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Ethical and FAIR data policies for tsunami warning systems: challenges for Northern Africa

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Abstract

This article focusses on community-driven data, ethical open data sharing policies for tsunami preparedness, risk reduction and real-time crisis management. Accurate real-time earthquake monitoring is crucial for decision-making when events might potentially trigger tsunami waves for both near- and far-field case studies. The efficiency of tsunami warning systems is undoubtedly interconnected with the application of the FAIR principles in Geosciences. The research examined case studies in the Pacific (Chile) and in the Atlantic (French Atlantic Coast) which showed the importance of improving computations of real-time automatic seismic solutions with short-band low-cost seismic stations from the Raspberry Shake Community. Preliminary tests of urban noise in Algiers (Algeria, North Africa) using a three-component raspberry shake station are also included in this study. An attempt to explore how data management policies could meet the FAIR principles in Western Mediterranean for Northern Africa is proposed using a multidisciplinary analysis (socio-ethical geosciences) as an outcome of this study. The results highlight the possibilities of harnessing community-based earthquake detection network and FAIR principles in data management to improve tsunami early warning systems and international cooperation in the sciences for disaster resilience.

Keywords: Tsunami Warning Systems, Western Mediterranean, North Africa, Real-time earthquake monitoring, Ethical data policy, Community-driven data, Citizen science, FAIR principles, Disaster Risk Reduction.

1. Introduction

Fast urbanization growth has increased exposure and vulnerability to tsunamis across the coastal communities in the world. Early warning systems play a vital part in reducing the impact of tsunamis to the exposed communities. Geoethics guide how scientists and officials design and operate early warning systems. It ensures these systems, which track hazards, respect human life, provide honest data, and protect vulnerable communities. Pros and cons for open data in geosciences are some of the most challenging debates of recent times. Understanding how the scientific community can improve warning systems by using appropriate strategies for sharing data requires a thorough reflection. Dallo et al. (2023) highlighted how open science, transdisciplinary approaches, and ethics help to question, build and strengthen the bridge between scientific knowledge and societal actions. Key concerns include the risks of misinterpreting or misusing scientific results, uncertainties in forecasting, and the consequence of false alarms or missed predictions (Dallo et al., 2022, 2023). In 2000, Lynn introduced an ethical perspective on the moral dimensions of geography. Not only did he emphasize the existence of different interpretations of ethics and geography, but he also warned of the major pitfalls involved in seeking ways to integrate the two fields (Lynn, 2000). Di Capua and Peppoloni (2021) further stressed the ethical necessity of distinguishing the roles of scientific advisors and decision makers. While having in mind to prevent from the costs of false-alarms and failures-to-predict, they indicated that ethics issues have to be raised with implications for actions related to (1) open science commons, (2) risk mitigation, and (3) private sectors (Di Capua and Peppoloni, 2021). In this paper, the moral issues surrounding data sharing within warning systems are examined. The impacts of disasters are closely linked to social resilience. The paper explores how reflexivity – a concept of ethical self-awareness discussed by Lynn (2000) – can strengthen geoethical practices and support disaster risk reduction efforts. Overall, the study highlights the critical role of ethical reflection in improving the trustworthiness and effectiveness of warning systems for the benefit of society.

Tsunami warning systems have been set up and are coordinated by Intergovernmental Oceanographic Commission (IOC) of UNESCO. Thus far, four major regional tsunami warning systems have been set up in the aftermath of major tsunamis in the (1) Pacific, (2) Indian, (3) Caribbean and (4) North-Eastern Atlantic and Mediterranean (Bernard and Titov, 2015). Technological advancements, propelled by the digital revolution, have enhanced these warning systems, as noted by Amato (2020). Systematic data collection is one of the four key pillars outlined by the United Nations Disaster Risk Reduction (UNDRR) for effective risk assessment. A consistent and standardized methodology is used so that data can be reliable, comparable and reusable. Data are collected, organized, documented and managed following predefined protocols. The Figure 1 hereafter summarizes the four FAIR guiding principles for easy access to data: Findability (F); Accessibility (A); Interoperability (I); Reusability (R) (Jacobsen et al., 2020). As technologies and communication protocols evolve, the "FAIRification" of data within data-driven communities aims to enhance the efficiency of tsunami warning systems in vulnerable regions by ensuring that data are (1) well managed, (2) machine actionable, and (3) ready for reuse (Figure 1). For earthquakes, the timing challenge is in seconds, for tsunamis it is in minutes (Amato, 2020).

