variability in recharge. Gleeson et al. (2009) tracked snowmelt recharge to groundwater using 15 bedrock wells in a humid Canadian catchment with flat topography. In addition to widespread slow recharge, they found fast, localised recharge in areas with both thin soils and fractured bedrock. Riparian soils can form a fast conduit to groundwater, where a higher fraction of gravel leads to hydraulic conductivities an order of magnitude higher than the hillslope soils (Detty and McGuire, 2010a).

Characteristics of the groundwater aquifers are also important. Winter et al. (2008) and Tiedeman et al. (1998) monitored 31 bedrock wells and found water table gradients

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caused by different geological units within a catchment. Even in a headwater catchments, variability in groundwater dynamics has been found due to multiple underlying aquifers (Kosugi et al., 2011, 2008); with evidence provided by chemical stratification (Haria and Shand, 2004).

2 Study area

The Langs Gully catchment is in the South Island of New Zealand, in the headwaters of the Waipara River that rises in the foothills of the Southern Alps before emptying onto alluvial plains. Langs Gully is typical of the Canterbury foothills landscape. This area is the source of many rivers and aquifers that provide essential irrigation water for the drier and intensively farmed plains; however the hydrology of the area is poorly understood.

The 0.7 km^2 catchment ranges from 500–750 m in elevation, and is drained by two tributaries. Annual precipitation ranges from 500 to 1100 mm, mean 943 mm. In winter the catchment has relatively frequent frosts and occasional snow. The land cover is grazed pasture for sheep and beef cattle farming, with a partial cover of sparse Matagouri (*Discaria toumatou*) shrub. The geology is greywacke, a hard sandstone with poorly sorted angular grains set in a compact matrix. Soils are shallow gravely silt loams derived from the underlying greywacke, and were classified as midslope, footslope or spur (Fig. 2), based on expert knowledge and the S-MAP New Zealand soils map (Lilburne et al., 2004), which uses soil survey data, and topography-based interpolation (Schmidt and Hewitt, 2004). The mapping also provided estimates of fractions of stone, sand and clay for each soil type. Fractions of stone and sand decreased from spurs to footslopes, while fractions of clay increased (spurs: stones 30–80 %, sand 10–50 %, clay 10–25 %; footslopes: stones 5–20 %, sand 5–40 %, clay 20–35 %. Figures for 0–30 cm depth). Stone and sand fractions increase with depth for all soils (e.g. footslopes: 0–30 cm depth: stones 5–20 %, sand 5–40 %, 30–60 cm depth: stones 35–80 %, sand 10–40 %).

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3 Materials and methods

The aim of our experimental design was to study the temporal and spatial variability in water storage within the catchment. We installed sensors to measure rainfall, climate variables, streamflow, soil moisture and depth of shallow groundwater. Our aim was to take measurements at locations representing the variability of hydrological conditions within the catchment, and where possible to co-locate sensors in order to understand relationships between different water stores. We selected two hillslopes for detailed measurements of soil moisture and shallow groundwater, with different aspects (North and South) (Fig. 1).

To support the sensor data, we took aerial photos and used GPS mapping to create a digital elevation model of the catchment (Fig. 2). These measurements were more detailed on the slope above the North-facing sites. A soils map was created using a combination of nationally available data and a field survey (Fig. 2).

3.1 Climate and flow monitoring

A compact weather station was located centrally within the catchment (Fig. 1). It uses a Vaisala WXT520 Weather Transmitter, which measures wind speed and direction, air temperature, barometric pressure and relative humidity. A LiCOR LI200 Pyranometer measures solar radiation. Rainfall was measured using an OTA OSK15180T 0.2 mm resolution tipping bucket gauge. All weather measurements were at 5 min intervals.

Flow was measured at three locations within the catchment (Fig. 1), all at 5 min intervals. The gauge type was chosen according to the flow magnitude: the upper two gauges are 45 cm H flumes, the downstream gauge is a v-notch weir. Periodical manual gaugings were used to confirm theoretical flow rates at all three locations.

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3.2 Soil moisture and shallow groundwater monitoring

Soil moisture and water table level were monitored by 16 instrument stations. The stations are divided into 2 groups; 10 on the North-facing slope, and 6 on the South-facing slope.

Our typical measurement site included Acclima TDT soil moistures sensor at 30 cm (base of the root zone) and 60 cm, and a well drilled to a fixed depth of 1.5 m (except where a high fraction of stones prevented the full depth being reached) equipped with a Solinst Levelogger to measure water level. On each hillslope, we centred the sites around a shallow gully surface feature, with sites in the centre of the gully and on each bank. The sites were designed in two rows, at 10 m and 20 m from the stream centreline (Fig. 1). In this way, we aimed to sample across multiple variables of depth, aspect, slope position and distance from stream. All sensors recorded at 5 min intervals, which were typically aggregated to 15 min before further analysis.

3.3 Telemetry

Each station aggregates sensor data and discards unneeded data. Each group is associated with a "master" station that polls the individual stations every 5 min for their sensor data. The master station comprises a Unidata Satellite NRT datalogger and a proprietary short-haul radio interface. The data received by the master station is stored temporarily in the logger until it can be relayed to a central database via satellite. Data in the central database is available to end users via internet and e-mail. To conserve power in the solar-recharged batteries, the sensors and radio system are only powered up to respond to data requests.

3.4 Study period

The data used in this paper were collected between March 2012 and July 2013 (Fig. 3). Climate and flow data are available for 14 months prior to this date. The largest storm

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event in the study period occurred in August 2012, which brought 80.6 mm of rainfall in 2 days, approximately a 1-in-2 year rainfall event when compared against the 62 year daily rainfall record from Melrose station, 2.0 km from the catchment. The 2012–2013 summer was unusually dry in many parts of New Zealand; but at Melrose the summer months December/January/February recorded a rainfall total of 196 mm, only marginally below the long-term average of 210 mm.

Some data gaps occurred during the study period, with short outages due to sensor or battery failure. A long outage occurred in the aftermath of the storm event in August 2012, which caused water damage to the telemetry system on the North facing slope.

