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Urban Flooding Management: the Turin Metropolitan Area Case Study (North-Western Italy)

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Abstract: The effects of global warming combined with the progressive expansion of urbanization have considerably increased exposure to urban flooding and runoff widespread erosion risk, also causing shallow landslides and mud flows, respectively in urbanized areas of lowland and hill/foothill environments. Increasing urban flooding resilience has become a priority at virtually all levels of governance. The analysis of a different hazard scenarios, in which various hydro-meteorological conditions and management alternatives are examined, should act as the basis for the effective design and evaluation of interventions to improve urban flooding resilience. Turin Metropolitan Area (TMA), located in north-western Italy, represents a unique case due to its complex orography, with a mountainous sector in the west side and a flat or hilly part in the east side. During the warm season, these environmental conditions make the urban area prone to severe atmospheric convection causing frequent hailstorms and rainstorms of high intensity that may impact on urban infrastructures (i.e., drainage system and road network), thus requiring an adequate management as a key factor to reducing risk and losses. The urban areas of TMA are monitored by polarimetric Doppler weather radars and by a dense rain gauges network. Analyzing several case studies of urban flooding, this research work assesses the feasibility of a meteorological radar early warning system based on the identification of rainfall thresholds that characterize urban flooding, occurring in the lowlands, and the runoff erosion phenomena affecting the urbanized hills and foothills.

Keywords: rainfall thresholds; rainstorms; runoff erosion; weather radar; early warning system; risk reduction; resilience

1. Introduction

Climate change is one of the greatest challenges facing humanity, as the risks it poses to the planet and future generations are enormous and require urgent action. Its effects are already having economic, social and environmental consequences, and tackling it is therefore one of the most urgent global public policy commitments for governments today. The European Region, and in particular the Mediterranean and Alpine regions, will have to cope with particularly negative impacts of climate change, which, combined with the effects of anthropogenic pressure on natural resources, make these areas two hot-spots of climate change [1,2]. In this context, cities are more vulnerable than other areas because they represent the territorial context in which most of the population is concentrated: more than 55% of the world's population live in towns and cities, that contribute around three-quarters of carbon dioxide (CO_2) emissions from global energy end-use [3]. The negative impacts expected at the urban level in the coming decades are mainly related to an exceptional increase in average and maximum temperatures (especially in summer) and an increase in the frequency of extreme weather events (heat waves, droughts and heavy rainfall episodes). In this framework, the intensification of the global water cycle will continue as global temperatures rise, with precipitation and surface water flow projected to become more variable over most land regions within seasons and from year to year. The severity of very wet and very dry events increases in a warming climate and water cycle variability and related extremes are projected to increase faster than mean changes in most regions of the world [4]. Urban areas, characterised by high levels of surface sealing (i.e., buildings and other impermeable surfaces such as roads, pavements and car parks), have low infiltration capacity of the soil leading to rapid run-off, thus exacerbating the impacts of heavy rainfall, storms and flash floods. As well as being part of the problem, cities can also be part of the solution, and tackling climate change, therefore, requires a major shift in approaches to urban and spatial planning, both in terms of mitigation and adaptation solutions. While mitigation policies can be developed through both local and global actions, adaptation is primarily a local issue, as the impacts of climate change take different forms and sizes depending on the territory and require specific responses from local communities. The European Commission has highlighted the important contribution that cities can make to the implementation of climate change strategies and is promoting this through major initiatives in which cities play a leading role. Firstly, the Covenant of Mayors, which since 2008 has involved and committed local and regional authorities to meet and exceed the European target of a 20% reduction in CO_2 emissions by 2020 by increasing energy efficiency and the use of renewable energy sources in their territories. In 2016, the Global Covenant of Mayors for Climate and Energy was launched to accelerate climate action at the local level around the world. More than 11,000 cities from 142 countries and 6 continents are now working together on climate action. In this context, the city of Turin, located in north-western Italy, has also developed a document outlining a clear local adaptation strategy to reduce the vulnerability of the territory and the population, while ensuring their health and well-being, the viability of the city and the continuity of services, putting the most vulnerable people at the centre of climate policy ([5], in Italian). With the City Council resolution of 28 July 2020, the Climate Resilience Plan was ratified by the local executive. This plan was developed with the participation of different local stakeholders, including (i) the Regional Agency for Environmental Protection of Piemonte (ARPAP); (ii) the Regione Piemonte; (iii) the Universities of Turin; and (iv) the water utility that manages the city's integrated water service of the city (i.e., Societá Metropolitana Acque Torino, SMAT). This plan identifies the main vulnerabilities of the territory and proposes a series of short and long-term adaptation measures, defining a catalogue of actions aimed at reducing the impacts of the main risks of climate change to which the city is exposed: namely heat waves and urban flooding.