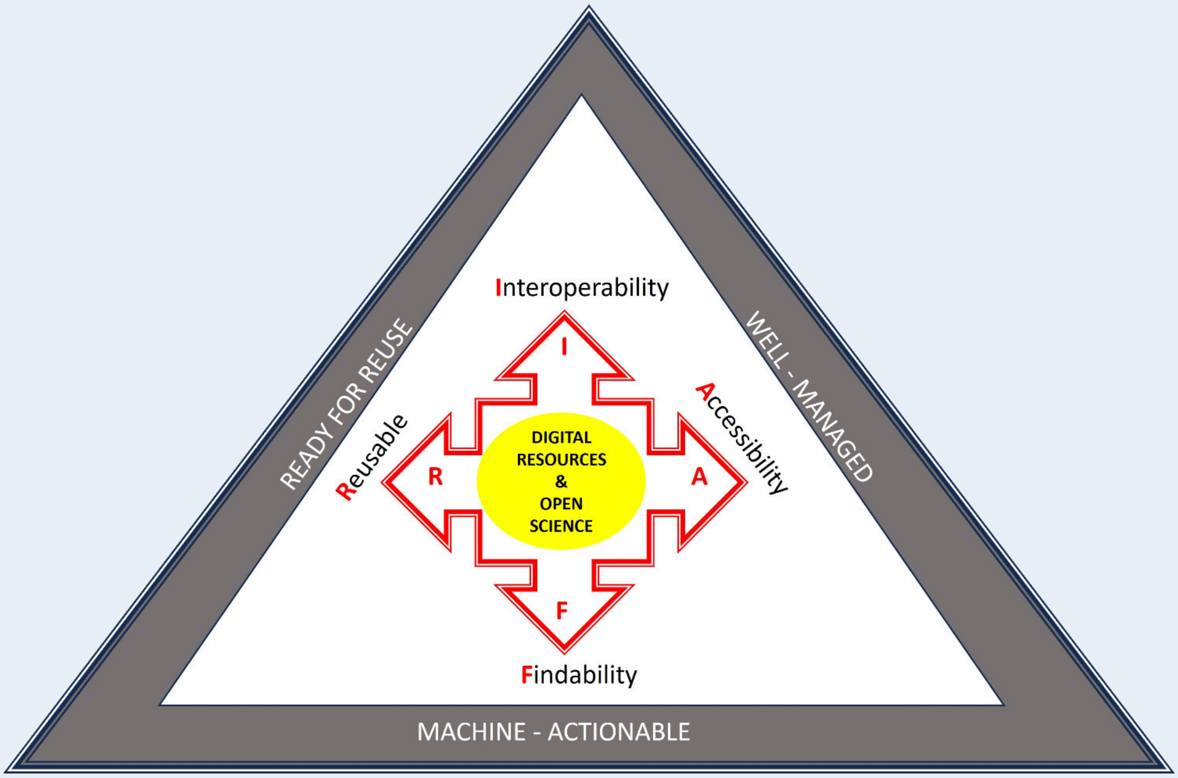


Figure 1. *The Four FAIR guiding principles. Jacobsen et al. (2020) defines all these principles as follows: (a) Findability: Digital resources easy to find for both machines and humans; (b) Accessibility: Protocols for retrieving digital resources explicit for both human and machines- include well-defined mechanisms to obtain authorization for access to protected data; (c) Interoperability: Possibilities to merge information when multiple digital resources into one digital entity – When a digital entity is capable of being processed by an online service, a machine should be capable of automatically detecting this compliance and facilitating the interaction between the data and that tool; (d) Reusability: Digital Resources are sufficiently well-described for both humans and computers such that a machine is capable of deciding if a digital resource should be reused and who to credit if it is reused.*

FAIRness, together with geoethical data-sharing policies and community-driven practices, is crucial for efficient warning systems and effective tsunami prevention and preparedness.

