Answers to Comments from Anonymous Reviewer #1

R1_Comment #1:

"…Literature cited in the paper may be enriched (for instance, for the early warning and the modeling part – first paragraph of introduction, P1 L15-19)…"

R1_Answer #1:

Thanks for the suggestion we will extend bibliographic reference.

R1_Comment #2:

"…P1 L20: Cross-correlation is a quite standard statistical tool (see Handbook of hydrology, Salas, 1993 - this must be cited)…"

R1_Answer #2:

Thanks for the suggestion, we will integrate this bibliographic reference

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R1_Comment #3:

"…P4 L20: Please provide more details on how the confidence lines have been determined (statistical significance threshold), i.e. the formula used…"

R1_Answer #3:

Confidence interval are the same as used in medical literature (*i.e.* Chaves, L.F., Pascual, M., 2006. Climate Cycles and Forecasts of Cutaneous Leishmaniasis, a Nonstationary Vector-Borne Disease. PLOS Med. 3, 1–9. doi:10.1371/journal.pmed.0030295). More in detail, the blue dashed lines indicate the 95% confidence intervals for the cross-correlation between two time-series composed by "*white noise*" with the number of samples ("n") equal to samples composing the monitoring time-series (Brockwell PJ, Davis RA (2002) Introduction to time series and forecasting, 2nd ed. New York: Springer. 434 p.)

$$CCF\ 95\% = \frac{2}{\sqrt[2]{n}}$$

Where "***n***" is the number of samples forming the time-series.

We recall, as explained in the manuscript P4 L20, that cross-correlation results have been considered acceptable if they were either above (if positive) or below (if negative) the +/- confidence threshold. Additionally, since some of the cross-correlation maxima were quite low, we have now computed the p-value corresponding to the identified cross-correlation maxima in order to strengthen our assessment. More in detail, by means of the p-value, the null hypothesis tested corresponds to the absence of correlation between variables. The results show p-values close to zero (from 0 to 7.8×10^{-98}) for all combinations, which support the significance of cross correlation results even in the cases of low maxima.

R1_Comment #4:

"…P4L23 Why a 5% threshold has been chosen, and not another one? The authors should possibly investigate if statistical tests aimed at verifying the significance of cross-correlation variation do exist. Though this issue may significantly change the time-lag interval around the maximum CCF value, the 5% threshold may be however accepted. What I just ask to the authors is to possibly justify this value and to verify the existence of above-mentioned statistical tests…"

R1_Answer #4:

Since most correlograms show CCF distributions that are somehow similar to "Gaussian", we decided to include the values of CCF at +/- 5% threshold from the peak (and the related time-lag intervals) in order to provide information about the "shape" (flatness: i.e. lower significance" or peakness, i.e. higher significance) of the cross-correlogram without having to provide figures for all cross-correlogram. And yes, we might have used a different value as well. The choice of 5% was arbitrary, and driven by the fact that generally, this is a familiar value in Gaussian distributions. However, since the correlograms are not precisely Gaussian, we agree with the reviewer that the 5% might not represent the same statistical significance for all correlograms (i.e. we might have asymmetric distribution around the peak), and this might be a weakness. Nevertheless, we still believe that in order to "intuitively" compare the different correlograms that cannot be reduced to a precise Gaussian distribution, it is necessary to use the same +/- threshold, even if it might not necessarily represent the same level of significance of cross-correlation. Thus, we believe that for the purposes it was meant for, the analysis of the statistical significance of the adopted +/- range would not add much information about the reliability of the correlation peak in terms of time-lag interval.

R1_Comment #5:

"…The authors should make scatter plots of one variable against the other at various time lags, in order to assess whether or not the statistical dependence between variables is LINEAR or NON-LINEAR. In the second case the authors should apply: or a transformation of the variables, or a non-linear (cross) correlation analysis. This is a crucial issue that the authors need to address for publishing the paper."

R1_Answer #5:

We have performed the requested time-lagged scattered plots and, as correctly assessed by the reviewer, non-linearity affects relationships “rainfall vs displacements” and “rainfall vs. piezometric depth”. At the same time we can confirm that a linear dependency can be reasonably assumed to exist (R^2 values between 0.6 and 0.78) for the following time series combinations: Piez. Depth vs. Piez. Depth.; Displ. Rate Vs- Displ. Rate; Piez.depth vs. Displacement Rate. However, it is also to be mentioned that, despite the fact that Corominas et al (2005) indicated non linearity between Piez. depth vs. Displacement in the long term, the scattered plots indicate linearity over the short term. Moreover, it should be noticed that we’ve here more explicitly indicated that, in order to apply the cross-correlation function (see also response to R2_Comment#1c), the displacement time-series had already been, in the submitted paper, converted into differential displacements, i.e. the displacement occurred within the 20 minutes sampling interval, which is essentially a displacement rate (velocity). Finally, we must say that, unfortunately, the non-linear correlation between precipitation and other variables cannot be reduced to any power law, so transformation (i.e. linearization) is basically impossible. Thus, being fully aware that this is the crucial issue for the acceptability of the paper, we propose to the Editor that we make a major revision of the paper by :

