GNSS-PWV and Intense Rainfall Events: An Analysis of Two Years of Observation Acquired by the SNIK CORS on the Bari Area (Italy)

Alberico Sonnessa[1(✉)], Eufemia Tarantino[1(✉)], and Alessandra Mascitelli[2(✉)]

[1] Department of Civil, Environmental, Land, Construction and Chemistry (DICATECh), Polytechnic University of Bari, Via Orabona 4, 70125 Bari, Italy
{alberico.sonnessa,eufemia.tarantino}@poliba.it

[2] Department of Advanced Technologies in Medicine and Dentistry (DTM&O), Center for Advanced Studies and Technology (CAST), University "G. d'Annunzio" of Chieti-Pescara, Via dei Vestini 31, 66100 Chieti, Italy
alessandra.mascitelli@unich.it

Abstract. Continuously Operating Reference Stations (CORS) play a crucial role in high-precision positioning and environmental monitoring. This study examines the relationship between Global Navigation Satellite System (GNSS) - derived Precipitable Water Vapor (GNSS-PWV) and intense rainfall events in Bari, Italy, using data from the SNIK CORS, operated by the AGLab of the Polytechnic University of Bari. The research aims to assess the potential of GNSS-PWV for nowcasting applications by analyzing two years of observations (July 2022–October 2024) in conjunction with precipitation measurements from local rain gauges. Results show a clear correlation between PWV peaks and intense precipitation, with PWV increases preceding rainfall intensity peaks by 5 to 105 min. A threshold-based approach for rainfall prediction was tested, successfully identifying 67% of heavy rainfall events, though some false positives and low rain events detections were observed. The findings suggest that GNSS-PWV could enhance short-term forecasting, but further validation with extended datasets and additional CORS networks is needed. Future work will integrate regional GNSS stations and refine predictive algorithms to improve the reliability of PWV-based nowcasting methods.

Keywords: GNSS-PWV · rainfall events · Rapid Onset Disasters (RODs) · GNSS meteorology · nowcasting

1 Introduction

Natural events, such as heavy rainfalls and floods, have an increasing impact on the built environment [1–4], causing, in some cases, also a significant detriment to human lives, especially in areas characterized by a high population density. Over the long-term period, the effects of relatively slow phenomena such as global warming, are worsening

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the frequency and incidence of these critical occurrences on the safety of populations. As possible consequence of the climate change, nowadays heavy rainfalls occur more frequently; their destructive effects have been tangible in the floods that affected over a short period of time the Emilia-Romagna region (Italy) in 2023 and 2024 [5, 6] and other countries all over the world, as deepened, for instance in [7–9]. Such critical events, by reference to the catastrophes they can lead to and the speed of their occurrence, can be included in the Rapid Onset Disasters (RODs) category [10], as stated by United Nation [11], and the management of their impact on the cities and their inhabitants [12] is one of the greatest challenges of our time.

In this frame, approaches encompassing the integration of different disciplines and skills are needed, both in the evaluation of the significance of the detected critical trends [13], and the development of proper tools aimed at preventing and monitoring possible dangerous events. Among these, geomatics play a key role through the processing and analysis of observations acquired by reference stations based on the Global Navigation Satellite System (GNSS), since these databases are widely employed in the development of weather models.

A Continuously Operating Reference Station (CORS) consists of a high-precision geodetic GNSS receiver coupled with an antenna, installed in a safe and stable location, that must operate 24 h a day, ensuring the logging and the redundant storing of raw observations. Since 1990-ies, CORS started to be installed, mainly by scientific institutions, with the aim of developing high-precision positioning applications. However, the GNSS signal in its travel from the satellite to the receiver positioned on the ground, is affected by a delay due to the traversing of the atmosphere, which can be estimated. A portion of this delay, that develops in the troposphere (i.e. the layer of the atmosphere in contact with the Earth's surface), is directly connected with Precipitable Water Vapor (PWV) content. Therefore, the estimation of this parameter [14, 15] provides support in climate studies [16–18] and is widely employed in the calibration and assessing of analogue datasets obtained with other satellite sensors [19, 20].The continuous monitoring of the PWV is useful to detect both its local variations, if spot measurements are available (as in the case of a single CORS), and changes at a territorial scale when network of GNSS receivers are established on wide areas [21, 22].