Urban flooding causes major impacts on the whole urban infrastructure (i.e., drainage system and road network), thus requiring adequate management at all governance levels as a key factor in reducing risk and losses. In this framework, there is a renewed urgency for truly effective early warning systems at the urban scale, which will enable better anticipation and preparedness, and lead to better management practices for effective design and evaluation of interventions to improve urban flooding resilience and give operational support for strategic planning. Several case studies of urban flooding causing damages and/or requiring operational management were analysed, evaluating the feasibility of a meteorological radar early warning system based on the identification of rainfall thresholds that characterise urban flooding in the lowlands and runoff erosion phenomena affecting the urbanised hills and foothills. Turin Metropolitan Area (TMA) has some unique characteristics that make it a feasible and interesting case study: its geographical location makes the urban area prone to strong atmospheric convection causing frequent hailstorms and severe thunderstorms that can be monitored by polarimetric Doppler weather radars and by a dense rain gauges network. This work is a preliminary study aimed to design an operational early-warning system based on real-time rainfall measurements and estimations. Investigating some case studies, the main purpose is to characterize principal factors associated with rainstorms that cause major impacts on the city (e.g., rainfall intensity, duration and distribution or hail occurrence).

2. Study area

The city of Turin is the capital of the Piedmont region, in north-western Italy. With a population of 842,612 inhabitants, Turin is the fourth-largest Italian municipality in terms of population. The

Turin Metropolitan Area (TMA) is located in an area with a complex orography, in the centre of a mountainous amphitheatre. The city, crossed by four rivers (the Po, the Dora Riparia, the Stura di Lanzo and the Sangone rivers), rises on the plain at the outlet of Valle di Susa, Valle di Lanzo and Val Sangone Alpine valleys, and the river Po separates the hilly part of the city from the plain (Figure 1). The study area experiences precipitation that varies significantly in both space and time, with a tendency towards rainfall induced by topography, exposure to humid air from the Mediterranean Sea, and relatively prolonged periods of dryness [6–9]. These unique characteristics make the area particularly prone, during the warm seasons, to strongly convective precipitation phenomena, which have rapid development and high impacts. The study area is monitored by two polarimetric Doppler weather radars and by a dense rain gauges network, managed by ARPAP and described in Section 3.1. The ARPAP rain gauges considered in this study, together with the location of the weather radar near the boundaries of TMA, are shown in Figure 1.

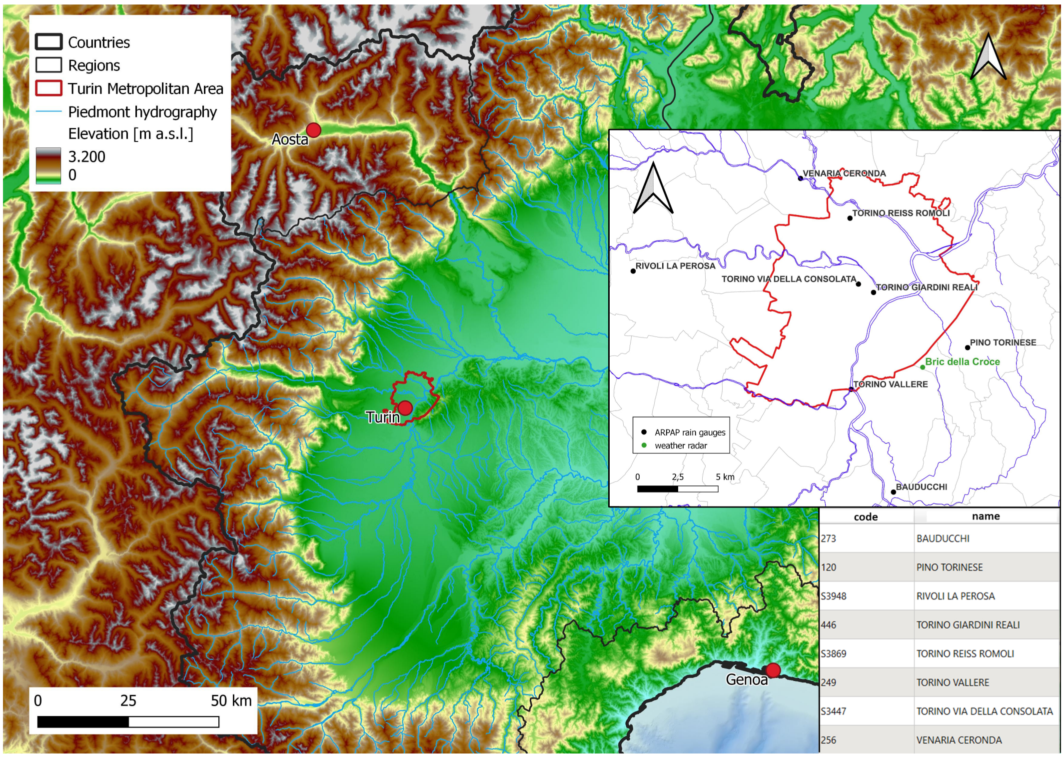

Figure 1. The study area including the main hydrography of the Piedmont region. The orography is based on a digital elevation model derived from the SRTM project, interpolated at 30m of spatial resolution (processed SRTM data version 4.1, available from http://srtm.csi.cgiar.org). The selected ARPAP rain gauges considered for this work (black dots), together with the location of Bric della Croce weather radar (green dot) are shown in the inset. Rain gauge names and codes are also shown in the lower right table.

