Extreme hydrometeorological events, a challenge for geodesy and seismology networks

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Abstract

The use of seismometer and gravimeter captures complementary data and brings a new understanding of the July 2021 catastrophic floods in Belgium and Germany. A sudden increase in seismic noise coincides with the testimony reporting on a "tsunami" downstream the geophysical station. Concurrently, the gravimeter evidenced a rising saturation of the weathered zone, thus showing less and less water accumulation. When rain re-intensified after a 3-hour break, the saturated state of the subsoil induced an accelerated increase of the runoff, as revealed by the river flow, in a much stronger way than during the rainy episodes just before. We show that a gravimeter can detect in real-time the saturation of the catchment subsoil and soil. This saturation resulted, when the rain re-intensified, in a sudden, devastating and deadly flood. This opens perspectives to use real-time gravity for early warnings of such events.

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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 and Germany.

Abstract

The use of seismometer and gravimeter captures complementary data and brings a new understanding of the July 2021 catastrophic floods in Belgium and Germany. A sudden increase in seismic noise coincides with the testimony reporting on a "tsunami" downstream the geophysical station. Concurrently, the gravimeter evidenced a rising saturation of the weathered zone, thus showing less and less water accumulation. When rain re-intensified after a 3-hour break, the saturated state of the subsoil induced an accelerated increase of the runoff, as revealed by the river flow, in a much stronger way than during the rainy episodes just before. We show that a gravimeter can detect in real-time the saturation of the catchment subsoil and soil. This saturation resulted, when the rain re-intensified, in a sudden, devastating and deadly flood. This opens perspectives to use real-time gravity for early warnings of such events.

Plain language summary

The use of seismometer and gravimeter captures complementary data and brings a new understanding of the July 2021 catastrophic floods in Belgium and Germany. A sudden increase in seismic noise coincides with the testimony reporting on a "tsunami" downstream the geophysical station. Concurrently, the gravimeter, able to measure the gravitational attraction of groundwater, evidenced a rising saturation of the ground, thus showing less and less water accumulation. When rain re-intensified after a 3-hour break, given this saturation, the ground could not absorb water anymore. This induced an accelerated increase in the amount of water running off the land surface, as revealed by the river flow. This resulted in a sudden, devastating and deadly flood. This opens perspectives to use real-time gravity for early warnings of such events.

Introduction

From July 13 to 15, 2021, the Bernd storm caused ravaging floods in north-western Europe. This resulted in 184 fatalities in western Germany and 38 in eastern Belgium. 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, as well as new opportunities to explore our environment. The variety of sensors and their vulnerability 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 (Cooke et al., 2021) networks provide information about displacement and acceleration of the ground, sensible to, among others, changes of mass distribution, to water vapor variation, to water content change in the ground, and noise, vibrations and shocks associated with the rapid flow in case of flood. 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.

The Bernd storm at the Membach Station, Belgium

In the case of the Bernd storm, the seismometer and gravity data from the Membach station - East Belgium (Van Camp et al., 2017)(Figure 1), situated along the Vesdre River, both show a strong signature of the event. They indicate that seismology and geodesy may bring unexpected and complementary information on such an extreme event.

Figure 2a presents a moving window spectrum of the recording of the vertical broadband seismometer from July 14 20h to July 15, 04h, 2021. 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 [SA] 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, will be analysed, together with other hydrologic information, allowing building a precise understanding of the disaster in its complexity.

Figure 2b presents the same spectrum, from July 13 18h to July 16 00h, 2021, together with the precipitation amount estimated from the weather radar observations combined with rain gauge measurements in a zone of 1 km^2 above the station (Goudenhoofdt & Delobbe, 2016; Van Weverberg et al., 2011), the equivalent water height estimated from the superconducting gravimeter, and the water flow of the Vesdre-Getzbach watershed (69 km^2) feeding the Eupen dam reservoir. This latter is the only available complete hydrogram measured upstream of the Membach station. This hydrogram is reconstructed from the level and discharge measurements at the Eupen dam, located 7.2 km upstream. This represents generally about 65% of the flow of the Vesdre near the station (Fränz Zeimetz et al., 2021), with similar dynamics.

