

1 **Hydrologically induced slope deformations detected by GPS and**
2 **clinometric surveys in the Cansiglio Plateau, southern Alps**

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Abstract

Changes in groundwater or surface water level may cause observable deformation of the drainage basins in different ways. We describe an active slope deformation monitored with GPS and tiltmeter stations in a karstic limestone plateau in southeastern Alps (Cansiglio Plateau). The observed transient GPS deformation clearly correlates with the rainfall. Both GPS and tiltmeter equipments react instantly to heavy rains displaying abrupt offsets, but with different time constants, demonstrating the response to different catchment volumes. The GPS movement is mostly confined in the horizontal plane (SSW direction) showing a systematic tendency to rebound in the weeks following the rain. Four GPS stations concur to define a coherent deformation pattern of a wide area (12x5 km²), concerning the whole southeastern slope of the plateau. The plateau expands and rebounds radially after rain by an amount up to a few centimeters and causing only small vertical deformation. The effect is largest where karstic features are mostly developed, at the margin of the plateau where a thick succession of Cretaceous peritidal carbonates faces the Venetian lowland. A couple of tiltmeters installed in a cave at the top of the plateau, detect a much faster deformation, that has the tendency to rebound in less than 6 hours. The correlation to rainfall is less straightforward, and shows a more complex behavior during rainy weather. The different responses demonstrate a fast hydrologic flow in the more permeable epikarst for the tiltmeters, drained by open fractures and fissures in the neighborhood of the cave, and a rapid tensile dislocation of the bedrock measured at the GPS stations that affect the whole slope of the mountain. In the days following the rain, both tiltmeter and GPS data show a tendency to retrieve the displacement which is consistent with the phreatic discharge curve. We propose that hydrologically active fractures recharged by rainfall are the most likely features capable to induce the observed strain variations.

Introduction

In the last decade, surface deformation attributed to hydrological processes has been observed with InSAR and GPS techniques in different aquifer systems. A number of papers reported measurable

46 effects in response to groundwater level changes in different geographical areas (Bawden et al.,
47 2001; Lanari et al., 2004; Argus et al., 2005). The San Gabriel Valley basin (Los Angeles,
48 California) experienced an expansion of about 1 cm and an uplift of nearly 5 cm due to a heavy
49 rainfall during winter 2004-2005 (King et al., 2007; Ji and Herring, 2012). Recently Diaz et al.
50 (2014) detected an unusual spectral signature in seismic data, recorded also as local strain
51 variations, that were related to the discharge of the Aragon River in the southern Pyrenees (Spain).
52 Rainfall and snowmelt episodes were identified to cause distinctive signatures in the seismic and
53 strain measurements throughout the discharge phase in porous and fractured media.

54 Also tilt measurements have been long known to be affected by various hydrologic processes at the
55 level of few micro-radians (μrad). One of the first works in Italy that claim for "micro-movements"
56 caused by local rainfall was carried out by Caloi and Migani (1972), in which a couple of
57 clinographs revealed a tilt towards SSE in correspondence of rain, in an area not far from our study
58 region (70 km NE of the Cansiglio Plateau). The hydrologic induced deformation could also be
59 linked to the seasonal modulation of the regional shallow seismicity in the southeastern Alps
60 (Braitenberg, 2000).

61 Similar studies in different environments revealed the effect of groundwater on tiltmeter
62 measurements (e.g. Edge et al., 1981; Evans and Wyatt, 1984; Kumpel et al., 1988; Takemoto,
63 1995; Dal Moro and Zadro, 1998; Braitenberg, 1999a; Jahr et al., 2008). More recently
64 Longuevergne et al. (2009), Jacob et al. (2010) and Tenze et al. (2012) have successfully measured
65 rock deformations induced by hydrological processes in different karst systems (respectively
66 Vosges mountains, southern French Massif Central and classical Trieste karst). The first two
67 investigations demonstrate that the observed karstic media deformations are likely due to water
68 pressure changes in nearby fractures. Strain variations due to pumping experiments have been
69 recently studied in California to constrain material properties of rock using the Darcy flow
70 approximation (Barbour and Wyatt, 2014).

71 In this study, we test the hypothesis of hydrologic induced strain observed using both GPS and
72 tiltmeter data in a karst system located in the southeastern Alps, the Cansiglio Plateau (CP), Italy
73 (see Figure 1 for location). Previous works in similar environments suggest that the occurrence of
74 such phenomenon is not isolated and uncommon, but could be recurrent especially in karst areas
75 providing new insights into hydrologic karst processes (Longuevergne et al., 2009; Jacob et al.,
76 2010; Tenze et al., 2012; Diaz et al., 2014).

77 The CP is an extensive polje located in the southeastern Alps halfway between the Veneto and
78 Friuli districts in Northeastern Italy. Its average height is about 1000m above sea level (asl),
79 bounded on the W-SE sides by a ridge of super elevated hills up to 1500m asl. The whole CP is a
80 limestone plateau with extensive karstic epigenic and hypogenic features typical of a mature karst
81 system, dolines are the most remarkable landscape features, both of dissolutional and collapse
82 origin, and hundreds of caves have been identified, a few of them several hundred meters deep. The
83 most sizable ones are: *Bus de la Genziana* 590 m depth, and *Abisso Col della Rizza*, reaching 800 m
84 depth, both of them are regularly inspected by speleological expeditions. The southeastern slope of
85 the CP is characterized by a thick succession of Cretaceous peritidal carbonates, while the central-
86 western part is characterized by slope breccia deposits, all capped by basinal marly carbonates
87 (Cancian et al. 1985). The surficial hydrography of CP is only modest and a deep aquifer, several
88 hundreds of meters below the top of the CP, is supplied by infiltration of meteoric precipitation (up
89 to 1800 mm/year) through, dolines, sinkholes and conduits of prevalent vertical development. The
90 aquifer yields significant quantities of water to springs at the lower limb of the anticline, where the
91 tectonized Mesozoic limestones are in contact with the Cenozoic and Quaternary impermeable units
92 of the footwall. Three main springs at the foothills drain most of the CP water forming the Livenza
93 River: Gorgazzo, Santissima and Molinetto, each bearing an average flow of 2-6 m³/s, yielding a
94 total flow of about 11 m³/s (Vincenzi et al., 2011).

95 The Gorgazzo spring is a typical Vaclousian spring that originates from a shaft, a few meters of
96 diameter, with the water running upwards. Occasionally, over periods of persisting drought, the

97 piezometric surface is lowered below the outlet elevation and the spring dries up. Since no
98 piezometric data are available, we presume that the springs at the foothills are located in a zone of
99 intermittent saturation. A quantitative model of the hydrology of the CP has not been developed up
100 to now and is therefore unavailable. In general, karst hydrology is complicated by the fact that the
101 hydraulic conductivity is inhomogeneous and anisotropic due to the presence of fractures and
102 shafts. Groundwater flows in the rock matrix, fractures and in conduits, where the conduit
103 component (cave-like tubes) is significant.

104 Although matrix porosity has been shown to be important in providing storage capacity, the
105 secondary porosity (conduits and fractures) dominates the pathways for groundwater flow (Ford and
106 Williams, 2007, p. 104). In our case the rainfall response (input–output) relationships are the only
107 means to treat the hydrologic system, as pumping experiments are not known to us. The latter are
108 probably very difficult to accomplish, as the watertable is many hundreds meters below the surface.
109 In the location of the tiltmeter the cave has been explored 600 m below surface before reaching the
110 ground water level. Relying only on the rainfall response of the springs, the hydrologic system
111 cannot be reliably parameterized. Parameters which could possibly be estimated and which
112 contribute to drainage are gross specific yields and continuum transmissivity for the different
113 portions of the aquifer (Shevenell, 2007). In order to accurately assess the deformation processes of
114 karstified aquifers a detailed hydrologic study is necessary, due to the presence of well developed
115 secondary porosity (fractures and fissures) and large conduits channeling most of the turbulent flow.
116 Our study is focused on geodetic movements and inclinations of the CP karst plateau, and currently
117 an accurate modeling of the deformation cannot be fulfilled due to lack of constraining parameters
118 on the hydraulic system.

119 The plateau is bounded on the southeast by a thrust fault (Caneva Thrust), part of the regional thrust
120 system (Cansiglio Thrust System), that demonstrates Late Quaternary activity (Galadini et al.,
121 2005). The main thrust plane is also associated with minor faults developing a quite wide cataclastic
122 zone, about 500 m width. The most recent destructive earthquakes occurred in 1936 at the foot of

123 the CP, associated to this thrust system with an $M=5.8$ event at 15 km hypocentral depth (Sirovich
124 and Pettenati, 2004).