3.5 Calculation of descriptive statistics

To provide an overview of the soil moisture content and groundwater level for different time/space locations, a selection of summary measures were used. To summarise the distribution of data, we calculated the median and 5th, 25th, 75th and 95th percentiles for each data series. This allows us to compare absolute soil water content and groundwater level between sites. However, we also want to compare the extent to which each location is likely to contribute to runoff; especially as runoff generation is typically conceptualised as a threshold process (Ali et al., 2013). We therefore additionally used statistics that described the wet extremes of the data. For soil moisture, we calculated the percentage of time that the soil was saturated, as this represents the condition where the location would generate both vertical drainage and overland flow. Soil saturation points were defined individually for each sensor, based on visual inspection of the soil moisture time series. For groundwater level, we calculated the percentage of time that the water table level was above the all-site 75th percentile. This quantifies locations where groundwater is closer to the surface and would therefore have faster lateral velocity according to typical findings that hydraulic conductivity decreases rapidly with depth (Beven and Kirkby, 1979).

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To understand how total water storage in the catchment changes through the year, we estimated the water stored in the soil moisture and groundwater components. For soil moisture, we divided the catchment by soil type, according to the classification described in Sect. 2. For each type, we estimated soil depth as the deepest functional soil horizon described in the S-Map database (Lilburne et al., 2004). For each time step, we derived the total soil moisture volume as:

$$\text{Total Soil Moisture } [\text{m}^3] = \sum_{\text{SoilType}} \sum_{\text{Aspect}} \left[\text{Area } [\text{m}^2] \cdot \text{Soil Depth } [\text{m}] \cdot \text{Fraction Soil Moisture} \right]. \quad (1)$$

Dividing by total catchment area then gave average depth of soil water.

For groundwater, we do not know the total aquifer depth, and therefore use instead groundwater depth above minimum recorded. For each time step, we derived the total groundwater volume above minimum as:

$$\text{Total Groundwater } [\text{m}^3] = \sum_{\text{Aspect}} \left[\text{Area } [\text{m}^2] \cdot \sum_{\text{Wells}} (\text{GW level } [\text{m}] - \text{Min. GW level } [\text{m}]) / \text{Number of wells} \right]. \quad (2)$$

Dividing by total catchment area then gave average depth of groundwater above minimum.

4 Results

4.1 Temporal controls on soil moisture and groundwater

Both soil moisture and groundwater level show strong variations over event and seasonal timescales. Figure 3 shows soil moisture, and depth to groundwater for the study

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period; for clarity we summarise the 32 soil moisture sensors and 14 water level sensors using eight and two series respectively, averaged by location.

In Figs. 4 and 5, we show the summary measures, split by season. The summary statistics show that both the mean and extremes of catchment water storage vary seasonally. The yearly cycle of soil moisture (Fig. 3) shows an extended wet season from April/May to November, followed by a slow drying until February when the catchment reaches its summer state. The return to wet conditions occurred over a very short time period during a May storm event. Water table dynamics also display a yearly cycle (Figs. 4 and 5), although the range during any season is large compared to seasonal changes. As shown in Fig. 4, soil moisture quantiles are typically lowest in summer, and water tables are lowest in summer and autumn. The driest conditions in terms of extremes (Fig. 5) occurred in late summer for both soil moisture and water table, and remains low into autumn particularly for the water table, suggesting that the lowest potential for runoff generation occurs at that time. Note that the autumn season values represent an average between the wetter conditions of the 2012 autumn and the drier conditions of the 2013 autumn, for example mean autumn (March–May) soil moisture at 0–30 cm for the upper rows of sensors was 17.9 % for 2012, 15.2 % for 2013.

Rainfall events are superimposed on the seasonal cycle. In winter, the large events cause saturation at many of the soil moisture sensors, and induce water tables at some sites. In early summer, rainfall can return soil moisture and water tables to winter levels, but only briefly. In summer, the catchment response to rainfall is highly subdued.

The strong seasonality of catchment conditions is due to seasonality in PET. Although rainfall depths are similar throughout the year, in summer the combination of higher temperatures, high solar radiation and frequent hot, strong winds from the northwest contributes to seasonal drying of the catchment. The effects are illustrated by storm runoff depths in winter vs. summer (Fig. 6). In summer, even large rainfall events produced almost no streamflow response.

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4.2 Spatial controls on soil moisture and groundwater

Figure 3 shows distinct differences between the water storage dynamics of the North and South facing slopes, and between the upper and lower rows of soil moisture sensors, with the lower row sensors on the South facing slopes showing more frequent and pronounced wetting events. For example, we defined a wetting event as a period of rainfall during which soil moisture rose by at least 3 %. Using this criteria, at 60 cm depth, South facing lower sensors recorded an average of 16 wetting events, with the 10 largest events having a mean soil moisture increase of 16 %. These values can be compared to South facing upper row sensors: 12 events with mean soil moisture increase of 6 %, North facing lower row sensors: 12 events with mean soil moisture increase of 12 %, North facing upper row sensors: 9 events with mean soil moisture increase of 6 %.

Spatial controls act differently on different water stores. These differences are illustrated in Figs. 7 and 8, using the same summary statistics as in the previous section. Figure 7 shows that when comparing North facing vs. South facing slopes, soil water content at 30 cm has similar distributions, but the underlying groundwater level is on average 20 cm closer to the ground surface for the South facing slopes, and has a smaller range. Spatial controls also act differently on average vs. extreme conditions; e.g. average soil moisture on the South facing slope is similar at 30 and 60 cm depths (Fig. 7), but the fraction of time that the soil was saturated is 11 % at 60 cm against 0.5 % at 30 cm (Fig. 8).

4.3 Temporal changes in total water storage and variability

To quantify the relative importance of different water storage components of the catchment, we calculated the average depth of water stored as soil moisture and groundwater using the method described in Sect. 3.5 (Fig. 9a). The groundwater component dominates, with an average depth of 0.27 m against 0.15 m for soil moisture. The difference is most pronounced in the wettest conditions, with groundwater storage peaking at approximately four times that of soil moisture. During the driest summer conditions, groundwater and soil moisture components have similar depths.

