Reviewer comments and author responses

Reviewer comment (RC1)

The study provides a conceptual workflow for the integration of geophysical imaging in local landslide early warning systems (LoLEWS). Increased spatio-temporal resolution of geophysical data in combination with corresponding laboratory-based transformations can contribute to reducing uncertainties commonly associated with geological conditions on local scales and improve landslide forecasting. The authors are also encouraged to revise the paper and address the following comments:

RC1-1. Please clarify if the conceptual framework for LoLEWS is limited to landslides triggered by changes in groundwater conditions.

RC1-2. Quantitative analyses of slope failures and landslide forecasting with physical-based landslide prediction models often require knowledge on shear strength of soil. The relationship between geophysical data and shear strength properties of soil is not clear. Will the shear strenght properties be derived from classical tests (e.g., direct shear and triaxial tests) and enriched with geophysical data or directly from geophysical data? In Figure 3, the slope-scale shear streght model is derived from laboratory resistivity/suction/stress relationships and laboratory derived Waxman-Smith model. Please clarify if the laboratory tests also include shear strenght tests and if they are sufficient to describe shear strenght properties of soil.

RC1-3. Although geophysical data can contribute to reducing uncertinties in in geological conditions, it is unlikely that uncertainties in geological properties will be completely eliminated. In addition to the uncertainties due to heterogeneous geological conditions, uncertainties will arise in, among others, the process of transforming geophysical data to geological parameters and landslide forecasting. The conceptual framework in Figure 1 and the roadmap in Figure 3 do not explicitly include steps or methodologies for dealing with uncertainties. Please clarify if a strategy for dealing with uncertainties is envisioned in the conceptual workflow.

RC1-4. Is the technology necessary for collecting geophysical data suitable for being installed in very steep and remote areas, without access to power or internet and subjected to harsh weather conditions, which are typically encountered in deployments of landslide monitoring systems?

Author response (AC1) to reviewer comment (RC1)

Thank you for your comments (RC1) on our manuscript, which comprise a series of considered clarifications and additions which will be incorporated in to a revised version. In response to your comments:

AC1-1. We will clarify that this framework applies primarily to landslides triggered by changes in groundwater conditions.

AC1-2. There are two approaches to estimating the shear-strength from geophysical data as outlined in Figure 3. As identified in the comment, one approach is to use ERT; in this approach, the ERT data are transformed to moisture content using the (laboratory-derived) Waxman-Smits relationship, then, the moisture content is related to soil suction (Fredlund et al., 2011) before being transformed to shear strength (Vanapalli et al., 1996). A second approach is to use direct laboratory measurements of shear-strength and shear-wave velocity and derive a relationship between the two properties. This can be achieved using direct laboratory measurements of shear-strength and shear-wave velocity (e.g., using direct simple shear testing and bender element measurements) and/or field measurements (using shear-vanes and field seismic measurements) (see Trafford and Long, 2020) or using a combination of database data and field measurements (see L'Heureux and Long, 2017). The difference between the means of estimating shear-strength (i.e., ERT data transforms and seismic laboratory and field relationships) and how they differ is not made clear in the manuscript, and further clarification can be added in revision.

AC1-3. Our central message in this brief communication is that the addition of geophysical instrumentation in establishing and operating LoLEWS provides subsurface information at spatiotemporal scales that cannot be practically replicated using existing approaches. Geophysical approaches have the potential to provide spatially and temporally rich information in areas and/or volumes of the slope for which there would otherwise be no information at all. Hence, the addition of these geophysical data can help to reduce the overall uncertainties in quantifying destabilising hydrogeological processes operating at the slope-scale. However, while we agree that the inclusion of geophysical data to LoLEWS will reduce, rather than eliminate, uncertainties surrounding geological properties, we also recognise that the use of geophysical and laboratory-based transforms will in turn introduce some new uncertainties to a LoLEWS system. We have not focused on uncertainties within this framework, as we aim to present a broad-scale route toward integration and inclusion of geophysical techniques in new and existing LoLEWS, and the uncertainties surrounding these are highly site-specific, and would need to be understood in a local context. While this brief communication does not have the scope to discuss in detail the propagation of uncertainties (as this is still very much an open question in research), we recognise that acknowledging and understanding uncertainties is a crucial part in establishing LoLEWS. Therefore, we will update the conceptual workflow in Figure 1 to include sources of uncertainty that must be considered, and will include a brief subsection outlining these sources of uncertainty.

AC1-4. Technological and hardware advances mean that geophysical systems are increasingly able to be installed in remote and difficult terrain (see Whiteley et al., 2019 and references therein). Examples cited in the manuscript and elsewhere (the limit on the reference count for Brief Communications in NHESS preclude inclusion of many examples) include deployments in “difficult” environments, for example: i) where mains power is not accessible, and local power has been generated by wind, solar or fuel cells (Uhlemann et al., 2017), ii) cellular networks have needed to be established in order to transmit data (Uhlemann et al., 2017), iii) equipment has had to be carried by hand over rough terrain rather than by vehicle access (Uhlemann et al., 2017), and iv) equipment has been subjected to harsh climatic conditions including annual freeze-thaw cycles in temperate environments (Holmes et al., 2020), monsoon conditions (Watlet et al., 2019), permafrost conditions (Uhlemann et al., 2021) and arctic studies (Cimpoiasu et al., 2021). Generally, the major limitations on installation of these systems are related to access, rather than shortcomings in the equipment. Another reviewer (RC2) has raised a similar point regarding cost and robustness, and we will include text to emphasise the points raised above, and in response to their comment.

Reviewer comment (RC2)

The submission is a brief conceptual paper that can be seen as a “case” for the use of time-lapse geophysical surveys in local early warning systems (LoLEWS) for weather-induced landslides. The arguments, clearly expressed and well framed in the context of reference literature, are centered around three well-designed and self-explanatory figures, highlighting the role that geophysical field measurements have in the workflow of activities needed for landslide early warning. The paper is almost ready for being published as is, yet the following minor revisions are suggested.

RC2-1. Some issues that are worth being considered in this discussion are the costs and robustness of the geophysical deployments, and the effectiveness of geophysical surveys in relation to different types of soils and landslides.

RC2-2. Always introduce the meaning of acronyms when they are first used (HHLO, DAS).

RC2-3. The first paragraph of conclusions does not derive from previous comments in the article. Thus, it is more appropriate to move it at the end of the conclusions.

Author response (AC2) to reviewer comment (RC2)

Thank you for your comments (RC2) on our manuscript, which will be incorporated in to a revised version. In response to your comments:

AC2-1. Another reviewer (RC1) has raised a similar point regarding the ability of equipment to be deployed in remote and difficult to access areas, and we will include further information on these aspects to emphasise the cost-benefit and increasing robustness of these systems. Please see reply to comment (AC1) for details.

AC2-2. We will properly introduce the acronyms in the manuscript.

AC2-3. The conclusion will be reorganised into a more logical format.

References for author comments

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