In this context, the process of land consumption, which follows the expansion of urbanized areas, exacerbates the impacts of heavy rainfall events over the urban area. According to the latest monitoring from the Italian System for Environmental Protection ([10], in Italian), Turin Metropolitan Area accounts for more than 34% of the overall phenomenon of land consumption in the Piedmont region (over 58,359 hectares of land consumed). Land consumption in the City of Turin is settled at 65% in 2021, corresponding to a surface of 8,460 hectares. Given the hydro-geological, meteoclimatic and anthropogenic characteristics of the area, heavy convective precipitation events are often associated with additional hazards, including floods and landslides, with their potentially damaging consequences for society, agriculture, industry, ecosystem services and essential infrastructure. In the heavily sealed area of the city, street flooding, damage to the water distribution network (soil erosion phenomena can lead to subsidence and consequent pipe breaks) and sewer overflows (with potential contamination of the surrounding environment as well as failure to properly dispose of rainwater, exacerbating flooding in streets and underpasses) are the main problems faced by the stakeholders involved in urban management. Figure 2 shows a map of the city of Turin with the most frequently flooded streets and road underpasses. The urban drainage network of Turin, as well as the whole integrated water cycle of the TMA are managed by SMAT and, considering Turin's sewer system, dating back to 1893, it is composed of two separate networks, one dedicated to rainwater and the other to sewage and faeces. This approach allows for more efficient wastewater treatment by avoiding dilution, which can lead to increased treatment costs and prevent unnecessary contamination of the less polluted rainwater. However, the system's design parameters did not consider the impact of climate change and may be at risk of frequent breakdowns during extreme rainfall events. Finally, the soils of the hilly part of the city of Turin are particularly affected in the most degraded parts of the forest, which are already affected by slope instability, and in the vicinity of anthropogenic barriers (bridges, siphons, weirs and canalised sections of streams), where the speed of runoff increases. The common landslide types affecting Turin Hill (Figure 2) are mainly caused by rainfall, and they can be subdivided into two main groups based on the depth of detachment surfaces and landslide size. From the triggering mechanisms point of view, landslide types can be also subdivided into gravitational phenomena caused by short and intense rainfall (rainstorms or heavy rainfall of duration <12h), heavy rainfall lasting more than 12 h and landslides that are influenced by antecedent precipitation (rainfall and snow melt values characterizing past weeks or months). The first group includes disintegrating soil slips (DSSs), mudflows (MFs) and shallow landslides (SLs). DSSs affect a few cm of soil (including grass cover) and are triggered by intense runoff causing sheet (for DSSs) and rill (for MFs, resulting from the coalescence of DSSs that converge in the impluviums) erosion starting from brief and intense rainfall, with a rainfall intensity triggering threshold of about 20 mm/h [11]. SLs have a surficial detachment surface (commonly from 50 cm to 2 m depth) and are characterized by low volumes of mobilized material (usually <500 m^3). SLs develop on slopes having a slope between 18° and 45°. SLs are triggered by rainfall of a duration greater than 12 h, with a triggering threshold of cumulative rainfall of 60 mm for a duration of 12 h, 70 mm for a duration of 24 h and 80 mm for a duration of 36 h [12]. The second landslide group includes landslides characterized by the deepest detachment surface (>2 m), such as translational slides (TSs), rotational slides (RSs), earth flows (EFs) and slope debris flows (SDFs). EFs, SDFs and small RSs are triggered by heavy rainfall with a duration longer than 12h with the same triggering threshold values of SLs. Unlike other types of landslides, the TSs do not develop in the debris-colluvial covers but in the sedimentary bedrock of Turin Hill causing the sliding of rock-blocks along stratification or fracture surfaces. They are less common than other landslide types of the Turin Hill and, like large RSs and deep landslides characterized by complex kinematics, their triggering is strongly dependent on antecedent precipitations amount over a variable time-lapse, different from case to case [13].

