Title:

Extreme hydrometeorological events, a challenge for gravimetric and seismology networks

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Key points

-Real-time gravity monitoring is a tool for early warnings of flash floods.

-The gravimeter detects the saturation of the catchment subsoil and soil.

-Seismometer and gravimeter bring a new understanding of the July 2021 catastrophic floods in Belgium.

Abstract

Extreme events will become more common due to global change, requiring enhanced monitoring and pushing conventional observation networks to their limits. This encourages us to combine all the possible sources of information to obtain a complete picture of extreme events and their evolution. This commentary builds on an example of the July 2021 catastrophic floods that hit northwest Europe, for which the use of seismometer and gravimeter captures complementary data and brings a new understanding of the event and its dynamics. A sudden increase in seismic noise coincides with the testimony reporting on a “tsunami” downstream of the geophysical station. Concurrently, the gravimeter showed increasing saturation of the weathered zone, showing less and less water accumulation and increasing runoff. When rain re-intensified after a 3-hour break, the subsoil’s saturation state induced an accelerated runoff increase, as revealed by the river flow, in a much stronger way than during the rainy episodes just before. We show that the gravimeter detected the saturation of the catchment subsoil and soil in real-time. When the rain re-intensified, this saturation resulted in a sudden, devastating and deadly flood. Our study opens up the possibility of integrating real-time gravity in early warning systems for such events.

Plain language summary

Global change will require increased Earth monitoring and push conventional observation networks to their limits. This challenge encourages us to be open to all the possible sources of information to obtain a complete picture of extreme events and their evolution. This commentary illustrates this using seismometer and gravimeter complementary observations that bring a new understanding of Belgium and Germany’s July 2021 catastrophic floods. A sudden increase in seismic noise coincides with the testimony reporting on a “tsunami” downstream of the geophysical station. At the same time, the gravimeter, which can measure the gravitational attraction of groundwater, showed that the soil was becoming increasingly saturated and could store less and less water. Given this saturation, when rain re-intensified after a 3-hour break, the ground could not absorb water anymore. The saturation induced an accelerated increase in water running off the land surface, as revealed by the river flow, causing a sudden, devastating and deadly flood. Our study opens up the possibility of using real-time gravity in early warning systems for such events.

Introduction

From July 13 to 15, 2021, the Bernd storm caused ravaging floods in northwest Europe, resulting in 184 fatalities in western Germany and 38 in eastern Belgium (World Weather Attribution, 2021). The floods also destroyed hundreds of houses, caused considerable damage to the infrastructure, and disrupted water and power distribution systems and telecommunication. On September 1-2, 2021, Storm Ida hit New York, New Jersey, Pennsylvania and Connecticut, killing at least 43 people and leaving more than 150,000 homes without power. Later on, the series of floods in November 2021 caused unprecedented disruption of the transportation corridor linking Vancouver to the rest of British Columbia and Canada.

Extreme disasters also challenge the scientific communities. Those events are rare, making it difficult to assess their return period, the hazards and induced risks. They impose extreme stresses on geophysical monitoring networks. Flooding saturates the instruments, causes power and communication outages, or destroys probes, jeopardizing the quality and the continuity of long-term hydrological monitoring. Concurrently, the event strength and magnitude are such that they leave their imprint in many unexpected, or even unlikely, observational techniques. This opens new ways of understanding the event and new opportunities to explore our environment. The variety of sensors and their vulnerability, together with the impact of those events, make it mandatory to combine all available information to track the course of extreme events.

For example, geodetic (Miller & Shirzaei, 2019; Milliner et al., 2018) and seismological (e.g., Burtin et al., 2008; Cook et al., 2021) networks provide information about displacement and acceleration of the ground, sensitive to, among others, changes of mass distribution, to water vapour variation, to water content change in the ground, and in case of flood, to noise, vibrations and shocks associated with the rapid flow. Most of those phenomena are not part of the targeted measurements of classical hydrology sensors but are well traceable with geodetic and seismic instruments during extreme events. A seismic network can also act as a valuable early warning system: (Cook et al., 2021) demonstrated this possibility in the Himalayas, using data from a dense seismic network in Uttarakhand, India. They detected a catastrophic flow event initiated by a large rockslide and showed that a regional seismic network could provide downstream warnings within minutes of event initiation.