On July 13, the precipitation increased dramatically, accumulating an additional 48 mm between 20h [A] and 23h [B]. As expected (Delobbe et al., 2019; Meurers et al., 2007), 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. At the same time, the gravimeter evidenced a rising saturation of the weathered zone above, reaching progressively a full saturation, and 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 evidence how a gravimeter was able to detect in real-time the saturation of the catchment subsoil and soil. This reached saturation resulted, when the rain re-intensified, in a devastating flood. This opens perspectives to use real-time gravity for early warnings of such events.

In extreme conditions, every piece of information is invaluable, because of 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 types of data, combining all sensors, could be mandatory to develop early warning and risk mitigation, given the expected increase in the frequency and severity of such events.

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Data Availability Statement

The data set is available publicly here: https://doi.org/10.5281/zenodo.5724041

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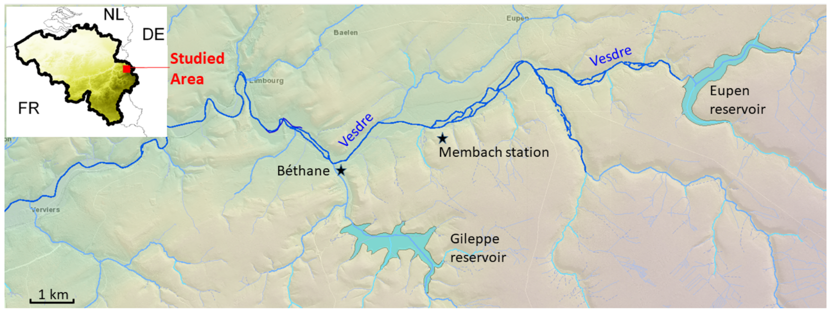

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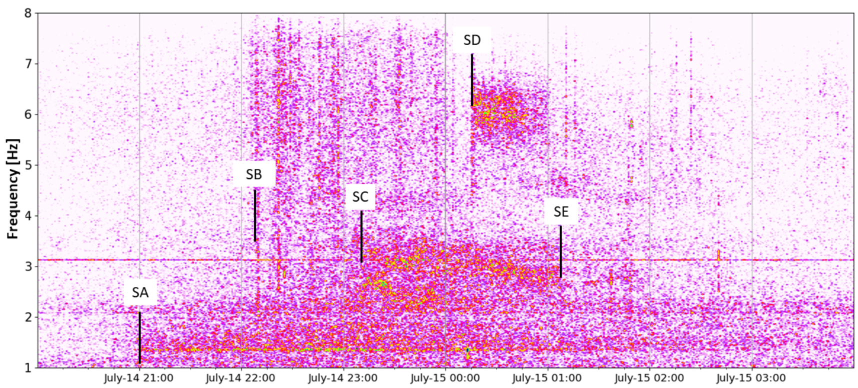
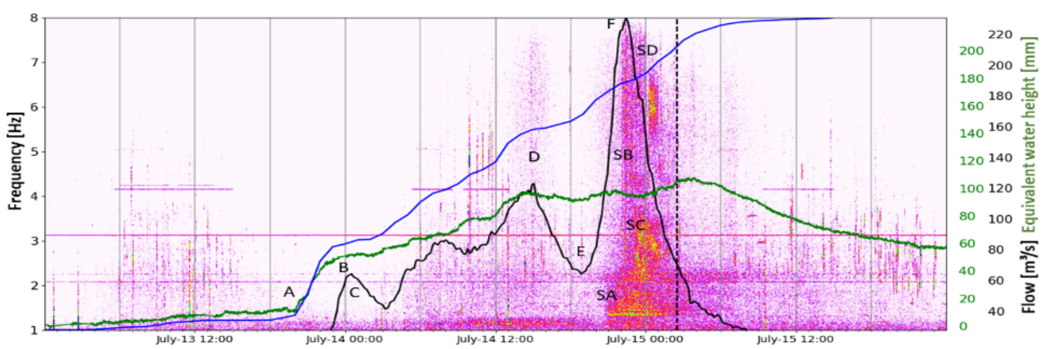


Frequency [Hz]
SA
SB
SC
SD
SE
July-14 21:00
July-14 22:00
July-14 23:00
July-15 00:00
July-15 01:00
July-15 02:00
July-15 03:00



Frequency [Hz]
Flow [m³/s]
Equivalent water height [mm]
A
B
C
D
E
F
SA
SB
SC
SD
July-13 12:00
July-14 00:00
July-14 12:00
July-15 00:00
July-15 12:00