To visualise the changes in variability over time for each store, we plotted the time series of standard deviation in soil moisture and groundwater; separated by aspect and sensor depth (Fig. 9b and c). All stores have the highest standard deviation in winter, and the lowest in summer, as the range in values tends to be compressed as the catchment dries out. This finding is different to previous studies (Sect. 1.1), where authors have more typically found that soil moisture variability rises in dry conditions. Soil moisture at 60 cm maintains a high standard deviation even during summer, as both slopes have one sensor that retains high soil moisture and therefore has a strong influence on the standard deviation value.

All of the soil moisture standard deviations rise sharply during rainfall events, especially in winter, which is due to saturation of some sensors, while others remained unsaturated. Accordingly, 30 cm North facing soil moisture has smaller rises, as those sensors do not typically saturate. Groundwater standard deviation has different behaviour by aspect: on the North facing slope, rainfall events cause the standard deviation to rise, on the South facing slope, rainfall events cause the standard deviation to fall. This finding reflects that on the South facing slope, all wells reacts to rainfall events, albeit at different speeds, but on the North facing slope, behaviour is more variable with one well often showing no response (i.e. water table lower than 1.5 m), and other wells split between weak or strong responses.

4.4 Controls on variability

As was apparent from the time series of flow, soil moisture and water table depth presented in Sect. 5.1, there is significant spatial variability between different parts of the catchment, but this variability is not constant. In this section, we investigate the specific types of variability which occur, and seek to attribute them to different catchment conditions.

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We found that an overarching driver of variability is the wetness condition of the catchment. As shown in Fig. 6, there is a strong seasonal cycle, which is demonstrated by changes in runoff coefficients through the year. This seasonal cycle determines which of the catchment water stores are active, and where the greatest scope for variability exists. To assist our description of the seasonal changes in variability, we selected one event which is typical of, and illustrates each variability type.

4.4.1 Dry-period variability caused by partial catchment response

One type of variability (Fig. 10a) occurs during the driest conditions monitored: that is, some locations show a hydrological response – an increase in soil moisture or water table rise – to a rainfall event, while the others show little or no reaction. The timing of this type of variability varies with depth for the soil moisture probes, i.e. 60 cm probes stop reacting earlier in the summer than 30 cm probes. The fact that shallow probes are more likely to react during dry conditions suggests that the variability is caused by infiltration of precipitation that only reaches a limited depth below the surface. An example is given in Fig. 10a, which shows the response of selected sensors to a March rainfall event. Figure 10b shows a spatial overview of all sensor responses for the same event. For this event, 8 of the 30 cm soil moisture probes showed a strong response, compared to 3 of the 60 cm soil moisture probes and 3 of the wells. There were two locations where the 60 cm probes responded but the 30 cm probes did not; as water tables were always below 60 cm, these cases suggest macropore flow that bypassed the upper sensor. There are 4/10 of the 30 cm soil moisture probes on the North facing slope that showed no response, compared to 1/6 on the South facing slope. This difference may be due to drier antecedent conditions on the North facing slope; North facing sensors have a mean soil moisture of 9.6 % prior to the rainfall event, compared to 11.4 % for the South facing sensors. Soil texture differences related to aspect may also play a role: South facing sensor locations were found to have higher clay content and higher stone content than the North facing locations.

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4.4.2 Wet-period variability caused by partial saturation and groundwater response speed

In winter, the catchment is typically in a continuously wet state, and all sensors respond to rainfall events, in contrast to the summer response. Variability between sensors is introduced because some locations experience saturation (either transiently or for prolonged periods), while others do not. Saturation is characterised by high peaks or plateaux in the soil moisture signal. For both the North and South facing slopes, saturation occurs earlier and more extensively for probes at 60 cm than at 30 cm, and is limited to the sites at 10 m from the stream, indicating a rise in the catchment water table to these probes, rather than transient or perched saturated layers in the soil column. Cross-checking against measured groundwater levels also shows that the peaks in the water tables reach the depths of the soil moisture sensors showing saturation, although they do not typically reach the land surface. Wells in the upper locations may also react at this time. The rise of the near-stream water table into the soil is consistent with our knowledge of the soil and bedrock structures, as there are no evident confining layers, rather an increase in cobbles and rock fragments with depth.

Figure 11 gives an example of the response of soil moisture and groundwater level to a series of storm events in October (3 distinct peaks over 15 days) occurring in the already-wet catchment. Saturation only occurs in 30 or 60 cm probes when lower probes also show saturation. These saturating locations are also typically the same as locations where a water table response was seen during the summer event described in the previous section. The consistency of locations suggests that relative groundwater levels are maintained across seasons, with the same locations always the most likely to display a groundwater response. These locations were not related to the gully/ridge features in the catchment, in conflict with our prior hypothesis, but instead may indicate preferential groundwater flow paths which channel water from the upper slopes. Such preferential paths were previously reported at Maimai catchment where there is a clearly defined bedrock interface (Graham et al., 2010; Woods and Rowe, 1996); our

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results suggest a similar outcome in the Langs Gully catchment despite the gradual transition from soil to broken bedrock. The cross-slope gradients needed to generate the preferential paths could be caused by deeper bedrock structures, or by local areas with high permeability such as the gravel-rich soil layers observed during installation of the soil moisture sensors. At Maimai, suggested causes were temporary hydraulic gradients in the soil such that saturated flow paths may change with time, and the potential for soil moisture deficit to control vertical drainage and hence local water table rises (Woods and Rowe, 1996).

Figure 11a (third panel) shows distinct differences in the speed of the groundwater response between locations. In some locations, there is a fast groundwater peak followed by a fast decline. In other locations, the groundwater is slower to rise, reaching a peak approximately 24 h later than the fast-response site, and much slower to decline. The characterisation of each site as either a fast or slow responder is consistent, as shown for the three consecutive events in Fig. 11. During some storm events, these two response types cause a double peak, or prolonged flat peak, in the storm hydrograph (lower panel). The differing responses are mapped in Fig. 11c. There is some spatial correlation with the saturation response shown in Fig. 11b, whereby locations with a flashy groundwater response correspond to locations where saturation rose to the 60 cm soil moisture sensor. Locations where the water table was detected in the upper row of sensors correspond to slow groundwater responses, but that peak slightly earlier than the downslope slow-response sites, which could indicate a delayed groundwater flow path from upslope.