These geophysical measurements act as opportunistic sensors (Jiang et al., 2019). They perform as short-range remote sensing, with relatively protected instruments that provide observations even when in-situ monitoring systems are down due to adverse conditions or unavailable in remote areas.

Unlike geodetic and seismic networks, space techniques can inform the hydrological state at the regional and continental scales, but not yet in real-time. Combined with hydrological models, they can be used to warn of potential hazards of drought or flooding. However, it is not yet possible to use space gravimetry to investigate local flash floods, given the insufficient time (10 days to a month) and space (300 to 400 by 300 to 400 km^2, that is, larger than Belgium) resolution. Similarly, while remote sensing monitors the soil moisture with a 1-3 km length resolution, which would be sufficient, its few days tie resolution remains insufficient to monitor extreme events. Moreover, the present microwave remote sensing techniques only inform on the upper few centimeters of the soil (Das et al., 2019; Peng et al., 2017, 2021). Today space techniques lack spatial and/or temporal resolution to monitor extreme events while ground geophysical networks, including ground deformation and seismic measurements, have brought valuable insights on these events and even open possibilities for early warning.

In this study, we show the possibility of using seismic and gravity measurements integrating the whole vadose zone (M. Van Camp et al., 2006) to monitor an example case, namely the July 2021 catastrophic floods that hit northwest Europe. Both measurements bring complementary information on the event and provide, together, a new early warning system, informing about the flash flooding hazard several hours in advance.

The Bernd storm hit the Vesdre Valley, Belgium

In eastern Belgium, the strongest precipitation during the Bernd Storm hit the Vesdre watershed (703 km^2, Figure 1a). The rain gauge in Jalhay (Figure 1) recorded the highest cumulative value ever recorded within 48 h in Belgium, that is, 275.4 mm of water from July 13 00h00 to July 14 23h59 (Journée, 2022; Zeimetz et al., 2021). Above the Vesdre watershed, the return period of the cumulative precipitation over 48 h is estimated to be over 200 years. This estimation is accompanied by considerable uncertainty, from 60 to more than 1000 years (Zeimetz et al., 2021). The Vesdre River flood killed 24 people, and at its mouth, at Chênée, Liège, Zeimetz et al. (2021) estimate a maximum flow of 640 m^3/s with confidence interval 448-832 m^3/s, whereas the average flow is 11.3 m^3/s. In the valley, the water reached a level of at least 30 cm on the ground floor of 16,376 habitations, seriously damaging them, and at least 182 buildings were or had to be demolished (Royen, 2021).

The Membach station

The seismometer and gravity data from the Membach station (Michel Van Camp et al., 2017), situated along the Vesdre River (Figure 1), show the event's strong signature. While the seismic data bring complementary information on the sequence of events, the gravimeter showed, unexpectedly, that it can act as an early-warning device, a couple of hours before the extreme event.

Given its footprint, the gravimeter of Membach provides a reliable three-dimensional view of the water content variations of a volume of about 10 million m^3, integrating the soil water in a radius of about 400 m around the instrument. It allows working at scales that would be difficult to imagine with traditional soil moisture probes or a lysimeter. It also captures rainfall at a larger spatial scale than traditional rain gauges, as -0.39 nm s^{-2} corresponds to 1 mm of water at the Membach station (Delobbe et al., 2019; Meurers et al., 2007).

Since we started in 2004 the comparisons between the gravimeter, soil moisture and rainfall, the gravity has always reacted proportionally to precipitation (Delobbe et al., 2019; Meurers et al., 2007; M. Van Camp et al., 2006). The signal is induced by the water accumulating in the 1-10 m thick weathered zone, 48 m above the gravimeter. In the past, we have noticed decreases in gravity of up to 41 nm/s^2 in 48 hours, between 8 and 10 July 2014, for cumulative precipitation of 117 mm. Between 13 July 2021 00h and 15 July 03h, gravity decreased by 43 nm/s^2, which is unprecedented, especially considering that the decrease in July 2021 started at a level 20 nm/s^2 lower than in July 2014. The spring and summer of 2021 were so wet that the gravity level was already in a regime similar to that of winter, with the fall on 13 July starting 40 nm/s² below the level expected in a dry summer.

