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Interactive comment on "Geostatistical investigation into the temporal evolution of spatial structure in a shallow water table" *by* S. W. Lyon et al.

S. W. Lyon et al.

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Reviewer 2 is thanked for providing very in-depth and helpful comments on this manuscript. The first main concern of the Reviewer 2 is that the definitions of some of the terms used in the manuscript are not well defined. By clarifying the terminology used in the manuscript, the presentation becomes more concise and removes any speculation in the process. With respect to hydrological terms, Reviewer 2 comments that an "understanding of [the role of groundwater flow in runoff generation by the saturation overland flow mechanism] should be at the core of any analyses and understanding the role and effect of topography in representing spatial patterns and spatial dependences of groundwater head distributions at saturation overland flow runoff source areas must be described". We agree that such an understanding should be

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a main focus of this research and that this can be achieved with better description of processes.

For this hillslope and on shallow soils characterized by a highly conductive topsoil underlain by a dense subsoil in regions where the groundwater is close to the soil surface, runoff can be generated from regions that are or become saturated during rainfall events (Steenhuis et al, 1995). Rainwater easily permeates these soils and, by-and-large, runs laterally as subsurface flow on top of the restrictive layer down-slope to accumulate in converging areas making these regions prone to saturation. More water can be added to these regions via direct rainfall or exfiltration from higher on the hillslope. When these regions saturate they produce runoff that is commonly termed saturation excess overland flow. How (i.e., exfiltration of converging subsurface flow or direct rainfall onto saturated areas) and what (i.e., old or new water) water finds its way to these regions is not fully understood making the variability in physical patterns of saturated areas difficult to monitor and predict (Burns, 2002; McDonnell, 2003; Walter et al., 2005). Thus, the research is focused on identifying these patterns and their changes through time.

Reviewer 2 also comments on the use of “groundwater structure” in the manuscript stating “a structure suggests a fixed property while groundwater is a dynamic by nature”. The authors agree with this statement. In the manuscript, ‘structure’ was consistently, and we feel correctly, used to describe the spatial structure of the measurements and not in representing an inherent groundwater structure.

The second general concern of Reviewer 2 is the lack of statistical evaluation of the dataset. In addition, there is concern with “arbitrariness” of some of the results. These problems are remedied with the inclusion of statistical analysis of the dataset. With respect to the runoff measures, the percentage of flow measurements that were outside the range of the rating curve was reported in the original manuscript (Pg1691,ln3). These values may suffer due to extrapolating beyond the defined rating curve. Checking for outliers in runoff, Maidment (1992) recommends including any high outliers

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when no historical record is available such as at this field site. But to check for consistency, there is a historical record for a USGS stream gauge that receives water from a 37-km^2 watershed containing this field site. For the sampling period of this study, the stream data sampled at our field site correlated with this downstream gauge with an R^2 above 0.80. Since there is strong agreement between our measurements and the outlet measurements, it is assumed that the runoff values reported are consistent and contain no anomalies.

In addition, Reviewer 2 comments on the assumptions for saturation. Lyon et al. (in press) investigated different depths to water table below the soil surface to be considered saturated at this field site. Using a depth of 5 cm, the spatial structure of the surface saturated areas is represented well without incorporating the structure of the water table itself. Observations of saturation have reduced sensitivity to slight undulations in topography and uncertainty with defining the soil surface when using a depth of 5 cm for saturation. The reviewer comments on the 'claim that over 65% of the hillslope area is saturated" as not being realistic. These times when 65% of the hillslope is saturated are few and occur only when the median water table is very close to the soils surface. Even though they are few, they are realistic values. To demonstrate this, we have modeled the saturated areas for the watershed containing the field site for a 30-year period using the methods of Steenhuis et al. (1995). The model predicts that 10% of occurrences of saturation result in greater than 50% of the watershed saturating. This is in agreement with Figure 4C from the manuscript where, although the majority of the time the percentage of hilllslope saturated is below 50%, large rainfalls on high water tables can saturate greater than 50% of the hillslope.