As the PWV content is related with rainfall events, [23–25], the analysis of its trend and can help to characterize a specific site in relation with this parameter and, since the oscillation of this feature could be indicative of the occurrence of intense precipitation, the PWV retrieved by GNSS observations (GNSS-PWV) have a potential, partially unexplored, for application in forecasting-nowcasting activities [26, 27].

2 Objectives

This study aims at analyzing the correlation between intense rainfall events and the corresponding GNSS-PWV trend in the Municipality of Bari. The relationship between the content of PWV in the troposphere and rainfall events is well known; nevertheless, this correlation has never been deepened in the investigated area. For this purpose, hereafter the results of the analysis of two year of observations acquired by the SNIK CORS installed at the Polytechnic University of Bari (Fig. 1) and managed by the Applied

Geomatics Laboratory (AGLab) of the Department of Civil, Environmental, Land, Construction and Chemistry (DICATECh) are shown. The GNSS-PWV parameter has been jointly analyzed with the measurements retrieved by the rain gauges operating in the area, belonging to the Civil Protection network, and run by the Centro Funzionale Decentrato della Sezione Protezione Civile della Regione Puglia (Decentralized Functional Center of the Civil Protection Section of the Region of Apulia).



Fig. 1. The SNIK CORS, installed in September 2021 on the Water Engineering building within the area of the Polytechnic University of Bary.

3 The Study Area: The Municipality of Bari and the Employed Sensors

Located in the south of Italy and provincial capital of the Apulia region, Bari is a municipality of about 316000 inhabitants which spreads over a mostly flat territory of 116 Km^2 [28], bordered on the north-eastern part by the Adriatic Sea (Fig. 2). The average elevation of the considered territory is few meters above sea level.

The CORS identified as SNIK (following the National Geodetic Survey rules), consisting of a Stonex SC2200 GNSS receiver equipped with a SA1500 choke-ring antenna, has been installed in September 2021 on the Water Engineering building within the area of the Polytechnic University of Bary, and, since January 2023, is included in the EUREF Permanent Network [29], which oversees the maintaining of the European Terrestrial Reference System (ETRS) [30].

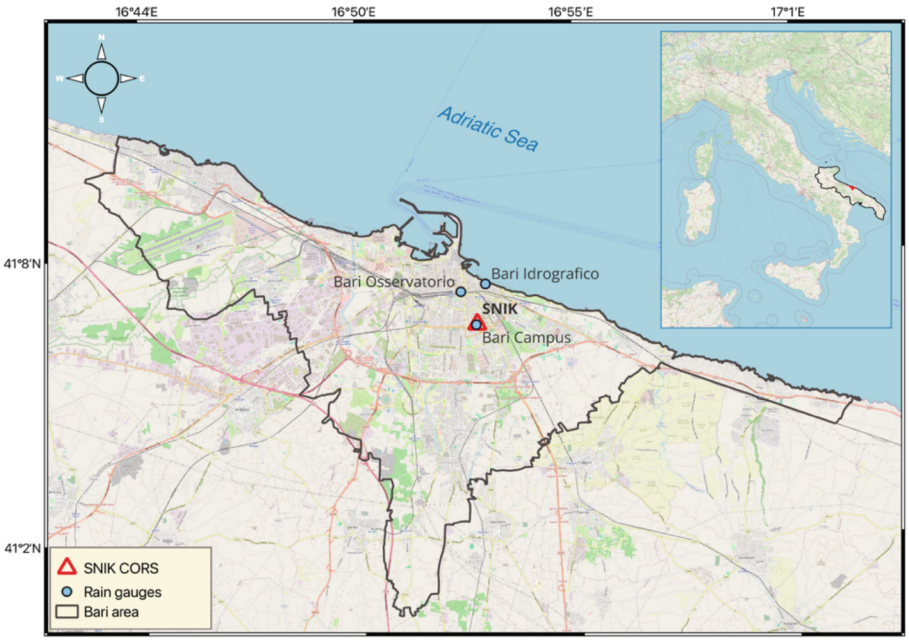

Fig. 2. The Municipality of Bari, provincial capital of the Apulia Region (which borders are showed in the thumbnail on the right). The location of the SNIK CORS and the rain gauges are displayed on the map (base layer: OpenStreetMap).