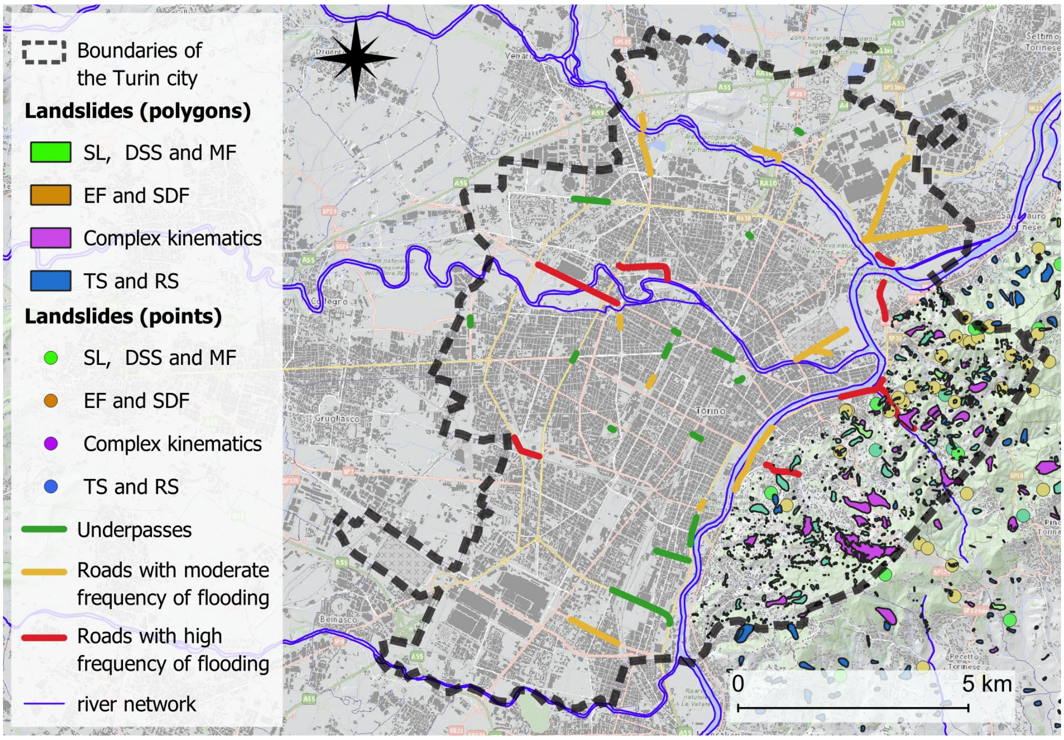

Figure 2. Map of the city of Turin with the most frequently flooded streets and road underpasses. Landslide types are shown in hilly environment of the city (available from https://webgis.arpa.piemonte.it/ags/services/rischi_naturali/SIFraP_SI_Frane_Piemonte/MapServer/WMSServer, accessed 2023-04-13). Roads and underpasses map was drawn up for the Municipal Civil Protection Plan, approved by Council resolution in 2021 (available from http://www.comune.torino.it/protezionecivile/piano/2020/28_RI_06_Rischio_idrogeologico-allagamenti_viabilita.pdf, accessed 2023-03-27).

3. Materials and Methods

Thunderstorms, which are characterized by violent precipitation and dangerous phenomena like lightning, hail, strong winds, and possible tornadoes, are among the most dangerous weather events found in the mid-latitudes. In the study area, they can be classified into two categories: heat thunderstorms and frontal/pre-frontal thunderstorms. These storms typically occur during spring, summer, and early autumn. Heat thunderstorms, which are prevalent in Alpine and Alpine-foothill regions, occur when the humid air becomes unstable during the day due to intense solar radiation, resulting in the development of cumuliform clouds and rising air along the mountains. They usually take place in the afternoon during summer. Frontal and pre-frontal thunderstorms, on the other hand, are the most intense and long-lasting. They are associated with high instability, sudden drops in pressure, the influx of cold air after a warm period, strong convergence in the lower layers, intense convective motion, and the absence of strong winds that hinder the development of vertical motion.

Among the summer precipitation events that affected the urban infrastructure network, specifically causing flooding in the areas indicated in Figure 2 or requiring the intervention of SMAT operational teams or that were the subject of an event report by ARPAP, the events to be analysed were identified from the five-year period 2017–2021. By using a bottom-up approach, it becomes feasible to track the geographical extent, initiation time, and duration of these pivotal events. Furthermore, this method helps detect the maximum amount of rainfall associated with these events by accumulating precipitation data over specific time frames such as 10, 20, 30 min and 1 h. Precipitation maxima are taken between one of the eight rain gauges shown in Figure 1. If it is not viable to extract the ground precipitation data gathered by rain gauges, it is still possible to achieve this estimation by using polarimetric Doppler weather radar data, which is also used to monitor the study area and which can distinguish both the type of precipitation (rain or hail) and, in the case of hail, the size of the hailstones. From this analysis, correlated to the precipitation type, it is possible to trace the significant intensities back to hydrological maxima. From these maxima, the return times can be estimated.