125 At 33 km distance, in a very similar tectonic setting, the subsurface structures are being used for
126 temporary storage of gas Methane (Edison, 2014), where periodically fluids are injected and
127 extracted from the subsurface. Due to the analogous tectonic setting, the full understanding of the
128 hydrologically induced deformations on the Cansiglio plateau could be useful to understand the role
129 of water-induced deformations at the Methane deposit.

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Data and method

132 Since 2005 the University of Trieste manages a tiltmeter station in a natural cave named "Bus de la
133 Genziana" placed at 25m depth (Grillo et al., 2011). This deep shaft has been recently demonstrated
134 to be hydrologically connected to the drainage system of the Livenza River headwaters (Santissima
135 and Molinetto) in the SE foothills of the Cansiglio (Vincenzi et al., 2011). The tiltmeters consist of
136 two Marussi type, horizontal pendulums with Zöllner suspension oriented NS and EW. Each
137 pendulum is hosted in a cast-iron conic housing and the records are digitalized with a nominal
138 angular resolution of 2.5 nrad and a sampling rate of 1 hour (Braitenberg, 1999b; Zadro and
139 Braitenberg, 1999).

140 We also installed a few GPS stations and analyzed all available GPS data in order to characterize
141 the regional surface deformation. Currently two permanent GPS stations on the CP are available:
142 the Caneva station (CANV), part of the FReDNet geodynamic network
143 (<http://www.crs.inogs.it/frednet>) owned by the OGS (Istituto Nazionale di Oceanografia e di
144 Geofisica Sperimentale) and the Tambre station (TAMB) owned by the local governmental
145 authority Regione Veneto (<http://147.162.229.63/Web>). The CANV station is materialized on a
146 reinforced concrete pillar founded on the bedrock and the TAMB station is placed on the roof of a
147 recently restored stone building. The GPS data were processed as described in Devoti et al. (2011),
148 estimating daily station positions in the IGS08 reference system. We also filter out the common

149 mode noise (Wdowinski et al., 1997) using 28 selected GPS stations positioned in a great circle of
150 roughly 50 km radius around the CP, and compute the station residuals at CP stations subtracting
151 the long term tectonic drift estimated at CANV station. The average root-mean-squared (RMS) of
152 the residuals of our station coordinates is 1.2 mm in the horizontal and 3.7 mm in the vertical
153 components. CANV shows unusually high residuals in the horizontal plane, 3.3 mm in the north
154 and 2.7 mm in the east component, which represents only about the fifth percentile of all the other
155 station residuals.

156 The rainfall data were collected at the weather station located on the plateau, (loc. Tramedere,
157 <http://www.arpa.veneto.it/>; see Figure 1) placed at about 8 km north from CANV station and 2.5 km
158 from the tiltmeter location, whereas the hydrometric station of the Livenza river is located at the
159 foothills of the CP at about 4 km east from CANV station and 8 km east of the tiltmeter. The
160 Livenza river is thought to be the main CP aquifer discharge but very few experimental data are
161 currently available (see Vincenzi et al., 2011 for a discussion). We assume flow proportional to
162 head, and thus water table variations proportional to streamflow variations. Since only the gauge
163 height measurements are available continuously, we interpolate the streamflow measurements using
164 a fourth order polynomial relationship (see auxiliary Figure S1), and convert the hourly gauge
165 heights to corresponding hourly streamflow values. We study the correlation of the tiltmeter and
166 GPS anomalous displacements with the hydrologic parameters and discuss the results of an
167 extensive GPS measurement campaign on the CP slopes that suggest the existence of a deformation
168 anomaly acting at a regional scale (~10 km).

169 **Results and Modeling**

170 From the beginning of its operation in 2004, the GPS permanent station CANV exhibits regular
171 deformation patterns in the position time series, following each rain event. The daily positions show
172 sudden displacements that, due to our temporal resolution, can be considered simultaneous to rain
173 and are followed by a slow rebound towards the original position. Figure 2 shows the GPS time
174 series (GPS-E east, GPS-N north, GPS-V vertical) recorded at CANV station, together with the

175 daily rainfall from the Tramedere weather station. The horizontal components (GPS-E and GPS-N)
176 demonstrate remarkable shifts, roughly in the SSE direction, during rain episodes and the tendency
177 to rebound in the following days or weeks resembling the time evolution of the Livenza gauge
178 height. This is evidenced in Figure 3 where the behavior of both GPS and tiltmeter measurements
179 are compared during autumn and winter period 2010-2011. Three major rainfall events occur in that
180 period: November, 2, December, 24 and March, 17 with respectively 502, 368 and 200 mm rainfall.
181 In those days the GPS position shifts rapidly, respectively by 15, 13 and 10 mm in the SSE
182 direction.

183 The long term behavior of the CANV time series seems to suggest a residual deformation originated
184 from the karst-hydrological signal that cumulates over time. Figure 4 displays the horizontal daily
185 position residuals with respect to the secular drift of a nearby station (VITT, see Figure 1 for the
186 location), that well approximate the regional tectonic motion (~ 2 mm/yr towards N). For the sake of
187 clarity the two time series are arbitrarily shifted by 10 mm, respectively upwards and downwards.
188 The average long term drift in the E-W direction is similar in both stations, thus the residuals show
189 no average drift, whereas in the N-S direction the CANV station appears delayed (residuals
190 demonstrate a negative drift), especially noticeable after 2009 when the rainfall events are more
191 frequent. We observe an average 1 mm/yr deficiency in the northern secular rate at CANV station,
192 which can be interpreted as due to the anelastic part of the deformation that cumulates at each
193 rainfall, or alternatively caused by the incomplete elastic rebound during specific heavy rainy
194 periods marked by an incomplete aquifer discharge.

195 During the operational period of the CANV station (2004.5-2013.4) we identified a total of 57 rain
196 episodes characterized by uninterrupted rain, each of them lasting between 13 and 116 hours. In this
197 period we observe an average annual rainfall of 920 mm, with events ranging from a minimum of
198 47 mm to a maximum of 502 mm. We estimate the corresponding 3-D GPS displacements
199 computing the difference between post- and pre-event average station position. Furthermore at the
200 same epochs we were able to measure the gauge height variations of the discharge river. The

201 correlations of GPS displacements with rainfall and with gauge heights (or alternatively with the
202 river streamflow) are high for the horizontal displacements and insignificant for the vertical
203 displacement. The significance of the correlation coefficient is estimated using a Student's t-test to
204 test the null hypothesis of zero correlation. We define the critical correlation as being the value of
205 correlation, above which the t-test rejects the null hypothesis at the 95% confidence level, in other
206 words it represents the minimum correlation coefficient below which the variables can be
207 considered uncorrelated. At this confidence level the vertical GPS displacements could be
208 considered uncorrelated with rain (0.28) and with other hydrologic quantities, being always below
209 the critical correlation coefficient (0.3). The horizontal displacements are instead significantly
210 correlated with rainfall (0.92), with the gauge height variations (0.71) and streamflow variations
211 (0.63). Figure 5 shows the correlation plot for the GPS horizontal and vertical displacements versus
212 rainfall. The horizontal displacement is remarkably proportional to the amount of rainfall (2.9 mm
213 every 100 mm of accumulated rainfall). We note that the deformation is correlated to a lesser extent
214 with the river gauge height variations (or discharge streamflow) and hence with water table
215 variations. This is a strong indication that the cause of the deformation is more directly linked with
216 subsurface hydrologic processes in the karstic vadose zone rather than with deep rooted water table
217 variations in the phreatic zone. This observation is in agreement with the main findings of
218 Longuevergne et al. (2009) and Jacob et al. (2010) that identify hydrologically active fractures in
219 the vadose zone as sources of their observed tilt variations.

220 In order to ascertain the spatial limits of the deformation pattern, we installed five GPS stations on
221 the top of the CP and carried out an intensive measurement campaign during winter 2011-2012. The
222 GPS antennas were mounted on geodetic benchmarks, anchored on outcrops of the plateau. Each
223 benchmark, made by a stainless steel rod, has been drilled in the bedrock at a variable depth of 0.5-
224 0.8 m and fastened with epoxy resins. During the measurement campaign two significant rain
225 events occurred (on October, 26 and November 8 with respectively 183 and 271 mm rainfall),
226 causing recognizable surface displacements at other three stations. Figure 1 shows the displacement

227 vectors recorded at all available stations for the two rain events, indicated respectively with the red
228 and blue arrows. The horizontal GPS time series are shown in Figure 6, three stations (CN03, CN04
229 and CANV) demonstrate abrupt variations in correspondence of the rain events, followed by a slow
230 rebound that fully recovers the original pre-event position. Other two stations located on the plateau
231 (TAMB and CN01) show minor, or no reaction to the rain. The vertical time series are shown in the
232 auxiliary figure S2 and are less affected by rainfall occurrences (e.g. CANV, CN03 and CN01), and
233 show different responses to rain. The GPS campaign evidences the scale of the phenomenon, at
234 least $12 \times 5 \text{ km}^2$ area is subject to a coherent deformation, involving the whole southeastern slope of
235 the CP that reacts to hydrological stresses. The stations bordering the southeastern slope are
236 displaced by an amount of 4-9 mm by heavy rain, whereas the plateau is rather motionless or
237 moving in the opposite direction. Very interesting are the anomalous displacements visible at the
238 station CN03 in the first few days of year 2012. The GPS station, in spite of being anchored on
239 outcrop, shows a sudden back and forth displacement spanning a few centimeters and lasting only
240 4-5 days, it seems a very local effect (confined only at CN03) and apparently not permanent (it
241 doesn't show hysteresis), the cause of these oscillations has not yet been identified and is still under
242 investigation.