Three rain gauges, located in the Bari area, namely Bari Campus (BC – coordinates: latitude 41°6′23″, longitude 16°52′40″, elevation 23 m a.s.l.), Bari Idrografico (BI – coordinates: latitude 41°7′11″, longitude 16°52′54″, elevation 17 m a.s.l.), and Bari Osservatorio (BO – coordinates: latitude 41°7′2″, longitude 16°52′18″, elevation 34 m a.s.l.) are located in the vicinity of the SNIK station, at maximum distance of 1500 m. BC is installed at a distance of 40 m from the SNIK CORS.

4 Available Datasets

The case study analysis was carried out by using a multi-sensor approach. In this context, the rain data, acquired every 300 s, have been investigated to identify events of potential interest over the selected period, spanning from 22 July 2022 to 31 October 2024. GNSS raw observations acquired by the SNIK CORS, processed using the Precise Point

Positioning (PPP) technique [31] and the global pressure/temperature (GPT) model [14, 32, 33], through the goGPS software 1.0 [34], delivered the GNSS-PWV values at a sample rate of 300 s (Table 1).

Table 1. Dataset employed in the analysis

Sensor	Data Type	Acquisition frequency	Time span analysis
SNIK CORS (GNSS)	Raw observations	1s	22 July 2022–31 October 2024
	GNSS-PWV	300s	
BC (rain gauge)	Precipitations (mm)	300 s	
BO (rain gauge)	Precipitations (mm)	300 s	
BI (rain gauge)	Precipitations (mm)	300 s	

5 Identification of the Significant Events

As underlined, the precipitation data recorded by the three rain gauges allowed to identify the rainfall events, according to the definition deepened in [35], whereby a relevant rainfall event is preceded and followed by a dry period of six hours and characterized by a cumulative precipitation greater than or equal to 1mm, containing at least a measurement of rain height greater than 0.5 mm.

The rainfall events identified using these criteria are listed in the following table (Table 2).

Table 2. Rainfall events identified over the considered period by the BC, BO and BI rain gauges.

Sensor	Events identified	Min-max duration (min)	Min-max average intensity (mm/h)	Time span analysis
BC	81	5–1630	0.4–51.8	22 July 2022 – 31 October 2024
BO	90	10–1560	0.3–38.7	
BI	89	5–1595	0.4–43.2	

The detected events have been then classified according to [36].

Since the presented analysis intended to relate GNSS-PWV with intense events, only cases characterized by an intensity >6 mm/h and detected at least by the BC and one of the other two available rain gauges have been considered: in this step of the study, BO and BI served only as a check for the BC measurements (Table 3).

Table 3. Classification of the rainfall events.

Class	Average intensity (mm/h)
No rain	<1
Light rain	1–2
Weak rain	2–4
Moderate rain	4–6
Heavy rain	6–10
Very heavy rain	10–30
Cloudburst	>30

The identified rainfall events have been characterized through some significant metrics, obtained by processing the BC rain gauge measurements. Specifically, for each rainfall event, are indicated:

- the day and the start time;
- the duration;
- the average intensity;
- the intensity peak;
- the median value of the PWV, with reference to the considered year;
- the differences between PWV peak preceding the intensity peak and median annual PWV;
- the time differences between PWV peak and intensity peak.

Each identified event has been then related with the corresponding PWV time series provided by the SNIK CORS, in order to evidence possible correlations on the test site.

A time span of three and two hours, before and after the intensity peak respectively, has been investigated.

5.1 Heavy Rain Events

In the considered period, one heavy rain event has been detected on 19/08/2022, which trend is shown in Fig. 3, where the rain intensity trend is compared with the corresponding PWV trend. This comparison evidence a PWV peak occurring 55 min before the rain intensity peak. The PWV peak differs from the median PWV value, computed in the reference year, of about 27 mm.

5.2 Very Heavy Rain Events

Six very heavy rain events have been detected, which developments are shown in Fig. 4. The temporal delay between the two peaks ranges from 5 to 105 min, while the difference between the PWV peak and median value ranges from 0.1 to 26.7 mm.

Table 4. Heavy rain events.

