

Supplementary Materials for

Seismic velocity changes associated with a flash flood crisis as a proxy for slope instability

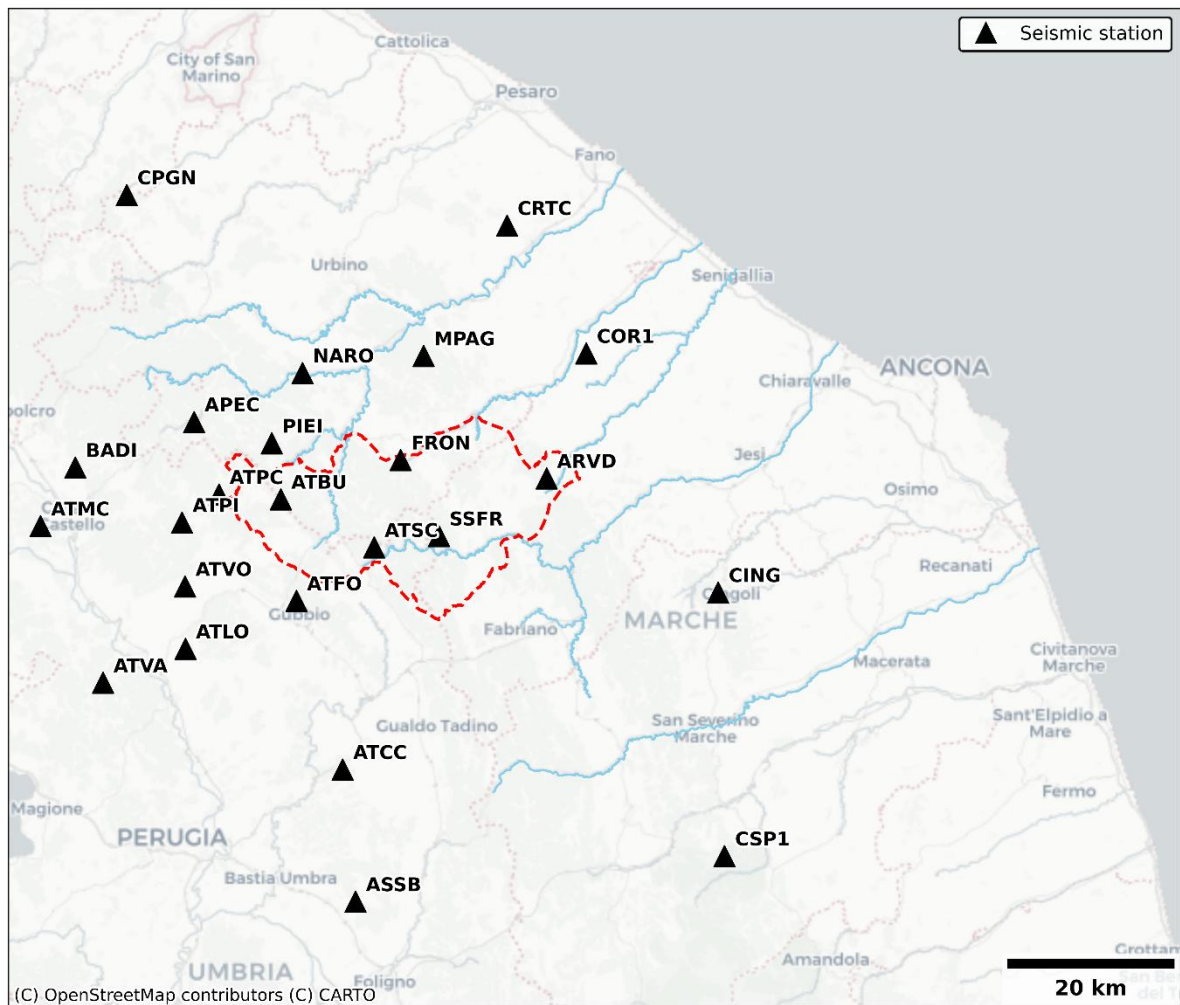
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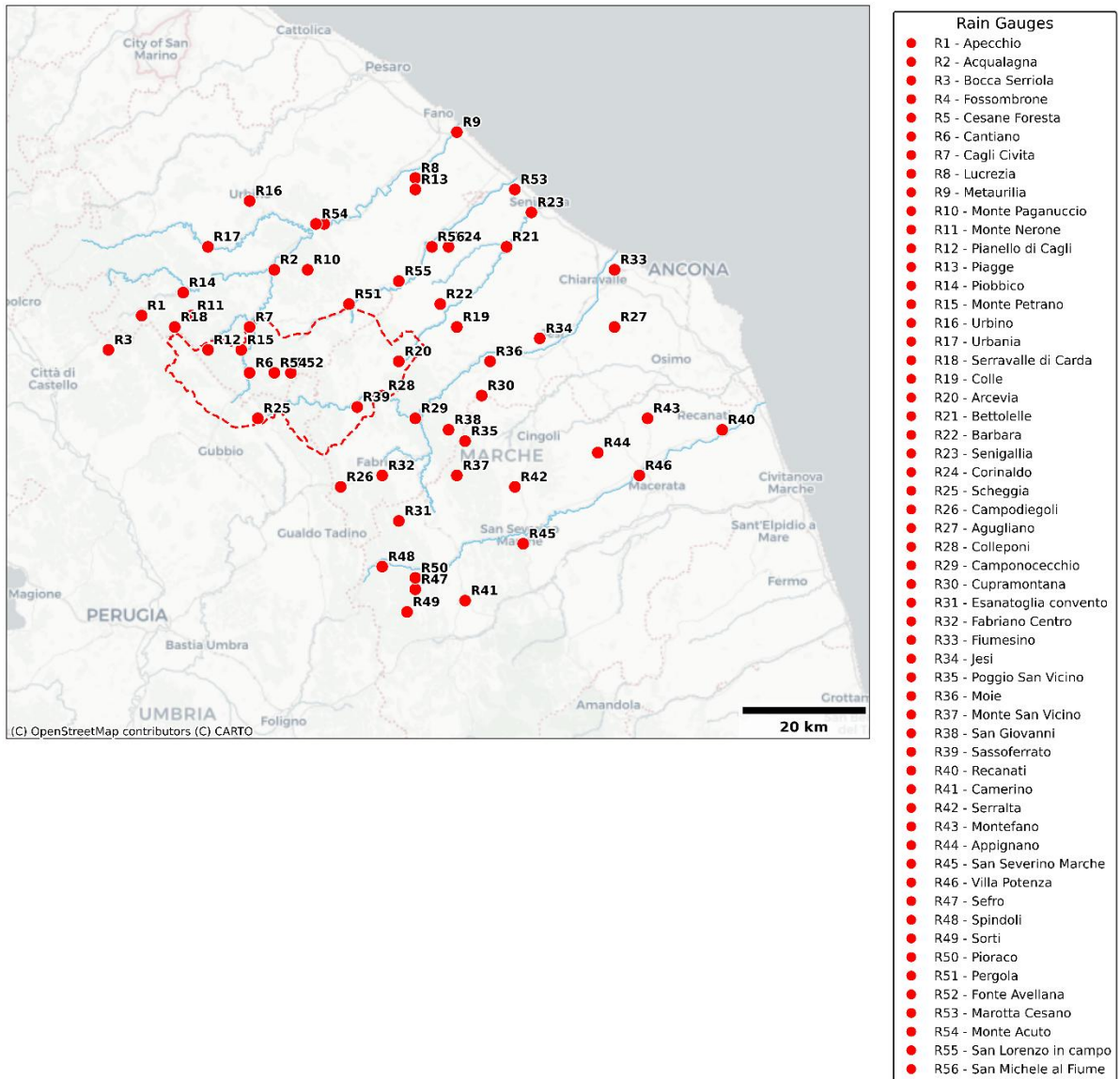
This PDF file includes:

Figs. From 1 to 34



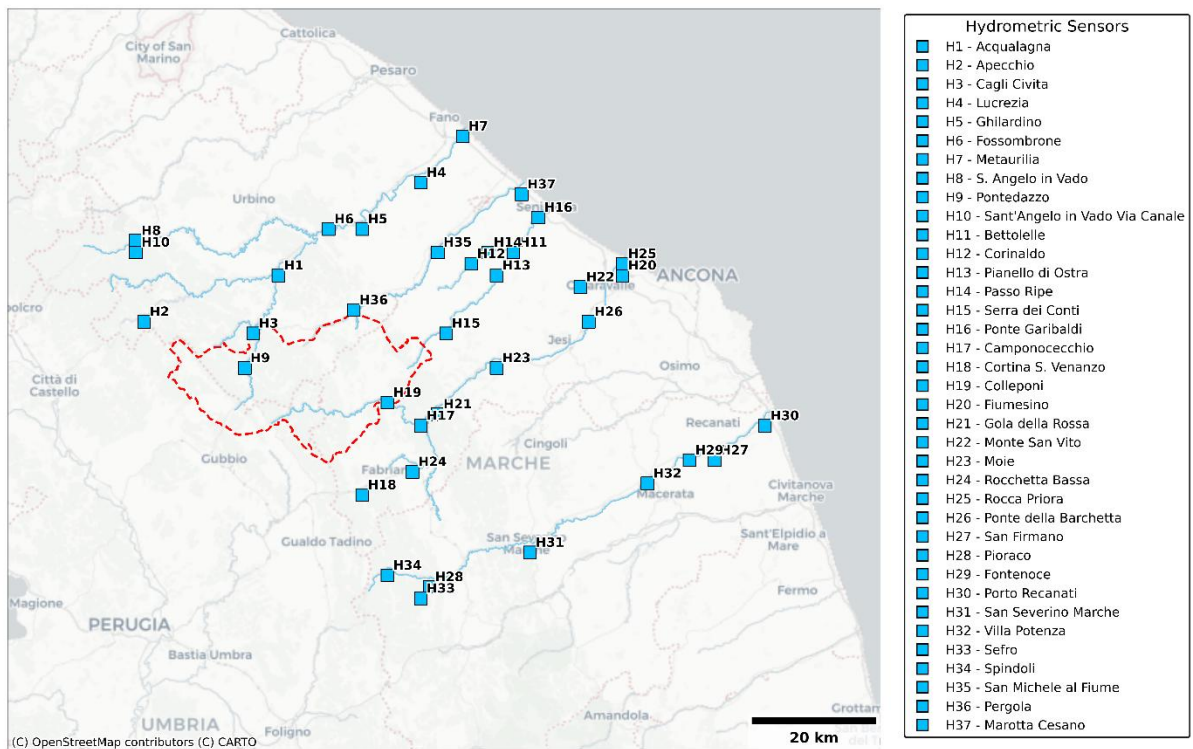
Supplementary Figure 1: Distribution of seismic stations.

Marche region seismic stations utilized in this work in the INGV IV network. The dashed red line delineates the landslide-affected area.



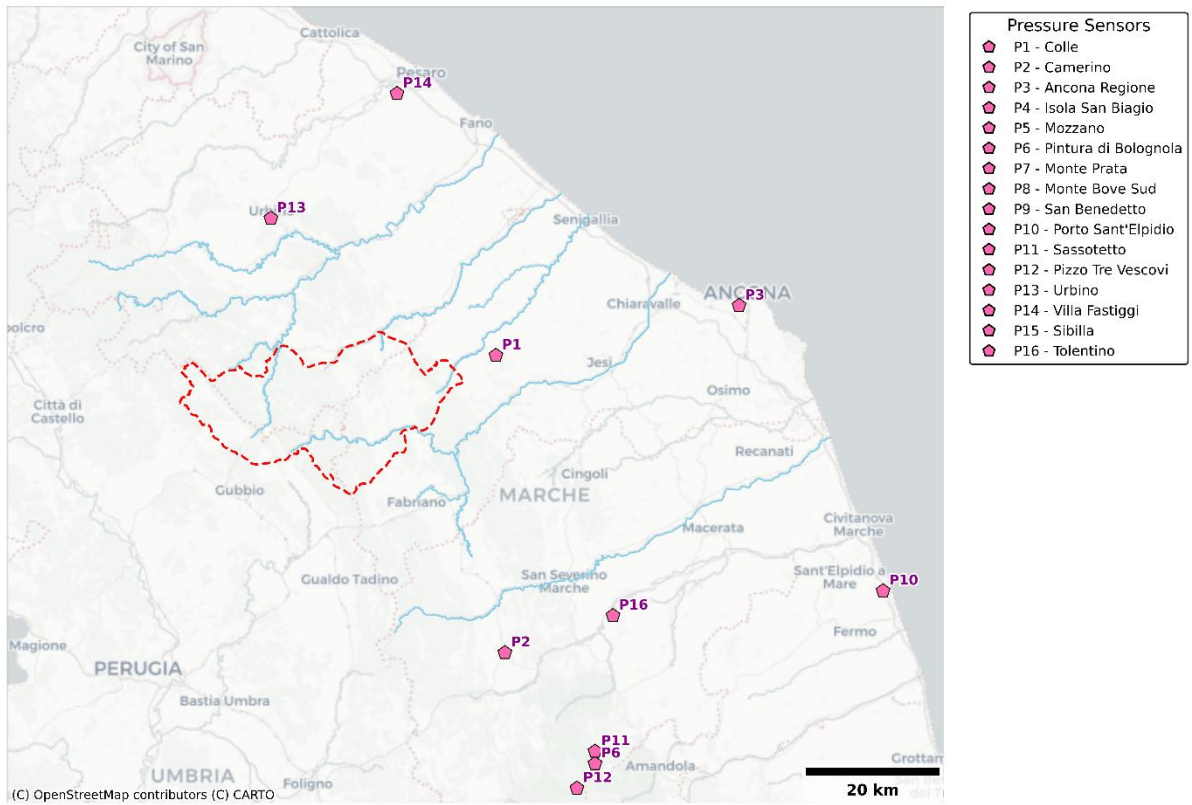
Supplementary Figure 2: Distribution of rain gauges.

Station names are provided in the legend. The dashed red line delineates the landslide-affected area.



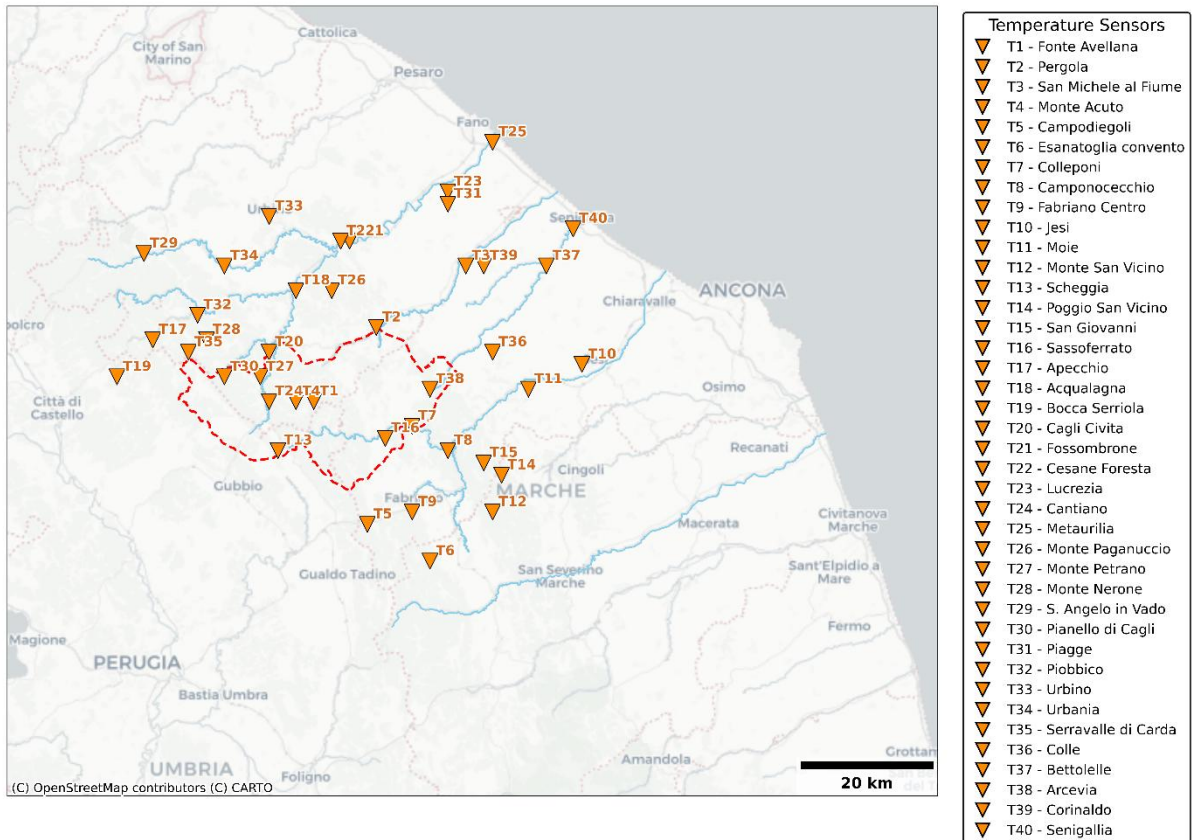
Supplementary Figure 3: Distribution of hydrometers.