4.4.3 Variability in seasonal dynamics: winter wet-up

The wetting up of the catchment at the start of winter is a major event (Fig. 3). In 2013 this occurred in late April, quickly transitioning the catchment from its dry summer state, to the wet state that it maintained throughout the winter. The typical pattern for soil moisture is a sharp rise over less than 24 h (e.g. Fig. 12, top panel, red lines), however some locations have a more gradual response (Fig. 12, top panel, blue lines).

On the South facing slope, this sharp rise is reflected in a sharp water table rise in some locations, and a more gradual rise in others. On the North facing slope, the water table rises only gradually in all locations (Fig. 12, middle and lower panels). The two locations with gradual soil moisture response had a soil layer containing larger rocks (5–10 cm diameter) at 45–60 cm depth. This feature may promote fast drainage and therefore slow the soil wetting process.

The winter wet-up is a critical event in terms of flow prediction, as was previously shown in Fig. 6 which illustrates the stark differences in runoff coefficients in winter vs. summer. However, the spatial variation shown here in the speed and magnitude of the wet-up illustrates that it is a complex phenomenon which occurs differently for hillslopes with a different aspect.

4.4.4 Variability in event dynamics: recession characteristics

During a dry period, catchment soils, water table and flows undergo a recession. It is common to collate flow recessions, to specify a master recession shape which can then be used directly to calculate model parameters relating to baseflow generation. Recessions are typically expected to show a convex shape; initial drying occurs quickly from loosely-bound water, but drying slows as more tightly-bound water remains. In the Langs Gully catchment, we were surprised to find strong variations in recession shapes. This is illustrated in Fig. 13, which shows the recession shapes of soil moisture at 30 cm on the North facing slope after a September rainfall event, including both convex and concave shapes. We found that at different times of the year, the same soil moisture sensor at the same soil moisture content could display either convex or concave behaviour, suggesting that this finding is not an artefact of the soil moisture sensor calibration or the particular soil tension characteristics. It can also occur across the range of soil moisture contents. Instead, the difference in recession shapes could be due to either transient downslope flow towards the sensor, similar to the theoretical case described by Henderson and Wooding (1964), or seasonally varying vegetation characteristics. For example, the unusual concave responses could be due to plants exhausting near-surface soil water stores and therefore starting to extract water from the slightly deeper location of the soil moisture sensor.

5 Summary and implications of variability

Our results have shown multiple modes of spatial and temporal variability in the Langs Gully catchment. Catchment behaviour is strongly controlled by the seasonal wetness cycle, which drives variability in water stores and dynamics. 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. The shift is exaggerated by changes in total water storage volumes in the catchment; during summer, the volume of water in soil moisture and groundwater stores is similar, but in winter, groundwater volume can be up to 4 times that of soil moisture. In the shoulder seasons, there is a spatially variable shift between these two extremes of shallow vs. deeper processes, and landscape position is important in controlling that shift. The sensors that shift most quickly into winter mode, and dry most slowly in the summer mode, are in the same locations that showed a rise in water table in the selected summer and winter events. These sensors are in the lower rows (10 m from stream), but were not related to topographic gully or ridge features. The change from shallow vertical flow in dry conditions to vertical bypass flow and lateral flows from upslope in wet conditions is very similar to that found by Detty and McGuire (2010b).

Soil moisture and water table show different variability characteristics. Soil moisture on the North facing slope is qualitatively different to that on the South facing slope: it does not have the long winter plateau seen on the South facing slope. We also quantified the differences in soil moisture by calculating the number and size of wetting events; South facing slopes had 33 % more events that were on average 22 % larger than North facing slopes. Groundwater variability appears to be more location specific, with both North and South facing slopes showing a combination of fast and slow

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water table responses to rainfall events. In summer, water penetrates to the 30 cm soil moisture probes but often does not reach deeper soils or groundwater. This type of variability in the upper soil layers may be disconnected from the channel and therefore not directly affect the flow response, however it affects land surface processes such as evapotranspiration, and may have a lagged effect on the autumn/winter wetting-up process.

The relationship between the seasonal cycle and controls on variability shows how spatial and temporal variability are connected. As locations switch between summer and winter modes at varying speeds, spatial variability is increased. This effect is particularly evident on the North facing slope, where soil moisture standard deviation at 30 and 60 cm has a sustained rise during the spring drying period. Previous work in New Zealand also noted that high spatial and temporal variability tend to co-occur, for example in variability of recession shapes (McMillan et al., 2014). Measuring variability simultaneously in soil moisture and water table levels gives insights into the merits of different measurement strategies. Patterns of strong response differ between soil moisture and water table level, so soil moisture variability may provide an insufficient guide to winter runoff generation pathways, as also found by Tromp-van Meerveld and McDonnell (2005). However, high water table locations remain consistent between seasons and therefore reduced groundwater sampling may be possible.

The many types of variability occurring in this catchment have important implications for prediction of runoff generation. It is common for some parts of the catchment to wet-up or become saturated, and hence potentially contribute to a runoff response, while other parts of the catchment remain dry. The relative wetness of different locations can also change during the year – e.g. the pattern of soil moisture sensors wetted by saturation from below is different to those wetted by infiltration from above – suggesting that runoff generation processes and emergent behaviour may also change due to different contributing locations. Changing contributions of different parts of a headwater catchment as storm precipitation depth increases has been noted by previous authors (Fujimoto et al., 2008, 2011). Rainfall-runoff model structures that delineate catchment

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landscape components according to dominant processes (e.g. Gharari et al., 2011) may need to use different spatial disaggregations for soil water and ground water. Signatures of the catchment variability are seen in the flow response, such as a double or prolonged peak caused by slower groundwater pathways, and seasonally variable changes in contributions between different hillslopes. These features suggest that understanding catchment variability is essential to predicting the hydrograph.