243 The tiltmeter time series demonstrate a clear causal relationship with the pluviometric and the
244 hydrometric data, but its variations are not as regular as the GPS. The tilt variations in
245 correspondence of rainfall vary from fractions of micro-radians, up to $30 \text{ }\mu\text{rad}$ and exhibit sudden
246 spikes in both the N-S and E-W directions, generally more pronounced in the N-S direction (see
247 Figs 3 and 7). These variations are two orders of magnitude larger than solid Earth tides tilt
248 variations. The observed impulsive tilts show sporadic changes in the direction, tilt variations are
249 mostly directed towards N or NNW (75%) but sometimes, and to a less extent, flip to the opposite
250 direction (25%) (Grillo et al., 2011). In order to assess the tiltmeter response, we further zoom into
251 the event of December 2010 (Figure 7), where the displayed recordings of tilt and rain are sampled
252 at hourly intervals. The tilt response to rainfall is first a back-and-forth movement towards N-NE,

253 almost contemporaneous to rain and lasting only a few hours, followed by a successive slow
254 rebound over days that is similar to the GPS and the Livenza gauge height trends. To characterize
255 the fast-moving tilt spikes we automatically detect the transients of tilt amplitudes (EW-NS
256 modules) after eliminating the long-period trend from the data (low pass filter with cut off at 1/70
257 days, cosine filter tapering). A tilt spike is identified if its variation is greater than 1.5 times the
258 noise-threshold, the latter defined as the double standard deviation of the detrended data. At each
259 spike epoch we determine the duration of the anomalous variation. Figure S3 shows the histogram
260 of time lags for the 57 detected spike events, it evidences the very fast response to rainfall lasting
261 only a few hours with long lasting tilts up to 11 hours for the more intense rainfalls. To evaluate the
262 tilt-rainfall correlation, we integrate the rain in a time window right before the spike epoch,
263 choosing the window span being equal to the spike duration and placing the tail of the window at
264 the spike epoch. Figure S4 shows the scatterplot and the linear interpolation of tilt and rainwater, we
265 obtain a correlation coefficient of 0.38 which results to be just above the critical threshold. In
266 conclusion the spikes are very short lived events, which correspond to the fast runoff of rainwater
267 through the highly fractured epikarst. This fast infiltration is obviously below the resolution
268 capability of our GPS time series. The prevalent NNW tilting direction is however coherent with the
269 observed GPS displacement direction.

270 The discharge style of the karst aquifer can be tracked down from the stream hydrographs of the
271 Livenza river. The maximum flow is systematically delayed with respect to the rain peaks by a time
272 lag that depends on the groundwater travel path through the karst system. The time lag represents
273 the travel time the rainwater needs to reach the bottom of the hill. Analyzing the entire dataset we
274 estimated a time lag of 9 hours (median), which reflects the characteristic conductivity of the entire
275 karst system for the rapid flow through the most receptive conduits. In Figure 8 we plot the
276 streamflow trends of the recession phase after main floods in a semi-logarithmic scale. Linear
277 trends in the logarithmic hydrographs follow from a linear relation between hydraulic head and flow
278 rate, which is commonly found in karst baseflow (Maillet, 1905). Almost all recession curves in

279 Figure 8 are characterized by a rapid runoff phase lasting 10-48 hours, followed by a slow discharge
280 rate lasting a few weeks (dashed lines show the prevailing trends). We evaluate the following half
281 periods (i.e. the time required for the streamflow to halve) for the fast discharge ($t_{1/2}=10$ hours to
282 2.3 days) and for the slow discharge ($t_{1/2}=12$ to 22 days). Therefore the initial rapid flow in shafts
283 and conduits through the vadose zone, causes the baseflow to rise to its maximum within 9 hours
284 after the rainfall peak, and it persists in proportion to the total rainfall corresponding to the observed
285 rapid runoff (10-48 hours). In this stage the effective hydraulic conductivity of the whole karst
286 system is of the order of $4\cdot 5\cdot 10^{-2}$ m/s, which is characteristic of flows through coarse gravels. This
287 phase ends within the first 48 hours after the flood and saturates eventually the secondary porosity
288 (fractures and fissures) of the rock matrix. Afterwards the drainage progresses slowly, fed mainly
289 by infiltration through the secondary porosity of the karstic medium, similarly to what has been
290 observed in different contexts (e.g. Shevenell, 2007). In this stage the conductivity reduces by two
291 orders of magnitude to about $7\cdot 10^{-4}$ m/s (assuming 17 days of average decay time), corresponding
292 to an intrinsic permeability of 10^{-10} m², which is still several orders of magnitude higher than the
293 permeability observed in unfractured porous limestones (e.g. Jaeger et al., 2007). Thus we infer that
294 the slower drainage is caused mainly by the secondary porosity as a response from narrower
295 fissures and fractures. Assuming a Darcian flow and assuming the validity of the cubic law for the
296 flow through fissures (Witherspoon et al., 1980), we evaluate an equivalent fracture opening of 40-
297 50 μ m to explain the observed flow. Thus we conclude that the drainage through a connected
298 texture of fractures and fissures is not negligible and may well explain the observed permeability.

299 The change in strain induced by a sub-vertical fracture may be properly modeled in the far-field by
300 a simple Okada-type model (Okada, 1985). A single vertical tensile source is used to model the
301 expected deformation in a homogeneous elastic medium. This idealized source could be a very
302 crude approximation of the complex karstic fractures system, in which the observed displacements
303 result from the cumulating effect of distinct individual sources. However the simplified model is
304 useful for arguing on properties of the source geometry, even though only achieving qualitative

305 findings. Figure S5, panel a), shows the expected displacement field of a vertically oriented
306 rectangular source, simulating a tensile dislocation of 2 cm, in a typical elastic medium (modulus of
307 rigidity $G=30$ GPa and Poisson ratio $\nu=0.25$) computed using dMODELS software (Battaglia et al.,
308 2013). Panel b of Figure S5 shows the profile of the predicted surface displacement and tilt across
309 the source strike. It is worthwhile to note that the displacement and angular observables decay at
310 different rates at increasing distance from the source. Strong tilt variations, up to tens of μrad , will
311 occur only in the near proximity of the source (within 5% of the total source length), whereas the
312 surface displacements demonstrate a longer wavelength, being greater than millimeters at
313 substantial proportions of the source length (within 80% of the total length). Therefore, given the
314 observed displacements and tilt variations on the CP, we expect the tiltmeter being particularly
315 sensitive to nearby fractures whereas, on the contrary, the GPS being sensitive to a wider integrated
316 source domain. Another important conclusion arises from the ratio between the horizontal and
317 vertical displacement (h/ν) observed at the CANV station. We derive the h/ν proportion computing
318 the ratio between the average horizontal and vertical deformations (straight lines in Figure 5),
319 estimating a mean value of $h/\nu=2.5$. This value can be considered as a ceiling threshold for the h/ν
320 ratio since, on the average, no higher values are expected at CANV station. In Figure 9 we simulate
321 a family of maximum h/ν values achieved with variable source width and tip depth. At $h/\nu=2.5$, and
322 increasing the source width, the curves show a corresponding increase in the tip depth of the source,
323 so that width and depth are the same. Thus the curves suggest that the source width should be at
324 least as wide as the tip depth, such that a near surface fracture is in proportion shorter (small source
325 width) than a deeper one and conversely, long fracture paths should extend very deep in the
326 mountain. Since these conclusions rely on a single GPS observing station we cannot draw any
327 definitive conclusion until more monitoring stations are available in order to figure out a more
328 realistic source geometry.

329 The observed high tilt variations (on the order of μrad) could only be obtained with shallow
330 sources, and also the change in direction of the tilt, peculiar of the CP (this publication and Grillo et

331 al., 2011 compared to e.g., Braitenberg et al., 1999b, Tenze et al., 2012), demand for a complex
332 system of nearby fractures placed at different depths and relative positions. The change in direction
333 of the tilt is peculiar of the Cansiglio Plateau, as it has not been observed in the other tiltmeter
334 stations of the same network. As an example, we could imagine that the geodetic stations first sense
335 an upper crack and move in one direction, then a lower crack is filled, and the induced signal is
336 summed to the first one, creating the direction inversion in the tilt response and possibly also in the
337 GPS measurement, depending on the relative positions.