Real-time earthquake monitoring is a vital part of any tsunami warning system. Protocols can be improved for Northern Africa through community-driven data and ethical open data. In this paper, examples of automatic real-time seismic parameters for earthquakes in near- and far-field tsunami regions are presented. This study underlines the contribution of citizen seismology in complementing broad-band seismic network Automatic Seismological Estimations.

2. Methodology

2.1. Citizen seismology

Citizens and seismologists have collaborated since the end of the nineteenth century and early twentieth century. Contribution from local inhabitants, who described the effects and personal experiences of earthquakes and tsunamis, have been essential in documenting past events in peer-reviewed studies. Macroseismic observations have provided valuable insights into historical seismology.

Montessus de Ballore belonged to a group of great pioneers in seismology from the early twentieth century (Cisternas, 2009). He devoted his life to seismology by documenting earthquakes and volcanoes in the field and in libraries. Between 1885 and 1907, his investigations led to a catalogue of earthquakes with around 170 000 events. Using qualitative and instrumental data from the first generation of reliable 3-component seismographs, he established fundamental seismological laws on the geographical distribution of earthquakes and size of earthquakes and highlighted the Pacific zone as one of the greatest lines of seismicity (Cisternas, 2009). By collecting oral interviews reported in written documents, he developed historical seismicity, enhancing the input of qualitative data.

The tsunamis of 1868 and 1877 in Iquique (Northern Chile) show the importance of considering as a major input the voice of citizens who described the effects of the destructive earthquakes and water waves that flooded a region where cities have been later on rebuilt (Montessus de Ballore, 1912; Monge, 1992). Prior to the 15^{th} century, the Mapuche community (Chile) used to rely on a legend that encouraged them to climb to the top of the hills with food when an earthquake occurred (Ruiz and Madariaga, 2018). Finally, the 1960 Mw 9.5 Valdivia earthquake and the related trans-oceanic tsunami in the Pacific led to the establishment of an international Pacific-wide tsunami system in 1965 (Bernard and Titov, 2015).

In fact, citizen seismology has always existed and was the first qualitative approach in the science of seismology and in disaster research. Nowadays and since the twenty first century, Macroseismic Did You Feel It (DYFI) data collected by websites as USGS (United States Geological Survey) and EMSC (European Mediterranean Seismological Centre) are important contributors to citizen seismology. Lastly, Christensen and Blanco Chia (2017) created a citizen scientist network for the need of universal, quick, and accurate earthquake detection. Since 2016, affordable and citizen-led seismic monitoring is now possible around the planet thanks to the development of short – band Raspberry Shake (RS) seismometers. These low-cost seismic stations reinforce earthquake preparedness and detection in many areas at risk (geothermal activity, landslide, volcanic, and active faulting), in complement with broad-band stations from academic institutions (Taruselli et al., 2019; Holmgren and Werner, 2021; Clive et al., 2024; Hughes et al., 2025). In this work, tests using the Raspberry Shake citizen network are presented.

2.2. Real-time Earthquake Monitoring: The SeisComP Software Package

In the aftermath of the 2004 Sumatra-Andaman Mw 9.3 Earthquake and Tsunami, the German Research Center for Geosciences (GFZ) developed the SeisComP3 software package (Version 3.0) to meet the needs for reliable seismic parameters' estimations within 5 to 10 minutes. The SeisComP software package offers the possibility to acquire, in real-time, seismic waveforms (GFZ and gempa GmbH, 2008). Moreover, the Federal Digital Seismic Network (FDSN) and several other online platforms enable the upload of seismic dataset widely used by worldwide seismological observatories and tsunami centres. Fully automatic earthquake's location and magnitude are computed in real-time (Hanka et al., 2010). Later, seismologists manually revise and assess all seismological parameters. The importance of dense seismic networks and open data access is here underscored for expert response in tsunami scenarios. Here, several tests using the SeisComP5 software package (Version 5.0) have been carried out to evaluate the accuracy of seismological automatic solutions. The real-time seismic activity was monitored in the Pacific (Chile) and in the Eastern Atlantic (French Atlantic Coast). Near-field and far-field tsunami risk characterize both regions. These two examples have been considered to illustrate the necessity for waveform data to remain open for research and transparency when deploying citizen science for hazards such as tsunamigenic earthquake. In addition, the Chile (Pacific and Chile Tsunami Warning Systems) and the Western France (European Mediterranean Seismological Centre and French and North-Eastern Atlantic and