3.1. Precipitation observational network

Several sources of observations are available for the quantitative monitoring of precipitation in the study area: radar measurements and rain gauges data managed by ARPAP (Figure 1). Weather radars provide indirect estimations of the rainfall rate, while rain-gauge data provide direct measurements of the precipitation at ground level.

The rain gauge monitoring network of the study area is part of the real-time meteo-hydrographic network of the Piedmont region. It reaches an average density of one station per 100 km^2 and is able to define the synoptic framework of the region from a meteorological point of view. The rain gauges network consists of tipping-bucket sensors (bascule with calibrated 1000 cm^2 orifice) in accordance with the World Meteorological Organisation recommendations with a measuring range between 0 and 300 mm/h of precipitation and a resolution of 0.2 mm of rainfall. One-minute rainfall observations are corrected for underestimations at high rain-rates according to Lanza et al. [14] and Vuerich et al. [15].

ARPAP manages two polarimetric Doppler C-band weather radars (f = 5.6 GHz, $\lambda \approx 5$ cm) capable of providing precipitation estimates in the study area with an operating range of 150-200 km, 800 m resolution: Bric della Croce (located nearby Turin at 736 m a.s.l., latitude 45.03N, longitude 7.73E) and, in collaboration with the Liguria Region, Monte Settepani (located at 1390 m a.s.l., latitude 44.25N, longitude 8.20E). Both systems are Doppler polarimetric radars and perform a volumetric scan every five minutes, collecting data on conical surfaces corresponding to predetermined heights between approximately 0 and 30 degrees [16,17]. The Piedmont weather radar can also estimate the probability of hail (POD) according to Holleman [18]: the operational POD product has been used to evaluate the chances of hail during the severe thunderstorms that hit downtown.

The integration of radar measurements with the rainfall network is necessary to bridge the observation gap in the lower layers of the atmosphere and to ensure a good agreement between the direct measurements of the precipitation in the soil and the radar estimate.

3.2. Case studies and ground effects

Urban floodings are typically brought on by locally heavy rains that surpass a pipe's capacity and pressurize it, causing surface flooding. According to [19], the severity of floods is primarily influenced by the spatial-temporal variability of rainfall, the size of the catchment, and the properties of the soil. Severe convective storm typically causes local floods, transportation damage, hail accumulations and tree fall. High environmental and social costs from floods might result in significant financial losses. Some of these effects involve harm to public infrastructures, individual properties, and materials, and occasionally they directly impact the population, necessitating analysis and mitigation of their causes and effects.

The first part of the study has been devoted to identifying the occurrence of severe weather conditions over Turin between 2017 and 2021. Three sources of information have been used:

1. Event reporting on severe thunderstorms by ARPAP;
2. News on severe weather that hit the city collected from websites and social media (e.g., Twitter);
3. Damages and impacts on the city reported by SMAT.

Table 1 lists the summer events selected for this study, indicating the area of the city of Turin that was most affected and the type of ground effect.

Table 1. Severe storms that hit Turin, Italy, from 2017 to 2021.

Date	Impact area	Impacts
2017-06-05	west TMA	subways and belt road floods
2017-06-27	central-south TMA	flooded roads, fallen trees, hail >2 cm
2019-08-11	whole TMA	roof blow-offs from high winds, fallen trees, hail
2020-06-03	whole TMA	hail accumulation
2020-06-07	whole TMA	subways floods, hail accumulation
2020-06-15	north TMA	overflow of small streams, disintegrating soil slips, mudflows, falling trees, hail
2020-06-17	west TMA	subways and roads floods, high winds, large hailstones and hail accumulation
2020-08-17	whole TMA	diffuse road floods, public transportation failure, falling trees, roof damages
2020-08-28	central TMA	flooding, falling trees
2021-06-22	north TMA	subways floods
2021-07-08	north TMA	flooding, falling trees
2021-07-13	whole TMA	large hailstones, falling trees
2021-08-01	whole TMA	hail, high winds

From 2017 to 2021, 13 severe storms affected the urban infrastructure network, causing damages or requiring the intervention of operational teams. Most of the events involved the whole of the TMA, with flooding on the roads and affecting public transportation, fallen trees and hailstorms. In the five-year period considered in this study, only one event was recorded as triggering DSSs and MFs because of the location of the most intense peak of the rainstorm that has mainly interested Turin hill, contrary to the other thunderstorms that have affected downtown areas. Turin is a very old town, founded during the Roman Age. A combination of inconsistent public design standards over time and constrained private design standards play a main role in flash flooding. In the past, there were no minimum first-floor elevation requirements for developments, and the City had minimal control over design. This led to numerous flooding problems that are still today challenging to resolve.

4. Results

Return periods for several rainfall duration are the most common variables used for rainfall analysis. It could be challenging to predict the return period of urban flooding at a single defined site based on the return period of the rain. The complexity of a flood, where water runs through the drainage system, surcharges the drainage system and also flows on the surface to depressions in the topography, may cause a non-monotonic growing relationship between the intensity of the rain and the highest water level at a particular location. These non-monotonicities will be made worse by additional hydraulic features like pumps, weirs, gates, retention basins, etc. in the drainage system, preferential flow routes, and ponding on the surface [20].