Date	Duration (min)	Average intensity (mm/h)	Rainfall intensity peak (mm/h)	Median annual PWV (mm)	PWV peak (mm)	Δ PWV (mm)	Δ time between peaks (min)
19/08/2022 16:20	30	7.4	16.8	22.1	48.9	26.8	55

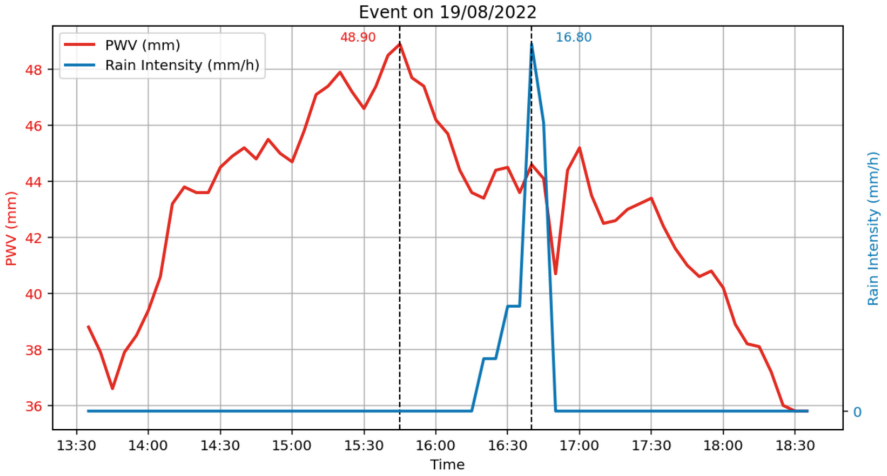

Fig. 3. Heavy rain event detected between 22 July 2022 and 31 October 2024.

Table 5. Very heavy rain events.

Date	Duration (min)	Average intensity (mm/h)	Rainfall intensity peak (mm/h)	Median annual PWV (mm)	PWV peak (mm)	Δ PWV (mm)	Δ time between peaks (min)
05/06/2023 12:50	20	29.4	54.0	20.1	39.6	19.5	5
05/08/2023 21:10	15	11.2	16.8	20.1	36.8	16.7	105
23/09/2023 19:10	100	24.5	116.4	20.1	45.9	25.8	10
11/03/2024 05:35	40	22.9	82.8	22.3	24.6	2.3	30
16/03/2024 20:55	100	10.7	33.6	22.3	22.4	0.1	15
19/08/2024 04:10	30	21.4	46.8	22.3	49.0	26.7	35

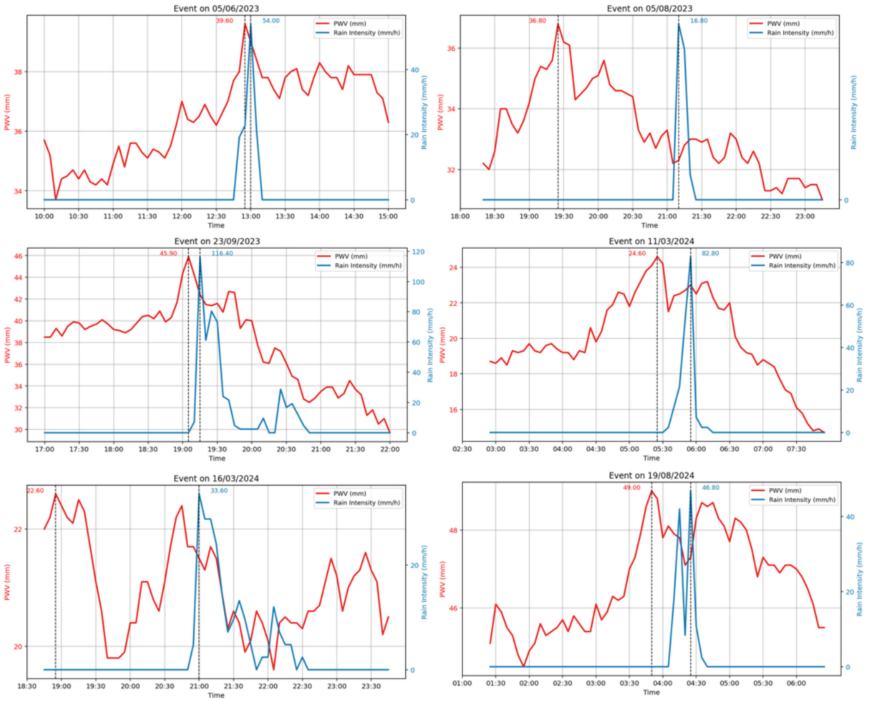

Fig. 4. Very heavy rain events detected between 22 July 2022 and 31 October 2024.