Station names are provided in the legend. The dashed red line delineates the landslide-affected area.



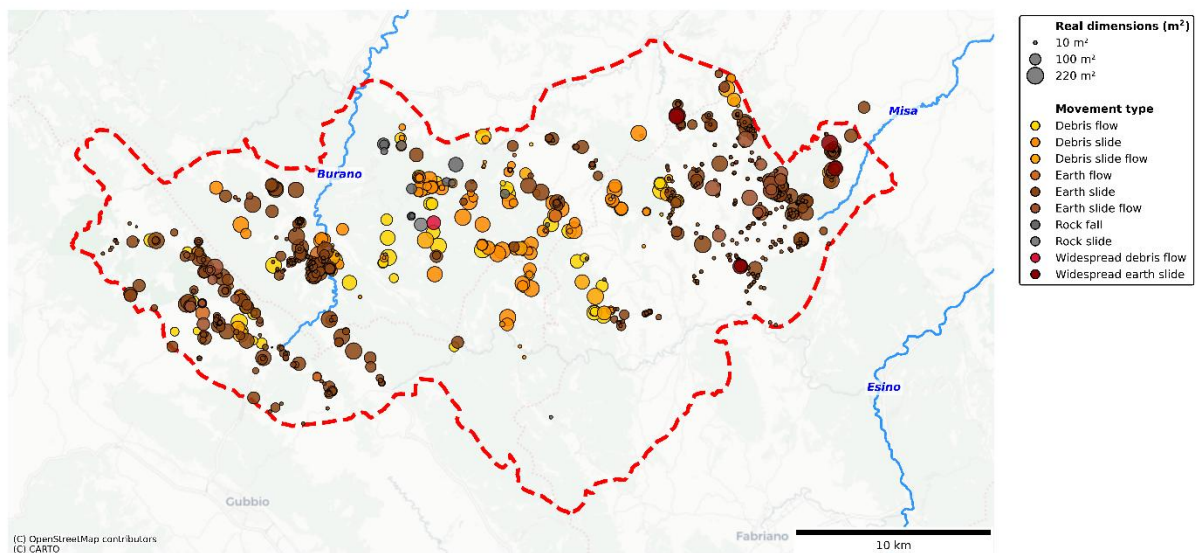
Supplementary Figure 4: Distribution of atmospheric pressure sensors (barometers).

Station names are provided in the legend. The dashed red line delineates the landslide-affected area.



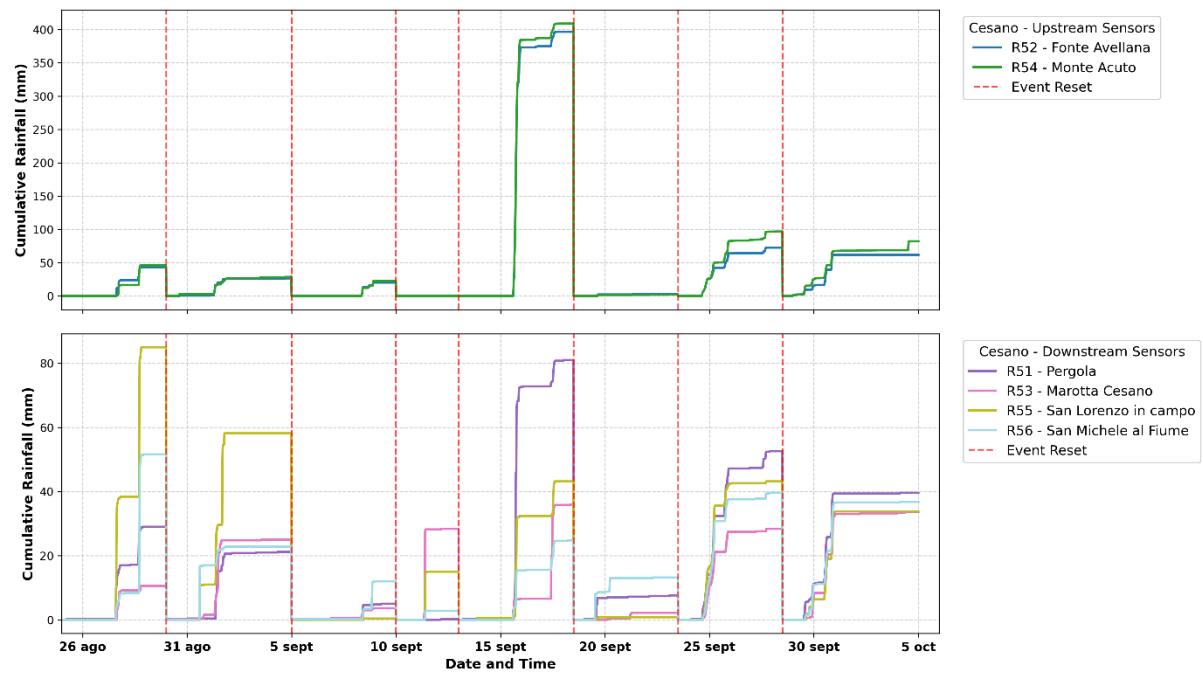
Supplementary Figure 5: Distribution of temperature sensors (thermometers).

Station names are provided in the legend. The dashed red line delineates the landslide-affected area.



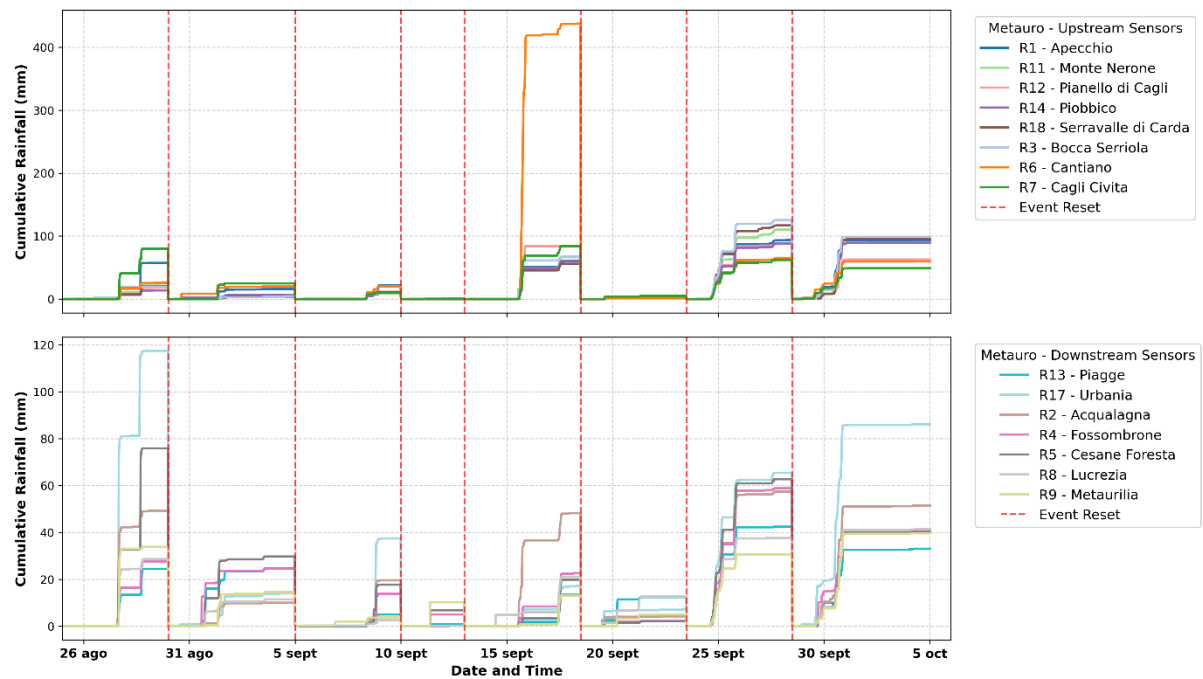
Supplementary Figure 6: Distribution of landslides.

Detailed map of landslide-affected area. Coloured circles denote landslide events, with diameters proportional to the affected area (not in scale, see legend) and colours indicating the landslide movement type (as defined in the legend).



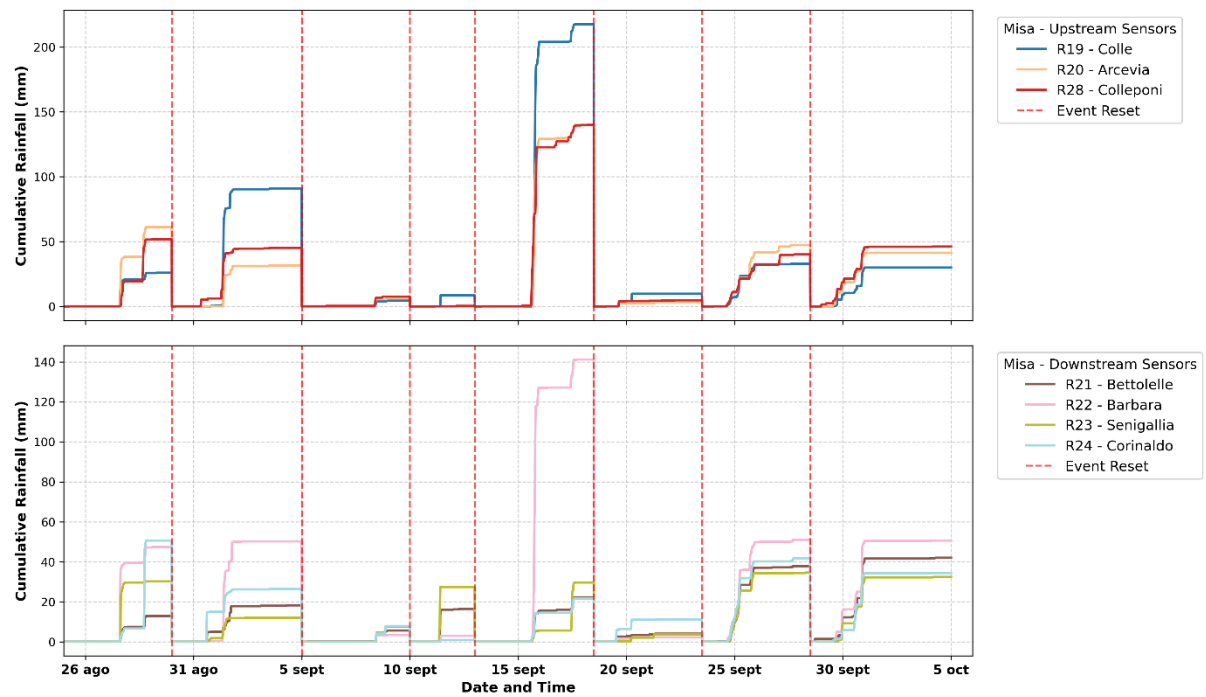
Supplementary Figure 7: Cumulative time series of Cesano river rain gauges.

Rainfall time series for rain gauges located upstream (top) and downstream (bottom). The legend indicates the station name, network code, and corresponding colour. The data streams display temporal interruptions corresponding to the resets of the cumulative rainfall series (dashed vertical red lines).



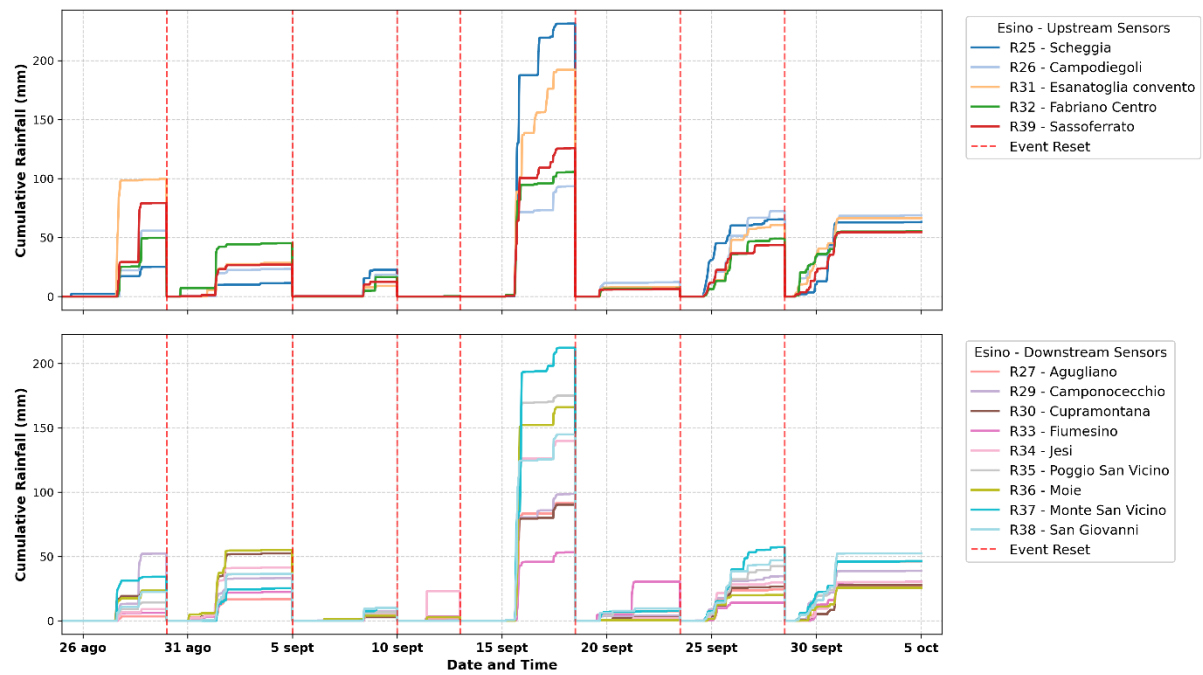
Supplementary Figure 8: Cumulative time series of Metauro river rain gauges.

Rainfall time series for rain gauges located upstream (top) and downstream (bottom). The legend indicates the station name, network code, and corresponding colour. The data streams display temporal interruptions corresponding to the resets of the cumulative rainfall series (dashed vertical red lines).