Understanding catchment variability has further implications for other aspects of catchment behaviour. Variability controls which parts of the catchment are generating runoff and controlling water partitioning: it therefore controls uncertainty in flow predictions, depending on our knowledge or lack of knowledge about those water stores or fluxes. Variability also provides clues into unmeasured fluxes which are important for catchment response; for example areas with more rapid water table movement suggest locations of preferential flow paths, either vertical or horizontal.

6 Conclusions

We made distributed measurements of flow, soil moisture and depth to groundwater in a New Zealand headwater catchment, to characterise controls on variability. The measured data showed a strong seasonal cycle, with event dynamics superimposed. Spatial controls (aspect, hillslope position, distance from stream) were different for soil moisture and water table, and for the distribution mean compared with the extremes. Relative wetness of different locations was not consistent in soil moisture content compared with water table level, but was consistent for high water table locations across seasons. The groundwater storage component of the catchment is larger than the soil moisture component by a factor of two, and the difference increases in wet conditions. Measuring variability as the standard deviation of soil moisture or groundwater values, we found that the variability is larger in winter than in summer, and variability peaks during rainfall events with the exception of wells on the South facing slope where variability decreases during rainfall events.

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We examined typical catchment responses in dry and wet conditions to investigate causes of variability. In dry conditions, variability involves a response of only part of the catchment to a rainfall event, e.g. partial response of soils in the summer months. In wet conditions, some parts of the catchment respond more strongly than others, as in the partial saturation responses seen in winter. Temporal variability ranged from seasonal timescales, i.e. timing of winter wet up, to event timescales, i.e. different speeds of groundwater response and different recession shapes.

In summary, we found that catchment variability is composed of multiple variability types and is dominated by different stores according to catchment wetness condition. Variability is strongest for stores where typical water content is close to a threshold such as saturation. We therefore recommend that attempts to predict emergent catchment behaviour created from small-scale variability should account for these multiple and time-dependent variability components. Signatures of variability were observed in the flow response and so suggest that understanding catchment variability is essential to predicting the hydrograph in this headwater catchment.

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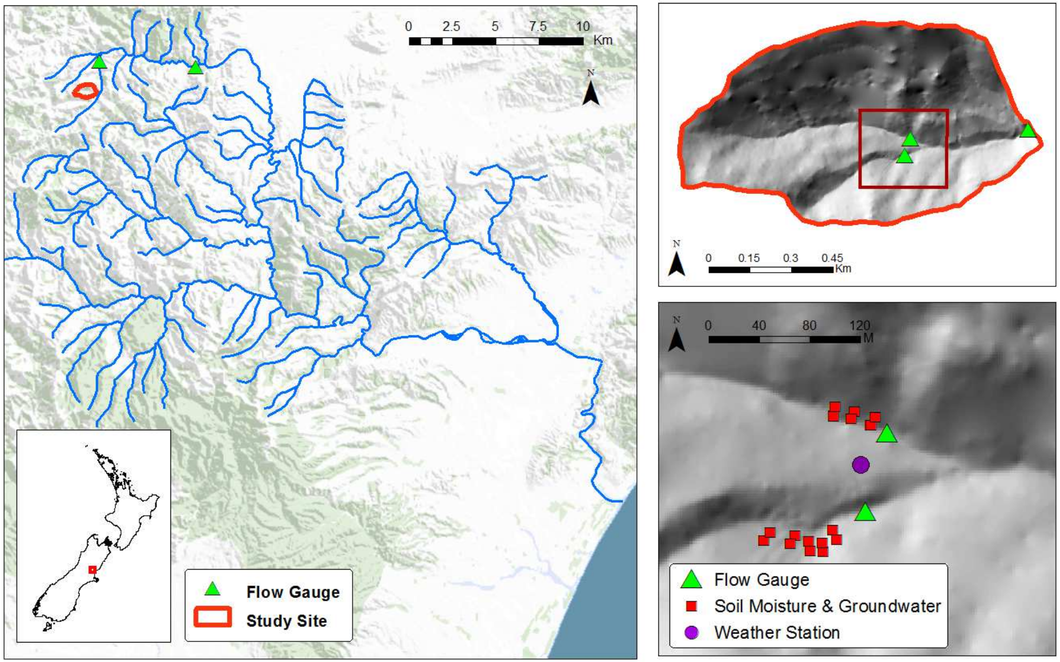

Figure 1. Catchment location and Instrumentation.

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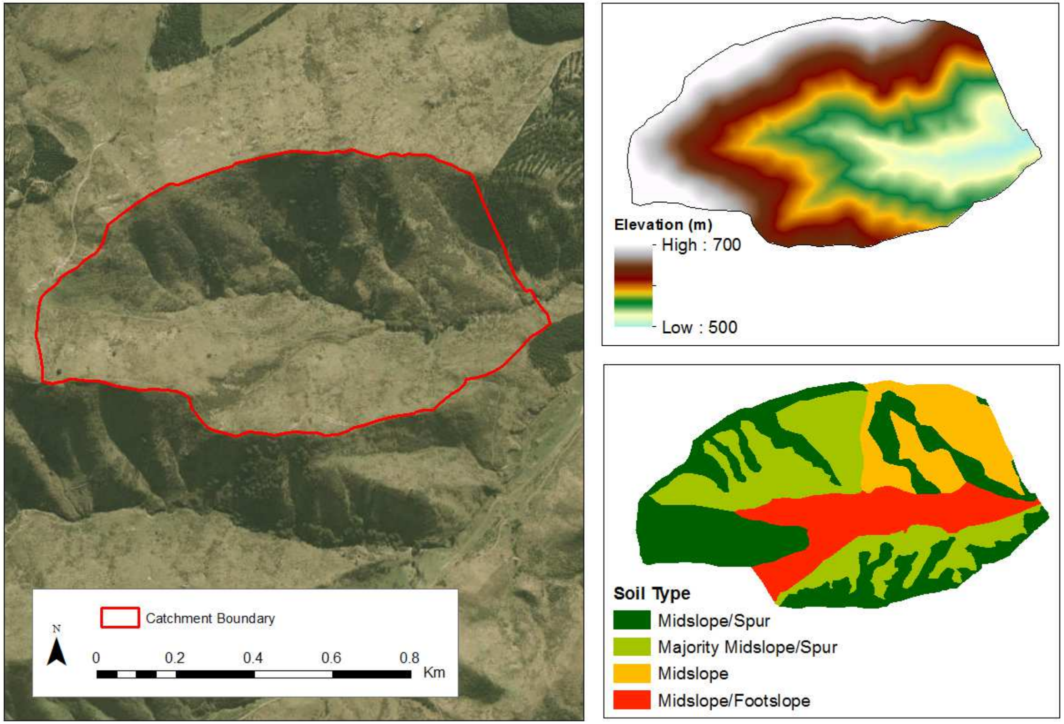

Figure 2. Catchment aerial photo, topography and soils.