5.3 Cloudburst Events

Two cloudburst events have been identified over the reference period, as shown in Fig. 5. The temporal delay between the PWV and intensity peaks ranges from 5 to 25 min, while the difference between the peak and median PWV value ranges from 25.8 to 27.3 mm.

Table 6. Cloudburst events.

Date	Duration (min)	Average intensity (mm/h)	Rainfall intensity peak (mm/h)	Median annual PWV (mm)	PWV peak (mm)	Δ PWV (mm)	Δ time between peaks (min)
30/07/2022 17:40	20	44.4	91.2	22.1	47.9	25.8	25
05/09/2024 12:55	30	51.8	150.0	22.3	49.6	27.3	5

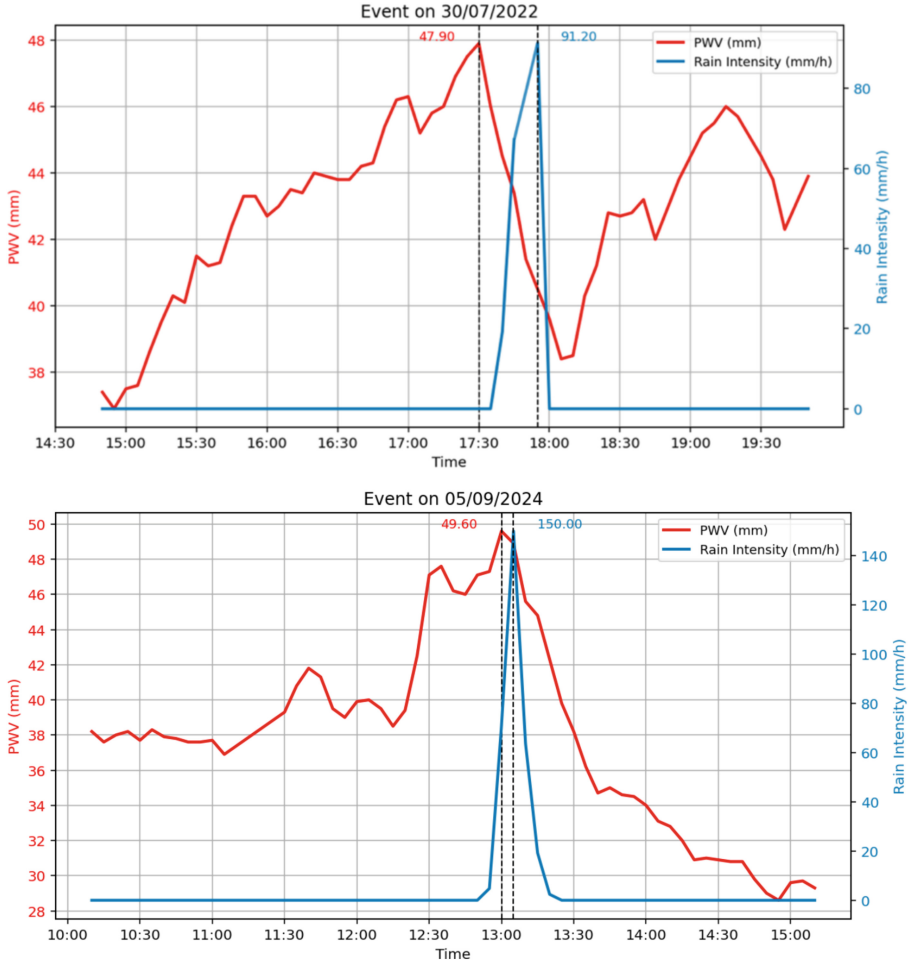

Fig. 5. Cloudburst events detected between 22 July 2022 and 31 October 2024

6 Analysis of the Results

The comparison of the intensity rainfall and GNSS-PWV time-series on intense rainfall events highlights the known relation between the two parameters, where every rain intensity peak is preceded by a PWV peak at the top of an upward trend, with a very variable temporal distance (from 5 up to 105 min) between the peaks. This would suggest the possible use of the PWV measurement for nowcasting activities. To this aim, a simplified test has been carried out by coupling the BC rainfall records with the corresponding PWV series over the whole considered period. The median PWV peak (equal to 45.9 mm), derived by the events characterized by an intensity >6 mm, has been used as minimum threshold to filter the dataset.