Another concern of this reviewer is the selection of kriging algorithms, indicator methods, and semivariogram models. With respect to kriging, the reviewer questions the assumption of ordinary kriging that "assumes phenomenon under study has constant mean and also second order stationarity". Ordinary kriging does indeed require stationarity assumptions. Since we use a non-linear transformation of the data set (indicator variables), the stationarity requirement does not apply to the phenomenon, but the indicator variables. Keep in mind; the analysis in this study is actually indicator kriging, which happens to employ the same kriging algorithm as ordinary kriging after the non-linear transformation. Indicator approaches allow for comprehensive structural analysis and are robust to outlier values (Journel, 1983). In this way, indicator approaches allow for greater spatial correlation of extreme values (Journel and Alabert, 1989; Rubin and Journel, 1991). By using a time-variant median, and thus guaranteeing that half the points are above and half below the threshold, we obtain the best defined, with greatest range of continuity and some confidence for sparse data indicator semivariograms (Journel, 1983). This makes indicator kriging more appropriate than ordinary kriging when dealing with highly variant phenomena. As for the selection of the semivariogram model, we have investigated exponential and spherical models, both of which are widely used and offer adequate representation of lags within the range of the sample semivariograms, for ability to fit the sample semivariograms using a weighted least-squares method (Cressie, 1985). The exponential model had a lower average mean squared error versus the spherical model (3.94 and 5.65, respectively) and a lower standard deviation of mean squared error (2.52 and 3.87, respectively). Thus, the exponential is justified as it both describes the phenomena being modeled and fits better than the spherical model.

Reviewer 2 inquires on clear interpretations of the semivariograms. “Sometimes it is stated that [semivariograms] describe spatial patterns, sometimes the term structure is used, sometimes correlations over increasing distances (e.g. correlation length) are mentioned. A clear (geostatistical) understanding of a semi-variogram should be gained”. This is an excellent comment that addresses the heart of this manuscript. To clarify, a distinction needs to be made between what semivariograms represents and what kriging represents. Semivariograms give a measure of the spatial variability for observations as a function of separation distance. This represents the spatial structure of the observations. This structure is then used in kriging, an interpolation method, to visualize spatial patterns of the observations.

The majority of Reviewer 2 comments are addressed above. Below is the response to detailed comments with the reviewer comment in *italics*. All typos and minor wording suggestions from the reviewer have been corrected and accepted.

Pg1687,ln5: measurement techniques provide "new" information is clearly an overstatement since it is common practice to observed water tables by data loggers... The focus here is on the ability to sample at high temporal resolution with relatively good spatial coverage. This is an option that has not been available due to the cost associated with data loggers in the past.

Pg1694,ln19: just referring to a method of Goovaerts (1997) is inadequate but the approach should be elaborated on... Residuals were evaluated between the hard data available at sampling locations and the soft data map. These residuals where then interpolated and merged with the soft data to incorporated prior probability.

Pg1965,ln18: According to Figure 3A high intensity storms occur more frequent... The reviewer points out confusion do to word selection on the part of the authors. The rainfall record characterized by low intensity storms in the first half and high intensity storms in the second half.

Pg1695,ln20: The two largest runoff events occurred after ... According to Figure 3B this is not true... This has been justified by giving a statistical characterization of the data set and the antecedent rainfall conditions for the two largest runoff events. From this, it is seen that the largest two events (May 26^{th} and July 27^{th}) have 1-day antecedent rainfalls over 1 cm and coincide with rainfall amounts over 2 cm in depth.

Pg1696,ln5: The observed behavior in Figure 4A should be explained in the text; just describing what is observed is insufficient and has too limited added value to science... This is a great comment. The ranges for the short time interval indicator semivariograms decreased as the median water table rises (Figure 4A). This is due to transitioning from a smooth, continuous spatial structure to one that is more discontinuous. This trend changes when the median water table was about 10 cm deep. After this

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point, as the median water table rises closer to the soil surface the ranges began to increase. This increase in range is the spatial structure of the wettest sampling locations becoming more continuous over the field site.

Page 1697 Line 17: R^2 is not described and conclusions on values of R^2 in Figure 6 are not explained... The R^2 here is just given as a representation of the correlation coefficient. The important parameter from the linear relationship is the higher slope and positive intercept for March through May compared with June through August. This signifies the different relationship between topography and prior probability, which is addressed in the discussion. The text has been modified to reflect this.

Page 1700 Line 8: It is discussed where saturation commonly occurs. This however is not shown in the study and also cannot be verified based on the manuscript... The location where saturation occurs from this comment refers to locations observed in previous studies. It is shown in Figure 4D that saturation starts at low STWI values and then expands to lower values as the water table rises. Thus, converging zones and shallow soils tend to saturate first then expand up topographic lines as the water table rises. The lateral extent of expansion is captured with the decreasing minimum (and constant maximum) STWI for these saturated areas as the median water table approaches the soil surface (Figure 4D). Thus, saturation for this hillslope during wet conditions starts at the highest STWI values and spreads to locations of lower STWI. STWI values are highest at locations that combine large upslope areas, low local slopes, and shallow soils.

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