For the above-mentioned case studies, rainfall maxima at 10, 20, 30 and 60 min have been calculated from the eight automatic tipping-bucket rain gauges in the Turin area (Table 2). Given the rainfall maxima for the different intervals, the return periods corresponding to these values have been derived from the Atlas of Intense rainfall [21]. The last column reports for each event the hail presence, derived from POD products by weather radar and from news or social media reports: one asterisk means some chances of hail, meanwhile two asterisks mean diffuse hail, probably even large, with accumulation. All the case studies show return periods equal to or greater than two years and the presence of hail. Some events stand out:

1. 5th June 2017, 13th July 2021 and 1st August 2021, with low return periods. Here, the hailstorm probably played a role in occluding stormwater drains;
2. 17th June 2020 and 22th June 2021, with very high return periods and corresponding large impacts;

Table 2. Rainfall maxima of the selected case studies over 10, 20, 30 and 60 min time frame, together with return time estimation. Hail is also indicated:* refers to small hail (less than 1 cm), while ** refers to large hail (greater than 1 cm).

Date	Rainfall maxima (mm)				Return-period (years)				Hail
	10	20	30	60	10	20	30	60	
2017-06-05	10.6	18.0	24.6	32.1	<2	<2	2	2	*
2017-06-27	21.0	37.9	44.4	56.9	2	10	20	20	**
2019-08-11	19.8	26.8	27.6	27.6	2	2	2	<2	**
2020-06-03	18.8	24.0	24.0	24.0	2	2	2	<2	*
2020-06-07	16.0	23.5	29.7	30.9	2	2	2	2	*
2020-06-15	23.1	30.9	35.6	55.4	5	5	5	20	*
2020-06-17	25.8	38.6	43.6	48.2	5	20	20	10	**
2020-08-17	23.6	38.7	54.0	80.0	5	20	50	200	**
2020-08-28	33.4	43.4	44.0	44.0	20	20	20	5	*
2021-06-22	26.9	40.8	52.6	75.0	5	20	50	200	*
2021-07-08	12.6	19.2	26.0	47.7	<2	<2	2	10	*
2021-07-13	17.3	26.0	30.7	40.2	2	2	2	5	**
2021-08-01	14.3	19.8	21.8	22.0	<2	2	<2	<2	**

Generally, it can be stated that for rainfall intensities lower than a 2-year return period, it is improbable to have impacts on the city, while a return period greater than 10 years gives a high probability of urban floods. To check this hypothesis, the occurrences of rainfall intensities for the given durations and for 2,5,10 years return levels have been calculated from the rain gauges for 2017–2021 time interval.

Table 3 reports the number of days when one of the eight rain gauges exceeds the threshold for a given duration and return level from 2017 and 2021. Recalling that only 13 events had impacts on the city, it is worth noting that the 2-year return level occurs about two times with respect to the number of relevant events. When it moves for return levels between 5 and 10 years, then the number of occurrences has a good agreement with the number of events in the same period.

Table 3. Number of days with accumulated rainfall greater than thresholds relative to return-period of 2, 5, and 10 years during 2017–2021.

Accumulation	Return-period (years)		
(min)	2	5	10
10	31	13	3
20	37	23	12
30	38	20	13
60	20	20	11

4.1. Analysis of thunderstorms on 17st August 2020 and 13th July 2021

On 13th July 2021, the severe North Atlantic storm, which caused widespread flooding and heavy damage in Germany, Holland and Belgium, was also responsible for widespread instability over Piedmont, which affected almost the entire region at various times during the day. The arrival of very cold air at altitude easily destabilised the hot humid summer atmosphere, which thus showed a significant lapse rate over northwest Italy, i.e., a significant temperature difference between the various vertical atmospheric layers, easily higher in the central (hottest) hours of the day. Consequently, the instability indices convective instability indices were very high over Piedmont, especially in the first

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part of the day, with high values of convective energy available during the day, also ready for the initiation of thunderstorms afternoon-evening. The Convective Available Potential Energy (CAPE) recorded by Cuneo Levaldigi airport sounding (44.541N 7.620E) at 12 UTC was 2700 J/kg.

Figure 3 shows the rainfall accumulations and hail probability with an indication of large hail, according to [22]. This case study is characterized by low rainfall return periods for all durations, but the showers interested a large part of downtown (see Figure 3) with diffuse hail. In part of the hit area hail sizes greater than 4 cm have been reported. Hailstorms cause flushes of leaves that can accumulate on sidewalks and roadways into storm drains during and after storms. Large numbers of leaves can be problematic for homeowners, stormwater drainage systems, and water quality. Water can back up on the street and possibly into surrounding basements as a result of the leaves matting across the storm drain and obstructing water movement.

