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Hydrology and
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Interactive comment on "A new method for determination of Most Likely Initiation Points and the evaluation of Digital Terrain Model scale in terrain stability mapping" *by* P. Tarolli and D. G. Tarboton

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The authors thank Referee #3 for the detailed review and comments on this paper. Following is our response.

Referee #3 was critical of the paper for its reliance on the SINMAP model (Pack et al., 1998) with assumed steady state solution to rainfall infiltration coupled with an infinite-slope stability calculation. The referee noted that these assumptions had been criticised by Iverson (2000) for being restrictive. The present Most Likely Landslide Initiation Point (MLIP) paper was not written with the intent of being tied to or limited by any particular model. SINMAP was used as a convenient example. The contributions

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of the paper are the method for identifying the set of MLIP points as the set comprised of the most unstable points on each possible downslope flow path. We believe that there is value in this concept and the method to identify such a set regardless of the underlying terrain stability model. In the paper we show how MLIP points can be identified and how they compare to observations in terms of being at the upslope end of landslide scars. We show how MLIP points can be used with mapped landslide scars that include the run out zone to quantify the fidelity of a terrain stability map by evaluating the density of MLIP points within and outside the mapped landslide scars. The contribution of this approach is the new technique that it presents for the evaluation of terrain stability maps.

With respect to the restrictive SINMAP assumptions that referee #3 mentions, we believe that it is established in the literature that convergence of subsurface flow in topographic hollows or swales plays some role in the triggering of many shallow translational landslides (e.g., D'Odorico et al., 2005; Borga et al., 2002; Roering et al., 1999; Tucker and Bras, 1998; Montgomery et al., 1997). Hillslope flow processes are complex and involve preferential flow pathways and processes not always amenable to description using Richards equation. Nevertheless, following Beven et al. (1995), we feel that the general tendency of water to flow downhill is amenable to macroscale conceptualization and that the approach of SINMAP (Pack et al., 1998) and SHALSTAB (Montgomery and Dietrich, 1994) that relate the relative wetness at a location to the upslope contributing area captures these topographic effects in a simple way. Basically these models represent relative wetness as Ra, where a is the specific catchment area (contributing area per unit contour width) and R a constant that can be interpreted as steady state infiltration. But Ra can also more generally be interpreted as a proportionality constant reflecting the likelihood of greater wetness and higher pore pressures in convergent areas with larger a. Better models for the convergence of subsurface flow to capture this effect more precisely are certainly to be encouraged (e.g. Wu and Sidle, 1995; Borga, et al., 2002). However, one drawback of the Iverson (2000) approach is that the terms dropped during simplification of the dimensionless Richards equation

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from three dimensions to one dimension are the horizontal flow terms. This occurs both for long term behavior (Iverson, 2000 equation 7, page 1900) and short term behavior (Iverson, 2000 equation 16 page 1901). Without these horizontal flow terms the effect of the convergence of lateral flow is difficult to model. D' Odorico et al., (2005) present a model that combines the long-term response related to specific catchment area with the short term response using Iverson's (2000) approach. It would be interesting to cast this model in a geographic context so that its results could be used as an index for the MLIP approach. This is however beyond the scope of this paper where the focus is on the most likely landslide initiation point procedure with any index.

In revisions to the paper we will note the criticism of the SINMAP assumptions by Iverson (2000) and indicate that the MLIP approach is not limited to application with SINMAP, but can be used with any terrain stability model.

Referee #3 also commented on the density of LIDAR points, noting that "Ten-meter cells essentially capture all the point data." We disagree with this. After filtering the LIDAR the average density of bare ground LIDAR returns is 0.26 points per m2 (3.8 m2 per point). 10 m grid cells have an area of 100 m2, and are therefore on average based on 26 points. The highest resolution DTM grid derived had 2 m cells that have an area of 4 m2 that are on average based on 1.05 points. This was why we limited the analysis to grid cells larger than 2 m. We do note however that in areas of dense vegetation there are sometimes gaps in the LIDAR coverage. Figure 4 was presented to make readers aware of this issue, although we feel that this issue does not limit the results. Specifically there are no significant LIDAR point gaps for the areas shown in Figure 3 (Page 416) and Figure 11 (Page 424) of the paper. Figure 11 shows that the MLIP approach is effective at identifying points at the head of mapped landslide scars. The finding that 10 m DTMs result in the highest MLIP densities is, we believe, due to the 10 m scale DTM being best able to represent the slope and topographic convergence scale that is responsible for triggering landslides in this study area. DTMs at coarser scale miss detail, while DTMs at finer scale represent small scale topographic irregularities too small to trigger landslides. Though more information is available in the 2 m DTM, the 10 m DTM conveniently smooth's over finer scale lidar-derived surface detail that does not help in the prediction of this particular size of landslide.