338 **Discussion and Conclusion**

339 The GPS displacements of the stations located at the flanks of the CP show statistically significant
340 correlations with the karst hydrologic system, showing a very fast and impulsive response to
341 rainfall. We find that the permanent GPS station at Caneva (CANV), with 8 years of continuous
342 recordings, shows a succession of displacements triggered by moderate to heavy rainfall, showing a
343 repetitive time evolution. The cross-correlation analysis between the observed GPS horizontal
344 deformation and of the hydrological quantities, all demonstrate significant positive correlation. The
345 strongest correlation being with the local rainfall, evidencing that surficial hydrologic processes are
346 the most probable cause of the observed deformation. A couple of tiltmeters, installed in a cave at
347 the top of the plateau, show a less regular reaction to rainfall compared to the GPS stations. The two
348 hydrologically induced signals are distinct in their temporal evolution, which is due to the different
349 settings of the stations (flanks or top of plateau) and to different sensitivities to ongoing processes.
350 The geodetic measurements, as also the streamflow data show time constants of several days, as
351 they collect the water of the entire plateau. During the rain episodes the tilt response is much more
352 rapid and wide (in the order of hours and up to tens of μrad). For a subset of rain events, three
353 temporary GPS stations located in different places on the flanks of the Plateau, confirm the transient
354 deformation demonstrating an outboard oriented pattern of the deformation in response to rain.
355 After rainfall exceeding 40 mm, the whole plateau expands laterally in all directions, with only
356 small vertical deformation. The hydrologic induced movement observed at GPS stations, is

357 distinctive for the Cansiglio area, such strong effects have not yet been observed in other GPS
358 stations of the southeastern Alps.

359 The water intake of rainfall is drained through fissures and fractures of the carbonate platform of the
360 CP and emerges at the foot of the plateau from a Vauclusian-type spring, forming the Livenza
361 River. The river responds to rainfall episodes by a rapid increase of the hydrometric height
362 (maximum height reached 9 hours after the rainfall centroid) and followed by at least two distinct
363 runoff phases: a rapid discharge phase (runoff) lasting 10-48 hours and a slow discharge phase
364 (infiltration) lasting a couple of weeks. We argue that the fast runoff phase, characterized by a high
365 hydraulic conductivity, represents the early rainwater flow through open sinkholes and conduits
366 reflecting a turbulent flow through the karst. In parallel the drainage progresses as infiltration
367 through fractures and fissures, flowing with a slower discharge rate. In this latter phase the
368 permeability reduces by two orders of magnitude, which is still several orders of magnitude higher
369 than the permeability of unfractured limestones. We speculate that a congruous contribution to the
370 drainage may derive from a connected texture of fractures of 40-50 μm effective aperture width,
371 most probably of tectonic origin, i.e. shallow normal faults or extrados fractures formed on the
372 anticlinal crest (Philip and Meghraoui, 1983; Galadini et al., 2001). The lineament analysis of the
373 CP based on Landsat ETM+ imagery (Vincenzi et al., 2011), identifies two main patterns along the
374 NW-SE and NNE-SSW directions which are respectively parallel and orthogonal to the observed
375 GPS horizontal displacement (see figure 5 for GPS directivity). These lineaments follow the basic
376 active tectonic structures bordering the CP and are the most probable sources for promoting large
377 scale deformations caused by active fractures along the CP slopes. We suggest that micron-sized
378 fractures, filled by rainwater cause a prompt strain release, followed by a slow rebound as
379 groundwater discharges through fractures. Current data and observations on the CP do not allow a
380 reliable estimate of any source parameter, but a simple elastic model suggests that active sources
381 should be as deep as its length (source width). Since every 100 m of water column exerts a stress of

382 1 MPa, any deep-rooted fracture, tending to seal with depth, may well explain the observed surface
383 lateral deformation observed at the flanks of the plateau.

384 Concerning the tiltmeters, albeit the hydrologic induced tilt is generally observed, its impulsive
385 nature is atypical in this location. The typical signal of the other stations in the southeastern Alps is
386 limited to a response of smaller amplitude and lasting several days. The underground tiltmeter and
387 the GPS are observing different phenomena related to the hydrologic system. The tiltmeter is
388 susceptible to the small scale infiltration into the network of fissures of the most shallow layer of
389 the karst in the epikarst. This is the superficial fractured layer of the karst plateau, which can be up
390 to 20 m thick, overlying the more compact limestones. The water flows in the epikarst at much
391 higher velocity than the water drainage in the underlying layer due to the high volume percentage of
392 fractures, generally over 20% (Ford and Williams, 2007, p. 133). At the tiltmeter location, the
393 quantity of rainwater is only a fraction of the total flux supplying the springs at the base of the
394 plateau. The amount of the observed tilt deformation is orders of magnitude smaller than the
395 movements observed for instance by the GPS permanent station TAMB (installed at 400 m from the
396 tiltmeter). For instance a tilting of 1 μrad of a structure in the epikarst layer (characteristic length of
397 10 m), would produce a horizontal movement of only 10^{-5} m, too small to be detected by the GPS,
398 but well in the measuring range of the tiltmeter. Due to the small hydrologic volumes involved, the
399 deformation at the epikarst is therefore only seen by the tiltmeters. Due to the complicated network
400 of hydraulic conduits in the epikarst, the tilt signal can change in direction, though maintaining a
401 preferred tilt direction. Due to the higher hydraulic conductivity of the epikarst respect to the
402 underlying more compact layer, the water forms a temporary aquifer at the bottom of the epikarst.
403 We suspect that the complicated tilt response is due to the formation of this temporary aquifer,
404 which only forms if a threshold value of precipitation has been passed.

405 The present study demonstrates the direct link between the aquifer system cycles and the induced
406 surface deformation, providing interesting insights of karst style hydrological processes, that could
407 also be relevant in the assessment of hydrologic hazards. The GPS and the tilt observations are

408 complementary and sensitive enough to study and monitor the effects of water infiltration in karst
409 systems. The question arises whether a near real-time monitoring of the hydrologic deformation can
410 provide useful information to assess or predict seasonal hydrologic cycles and associated
411 environmental hazards in specific conditions, e.g. triggering of landslides and rock avalanches, well
412 recognized on both SW and SE slopes by the Livenza Basin Authority (<http://www.adbve.it>).

413

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430

431 **References**

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534 8.

535 **Figure Captions:**

536 **Figure 1.** Map of the Cansiglio Plateau area showing the Cansiglio Thrust System (C.T.S.)
537 bordering the southeastern flanks of the Plateau. The four letter words represent the GPS station ID
538 considered in this study, the red and blue arrows represent the displacements measured after two
539 rain events in autumn 2011 (see text for more details). (For interpretation of the references to color
540 in this figure, the reader is referred to the web version of this article.)

541 **Figure 2.** Three dimensional position time series of the permanent GPS station (CANV) located on
542 the Cansiglio Plateau (Italy), GPS-V, GPS-E and GPS-N are respectively the vertical, east and north
543 components, the bar plot on the bottom represents the daily rainfall at Tramedere weather station.
544 Major rain events are evidenced by vertical dashed lines.

545 **Figure 3.** Zoom of the daily GPS (GPS-V, GPS-E, GPS-N) and hourly tiltmeter (Tilt-N, Tilt-E)
546 time series in the autumn-winter period 2010-2011. The tiltmeter observations are smoothed out
547 with a running box window of 6 hours. The daily rainfall (bars) and Livenza river gauge height
548 (gray filled area) is also reported in the bottom of the graph.

549 **Figure 4.** Different secular rates measured at CANV and VITT permanent stations. Dots represent
550 the CANV daily position in the horizontal directions, North-South (N-S) and East-West (E-W).
551 Straight lines represent the secular rates of CANV (solid line) and VITT (dashed line). VITT is a
552 nearby permanent GPS station assumed to properly measure the regional tectonic drift.

553 **Figure 5.** Displacements versus rainfall amount as observed at CANV GPS station. The grey circles
554 represent the horizontal displacements whereas the open circles, the vertical displacements. The
555 inset shows the polar histogram of the displacement directions of all (57) rain events.

556 **Figure 6.** GPS time series of the intensive measuring campaign during winter 2011-2012. Panel a)
557 shows the daily station positions in the south direction and panel b) shows the station positions in
558 the east direction. The rainfall (blue bars) and Livenza river gauge height (cyan filled area) is

559 reported in the bottom of the graphs. (For interpretation of the references to color in this figure, the
560 reader is referred to the web version of this article.)

561 **Figure 7.** Zoom on tiltmeter evolution (East and North components) on December 2010. Rainfall
562 (black bars), tilt data (solid lines) and gauge heights (gray filled area) are all sampled at hourly
563 intervals.