The results are shown in Table 7. The detected events using the PWV parameter are highlighted in light blue, also in the previous tables.

Table 7. Periods where the reference threshold value is reached or exceeded.

Events detected	Intense events (>6 mm/h)		Other rain events	Dry events
	Detected	Not detected		
	6	3		
	30/07/2022 16:50 19/08/2022 14:40 05/08/2023 00:00 23/09/2023 13:30 19/08/2024 00.00 05/09/2024 12:30	05/06/2023 11/03/2024 16/03/2024		

A hypothetic nowcasting system would have detected 24 days whether the set threshold would have been reached or exceeded. Among these, 6 refers to the intense rainfall events already identified using the rules described in § 5, 7 refer to other rainfall events and 11 to days characterized by the absence of precipitations (false positives). 33% (3 out of 9) of the intense events have not been identified. It is noteworthy that the reaching (or exceeding) of the threshold in the 6 out of 9 intense rainfall periods evidenced in Table 7 occurs with an advance ranging from 25 to 1150 min with respect to the corresponding events shown in Tables 4, 5 and 6.

7 Conclusive Remarks and Future Developments

The presented work was aimed at investigating the relation between the GNSS-PWV and the intense precipitations in the Municipality of Bari, by processing the observations acquired over a period of about two years by the SNIK CORS, run by the AGLab of the Polytechnic University of Bari, and a set of rain gauges belonging to the monitoring network of the Apulia Region. The results obtained clearly evidence the well-known correlation between PWV trends and rainfall events. The identification of intense rainfall events using a set of specific criteria, namely cumulative precipitation, rain height, duration of the dry period and average intensity, allowed to define a PWV threshold, used to detect the period on which the threshold itself was reached or exceeded. The findings of this analysis highlighted a relatively good agreement in terms of capability to identify in advance (up to 1150 min) some intense occurrences. However, also a limited number of low/no rain events were identified, while some events were not detected at all.

The main limitation of the presented study is due to the relatively short dataset recorded by the GNSS, limited to two years of observations.

While is well known that PWV exhibits a strong statistical correlation with precipitation, its short-term predictive capability is constrained by the complexity of convective processes, as evidenced by the variability of the delay between PWV and precipitation peak. Accurate short-term forecasting necessitates incorporating PWV variability alongside key surface meteorological parameters (e.g. pressure) [37].

Although very simplified, this analysis provides a first overview on the potential of the GNSS-derived PWV parameters for nowcasting. Further developments encompass the integration of CORS stations belonging to the Apulia Region (Rete GNSS Regione Puglia) and the corresponding rain gauges in the proposed analysis, and the setting out of predictive algorithms to improve the reliability of PWV-based nowcasting methods.

The analysis of a more consistent database will also encompass additional performance metrics like statistics on lead time distribution between PWV and rainfall peaks, as well as a confusion matrix with false alarm and miss rates.