Mediterranean Tsunami Warning Systems) case studies help for more understanding of how calibration for far-fields alerts can avoid from unnecessary mass evacuations, ultra-fast near-field emergency protocols integrated into a highly coordinated cross-border multilateral network. This approach aims to better highlight (1) how a hyper-dense network can help SeisComP lock down seismological parameters (epicentre, depth) faster than a sparse professional network could alone and (2) all challenges Northern Africa and the Western Mediterranean face as for decision-making related to tsunami risk.

3. Results

This section firstly reports examples of real-time seismic monitoring for locations exposed to far-field and near-field tsunami hazard using the SeisComP software package (Chile, Pacific Coast and Western France, North Eastern Atlantic). Then, first tests from a raspberry shake station monitoring urban noise and hosted in Algiers (Algeria, North Africa) are presented.

3.1. Real-Time Seismic Monitoring Tests with SeisComP software package

The seismological software package SeisComP includes several interactive sub-packages (with graphical interface). In particular, to visualize information related to online seismic stations recording seismic waves (network status), ground motion, earthquakes occurrence (real-time, magnitude, depth), the module scmv, which stands for “SeiscomP Map View”, makes it easier to check out the worldwide seismic activity. The stations represented by triangles flash and change color (red by default) when they experience strong shaking. The module scolv, which stands for “SeisComP Origin Locator View”, analyze earthquakes parameters, revise and review origin and event information. Finally, the module scrttv which stands for “Screen Trace View” visualizes waveform data in miniSEED format in real-time or from archives of defined stream/stations, with phase picks. In this section, all results are presented using the graphical interface for scmv, scolv and scrtt sub-packages.

3.1.1. Example from the Chilean coast

The Chilean coast is regularly hit by moderate and major earthquakes. Due to its potential to trigger ocean-wide tsunamis across the Pacific, this region provides valuable insights into the main challenges associated with exposure and vulnerability to seismic risk, combined with the near-shore impacts of large tsunami waves. Chile has developed a robust and very dense broadband seismic network. In this work, the real-time monitoring is achieved using the IPOC seismic network, which stands for Integrated Plate Boundary Observatory, and operates since 2006 under the FDSN (Federal Digital Seismological Network) network code CX. This network is jointly operated by the GFZ German Research Centre for Geosciences (Postdam, Germany), the Institut de Physique du Globe de Paris (IPGP) (Paris, France), the Chilean National Seismological Centre (CSN), the Universidad de Chile UdC (Santiago, Chile) and the Universidad Catolica del Norte UCNA (Antofagasta, Chile) (GFZ and CNRS-INSU, 2006). Data are publicly available.

Figure 2 represents the real-time monitoring of earthquakes that hit the Maule region (Talca Province, Central Chile) on 22 February 2023. That day, several moderate earthquakes hit the region. Figures 2a and 2b display the real-time propagation of the seismic waves for the first seconds right after onset of the seismic shock. Figure 2b highlights the propagation of seismic waves showing a coloured contour that expands over time. This contour represents the P-wave front. As time progresses and the wave fronts propagate outwards of the source, contours (in yellow and in blue) mark all the positions reached by the P-wave fronts (Figures 2a and 2b).

Figure 3 below shows how the sub-package scolv revise and review origin and event information. The results demonstrate the effective contribution of real-time access to seismic waveforms for automatic preliminary' s automatic estimations (location, magnitude). Most of the time, the depth is fixed to a value (10 km, most often, eighth column in Figure 3). Parameters are then re-adjusted according to all data acquired