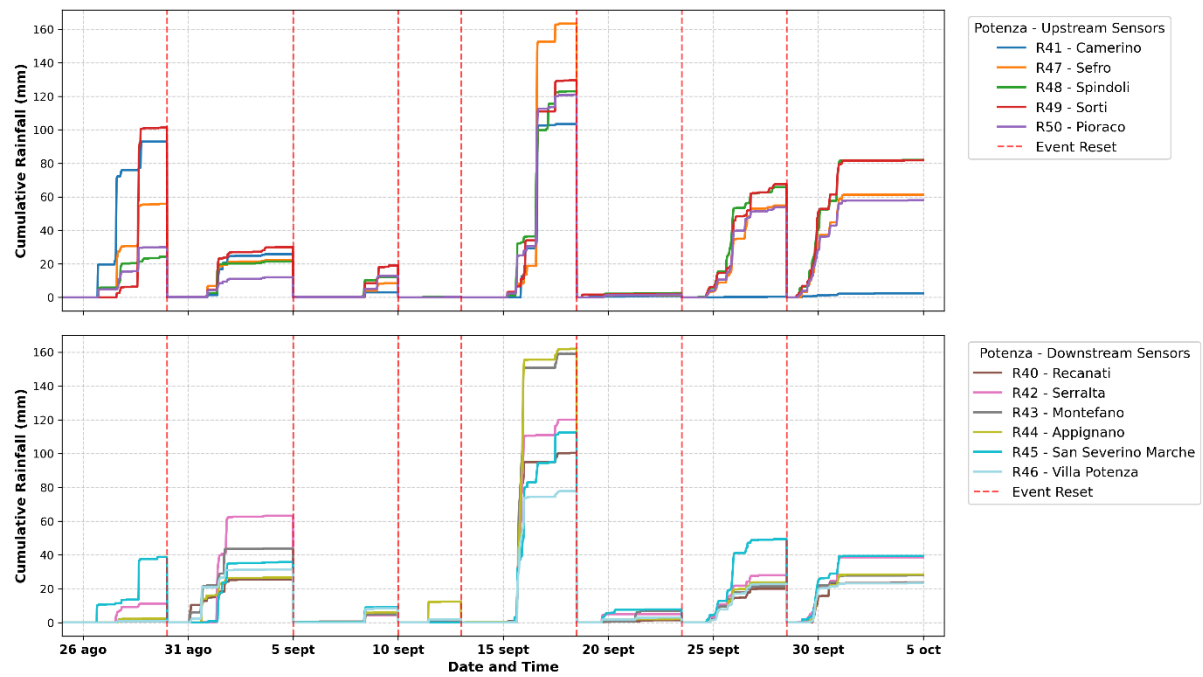
Supplementary Figure 9: Cumulative time series of Misa river rain gauges.

Rainfall time series for rain gauges located upstream (top) and downstream (bottom). The legend indicates the station name, network code, and corresponding colour. The data streams display temporal interruptions corresponding to the resets of the cumulative rainfall series (dashed vertical red lines).



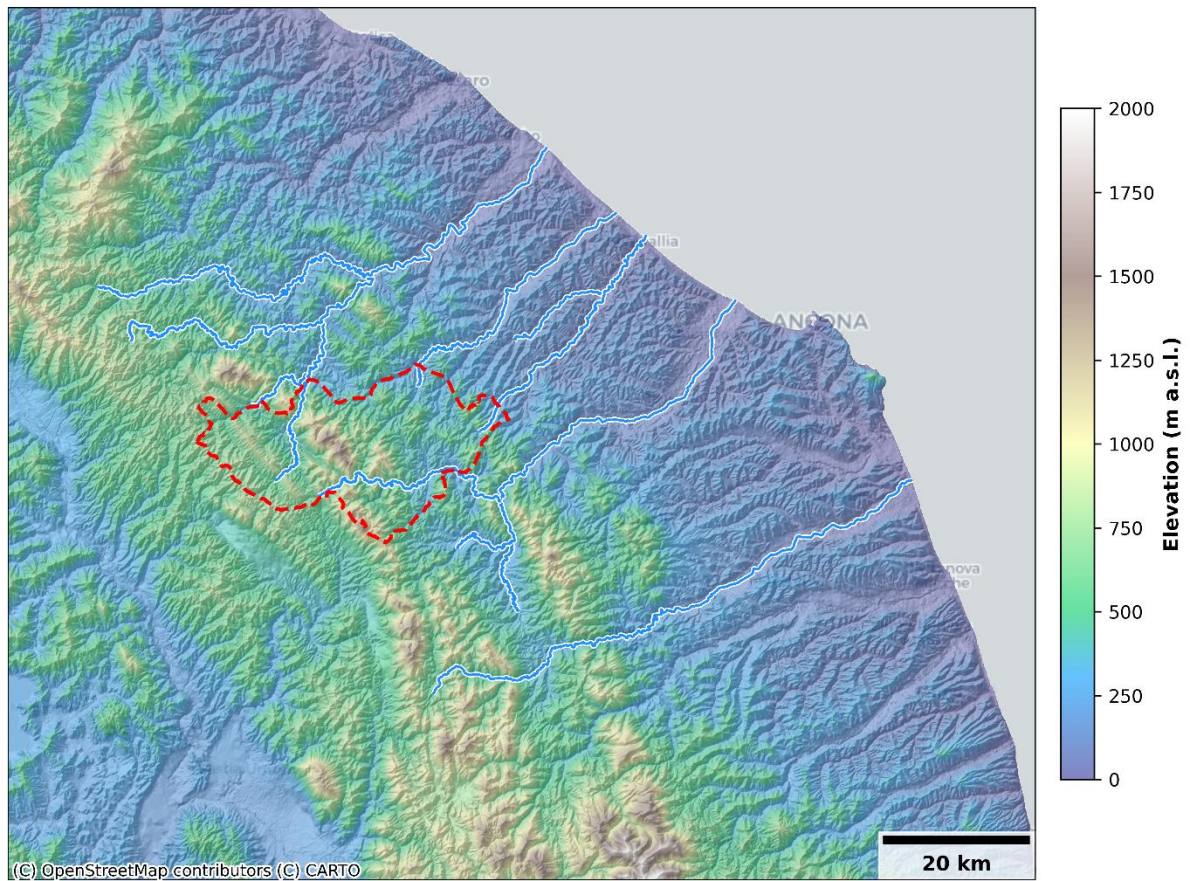
Supplementary Figure 10: Cumulative time series of Esino river rain gauges.

Rainfall time series for rain gauges located upstream (top) and downstream (bottom). The legend indicates the station name, network code, and corresponding colour. The data streams display temporal interruptions corresponding to the resets of the cumulative rainfall series (dashed vertical red lines).



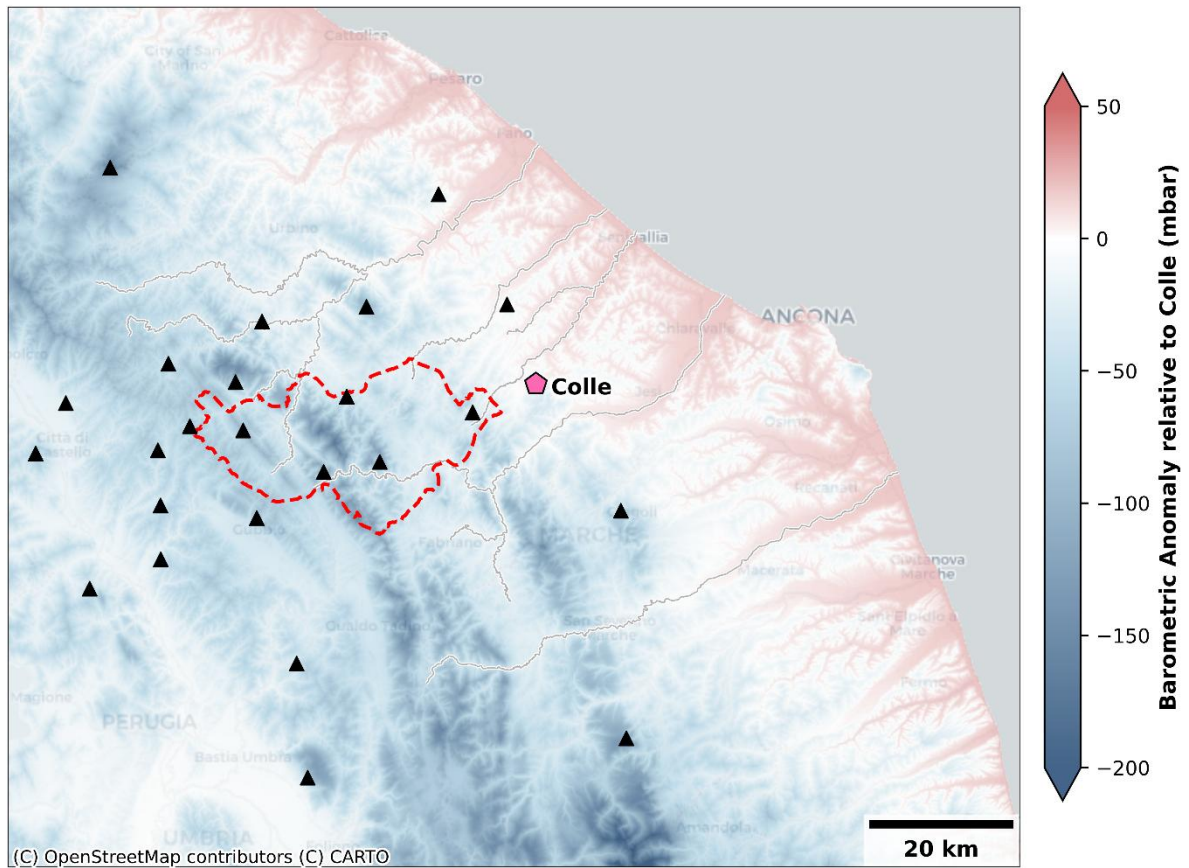
Supplementary Figure 11: Cumulative time series of Potenza river rain gauges.

Rainfall time series for rain gauges located upstream (top) and downstream (bottom). The legend indicates the station name, network code, and corresponding colour. The data streams display temporal interruptions corresponding to the resets of the cumulative rainfall series (dashed vertical red lines).



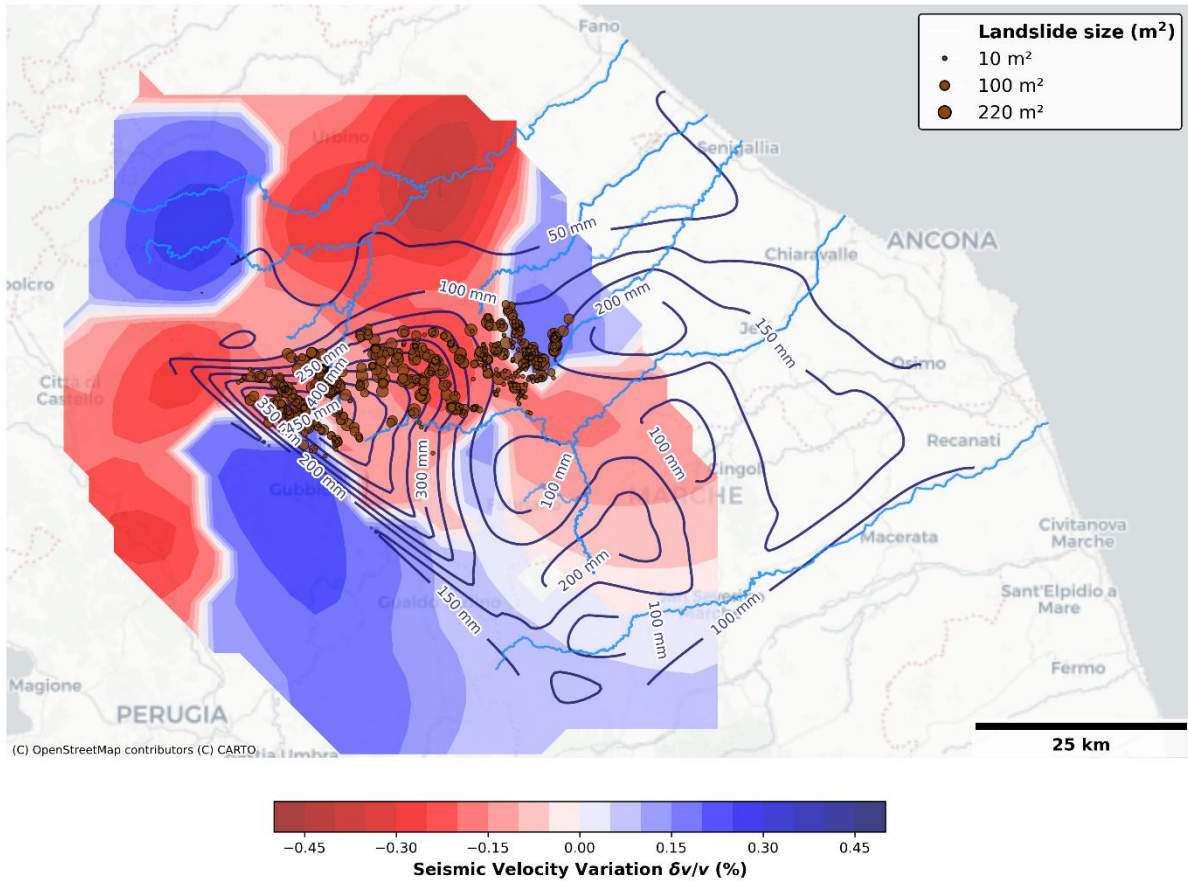
Supplementary Figure 12: Digital Elevation Model (DEM) model of the Marche Region.

Colour plot indicates elevation with respect to sea level. Blue lines represent the main rivers. The dashed red line delineates the landslide-affected area.