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References

1. Mascitelli, A., et al.: Cultural heritage resilience in the face of extreme weather: lessons from the UNESCO site of Alberobello. Sustain. (Switz.) **15** (2023). https://doi.org/10.3390/su152115556
2. Sonnessa, A., di Lernia, A., Oscar Nitti, D., Nutricato, R., Tarantino, E., Cotecchia, F.: Integration of multi-sensor MTInSAR and ground-based geomatic data for the analysis of non-linear displacements affecting the urban area of Chieuti, Italy. Int. J. Appl. Earth Obs. Geoinf. **117** (2023). https://doi.org/10.1016/j.jag.2023.103194
3. Cantatore, E., Esposito, D., Sonnessa, A.: Mapping the multi-vulnerabilities of outdoor places to enhance the resilience of historic urban districts: the case of the apulian region exposed to slow and rapid-onset disasters. Sustain. (Switz.) **15** (2023). https://doi.org/10.3390/su151914248
4. Gioia, A., Totaro, V., Bonelli, R., Esposito, A.A.M.G., Balacco, G., Iacobellis, V.: Flood susceptibility evaluation on ephemeral streams of Southern Italy: a case study of Lama Balice. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2018. ICCSA 2018. Lecture Notes in Computer Science, vol. 10964, pp. 334–348. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-95174-4_27
5. CNR-Irpi: Emilia-Romagna floods. https://polaris.irpi.cnr.it/emilia-romagna-due-ulteriori-alluvioni-nel-2024/#:~:text=Dopo%20le%20due%20grandi%20alluvioni,e%2019%2D20%20ottobre%202024. Accessed 16 Jan 2025
6. Arrighi, C., Domeneghetti, A.: Brief communication: On the environmental impacts of the 2023 floods in Emilia-Romagna (Italy). Nat. Hazards Earth Syst. Sci. **24** (2024). https://doi.org/10.5194/nhess-24-673-2024
7. Ferrario, M.F., Livio, F.: Rapid mapping of landslides induced by heavy rainfall in the Emilia-Romagna (Italy) region in May 2023. Remote Sens. (Basel) **16** (2024). https://doi.org/10.3390/rs16010122
8. Bosseler, B., Salomon, M., Schlüter, M., Rubinato, M.: Living with urban flooding: a continuous learning process for local municipalities and lessons learnt from the 2021 events in Germany. Water (Switz.) **13** (2021). https://doi.org/10.3390/w13192769
9. Reynoso Vanderhorst, H.D., Pathirage, C., Proverbs, D.: Navigating flood resilience: challenges, solutions, and lessons learnt from the dominican republic. Water (Switz.) **16** (2024). https://doi.org/10.3390/w16030382

10. Sonnessa, A., Cantatore, E., Esposito, D., Fiorito, F.: A multidisciplinary approach for multi-risk analysis and monitoring of influence of SODs and RODs on historic centres: the ResCUDE project (2020). https://doi.org/10.1007/978-3-030-58811-3_54
11. Assembly, U.N.G.: Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction (2016)
12. Santoro, S., Lovreglio, R., Totaro, V., Camarda, D., Iacobellis, V., Fratino, U.: Community risk perception for flood management: a structural equation modelling approach. Int. J. Disaster Risk Reduction **97** (2023). https://doi.org/10.1016/j.ijdrr.2023.104012
13. Gioia, A., Bruno, M.F., Totaro, V., Iacobellis, V.: Parametric assessment of trend test power in a changing environment. Sustain. (Switz.) **12** (2020). https://doi.org/10.3390/su12093889
14. Bevis, M., Businger, S., Herring, T.A., Rocken, C., Anthes, R.A., Ware, R.H.: GPS meteorology: remote sensing of atmospheric water vapor using the global positioning system. J. Geophys. Res. **97** (1992). https://doi.org/10.1029/92jd01517
15. Yang, F., Guo, J., Shi, J., Zhao, Y., Zhou, L., Song, S.: A new method of GPS water vapor tomography for maximizing the use of signal rays. Appl. Sci. (Switz.) **9** (2019). https://doi.org/10.3390/app9071446
16. Kuleshov, Y., Choy, S., Fu, E.F., Chane-Ming, F., Liou, Y.A., Pavelyev, A.G.: Analysis of meteorological variables in the Australasian region using ground- and space-based GPS techniques. Atmos. Res., 176–177 (2016). https://doi.org/10.1016/j.atmosres.2016.02.021
17. Suparta, W., Abu Bakar, F.N., Abdullah, M.: Remote sensing of Antarctic ozone depletion using GPS meteorology. Int. J. Remote Sens. **34** (2013). https://doi.org/10.1080/01431161.2012.746485
18. Torcasio, R.C., et al.: The impact of global navigation satellite system (GNSS) zenith total delay data assimilation on the short-term precipitable water vapor and precipitation forecast over Italy using the Weather Research and Forecasting (WRF) model. Nat. Hazards Earth Syst. Sci. **23** (2023). https://doi.org/10.5194/nhess-23-3319-2023
19. Bai, J., Lou, Y., Zhang, W., Zhou, Y., Zhang, Z., Shi, C.: Assessment and calibration of MODIS precipitable water vapor products based on GPS network over China. Atmos. Res. **254** (2021). https://doi.org/10.1016/j.atmosres.2021.105504
20. Wang, Y., Liu, X., Liu, Y., Zhan, W.: MODIS PWV correction based on CMONOC and regional function model. Wuhan Daxue Xuebao (Xinxi Kexue Ban)/Geomatics Inf. Sci. Wuhan Univ. **48** (2023). https://doi.org/10.13203/j.whugis20200183
21. Ferrando, I., Federici, B., Sguerso, D.: 2D PWV monitoring of a wide and orographically complex area with a low dense GNSS network. Earth, Planets and Space **70** (2018). https://doi.org/10.1186/s40623-018-0824-6
22. Ninsawat, S., Chitsutti, P., Chaudhary, S., Jindasee, P., Khamyai, T.: Development of near real-time PWV estimation system for monitoring the meteorological events in Thailand. Int. J. Geoinformatics **18** (2022). https://doi.org/10.52939/ijg.v18i3.2201
23. Kawo, A., Van Malderen, R., Pottiaux, E., Van Schaeybroeck, B.: Understanding the present-day spatiotemporal variability of precipitable water vapor over ethiopia: a comparative study between ERA5 and GPS. Remote Sens. (Basel) **14** (2022). https://doi.org/10.3390/rs14030686
24. Serrano-Vincenti, S., et al.: Harmonic analysis of the relationship between gnss precipitable water vapor and heavy rainfall over the Northwest Equatorial Coast, Andes, and Amazon Regions. Atmosphere (Basel) **13** (2022). https://doi.org/10.3390/atmos13111809
25. Realini, E., Sato, K., Tsuda, T., Susilo, Manik, T.: An observation campaign of precipitable water vapor with multiple GPS receivers in western Java, Indonesia. Prog. Earth Planet Sci. **1** (2014). https://doi.org/10.1186/2197-4284-1-17
26. Sapucci, L.F., Machado, L.A.T., de Souza, E.M., Campos, T.B.: Global Positioning System precipitable water vapour (GPS-PWV) jumps before intense rain events: a potential application to nowcasting. Meteorol. Appl. **26** (2019). https://doi.org/10.1002/met.1735