564 **Figure 8.** Livenza stream hydrographs of the recession curves after floods. The dashed lines
565 represent the average trends of the recession curves of the river in the fast flow (10-48 hours) and
566 slow flow (12-22 days) phases.

567 **Figure 9.** Modeled deformation ratio (h/v) for a family of vertical tensile sources varying in tip
568 depth (shown on the right) plotted against the source width. At CANV station we observe a
569 characteristic ratio of $h/v=2.5$ (highlighted).

570

571 **Auxiliary Figure S1.** Interpolation curve of the streamflow data obtained fitting a 4-degree
572 polynomial to a set of streamflow observations collected in the period 2011-2012. The interpolation
573 has been used to convert the hourly gauge height data to equivalent streamflow quantities.

574 **Auxiliary Figure S2.** Vertical GPS time series for the 2010-2011 measuring campaign, to be
575 associated to figure 6 in the text.

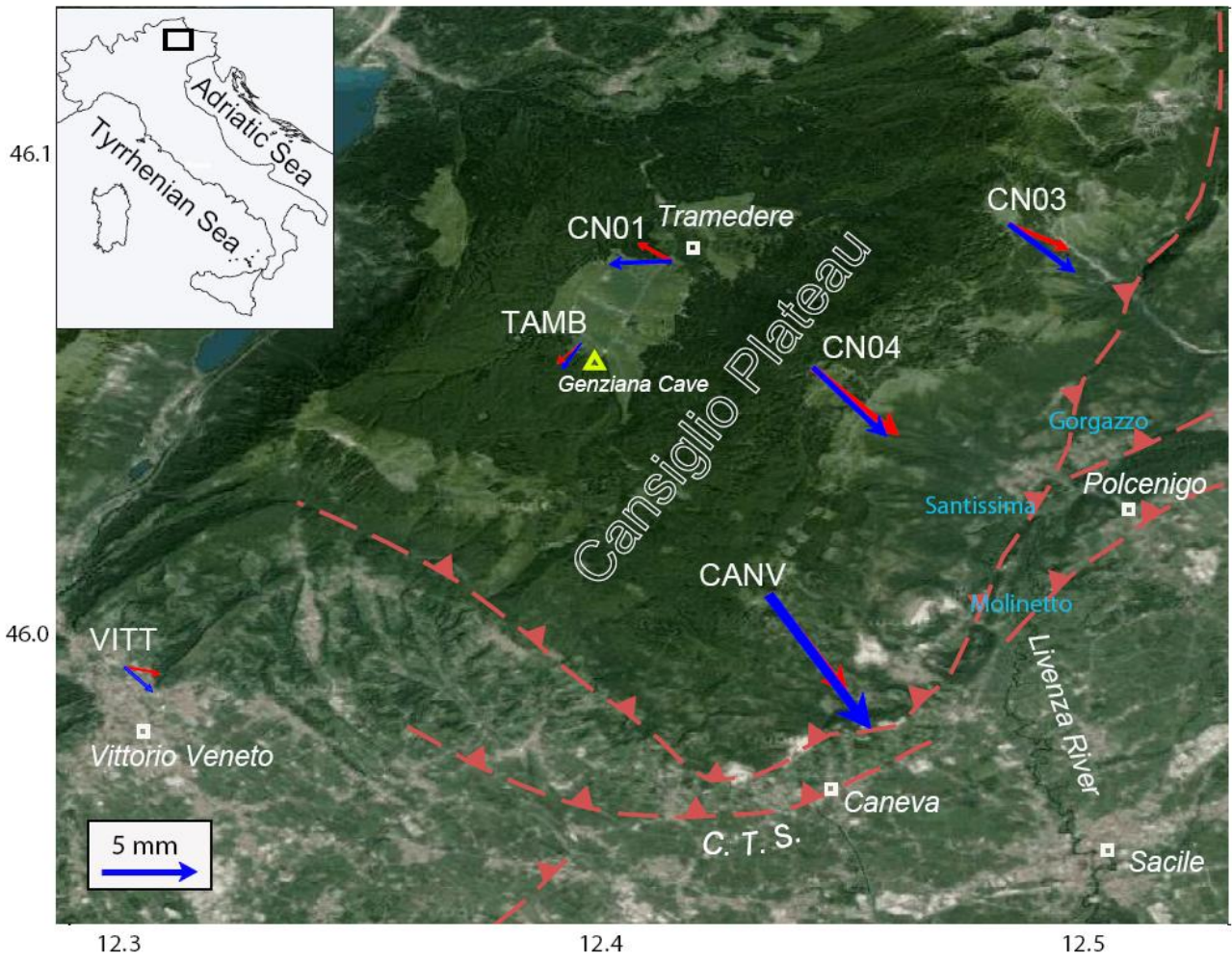
576 **Auxiliary Figure S3.** Distribution of tilt spike (abrupt variations) durations registered for 57 rain
577 episodes. We observe a characteristic duration (most recurrent) of 4 hours.

578 **Auxiliary Figure S4.** Correlation of the tilting amplitude with integrated rainfall. The rainfall has
579 been integrated in a time window right before the spike epoch, choosing the window span being
580 equal to the spike duration.

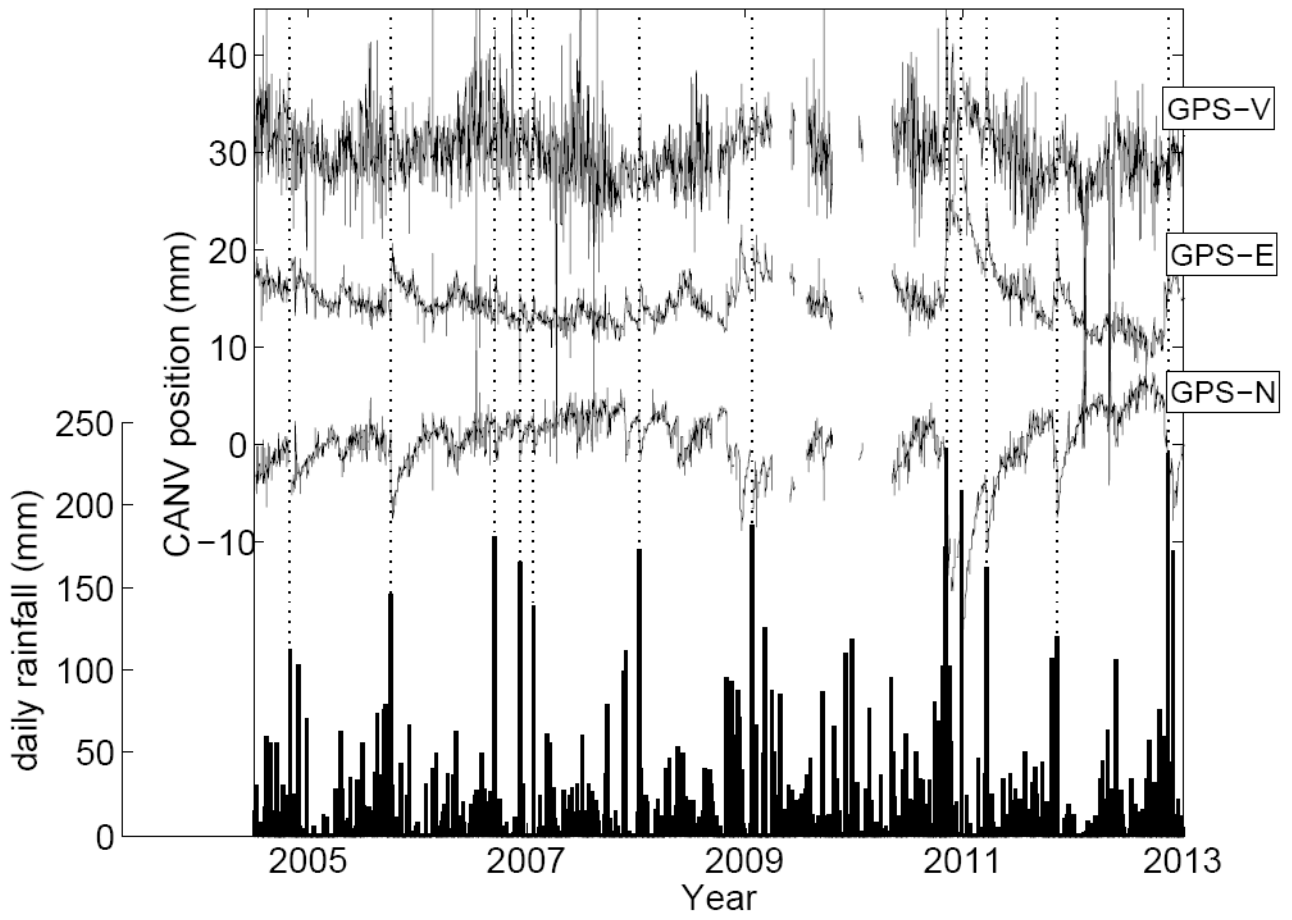
581 **Auxiliary Figure S5.** Deformation caused by a tensile dislocation of a rectangular source in an
582 elastic half space, oriented vertically downwards along the x-axis. The pseudocolor image in the top
583 panel represents the vertical displacement, whereas the arrows represent horizontal deformation on

584 the surface. The lower panel shows the cross-strike profile (A-A') of the vertical (solid line), the
585 horizontal (dash-dot line) and the tilt (marked line) deformations.