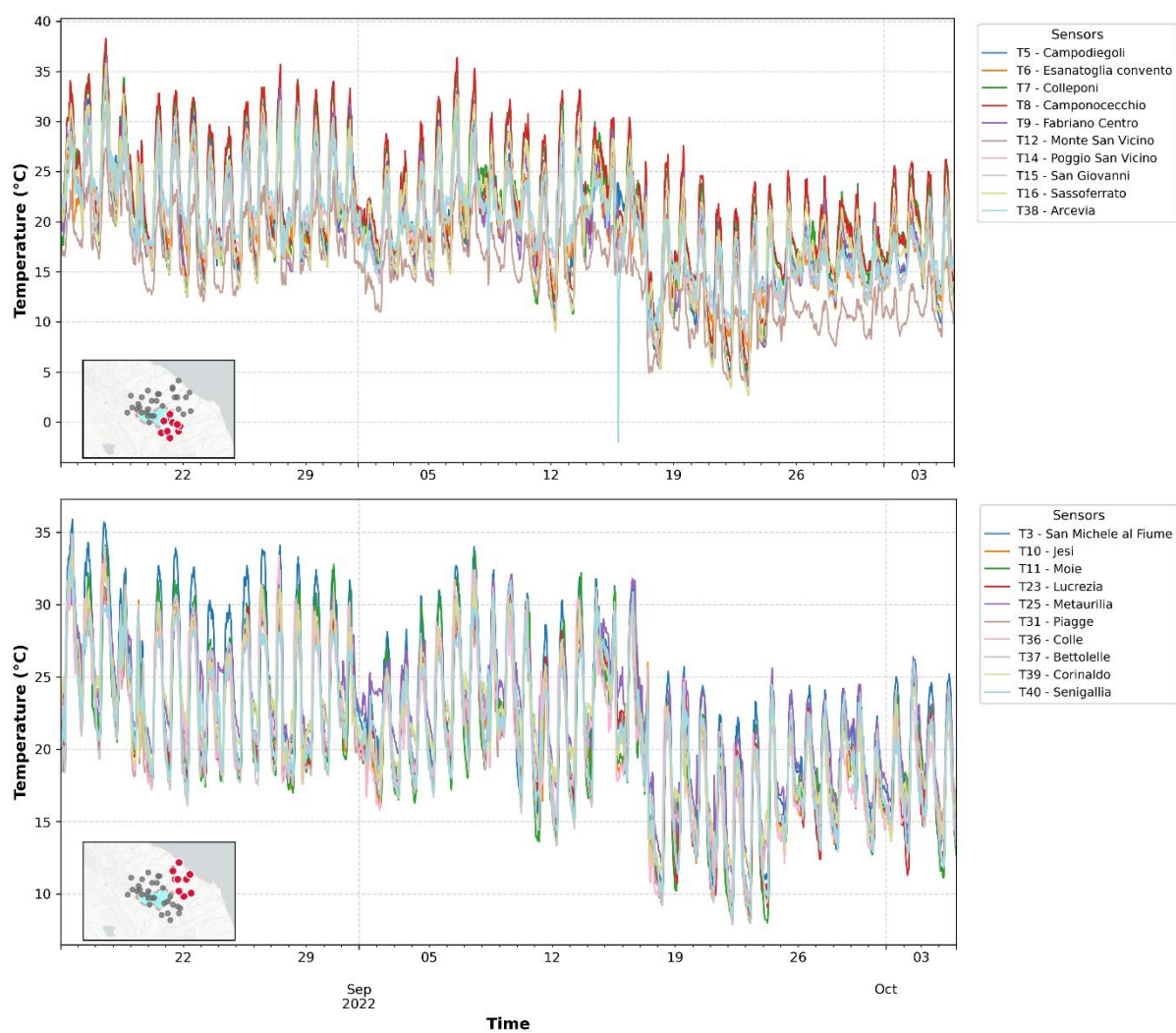
Supplementary Figure 13: Static atmospheric pressure anomalies map.

The dashed red line delineates the landslide-affected area. Black triangles are the seismic stations. The pink pentagon denotes the *Colle* pressure sensor, which serves as the reference elevation. The mapped values represent relative pressure differences (in mbar) with respect to this reference site.



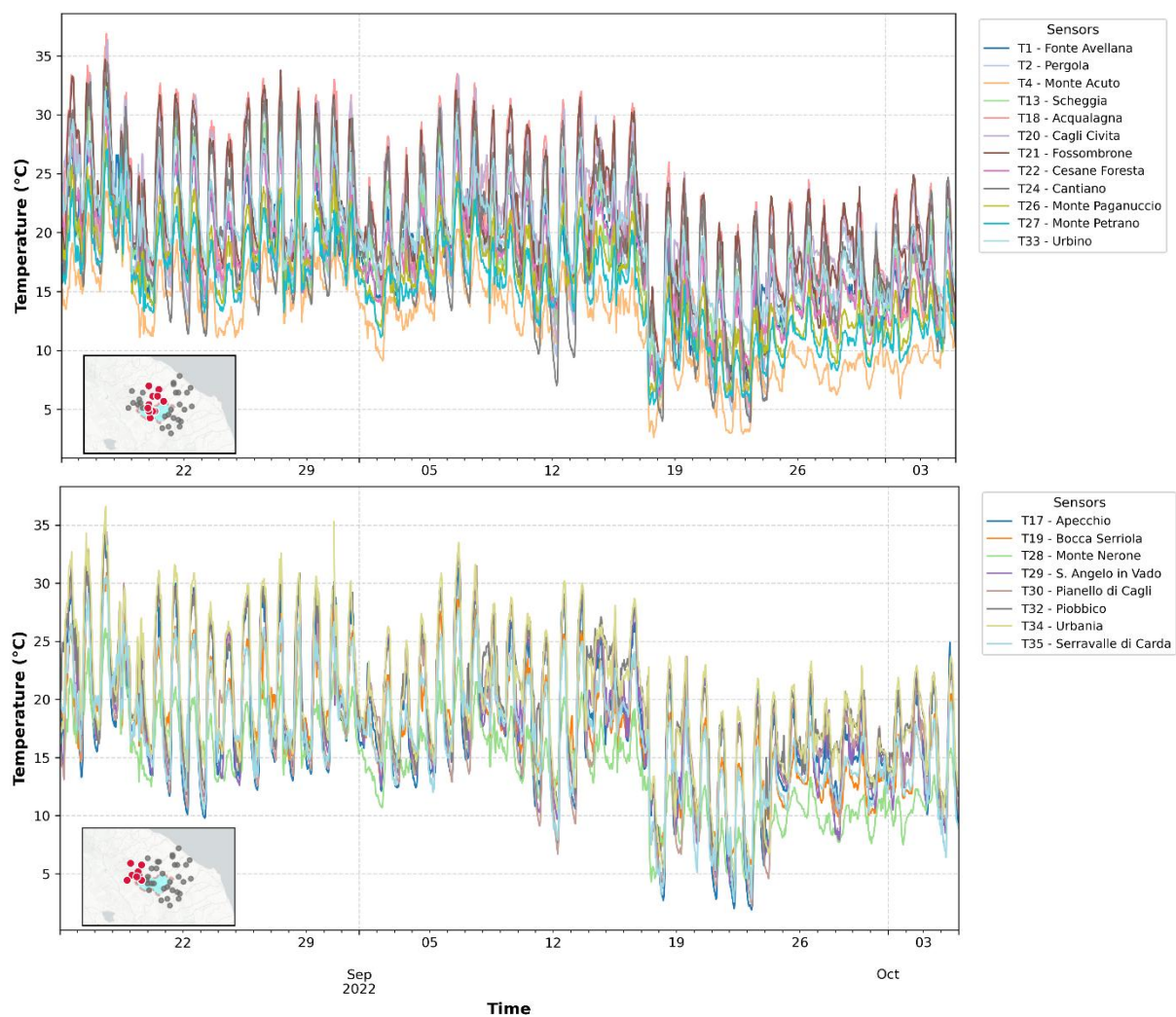
Supplementary Figure 14: Spatial distributions of peak relative seismic velocity changes with atmospheric pressure correction, cumulative rainfall and landslides.

The timeframe considered is September 10 to September 20, 2022. Spatial distributions of extreme relative seismic velocity changes in the 0.5-2.0 Hz frequency band are represented as a red to blue gradient colormap, incorporating the atmospheric pressure correction (described in the Methods section). See Supplementary Figure 13 for atmospheric pressure anomalies used for the correction. Level curves represent the cumulative rainfall data within the timeframe considered, which is spatially represented using a 2D linear interpolation. Landslide events are shown as brown circles scaled by affected area according to the legend (see Supplementary Figure 6 for the detailed landslide map).



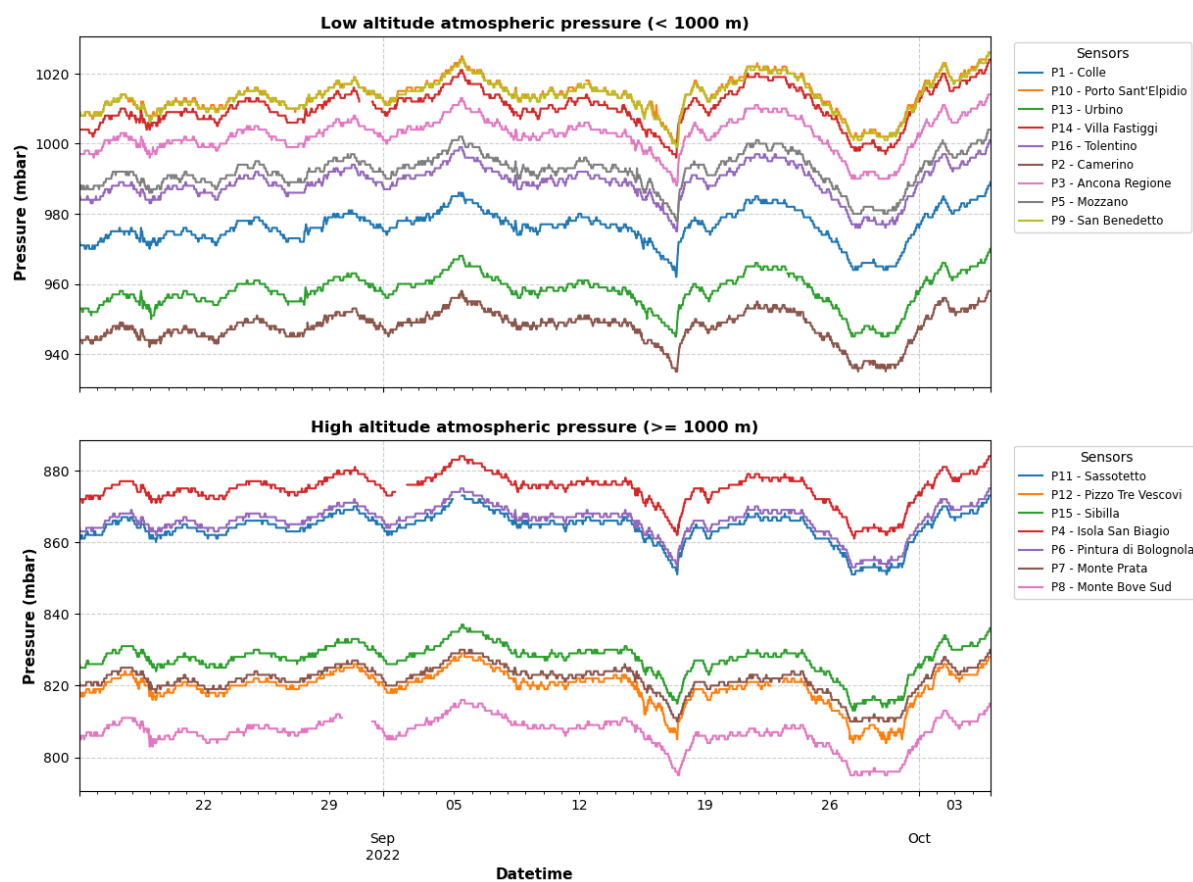
Supplementary Figure 15: Temperature time series (zone 1 and 2).

Temperature time series for thermometers in the Marche Region. The legend indicates the station name, network code, and corresponding colour. Basemap layers courtesy of OpenStreetMap contributors / CartoDB (Positron).



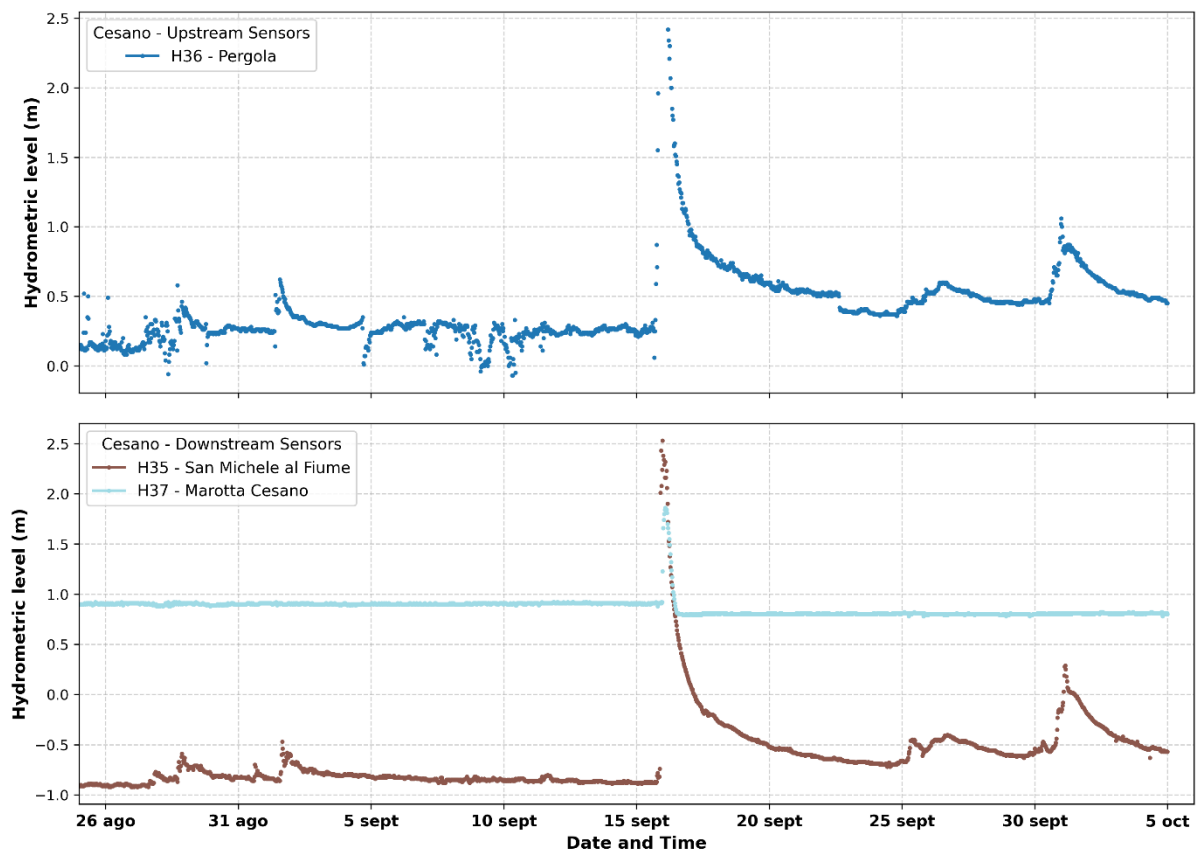
Supplementary Figure 16: Temperature time series (zone 3 and 4).

Temperature time series for thermometers in the Marche Region. The legend indicates the station name, network code, and corresponding colour. Basemap layers courtesy of OpenStreetMap contributors / CartoDB (Positron).



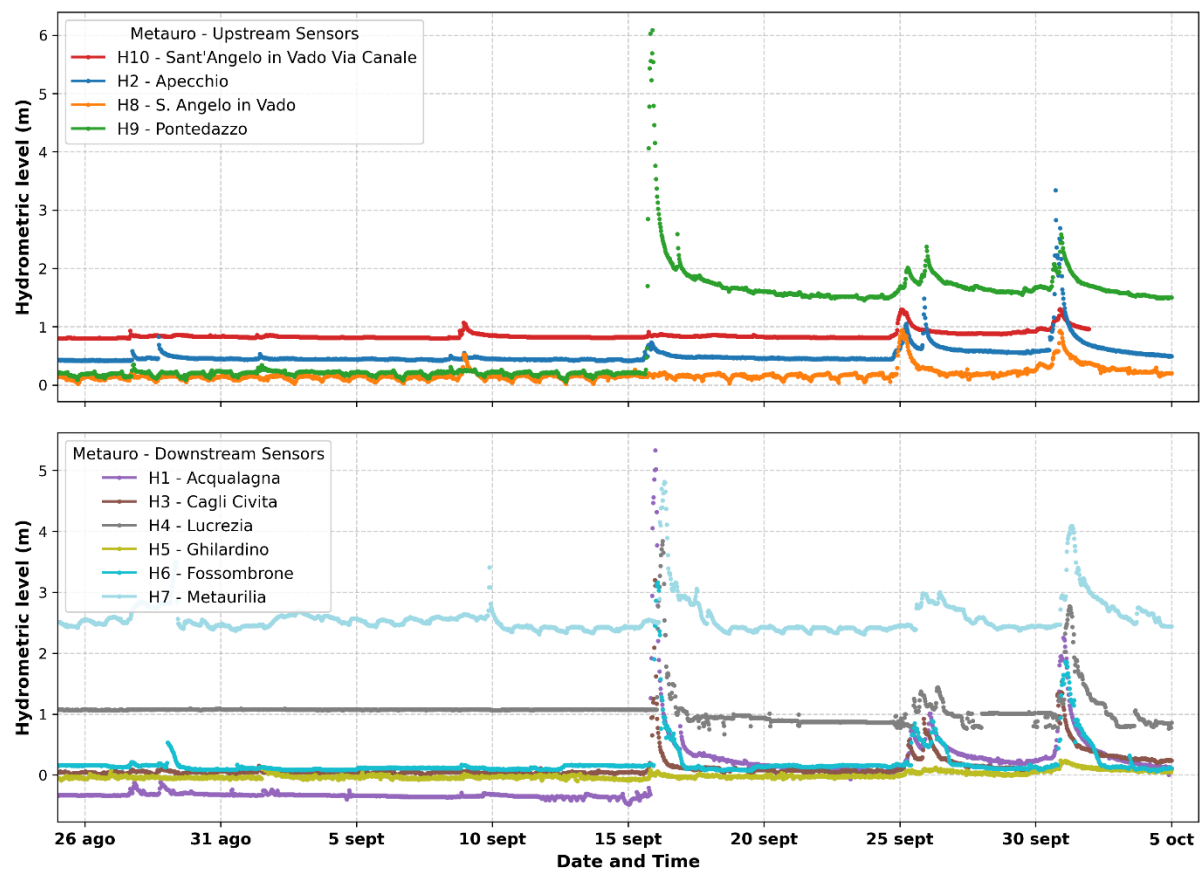
Supplementary Figure 17: Atmospheric pressure time series.