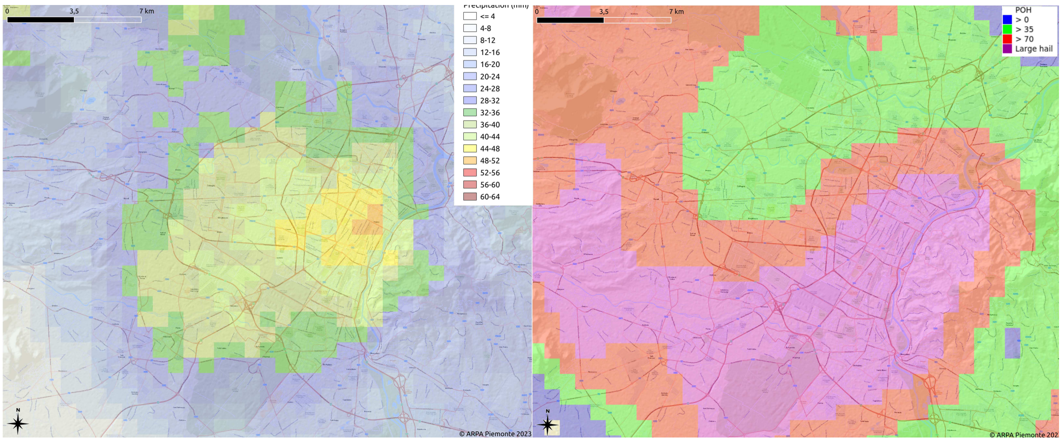

Figure 3. Storm on 2021-07-13: rainfall accumulation during the event on left; hail probability on right.

On 17th August 2021, an Atlantic low pressure has been affecting Western Europe since the middle of August. The centre of the low pressure gradually retreated toward the north-northwest over the course of the day, moving up toward the British Isles and thus away from the continent. At the same time, however, the drop in geopotential aloft in the mid-latitudes advanced slowly eastward, extending from Piedmont to the rest of northern Italy. The atmosphere remained unstable due to cold air aloft, associated with the Atlantic low, which in its eastward motion continued to overlook much of the Piedmont area. The CAPE recorded by Cuneo Levaldigi airport sounding at 12 UTC was 1857 J/kg. There was a temporary rise in temperature during the middle hours of the day, followed by a new partial cold intrusion from the north over Piedmont in the evening. In the afternoon of 17 August 2020, a number of particularly severe thunderstorms developed from the western pre-alpine areas, moving eastward. A thunderstorm system around 153:30–14:00 UTC hit Turin with hail and violent showers.

Figure 4 shows the reflectivity map (800 m $\times$ 800 m resolution) from the Piedmont weather radar composite on 17 August 2020 between 13:30 and 14:00 UTC. The map provides insights both into precipitation distribution and how fast the event was.

The severe thunderstorm was also accompanied by hail. Figure 5 shows POD product for 17 August 2020 in the TMA. Cyan colour locates in areas hit by hail with a size greater than 2 cm. Wind gusts were also significant, with wind speed exceeding 50 km/h in the Turin area.

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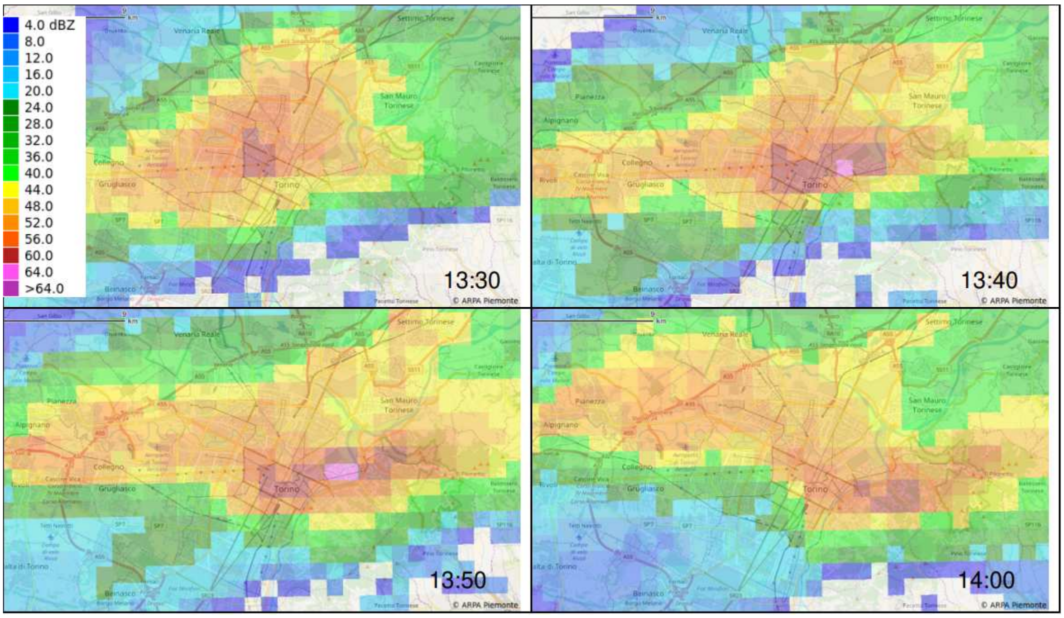

Figure 4. Reflectivity [dBZ] from Piedmont weather radar composite between 13:00 and 14:00 UTC.