586



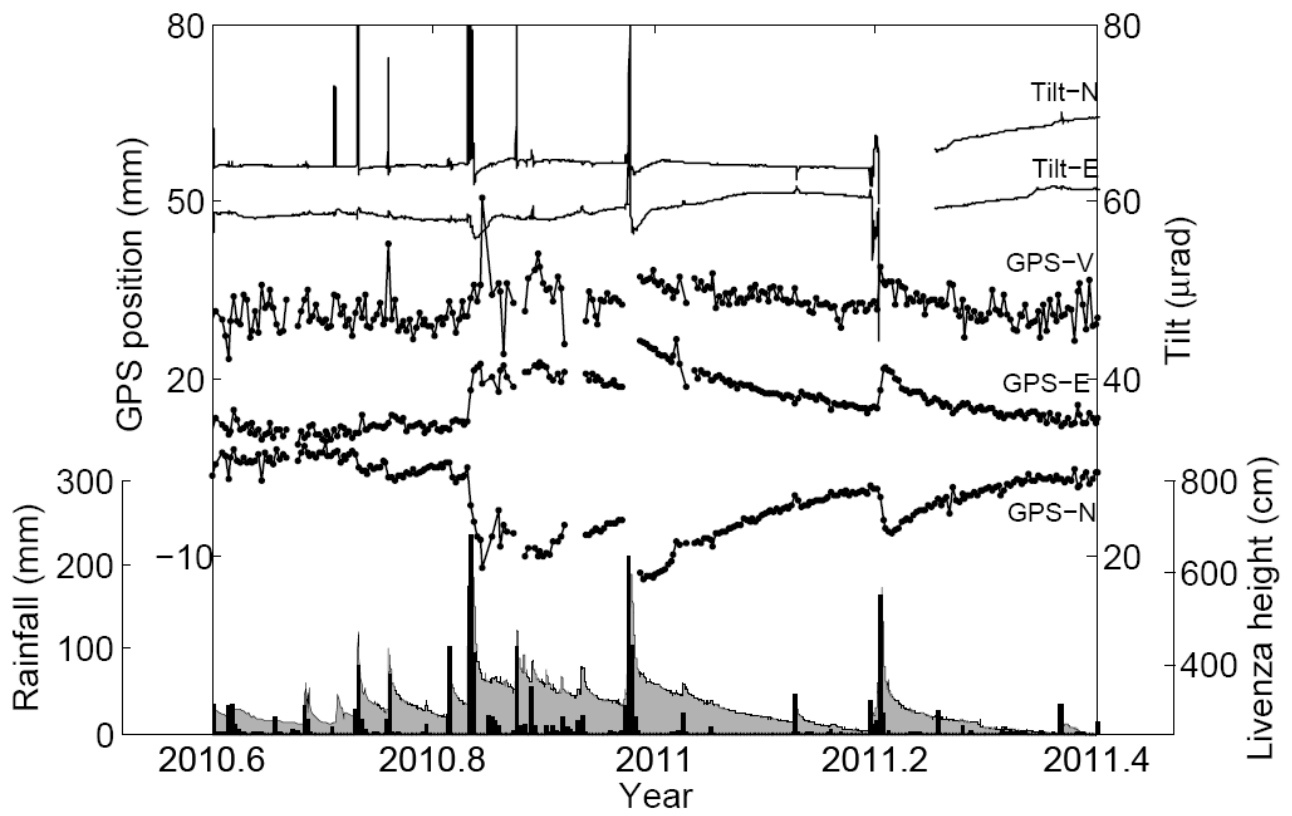
589 Figure 1



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592 Figure 2.

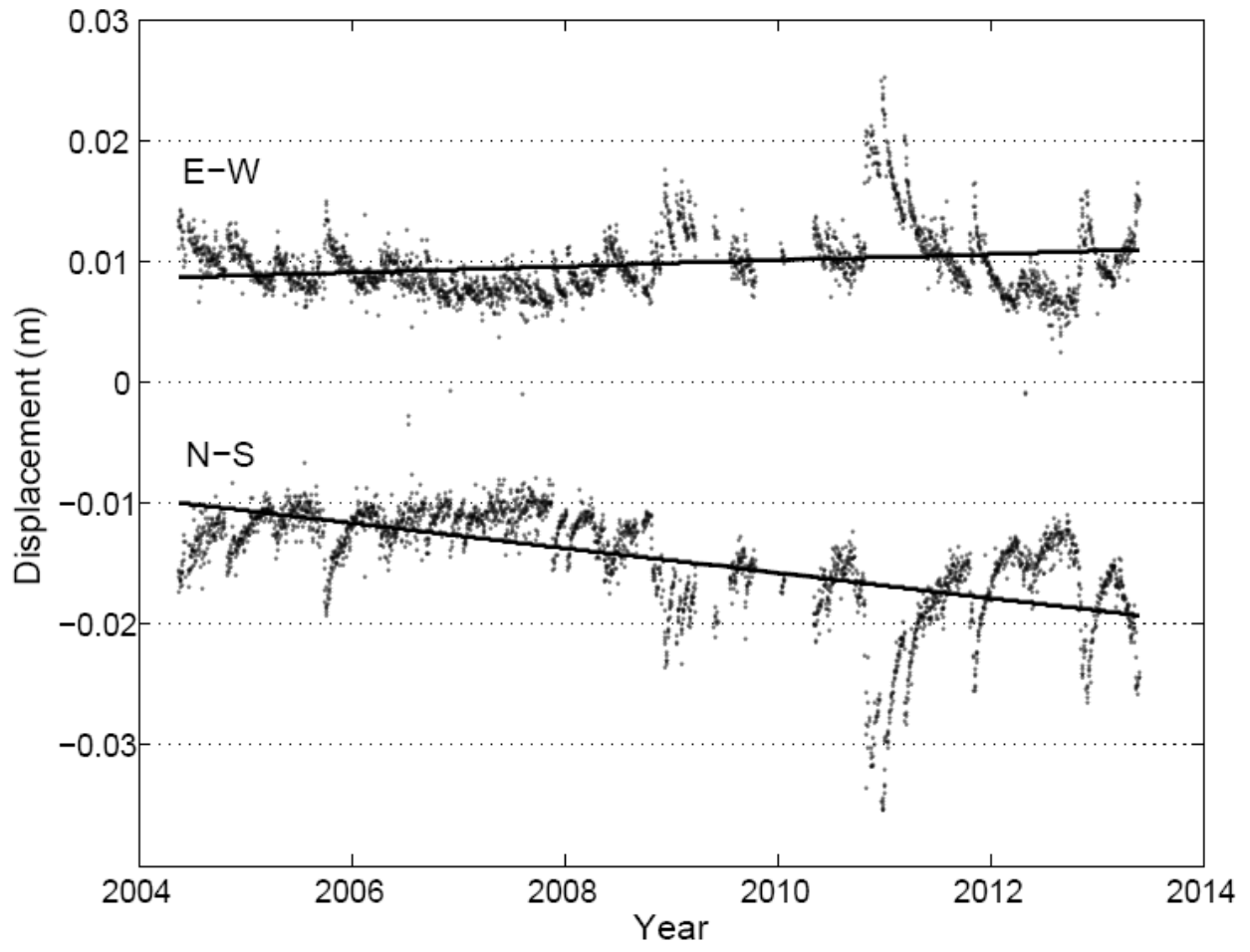
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595 Figure 3.