Seismic information

Figure 2a presents a moving window spectrum of the recording of the vertical broadband seismometer from July 14 20h to July 15, 04h, 2021 UTC. The rising stream turbulence, sediment and debris transport of the swollen river induced seismic noise (Burtin et al., 2008). Between 22h and 01h, in the 1-8 Hz band, the standard deviation of the seismic noise reached twice the level observed before, between 08h and 16h. During that night, there were at least four changes in the noise regime, most probably related to sudden changes in the river flow, undocumented by hydrological probes. There is an increase at 21h [label SA on Figure 1a] in the noise around 1.4 Hz. Then at 22:05 [SB], a kind of humming affects the 2-10 Hz band, probably caused by a dramatic elevation in the river flow that destroyed the station lifeline at 22h31, when two poles fell 250 m away from the seismometer. At 23h10 [SC], another burst appears in the 2-3.5 Hz band and fades at 01h15 [SE]. Finally, at 00h15 [SD], there is a last burst between 5 and 7 Hz. It coincides with the detailed testimony 3 km downstream in Béthane (Vincent Slits, 2021). There, the night warden of a factory severely damaged during the events reported a sudden roaring in the valley before the arrival of a flash flood, described as a “tsunami”, at 00h30, followed by a second one at 01h30, on July 15 2021. This sequence of events, reconstructed from seismic data, together with other hydrologic information, clarifies the understanding of the disaster in its complexity. Presently, interpreting the seismic spectrum in terms of e.g., water turbulence and bed load (e.g., Arnaud Burtin et al., 2011; Gimbert et al., 2014) would be speculative without a comprehensive investigation, including a local seismic network and appropriate monitoring of different parameters in the river.

For the last 10 years, the flow at the Eupen reservoir has never exceeded 56 m³/s (2014-07-09), while this reached 232 m³/s in July 2021. In Verviers, since 2005 the Vesdre flow never exceeded 73 m³/s (2019-03-16), 65 m³/s (2011-01-13), 60 m³/s (2014-07-09), 55 m³/s (2021-01-29 & 2021-01-30) or 52 m³/s (2007-01-19), while the July 2021 maximum flow is estimated at 440 m³/s (confidence interval 308-572 m³/s, Zeimetz et al. 2021). We looked at the seismic spectra during a week centred on those events, but apart from the typical alternations linked to working hours or usual variations in microseismic noise below 1 Hz, we could not evidence any signal similar to the observed one in July 2021.

Gravity, precipitation, river flow

Figure 2b presents the equivalent water height estimated from the superconducting gravimeter, the precipitation amount estimated from the weather radar observations combined with rain gauge measurements in a zone of 1 km² above the station (Goudenhoofdt & Delobbe, 2016; Van Weverberg et al., 2011) and the water flow of the Vesdre-Getzbach watershed (69 km^2) feeding the Eupen dam reservoir. This figure also includes the seismic spectrum, from July 13 18h to July 16 00h, 2021 UTC. The flow at the Eupen dam is the only available complete hydrogram measured upstream of the Membach station. This hydrogram is reconstructed from the reservoir level and discharge measurements at the dam, located 7.2 km upstream. This represents generally about 65% of the flow of the Vesdre near the station (Zeimetz et al., 2021), with similar dynamics. Downstream Eupen, there is no hydrogram available between July 14 and 15, as the Vesdre damaged or destroyed the limnimetric network.

The gravimeter as an early warning system

On July 13, at 20h UTC [label A], the precipitation increased dramatically, accumulating an additional 48 mm until 23h [B]. At that time, the soil was not yet saturated and, as expected (Delobbe et al., 2019; Meurers et al., 2007; M. Van Camp et al., 2006), the gravimeter provided a similar water equivalent height (40 mm). Concurrently, the flow into the Eupen dam reservoir increased to 66 m^3/s [C]. On July 14, between 02h and 15h, cumulated rainfall reached 80 mm above Membach and 59 mm (also radar-gauge, not shown) above the reservoir watershed upwards of the Eupen dam, causing an increase of the flow in the dam reservoir up to 125 m^3/s [D], accompanied by a first increase in the seismic noise, which rose again after 19h, as discussed in the previous section. At the same time, the gravimeter evidenced a rising saturation of the weathered zone above, reaching a full saturation progressively, thus showing less and less water accumulation. After 18h [E], the rain re-intensified after a 3 hours break, and the saturated state of the subsoil induced an accelerated increase of the runoff, as revealed by the flow feeding the Eupen dam reservoir increasing to 232 m^3/s [F], in a much stronger way than during the episodes [C] and [D]. Simultaneously, gravity remained essentially stable. This shows, for the first time to our knowledge, how a gravimeter was able to detect in real-time the saturation of the subsoil and soil of the catchment in a radius of about 400 m around the instrument. Of course, this does not represent the entire watershed area. Still, the hydrogeological characteristics are similar to those found on the plateau south of the Vesdre, where the most intense rainfall was concentrated. It is reasonable to assume that the gravimeter may have indicated the saturation limit, after which, when the rain re-intensified, a devastating flood hit the Vesdre Valley. This result opens perspectives to use real-time gravity networks for early warnings of such events and refine alert messages a few hours before.