27. Manandhar, S., Lee, Y.H., Meng, Y.S.: GPS-PWV based improved long-term rainfall prediction algorithm for tropical regions. Remote Sens. (Basel) **11** (2019). https://doi.org/10.3390/rs11222643
28. ISTAT: Commissione parlamentare di inchiesta sulle condizioni di sicurezza e sullo stato di degrado delle città e delle loro periferie Report Comune di Bari (2024)
29. AGLab: SNIK CORS in EPN. https://epncb.eu/_networkdata/siteinfo4onestation.php?station=SNIK00ITA. Accessed 16 Jan 2025
30. EUREF (Institution/Organization): EUREF Permanent GNSS Network. https://www.epncb.oma.be/_organisation/about.php. Accessed 4 May 2021
31. Zumberge, J.F., Heflin, M.B., Jefferson, D.C., Watkins, M.M., Webb, F.H.: Precise point positioning for the efficient and robust analysis of GPS data from large networks. J. Geophys. Res. Solid Earth **102** (1997). https://doi.org/10.1029/96jb03860
32. Mascitelli, A., et al.: Multi-sensor data analysis of an intense weather event: the July 2021 lake como case study. Water (Switz.) **14** (2022). https://doi.org/10.3390/w14233916
33. Kouba, J.: Testing of global pressure/temperature (GPT) model and global mapping function (GMF) in GPS analyses. J. Geod. **83** (2009). https://doi.org/10.1007/s00190-008-0229-6
34. Gatti, A., Tagliaferro, G., Realini, E.: goGPS free and open source GNSS software for tropospheric delay estimation. In: Proceedings of the EGU General Assembly Conference Abstracts, Vienna, vol. 20 (2018)
35. Sottile, G., Francipane, A., Adelfio, G., Noto, L. V.: A PCA-based clustering algorithm for the identification of stratiform and convective precipitation at the event scale: an application to the sub-hourly precipitation of Sicily, Italy. Stochast. Environ. Res. Risk Assess. **36** (2022). https://doi.org/10.1007/s00477-021-02028-7
36. CNR-Irpi: Polaris - Misurare la pioggia. https://polaris.irpi.cnr.it/misurare-la-pioggia/. Accessed 11 Feb 2025
37. Zhang, Z., Lou, Y., Zhang, W., Liang, H., Bai, J., Song, W.: Correlation analysis between precipitation and precipitable water vapor over china based on 1999–2015 ground-based GPS observations. J. Appl. Meteorol. Climatol. **61** (2022). https://doi.org/10.1175/JAMC-D-21-0200.1