Atmospheric pressure time series for barometers in the Marche Region. The legend indicates the station code (see Supplementary Figure 4), station name, and corresponding colour.



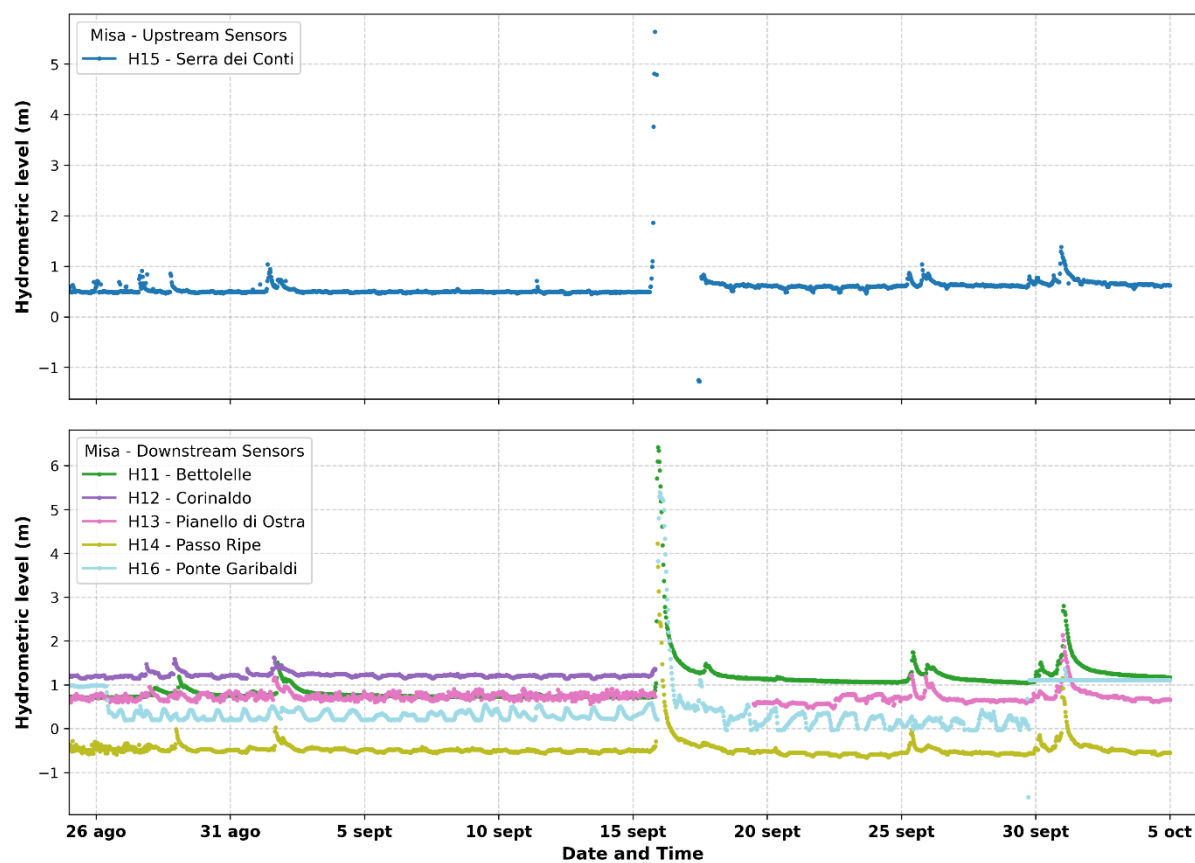
Supplementary Figure 18: Cesano river water level time series.

Water level time series for hydrometers. The legend indicates the station name, network code, and corresponding colour.



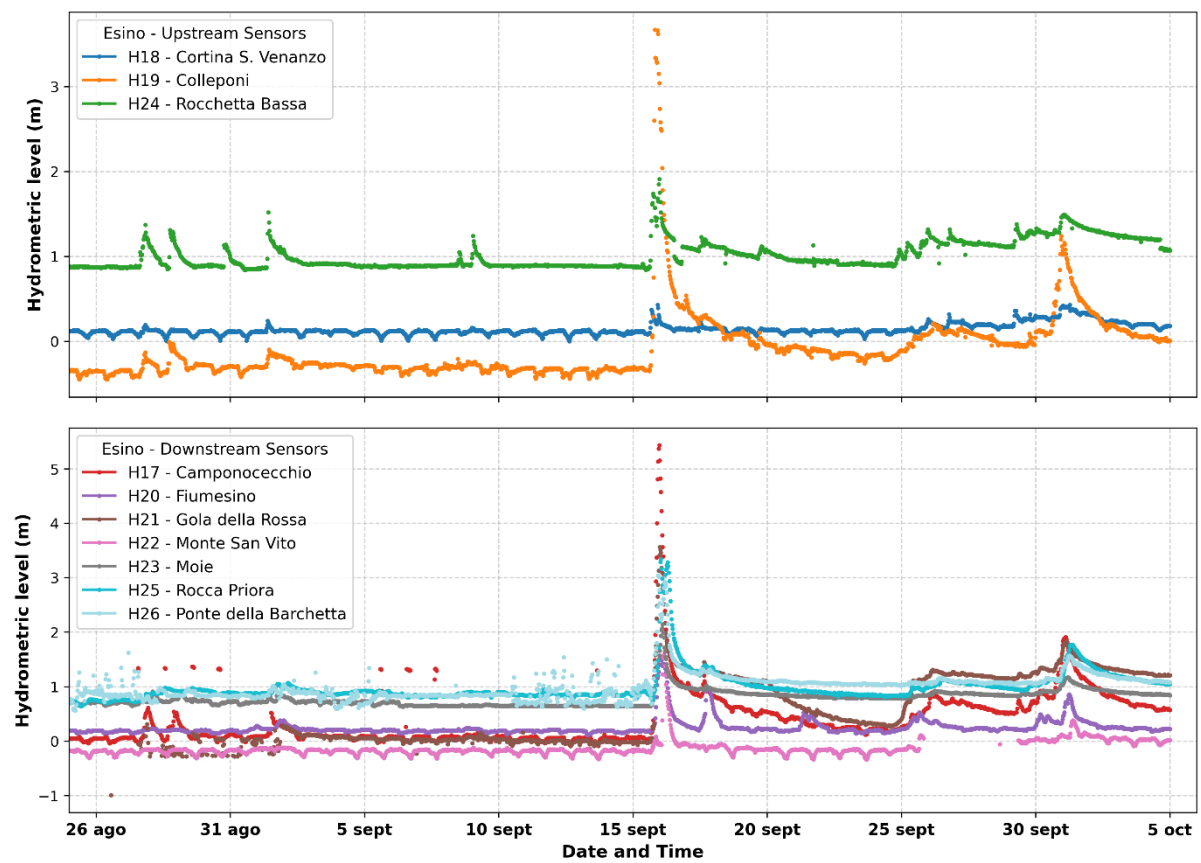
Supplementary Figure 19: Metauro river water level time series.

Water level time series for hydrometers. The legend indicates the station name, network code, and corresponding colour.



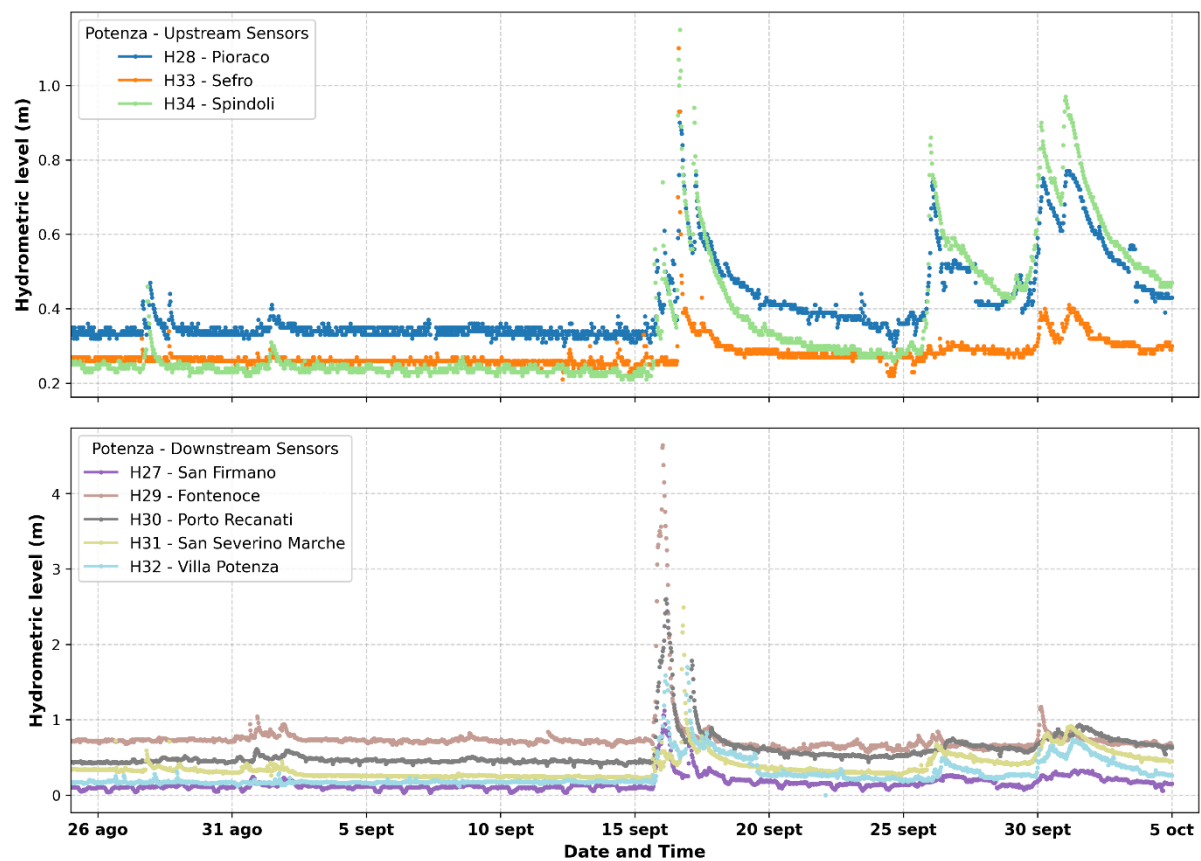
Supplementary Figure 20: Misa river water level time series.

Water level time series for hydrometers. The legend indicates the station name, network code, and corresponding colour.



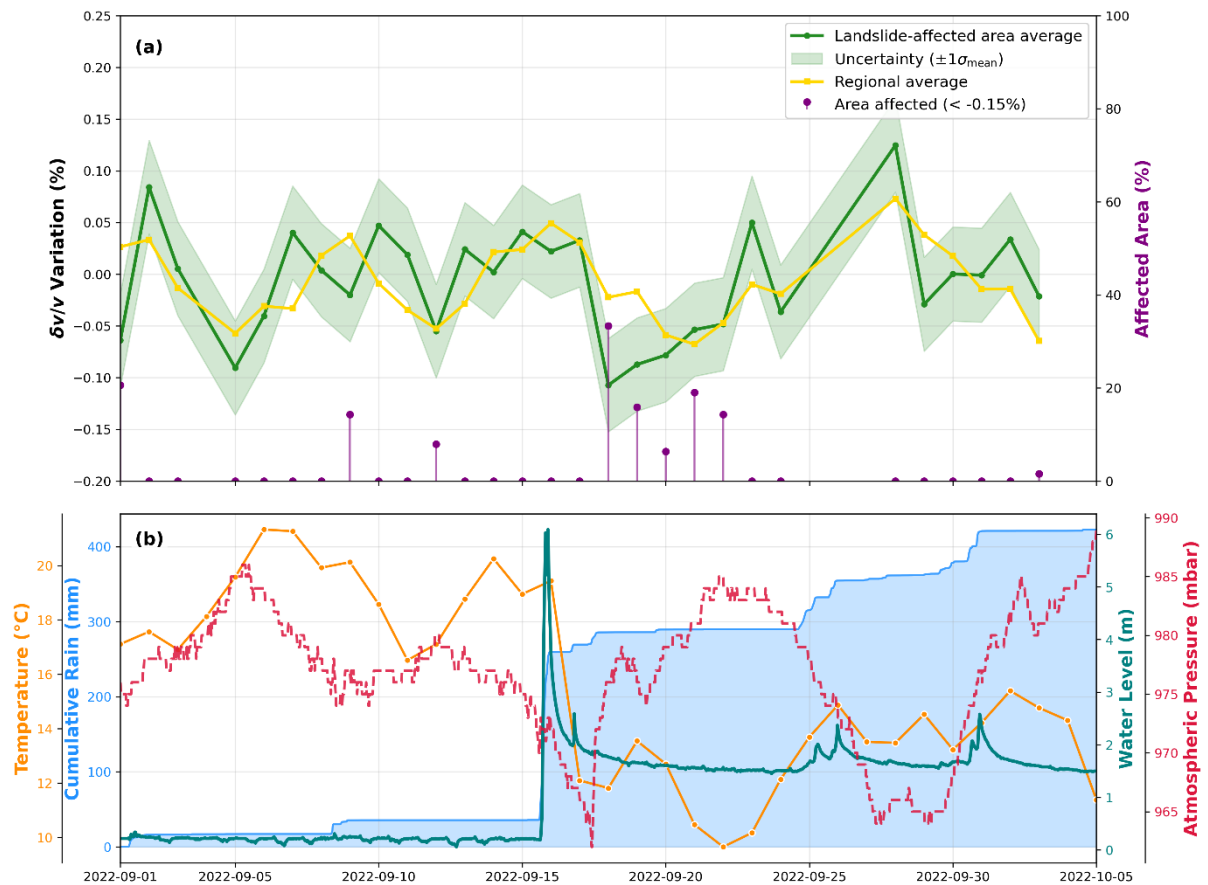
Supplementary Figure 21: Esino river water level time series.