Conclusions and perspectives

In extreme conditions or remote areas, every piece of information is invaluable due to the difficulty of maintaining the usual observation network in operation. This importance is reinforced by the complexity and atypical nature of the events themselves, but also their economic and human consequences. The accumulation of different data types and the combination of all available sensors, could be mandatory to develop efficient early warning systems and mitigate risk, given the expected increase in the frequency and severity of such events.

We illustrated one more application of seismic data that complements other hydrological studies of the flash flood event. Such independent information is very important to understand the course of the events and help identify explaining factors of the devastating floods and their impact in terms of fatalities and damage. Concurrently, we demonstrated that continuous gravity monitoring could improve early warning systems. In similar circumstances, an operational service should be able to release a warning in the few hours before the catastrophic increase of the Vesdre river flow.

In the near future, it will be possible to deploy arrays of low-cost microelectromechanical relative gravimeters, as well as absolute quantum gravimeters. These "gravity imagers", as named in a volcanic context by Carbone et al. (2020), should complete new early-warning systems to inform the degree of soil saturation in flash-flood prone areas, as in the case of the Vesdre valley discussed in this study. For further interpretation of the seismic noise spectrum, it would also be interesting to study the noise structure induced by the Vesdre River for different flow conditions, which will require the installation of a local seismic network and monitoring of the river (flow rate, water height, sampling of the particle size distribution of sediments and bed materials) (Bakker et al., 2020; Gimbert et al., 2014).

On a broader scale, global change will require increased monitoring, while conventional observation networks will be pushed to their limits. This encourages us to be open to all the possible sources of information to obtain a complete picture of extreme events and their evolution.

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Figure caption

Figure 1. (a) The Vesdre watershed (702 km^2) and (b) enlarged view around the Membach station, with the Gileppe and Eupen reservoirs, the Béthane hamlet and the Jalhay rain gauge. The water mass in the areas circled in black contributes 90% (solid line) and 95% (dotted line) of the gravity signal as monitored by the gravimeter. The purple square represents the footprint of the weather

radar. Maps from Walloon Geoportal https://geoportail.wallonie.be/walonmap.