- highlight the non-linearity between rainfall vs. piezometric level” and “rainfall vs. displacements” and discuss their dependence on a more qualitative level
- highlight, in order to avoid misunderstandings, that CCF was applied to “displacement rate” and not, as reader might erroneously assume, cumulative displacements
- limit the CCF analysis to the combinations that proved to have an acceptable linear dependency: we believe we would still be able to discuss the Vallcebre landslide dynamics under several perspectives, such as hydrogeological features (by means of “Piez. Depth vs. Piez. Depth” cross-correlation results), style of movement (by interpreting results from the cross-correlation between “Displ. RATE Vs- Displ RATE” time-series), hydro-mechanical processes (highlighted by the results of cross-correlation between “Piezometric depth vs. Displacement *RATE*”).
- add an appendix section with the lagged scatterplot (with R^2 values respect to linear trends and specific p-values) will be included in order to present the degree of linear dependency between analysed variables by means of the cross-correlation function.

R1_Comment #6:

“…Fig. 2: Significance of statistical analysis may be improved by adding other data. The data presented in the paper cover the years 1999-2002. From papers by the same authors it seems that other data do exists (e.g. Corominas et al, 2005). If this is the case, why not add these data to the analysis?

R1_Answer #6:

Yes, other data exist. However, we can argue that: (i) the analysed time interval (from 01-Jan-1999 to 01-jan-2002) covers 3 years characterized by variations of velocity and it is in any case representative of the “ordinary” mobilization pattern of the landslide (ii) the analyzed time interval it is the longest available interval characterized by full continuity of data. So yes, we might have analyzed also other periods, but on separate calculations, since continuity of the time-series is a discriminant for the application of the cross-correlation function. To exemplify our arguments, we might include in the revised paper (if the editor believes it might be necessary) the figure 1, which shows the average displacement trend of the landslide (≅25cm/year) over the 15 years-period of measurements, evidencing how the analyzed period is in line with all other “ordinary” years (that are different from the “unusual” period 1997-1998, which was characterized by velocities higher than the usual (≅50 cm/year)), and how, after 2002, some gaps start to appear in the time series.

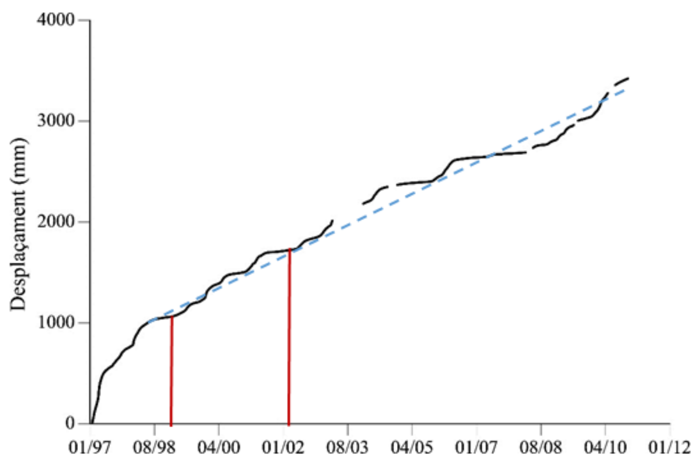

Figure 1: Cumulative displacements of the wire extensometer S-2 during the period 1996-2012.

R1_Comment #7:

Sect. 5: Paper organization mistake in the Results section: subsections report results relative to a variables combination that is different from that declared in the subsection title. The discussion of rainfall vs piezometric depth is missing. In detail: title of 5.1. should be rainfall vs displacement, 5.2 piezometric depth vs displacement, 5.3. displacement vs displacement, 5.4. piezometric depth vs piezometric depth. 5.5 is a repetition of 5.4.

R1_Answer #7:

Thanks, corrections will be performed.

R1_Comment #8:

“…Discussion (Section 6): Some of the conclusions seem to be not directly supported by the paper results, and are a rather subjective interpretation of the authors. Please better link discussion to results, and explicitly declare what should be assumed as a subjective/reasonable interpretation of the authors…”

R1_Answer #8:

We can edit the discussion, so to meet the reviewer requirements, in the following way:

The results obtained by means of CCF analysis can be discussed on the perspective of hydro-mechanical slope processes that are somehow more complicated that a direct relationship between groundwater and movements.
The presence of lagged response in open-pipe piezometers like those installed in the Vallcebre landslide should be beard in mind during the discussion of the results. Depending on the piezometer type, geometry and on the permeability of the local soil around it, different time lags are necessary to measure the 90% of the occurred piezometric level variation. Nevertheless, it should be taken in consideration that a complete level variation is not necessary for the CCF analysis to determine a time-lag value.
The time-lags between different piezometers from upslope to downslope range predominantly in the positive values (Fig. 7f), meaning that the response of each piezometer to groundwater level is driven by the variations occurred upslope. It is therefore reasonable to consider as a working hypothesis the presence of a downslope directed pore-pressure transfer-wave that, even in substantial absence of water transfer (given the low permeability of landslide materials), determines the major peaks of groundwater levels after rainfall. Therefore, pore-pressure transfer results to be the hydrological key-factor determining groundwater level variations in this portion of the landslide body rather than an actual groundwater filtration involving mass transfer. A tentative estimation of the apparent pore-pressure velocity transfer can be done by considering the time-lags obtained in the cross-correlation between piezometric depths and the distance between piezometers. On a such basis, the apparent pore-pressure velocity transfer can be estimated as: 2.1×10-2 m s-1 from S4 to S2; 4.1×10-1 m s-1 from S2 to S9; 3.1×10-1 m s-1 from S4 to S9. It can be speculated that the higher apparent velocity obtained in the sector from S2 to S9, in the lowest part of the landslide unit, might be related to the fact that it corresponds to a compression zone where, presumably, the pore-pressure transfer through the landslide body is more effective.
On a mechanical perspective, the cross correlation between displacements recorded by the wire-extensometers indicates that it is quite reliable to consider the assessment of a retrogressive evolution of movement propagation, with time series of displacement in downslope extensometers leading time series of displacement in upslope extensometers (see Fig. 7e for a synoptic view). The aforementioned evidence is in agreement with the results of the landslide evolution model proposed by Ferrari et al. (2011), in which the key-role of the toe erosion by the Vallcebre stream for the triggering of the landslide is stressed. On a hydro-mechanical perspective, the analysis of the relationship between piezometric depth and displacements confirm the leading role of piezometric depth variation since in all three monitoring sites displacement peaks result to occur after ground water peaks (Fig. 7b-c).
Considering all the aforementioned findings, it is therefore reasonable to assume that the response of the Vallcebre landslide is led by the following mechanism: the increase of pore water pressures is first noticed in the upper part of the landslide unit (S4 and S2), it is not high enough to produce the acceleration of the landslide. Once the increase of pore water pressure reaches the landslide foot (S9), then the acceleration takes place. Therefore, motion is driven from the foot of the landslide to its head. Thereafter, the advance of the landslide mass increase instability of the landslide foot, which combined with the torrent erosion, cause periodic small failures there, delivering slope

material to the valley bottom subsequently evacuated by the stream (Fig. 8). This triggers a retrogressive evolution of slope movements that affects all the lower unit of the Vallcebre landslide.

R1_Comment #9:

"…Sect P8 L16-19: please explain better the "second mechanism"…"

R1_Answer #9:

In the previous point we propose to edit the discussion, so to meet the reviewer requirements. Last paragraph essentially explains the mobilization mechanism occurring in the landslide (see answer above).

Eventually, the following sentence and the figure 2 can be added: "*We have evidences that the slope toe is being eroded (see Figure 2) and this erosion may lead to further displacement of the landslide foot as shown by Ferrari et al (2008). The interaction between the toe of the landslide and the Vallcebre torrent can be noticed in figure 2, were the evolution in time of the distance of the to respect to a benchmarck (boulder in the stream) can be followed through ten years (from 2003 to 2013). However, to erode the foot a minimum discharge of the Vallcebre torrent is required.*

2003

2008

2013

Figure 2 (top): local failure of slope toe deposited in the torrent bed; the deposits are removed by erosive activity of the torrent (middle) and new local failures are generated (bottom).

R1_Comment #10:

"…Sect Fig. 2b: is the plot of piezometric depth for S4 correct?..."

R1_Answer #10:

Yes, this is the groundwater depth recorded at the S4 site

R1_Comment #11:

"…P2 L6 perhaps replace "monitoring data" with "landslide-related variables" P2 L11: first 950 m then 1250 m; it should also be specified that elevation is measured a.s.l. (above sea level)…"

R1_Answer #11:

Thanks, we will follow your indications.

R1_Comment #12:

Is there a specific reason why borehole numbering has to be S4, S2 and S9? If not, why not renumber as SL1 SL2 and SL3 (where L indicates "Lower Unit")?

R1_Answer #12:

We have kept the borehole numbering presented in the previous papers (i.e. Corominas et al. 2005) in order to maintain consistency.

R1_Comment #13:

Sect Tables 1-5 replace "lap" with "lag"

R1_Answer #13:

Thank, the correction will be performed.

R1_Comment #14:

P10 L13 remove "350"

R1_Answer #14:

Thanks, we will erase it.