Water level time series for hydrometers. The legend indicates the station name, network code, and corresponding colour.



Supplementary Figure 22: Potenza river water level time series.

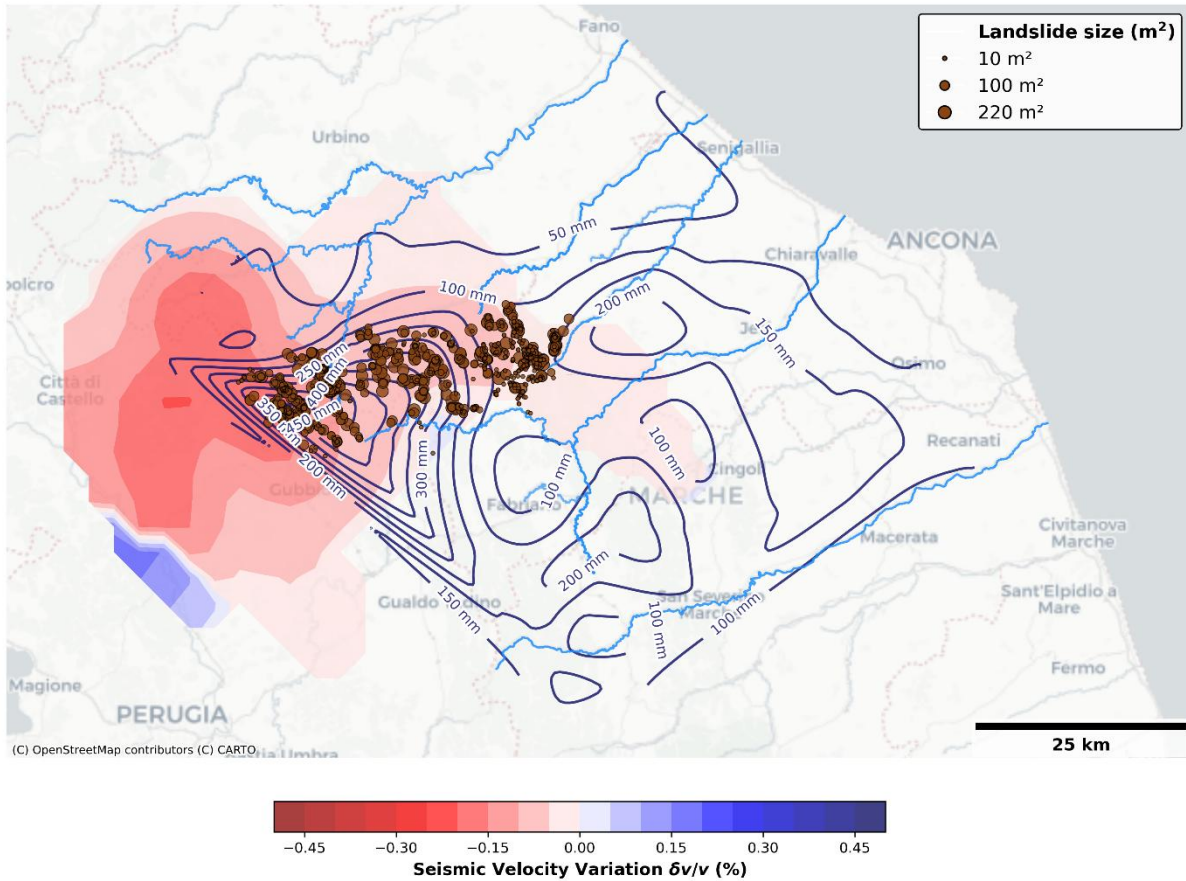
Water level time series for hydrometers. The legend indicates the station name, network code, and corresponding colour.



Supplementary Figure 23: Time series of estimated relative velocity variations with atmospheric pressure correction, cumulative rainfall, temperature, atmospheric pressure and river water level within the landslide area.

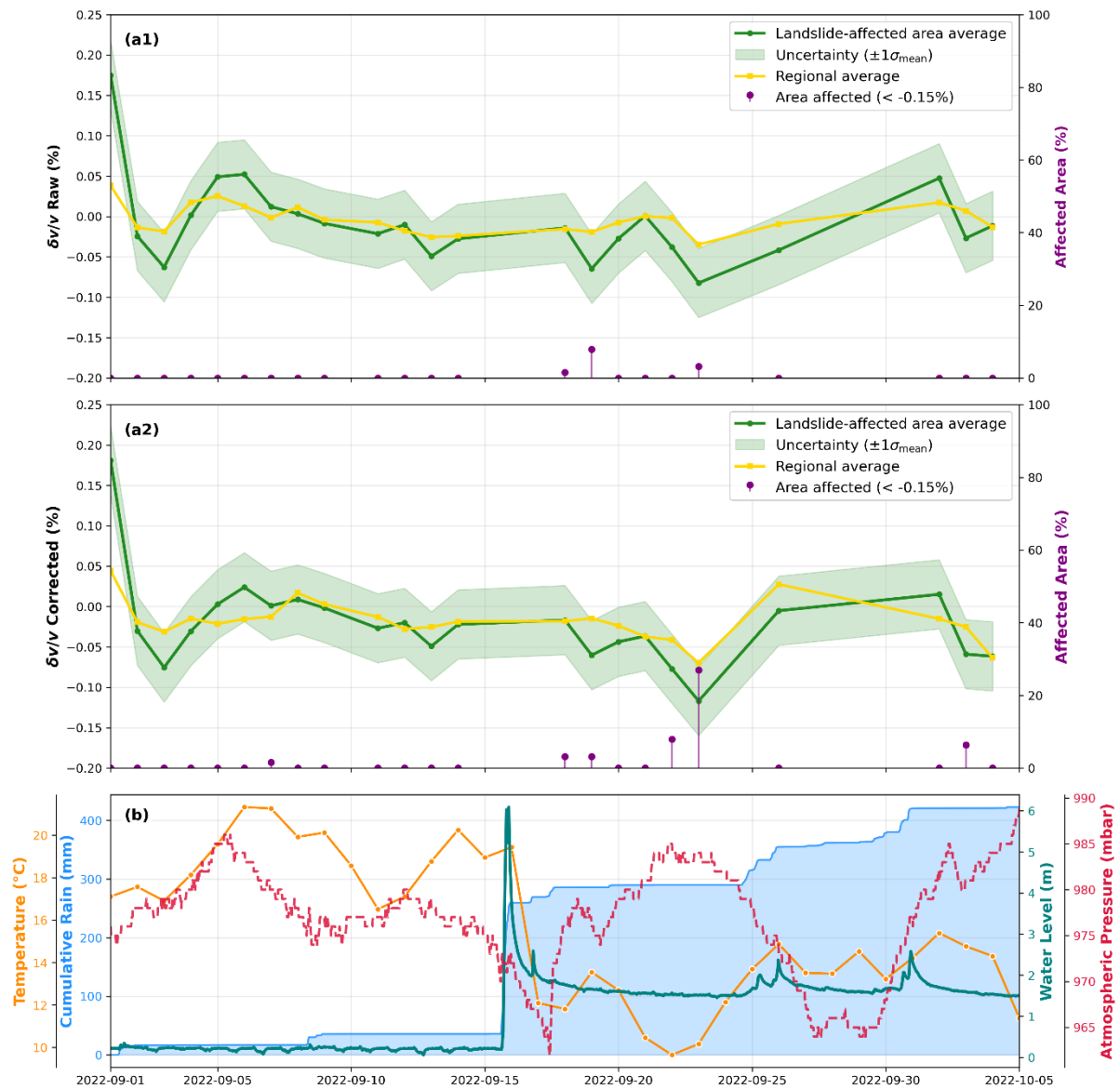
(a) Time series of estimated $\delta v/v$ for seismic data in the 0.5-2.0 Hz frequency range, spatially averaged within the seismic network region (yellow dots and line), within the landslide area (green dots and line), and their uncertainty (light green area). The purple stem plot represents the percentage of affected landslide area of $\delta v/v$ values less than -0.15%. $\delta v/v$ values incorporate atmospheric pressure correction. See Supplementary Figure 13 for atmospheric pressure anomalies used for the correction.

(b) Time series of cumulative rainfall, average temperature, water level of rivers and atmospheric pressure spatially averaged within the landslide area.



Supplementary Figure 24: Spatial distributions of extreme relative seismic velocity changes, cumulative rainfall and landslides.

The timeframe considered is September 10 to September 20, 2022. Spatial distributions of extreme relative seismic velocity changes in the 1.0-4.0 Hz frequency band are represented as a red to blue gradient colormap. Level curves represent the cumulative rainfall data within the timeframe considered, which is spatially represented using a 2D linear interpolation. Landslide events are shown as brown circles scaled by affected area according to the legend (see Supplementary Figure 6 for the detailed landslide map).

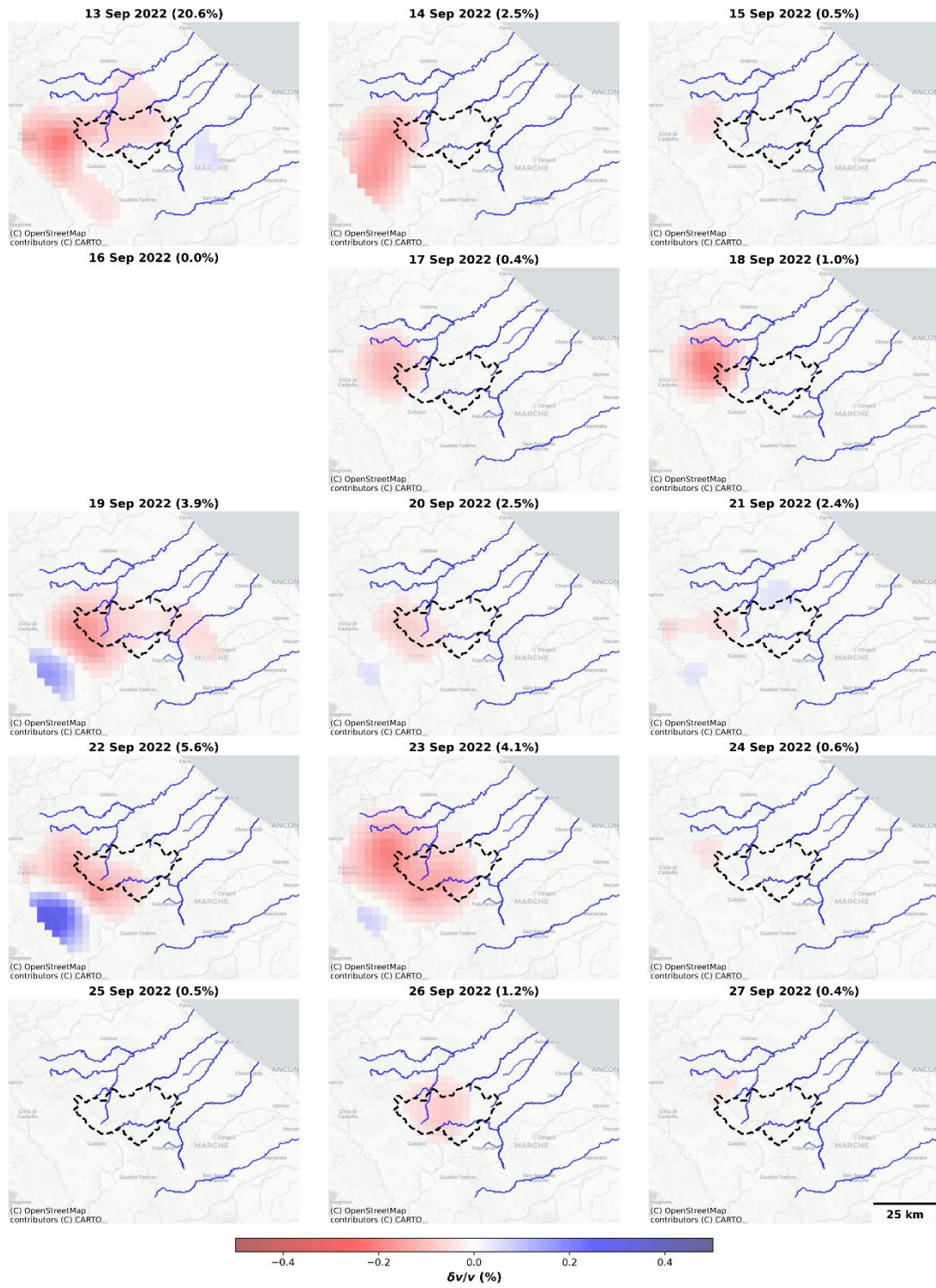


Supplementary Figure 25: Time series of estimated relative velocity variations, cumulative rainfall, temperature, atmospheric pressure and river water level within the landslide area.

(a1) Time series of estimated $\delta v/v$ for seismic data in the 1.0-4.0 Hz frequency range, spatially averaged within the seismic network region (yellow dots and line), within the landslide area (green dots and line), and their uncertainty (light green area). The purple stem plot represents the percentage of affected landslide area of $\delta v/v$ values less than -0.15%.

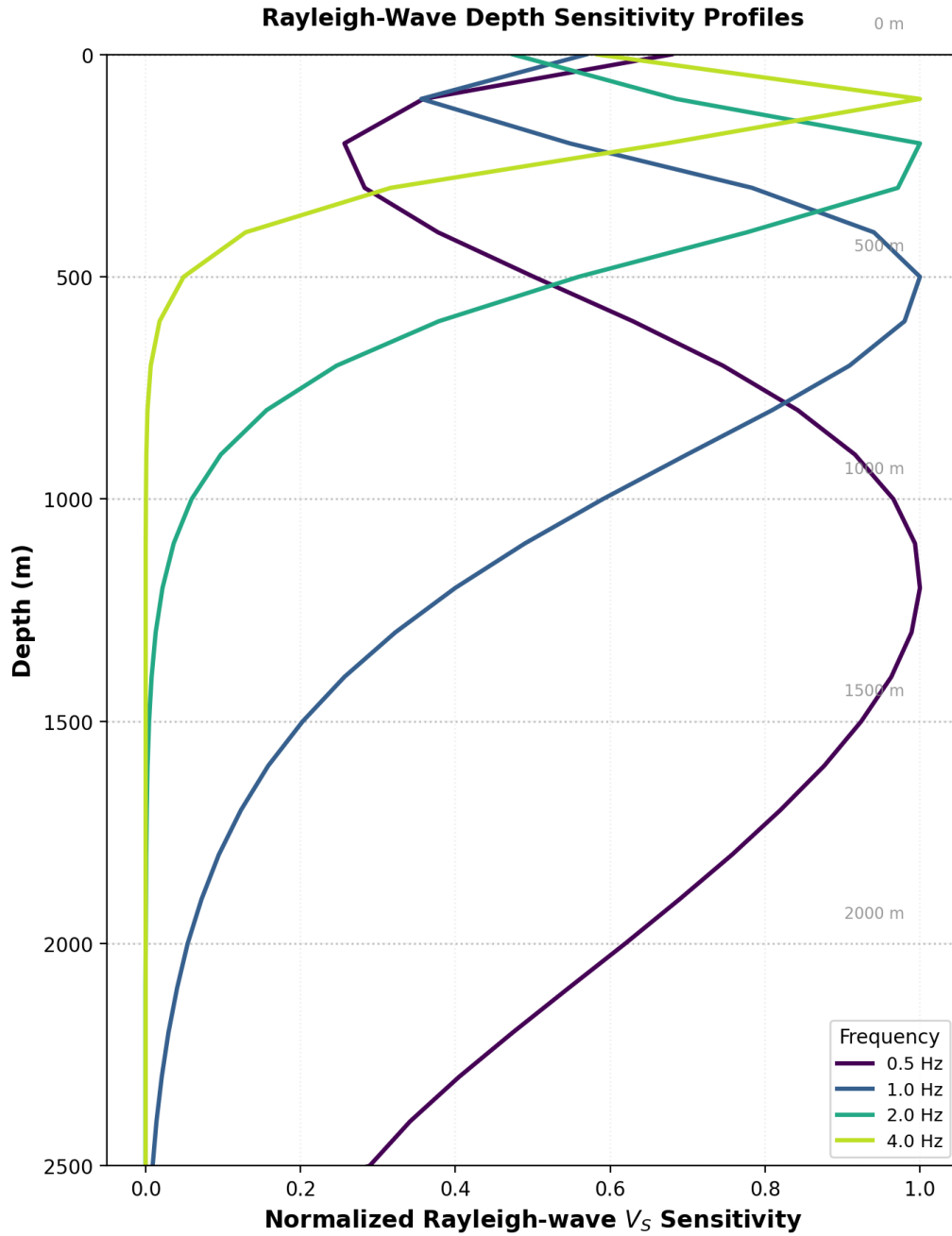
(a2) same plot as (a1) but with $\delta v/v$ values incorporating atmospheric pressure correction. See Supplementary Figure 13 for atmospheric pressure anomalies used for the correction.