Figure 1

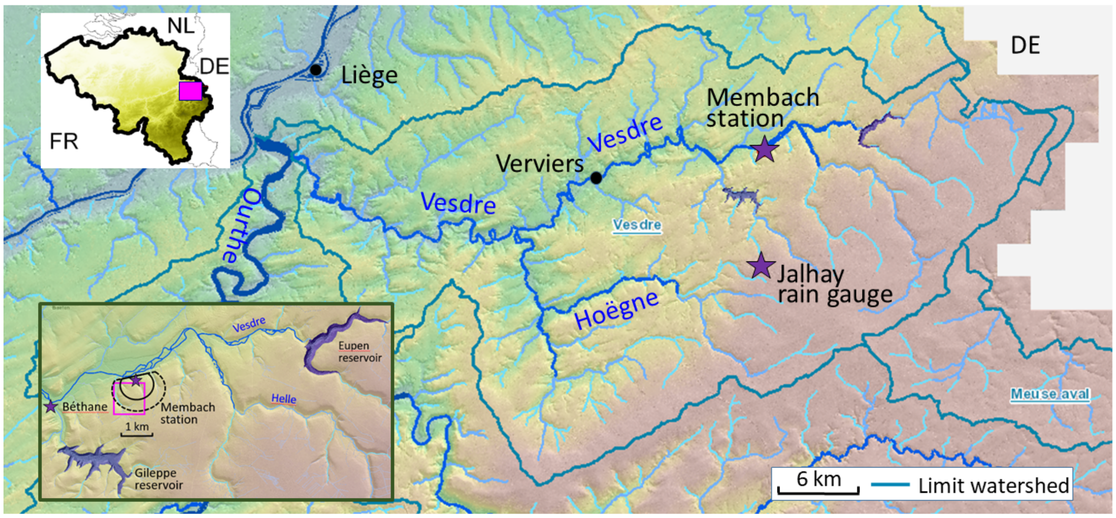


Figure 2 (a). From July 14 20 h to July 15 4h, 2021 UTC: moving window spectrum of the recording of the vertical broadband seismometer at the Membach station. The persistent signal around 3.12 Hz is typical of that station, its origin is unknown. (b) From July 13 18h to 16, 00h, 2021: moving window spectrum of the seismometer, radar-gauge rainfall (blue) and equivalent water height (green), inferred from gravity change by using an admittance of -0.39 nm/s^2/mm (Delobbe et al., 2019). The green scale on the right-hand axis refers to both the precipitation and gravimeter measurements. In black, the inflow in the Eupen reservoir and the vertical dashed line indicates the time at which the flow meter of Verviers, the nearest one, 14 km downstream (distance along the river), broke down. There is an increase in seismic noise during working hours, due to anthropogenic activities, to which is added the rising noise on July 14 caused by the flooding river. Time in UTC.

Figure 2a.

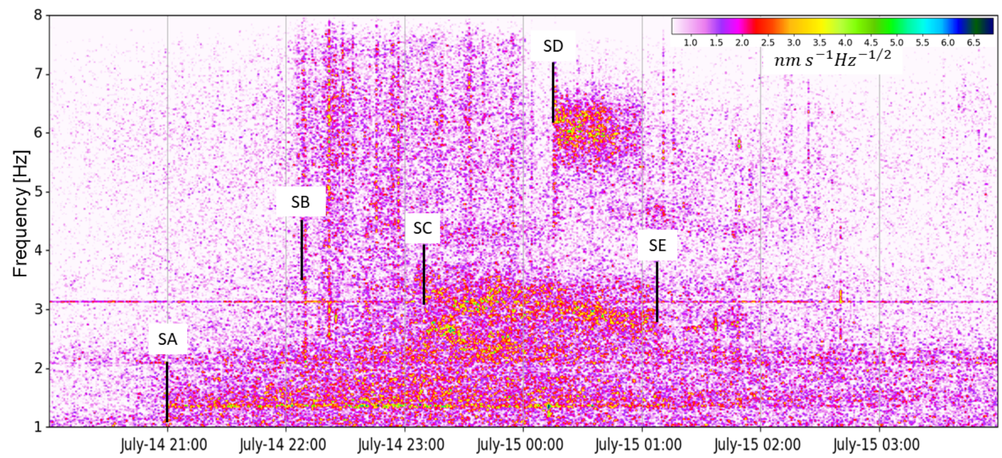
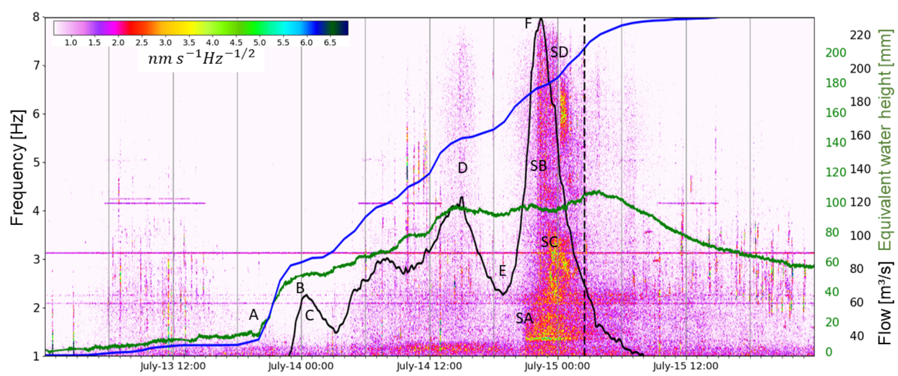


Figure 2b



Data Availability Statement

The data from the Walloon limnimetric network are freely available on http://aqualim.environnement.wallonie.be. The other data set is available publicly here: https://doi.org/10.5281/zenodo.6285424 . The raw data from the superconducting gravimeter and the broadband seismometer are also available on IRIS (https://www.iris.edu) through SG/MEMB and BE/MEM channels.

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