Referee #3 indicated that discussion of the physical meaning of the MLIP technique should be added. We will, in the revisions, do so. Physically MLIP points are the most unstable points along a downslope path from ridge to valley according to some terrain stability model. Conceptually they can be identified by tracing down from each grid cell until one exits the region and marking the point where stability index is the lowest. The actual algorithm for evaluating this works somewhat differently to take advantage of the efficiency of recursive GIS calculations as explained in the paper, but physically this is what they are.

We thank Referee #3 for the specific comments. The paper will be revised to address these points.

Specifically: 1. Title. We agree with the suggestion to add "landslides" after "likely" in the title. 2. We will try to limit the unnecessary use of acronyms. 3. The value reported for annual rainfall is actually rain and snow, so will be noted as annual precipitation between 1300 and 2500 mm in the revised paper. 4. Additional basic details about the soil and landslides will be provided. Part of the soil of Miozza basin is characterized by morain formations with vegetated talus deposits. These cover the 40% of total area. Others soils are calcareous, calcareous-marly, and arenaceous formations that cover the 35% of total area. Some of the landslides occurred at the bedrock interface while others occurred in the upper part of soil (˜0.5m deep). We do not have data on the specific rainfall that triggered the slides. The occurrence of landslides in complexes is not the result of a specific rainstorm event, but a combined effect of different events including both extreme short rainfalls, low intensity long duration rainfalls, and snow melt. 5. The interpolation of DTMs from point data can result in artificial pits. Pits are regions of the DTM surrounded by higher elevations that do not drain anywhere. The TOPOGRID algorithm is a spline technique that uses slope rather than curvature as the spline penalty function. This approach has been shown (Hutchinson, 1988; Hutchinson, 1989) to limit the occurrence of pits and produce DTMs that are hydrologically correct in the sense that there are no pits which result in internal drainage and incomplete contributing area values. 6. The paragraph on page 404, lines 18-24 has been rewritten to try make it clearer and use less jargon. The numerical evaluation of most likely landslide initiation points is achieved in three steps. Inputs are a grid of stability index values and a grid of flow directions determined from the digital elevation model. First, based on the flow directions, the minimum stability index value downslope of each grid cell is computed and saved as the minimum downslope grid. Then, also based on the flow directions, the minimum stability index upslope from each grid cell is computed and saved as the minimum upslope grid. Most likely landslide initiation points are then identified as those points where the minimum downslope, minimum upslope and original stability index grid values are all equal. This procedure was followed so as to take advantage of the efficiency provided by a recursive evaluation of minimum downslope and minimum upslope values adapted from the recursive evaluation of contributing area used by Tarboton (1997) with the D multiple flow direction model for representation of flow over a terrain surface. 7. In Table 2 the SI columns reports the percentage of terrain less than the specified SI threshold that falls within the mapped landslides scars. We will in the revisions try to explain this more clearly. Columns labeled SI in table 2 represent the percentage of terrain within landslide scars that is less than the indicated threshold. Specifically for the 50 m grid resolution all the terrain has SI $<$ 10 and 4.7% of the terrain is within mapped landslide scars so the percentage is 4.7. As the stability index threshold is reduced, moving up the column the percentage of terrain less than the stability index threshold that falls within the mapped landslide scars increases, reflecting the fact that a higher fraction of terrain with low stability index falls within the mapped landslide scar. This increase is a measure of the effectiveness of the stability index approach at discriminating terrain where landslide scars have been mapped. 8. At the scale of figure 10 it is difficult to see, in the complex in the upper left of the figure the precise positioning of the landslides. In the revised paper we will add a figure to expand this area. This figure shows that the string of MLIP points along the northern edge of this complex correspond to very steep slopes dropping in to the landslide scar.

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