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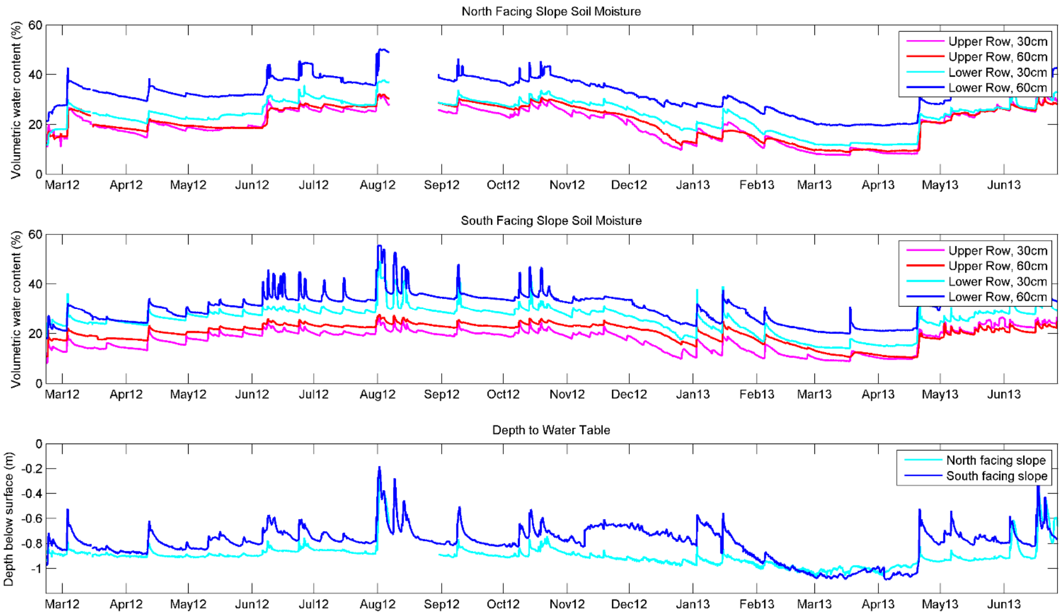

Figure 3. Time series of average soil moisture and groundwater level for the complete study period.

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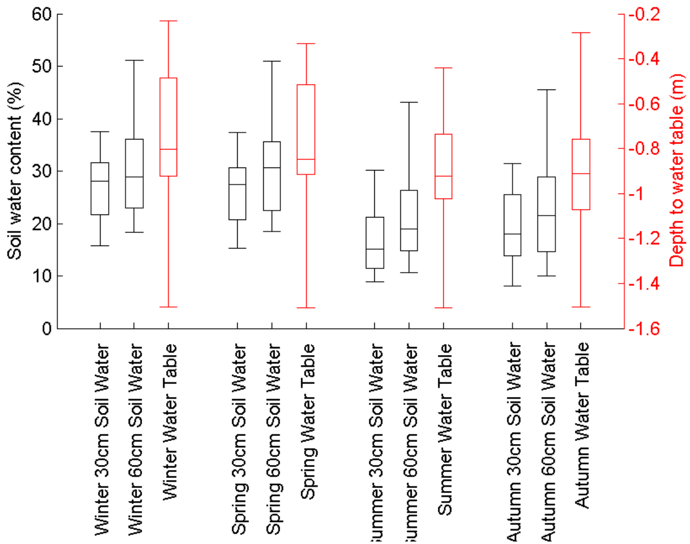

Figure 4. Summary statistics of soil moisture and groundwater values by season.

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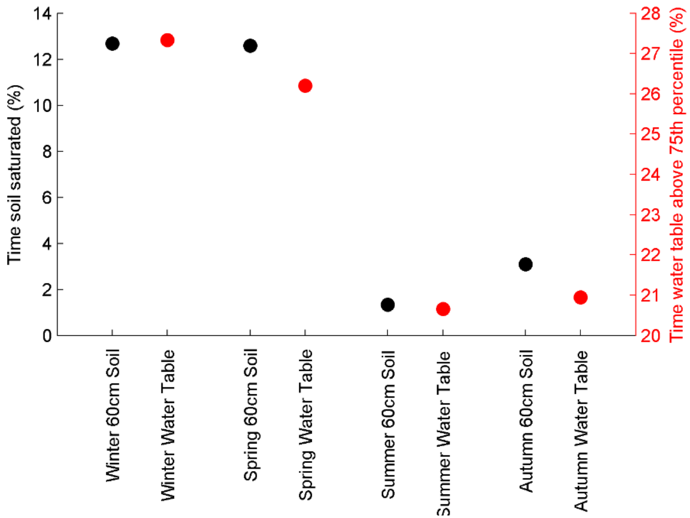

Figure 5. Summary statistics of soil moisture and groundwater extremes by season.