(b) Time series of cumulative rainfall, average temperature, water level of rivers and atmospheric pressure spatially averaged within the landslide area.



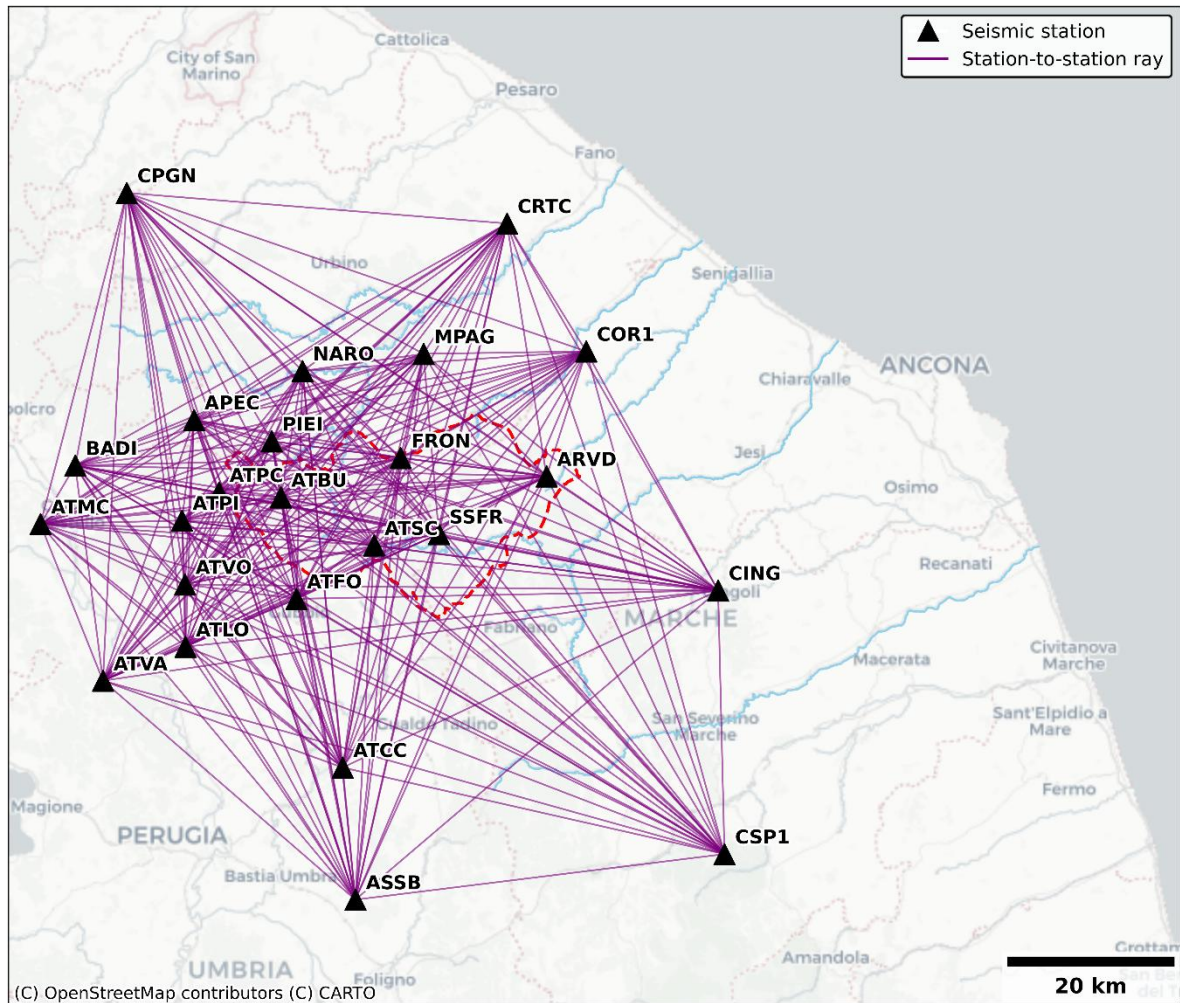
Supplementary Figure 26: Daily spatial distributions of relative seismic velocity changes.

From top-left to bottom-right, figures show $\delta v/v$ values in the 1.0-4.0 Hz frequency band from 13 to 27 September 2022. The black dashed line corresponds to the landslide-affected area. Values in parentheses represent the percentage of station pairs, relative to the total number of available pairs, that pass the CC threshold defined in Methods (see Supplementary Figure 28 for the complete map of pairs).



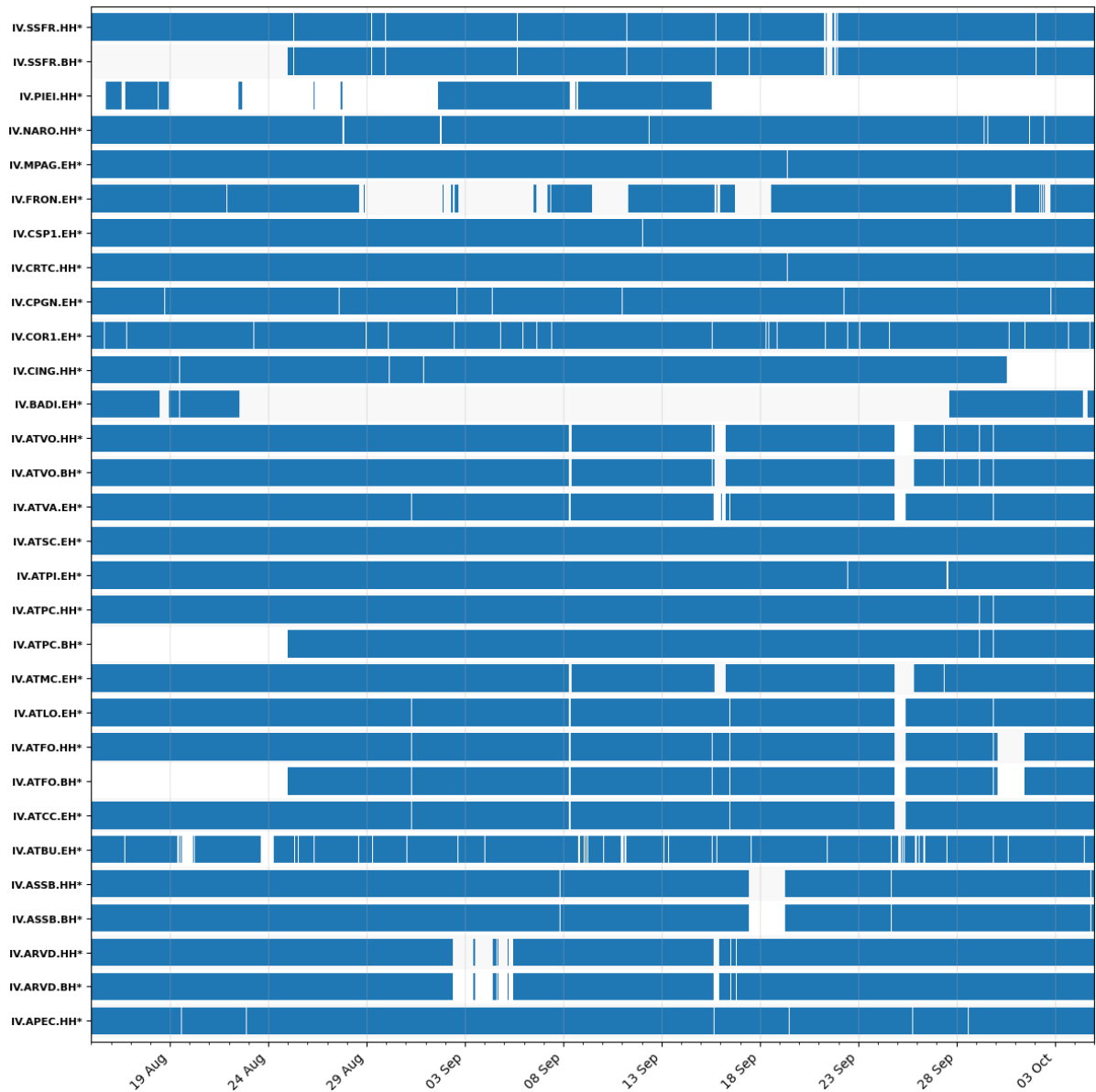
Supplementary Figure 27: Rayleigh-wave depth sensitivity curves for different frequency values.

These curves quantify the change in Rayleigh wave velocity induced by S-wave velocity (V_S) variations at a given depth. The effect of P-wave velocity (V_P) changes is negligible, being orders of magnitude lower than that of V_S . Profiles are based on a local 1D velocity model and inverted using the geopsy software (see Methods for details).



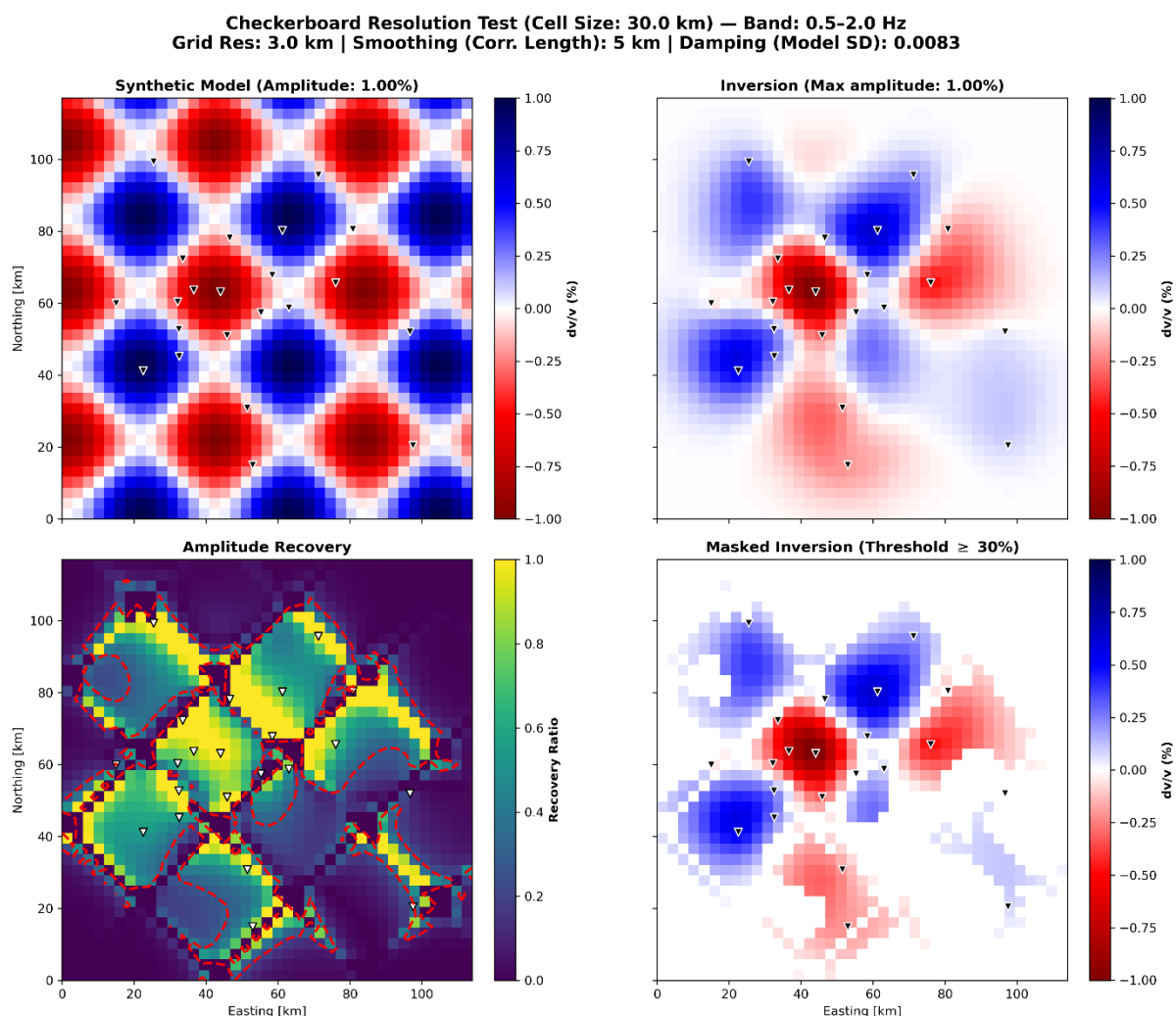
Supplementary Figure 28: Available station pairs and 2D spatial coverage of the seismic network.

The dashed red line delineates the landslide-affected area. Purple segments represent all available inter-station pairs connecting any two stations across the network. Note that the $\delta v/v$ values retrieved in the analysis are derived exclusively from the subset of station pairs that satisfy the cross-correlation (CC) threshold defined in Methods (see Methods for details).