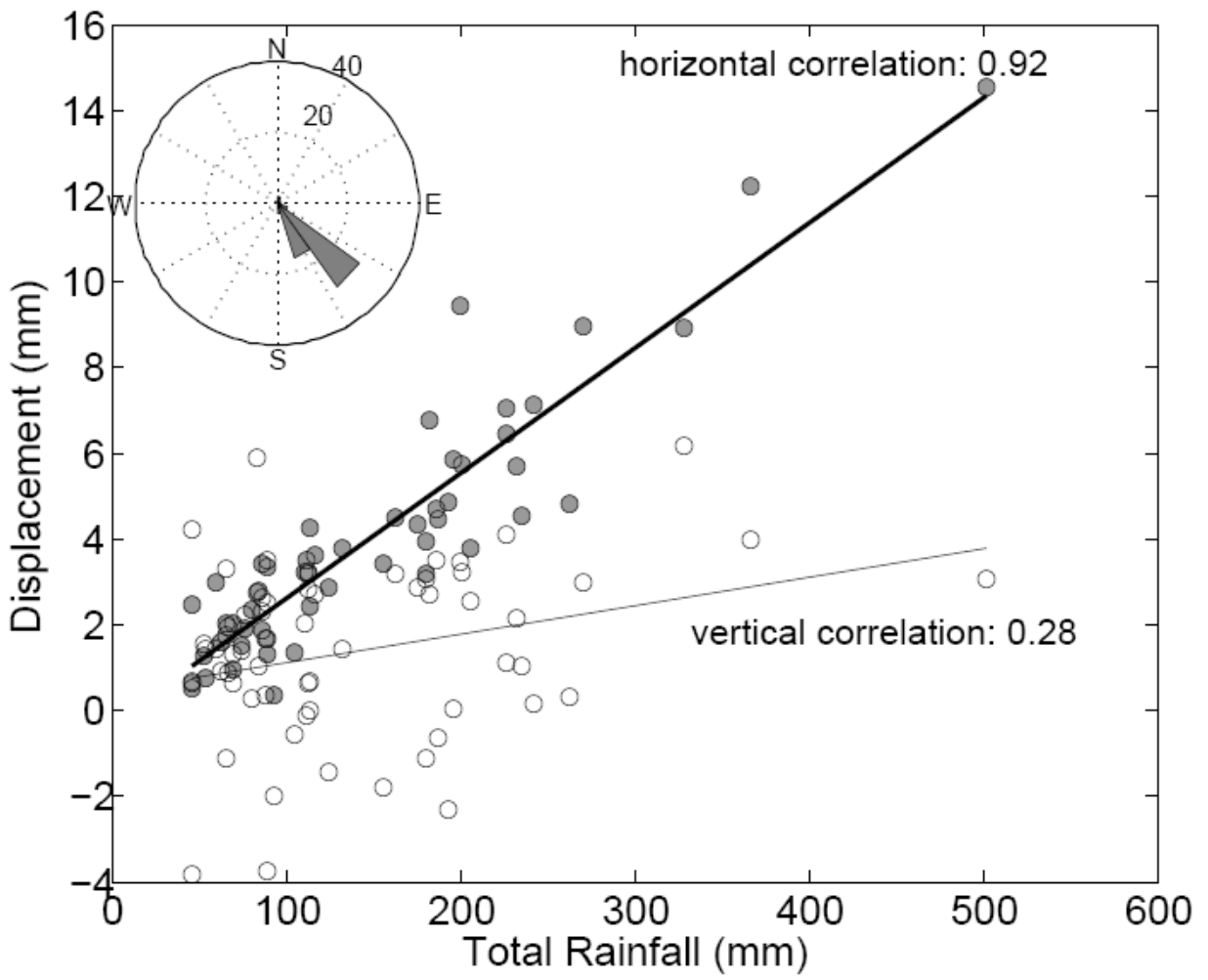
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598 Figure 4.

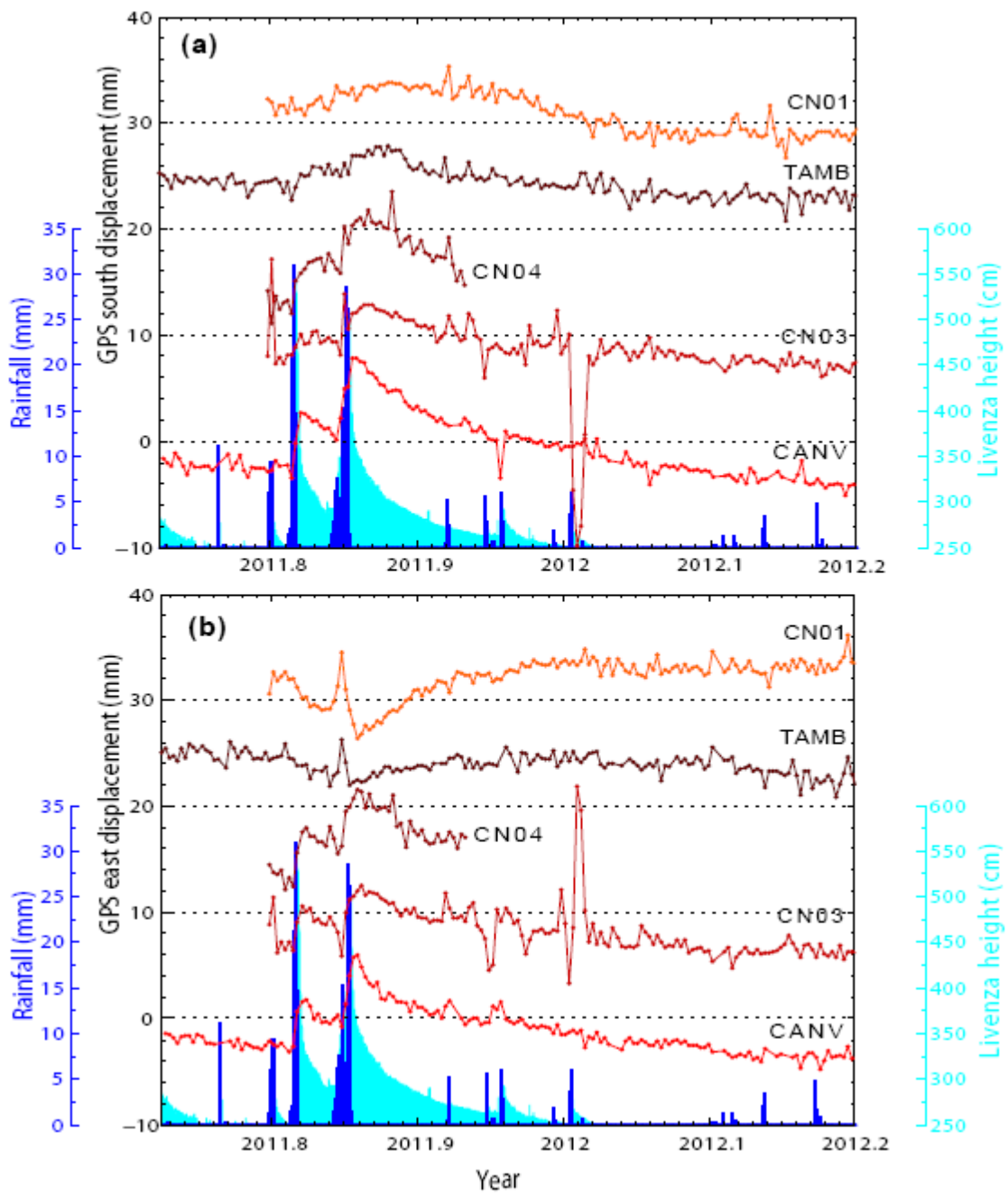
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601 Figure 5.

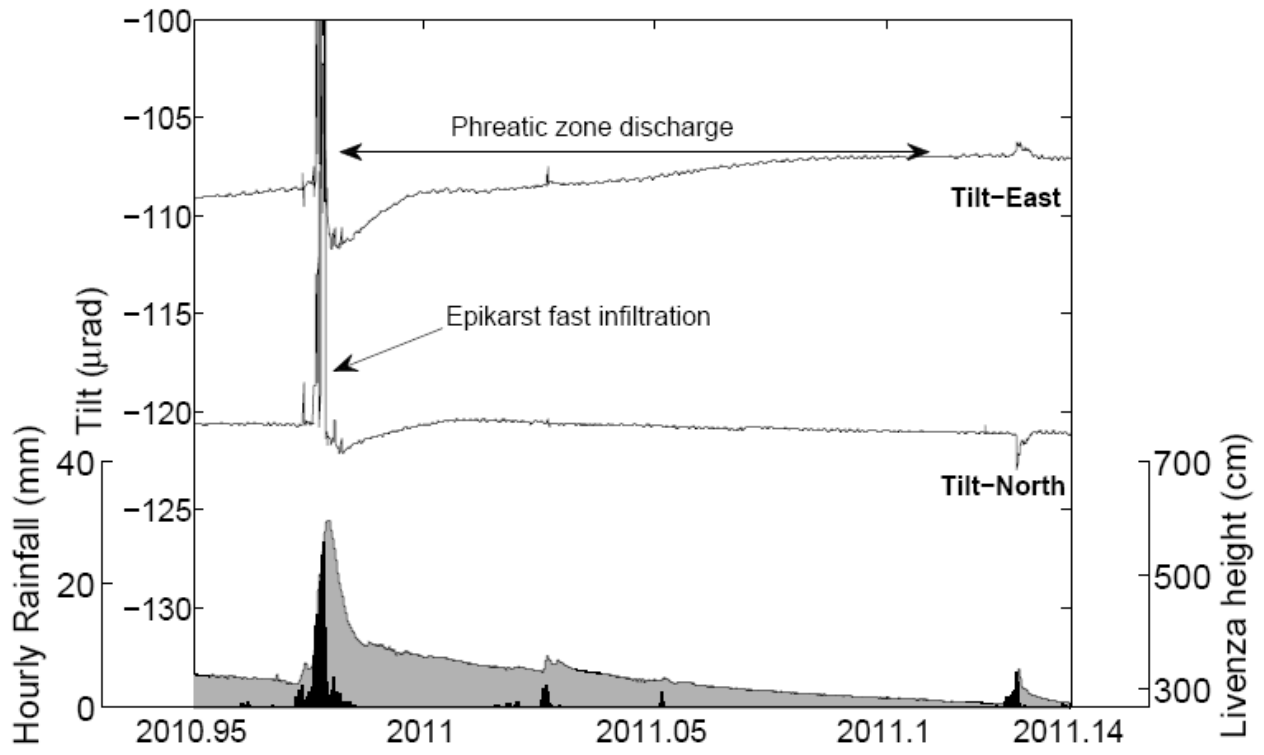
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604 Figure 6.