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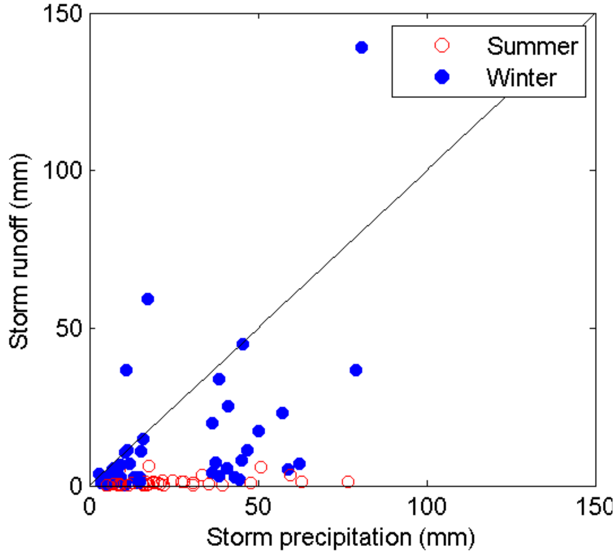

Figure 6. Storm Runoff against Storm Precipitation, split by season. This figure was created after pre-processing of the data to define storm and inter-storm periods, based on the method of McMillan et al. (2014) using thresholds for precipitation depth and inter-storm duration, and without baseflow separation.

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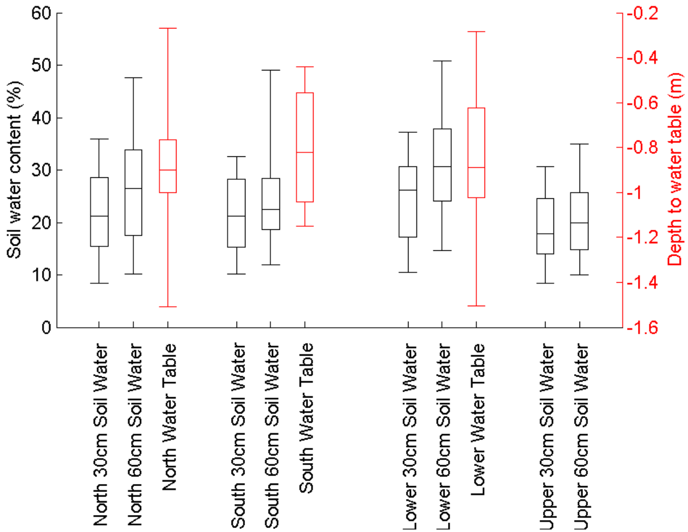

Figure 7. Summary statistics of soil moisture and groundwater values by location.

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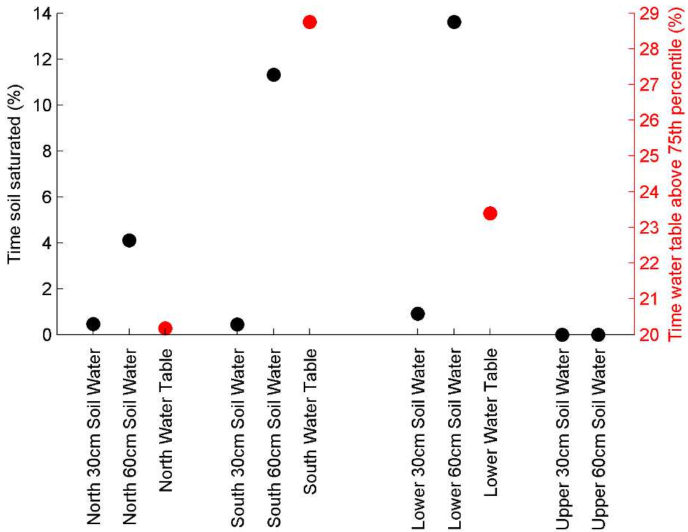

Figure 8. Summary statistics of soil moisture and groundwater extremes by location.

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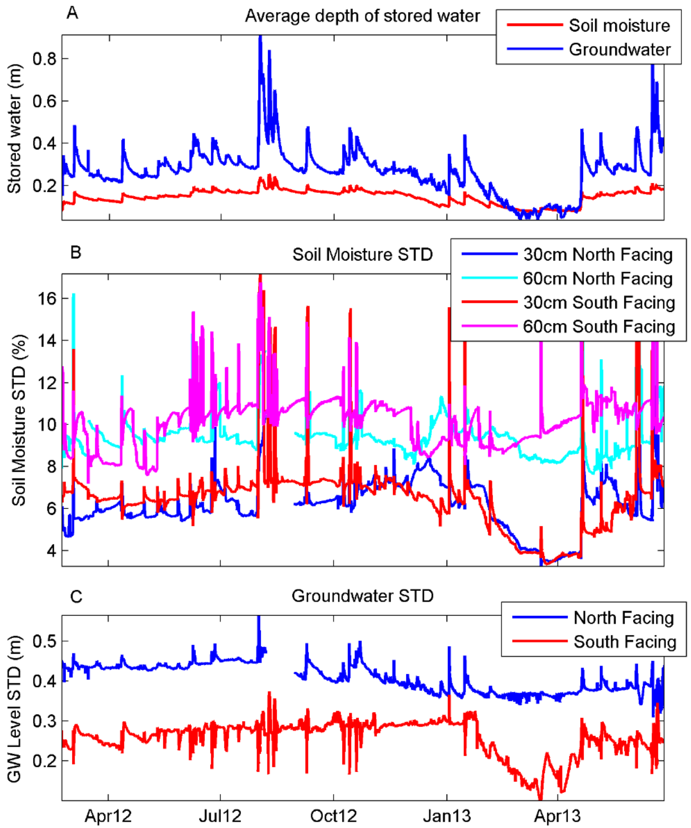

Figure 9. (a) Average depth of water stored in the catchment as soil moisture and groundwater **(b)** standard deviation of soil moisture values, by aspect and depth **(c)** standard deviation of groundwater levels, by aspect.