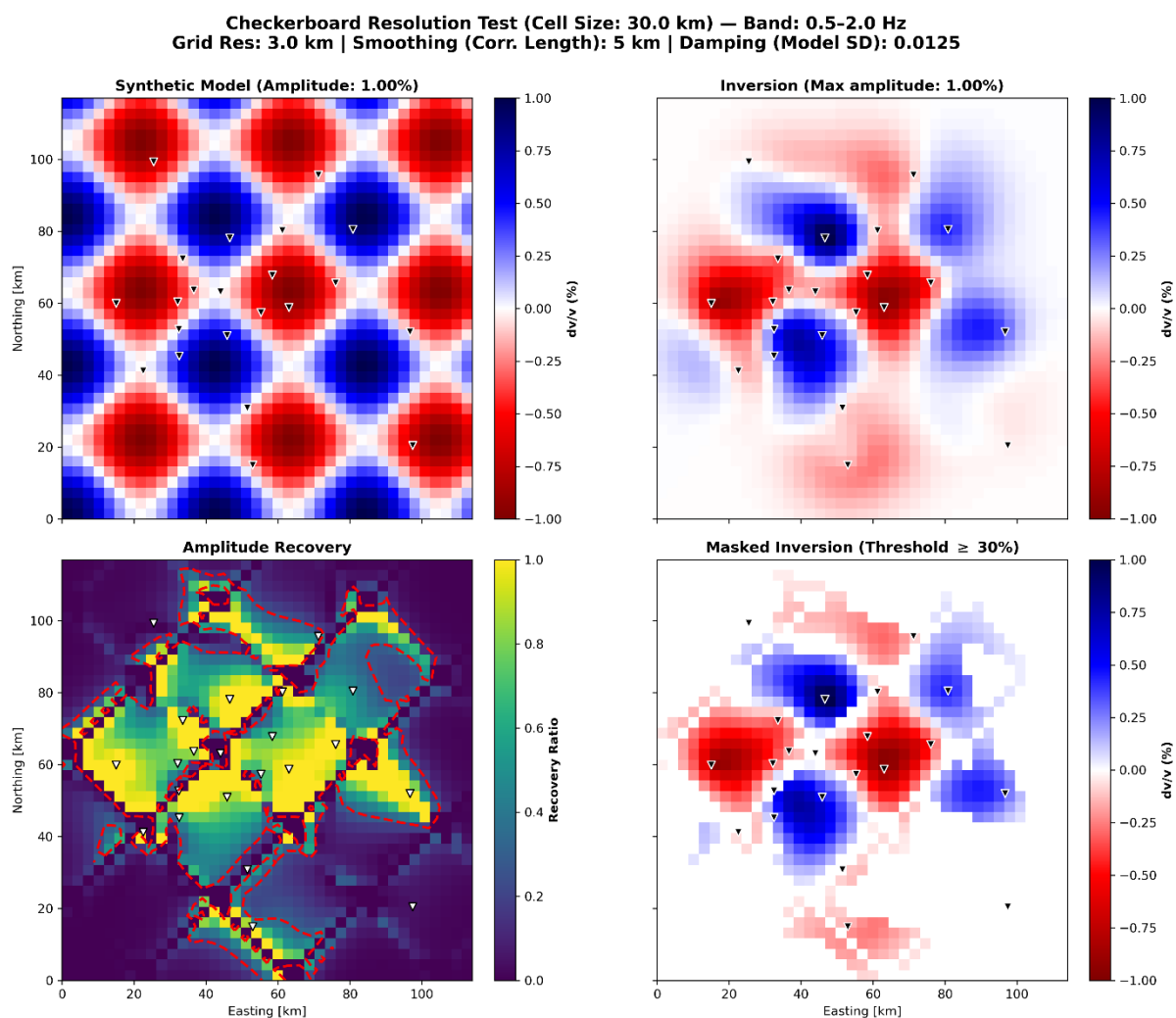
Supplementary Figure 29: Data availability VS time of seismic stations

Each row corresponds to a specific seismic station of network in Supplementary Figure 1. The format of the labelling is Network-Station-Channel. Blue segments indicate periods in which data was successfully acquired on at least one channel, whereas white spaces represent data gaps. For this reason, BADI and PIEI are not utilized in this study due to poor data availability.



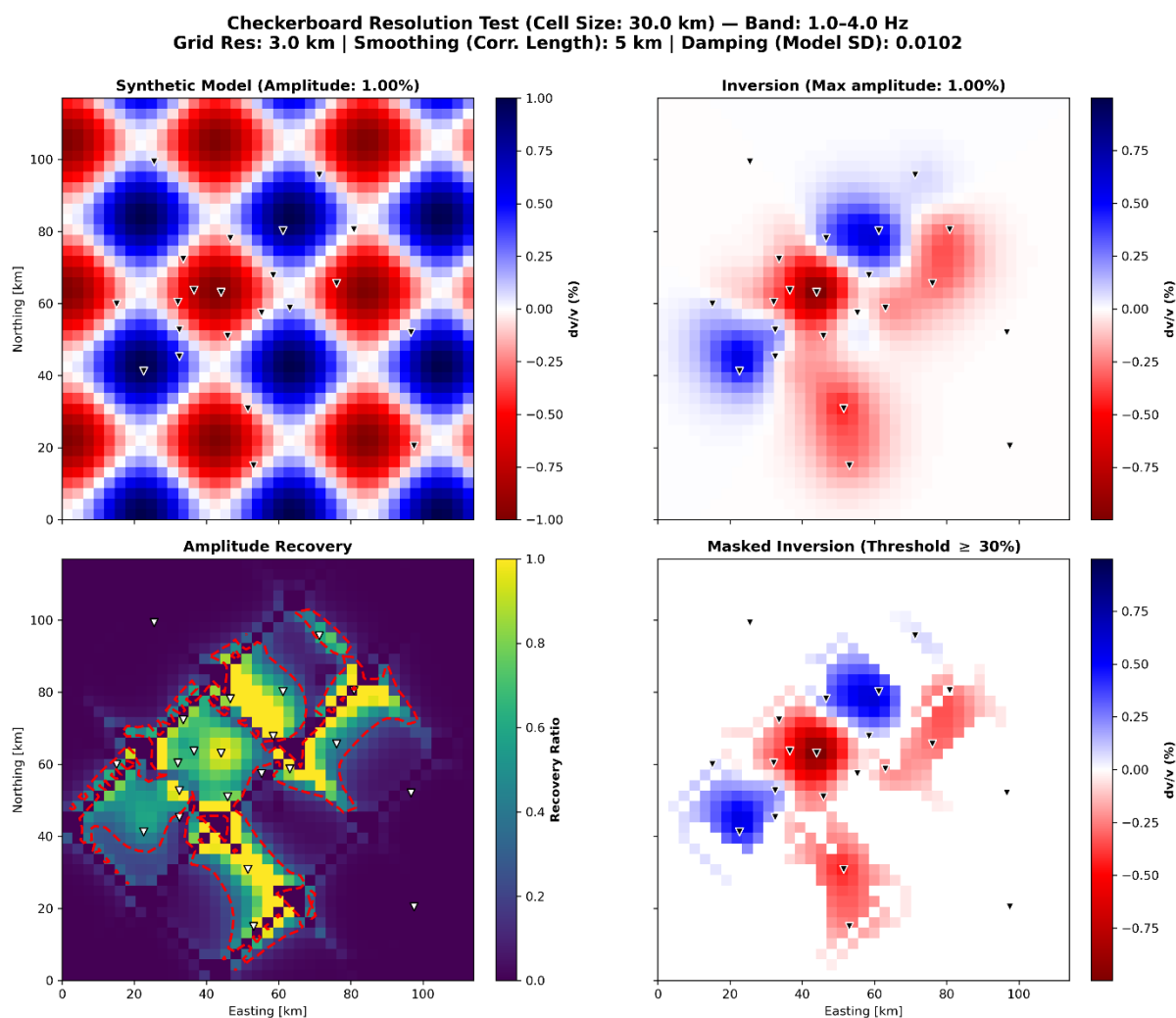
Supplementary Figure 30: Spatial resolution test (checkerboard test) for the 0.5-2.0 Hz frequency band.

The synthetic target model is generated using a 2D sinusoidal velocity perturbation pattern with an amplitude of 1.0%. The test evaluates the fraction of the anomaly amplitude recovered by the spatial inversion (the maximum amplitude value is indicated in the upper-right panel). The inversion parameters (correlation length and model standard deviation), the minimum spatial grid resolution, and the spatial dimension of individual anomalies (cell size) are specified in the figure title. A mask, corresponding to regions where at least 30% of the anomaly amplitude is recovered, is shown in the bottom panels to visually highlight the area with acceptable spatial resolution.



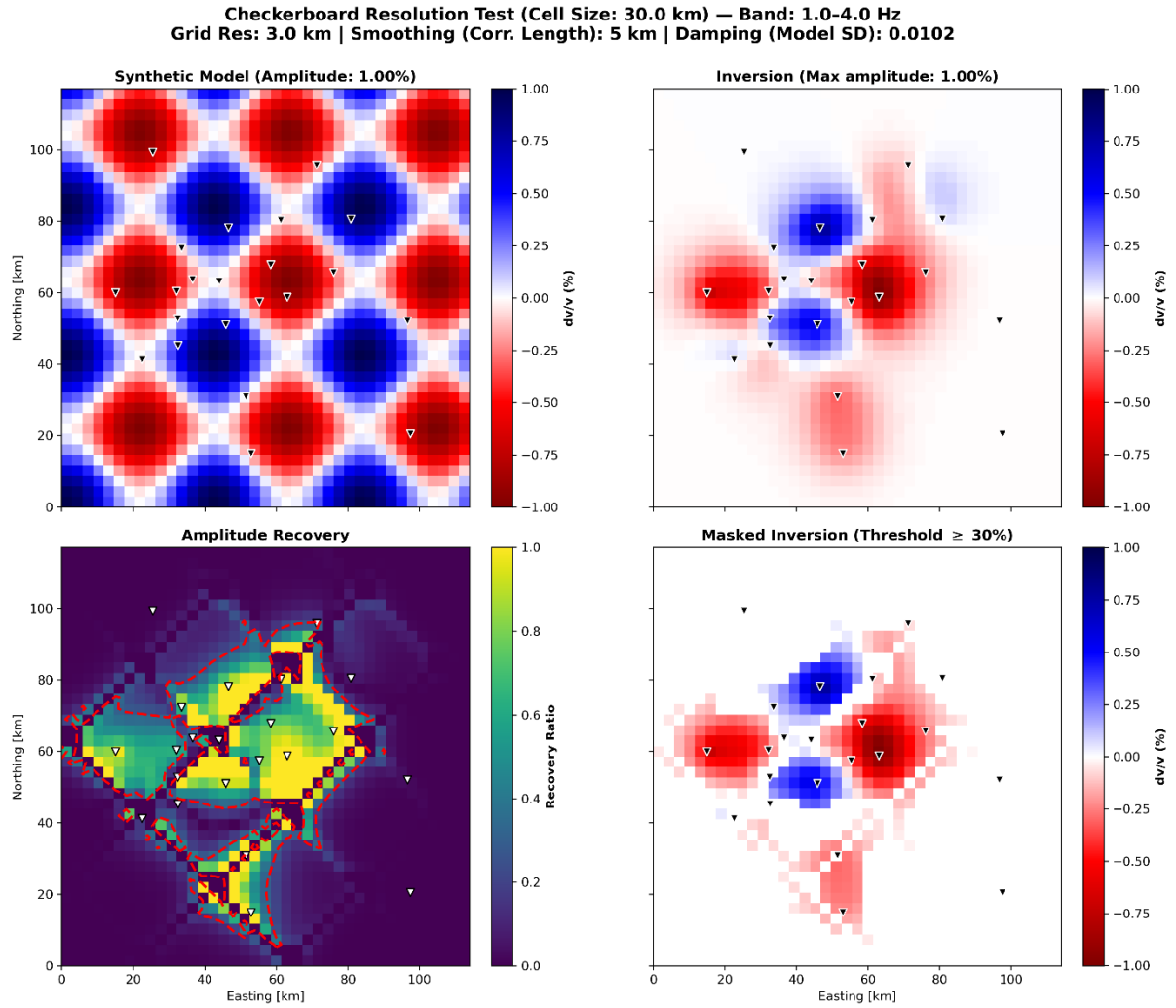
Supplementary Figure 31: Spatial resolution test (checkerboard test) for the 0.5Hz-2.0Hz frequency band.

A constant phase shift of $\pi/2$ was applied relative to the test in Supplementary Figure 30 to evaluate network sensitivity across the nodal regions of the original synthetic pattern, where velocity anomalies approach zero.



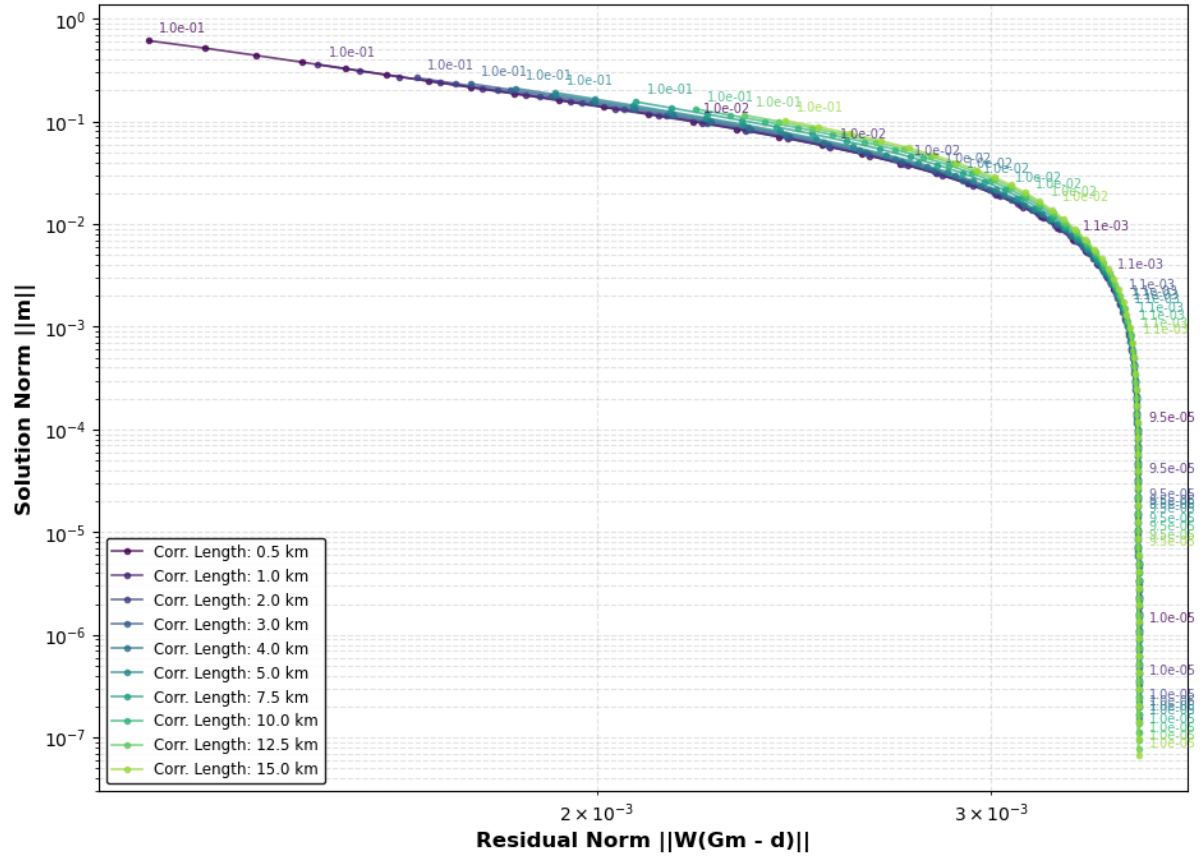
Supplementary Figure 32: Spatial resolution test (checkerboard test) for the 1.0Hz-4.0Hz frequency band.

Following the same setup as Supplementary Figure 30 but conducted at higher frequencies, this test highlights the impact of spatial attenuation. Because higher-frequency waves attenuate over shorter propagation distances, the network fails to accurately recover synthetic anomalies where station coverage is sparse. Consequently, reliable reconstruction is achieved only in the central region, where station density is highest.



Supplementary Figure 33: Spatial resolution test (checkerboard test) for the 1.0Hz-4.0Hz frequency band.

A constant phase shift of $\pi/2$ was applied relative to the test in Supplementary Figure 32 to evaluate network sensitivity across the nodal regions of the original synthetic pattern, where velocity anomalies approach zero.



Supplementary Figure 34: L-curve analysis

Solution norm versus weighted residual norm for the inversion problem (see Methods - Seismic velocity changes estimation and spatial inversion), using data from September 22, 2022, which was selected as the day exhibiting the highest overall coherence (defined in Methods, equation 3). The smoothing parameter is the correlation length (see legend), while the damping parameter is the standard deviation σ (values on curves). The weights applied to compute the residual norm are the reciprocals of the coherences associated with the $\delta v/v$ estimates.