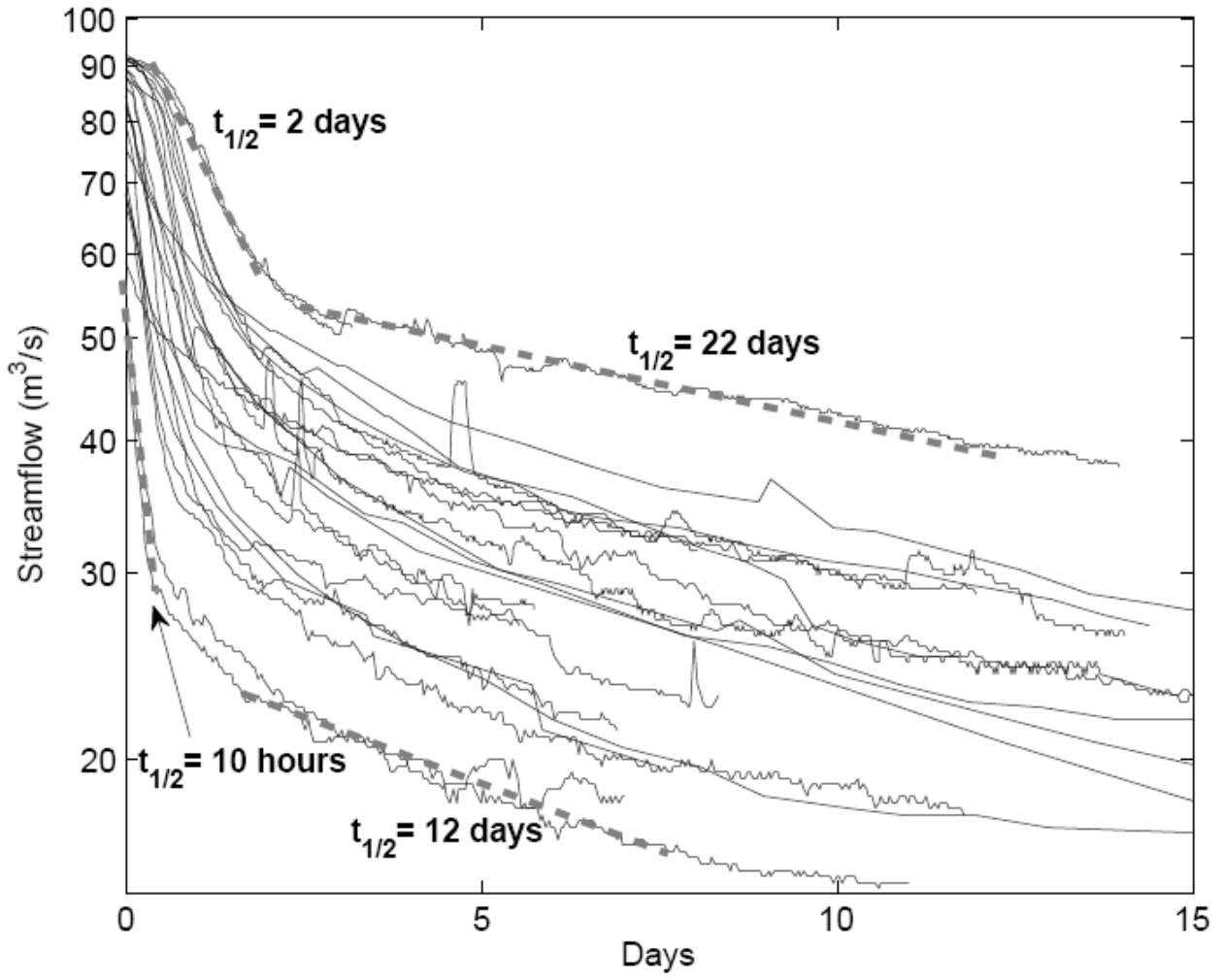
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607 Figure 7.

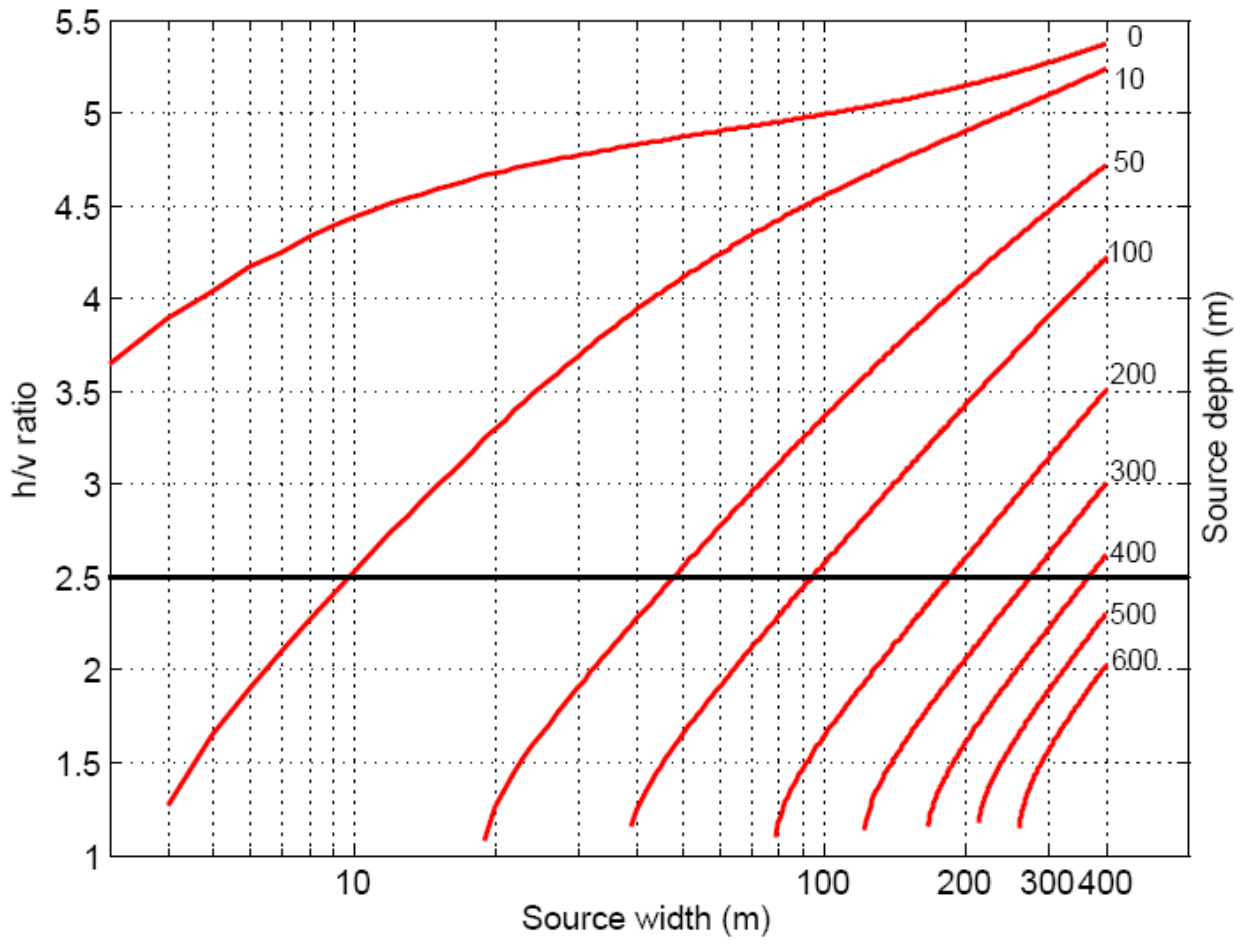
608



609

610 Figure 8.

611



612

613 Figure 9.