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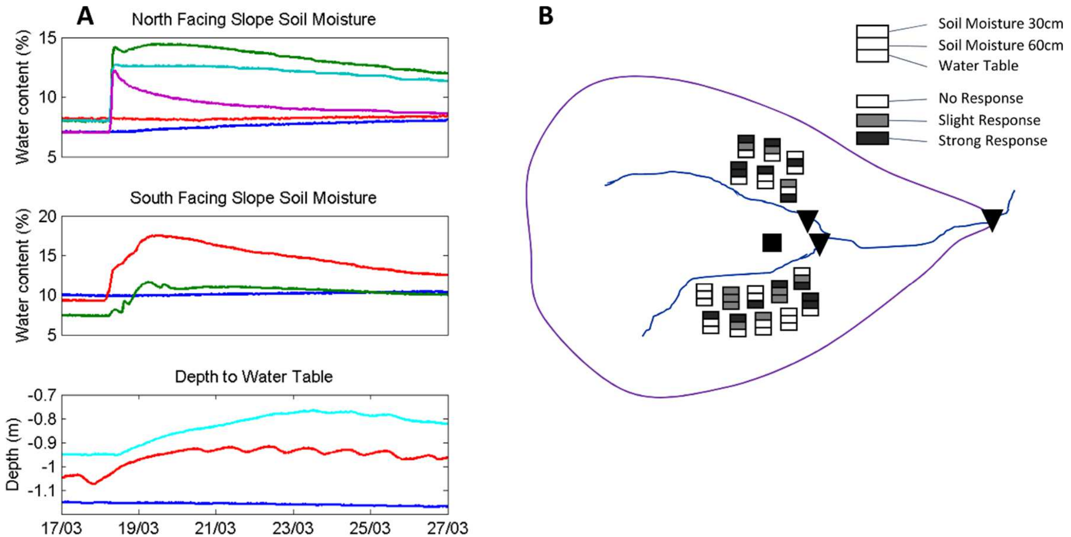

Figure 10. (a) Response of selected sensors to a March rainfall event. **(b)** Spatial overview of sensor responses to the March rainfall event.

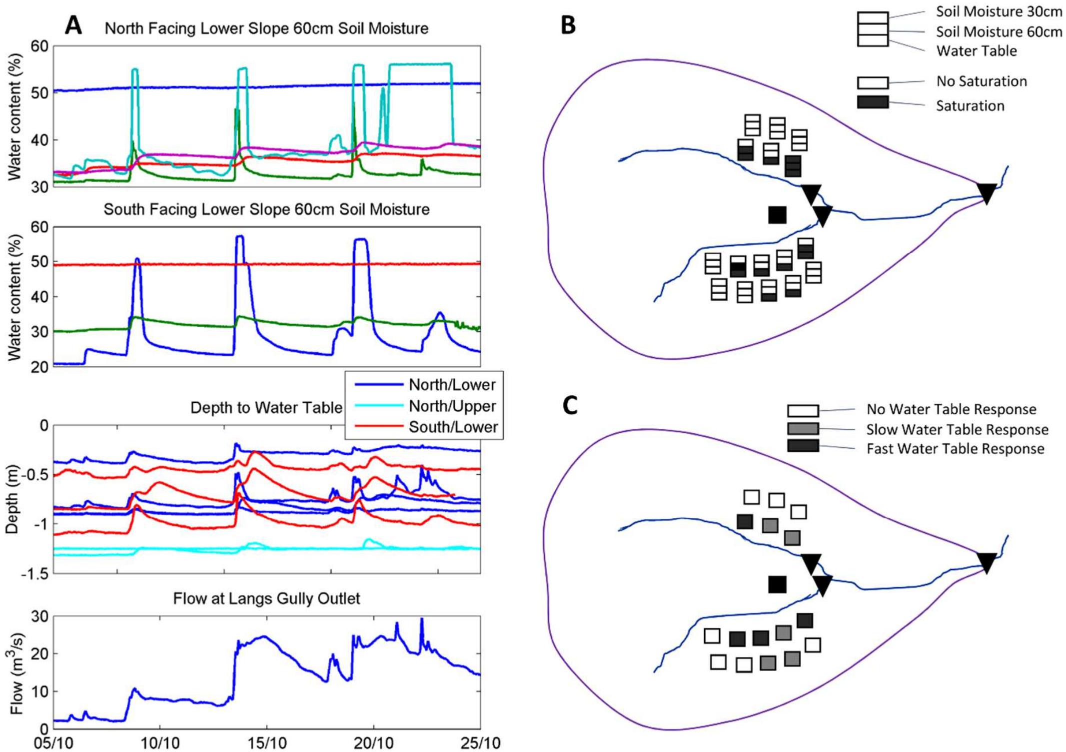

Figure 11. (a) Response of selected sensors to a Winter rainfall event. **(b)** Overview of saturation response to the Winter rainfall event. **(c)** Overview of speed of water table response to the Winter rainfall event.

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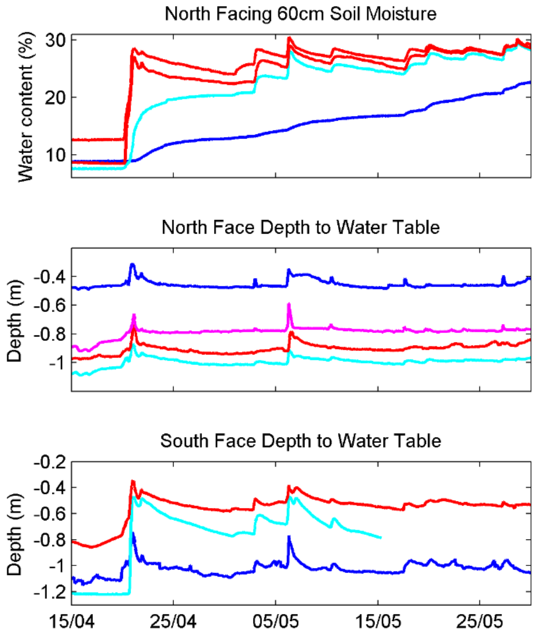

Figure 12. Winter wet-up response of selected soil moisture and water table sensors.

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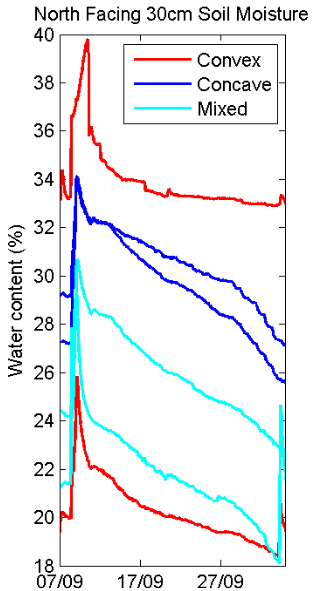

Figure 13. Selected soil moisture sensor responses during a recession.

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