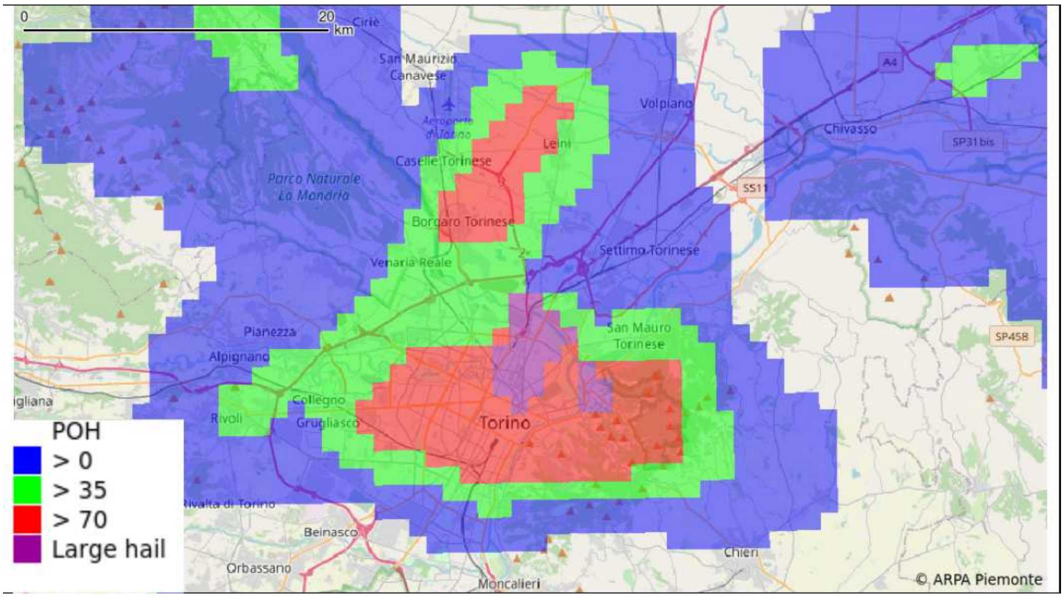

Figure 5. Probability of hail (POD) on 17/08/2020 in Turin: cyan colour shows hail size greater than 2 cm.

5. Discussion and conclusions

Urban floodings are serious threats to big cities causing economic losses and sometimes casualties. This preliminary study investigates the impacts of thunderstorms over the city of Turin, Italy. The aim is to design an operational early-warning system based on ground observations and weather radar data. Critical events that occurred during the last five years have been analysed and described in terms of return levels at sub-hourly and hourly rainfall maxima. The occurrence of hail has been also reported.

Precipitation events with return periods of less than 2 years are unlikely to have an impact on the ground, while return periods of 10 years or more have a high probability of causing damage in urban areas. In this context, precipitation events with a return period of fewer than 2 years seem to have an impact on the soil only if they are associated with hail, with an impact due to hail or fallen leaves accumulation. Summarizing the main findings, it can be stated that:

1. rainfall accumulation with return levels minor than 2 years generally does not have impacts on city roads, public transportation or stormwater drainage systems;
2. rainfall accumulation with return levels greater than 10 years most probably cause impacts to the urban area;
3. hailstorm accumulation and large hail have impacts on the urban area, regardless of rainfall accumulation.

Therefore, in order to outline a decision support system to face intense precipitation events in urban areas and to improve the management and safety of infrastructure, it is appropriate to improve the reliability of nowcasting of events with these characteristics.

However, further investigations are mandatory, extending the period of analysis and improving the observations in the TMA. Moreover, weather radar quantitative precipitation estimations (QPEs) need to be deeply investigated. To this aim, an increased density of rain gauges in urban areas, together with the integration of ground precipitation data and radar-estimated areal data, is essential to obtain precipitation fields that are reliable and accurate over the territory.

This underlines the great benefit of weather radar monitoring, and consideration is being given to further improving it by integrating the two C-band polarimetric Doppler weather radars with a polarimetric X-band weather radar. The improved spatial and temporal resolutions of rainfall fields in the TMA by the new observing system will allow further investigations with hydrological and hydraulic numerical modelling.

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