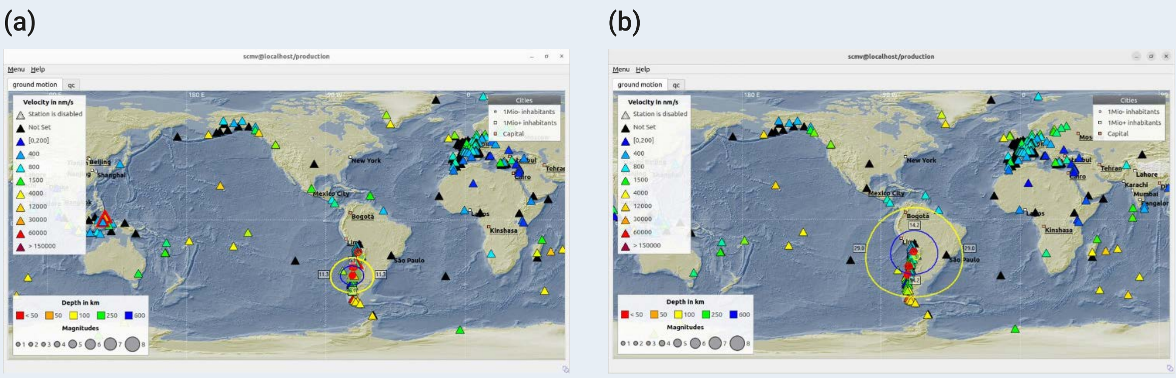
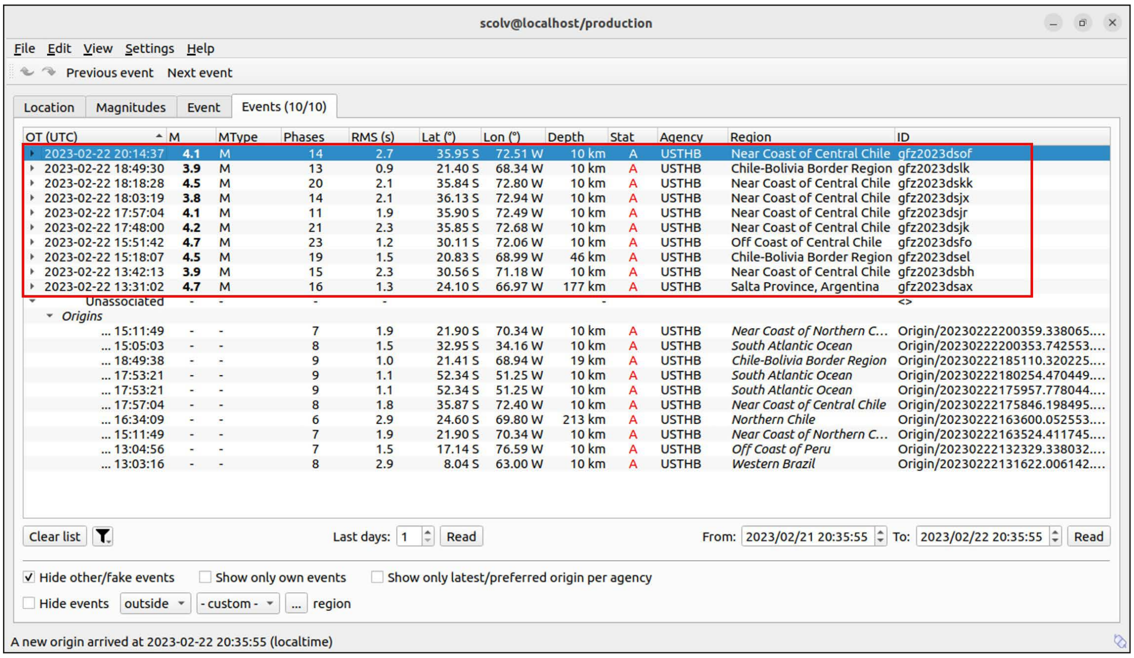


Figure 2. *Real-time seismic monitoring using the scmv module of the SeisComP seismological software. Panels (a) and (b) show the seismic activity in the Maule area (Talca Province, Chile) on 22 February 2023.*

minutes and hours later. The red rectangle indicates the final automatic solution based on all available real-time acquired seismic waveforms (A for automatic status, Figure 3, ninth-placed column labeled "stat"). The ID for final automatic seismic solution has been there set up with the default parameters (ID = "gfz2023jgmi", Figure 3, last column) and the agency label has been set up using the academic institution of the University of Sciences and Technology Houari Boumediene (USTHB). This test has been computed from 16 available seismic phases acquired in less than two seconds, with a root mean square travel time residual RMS (s) of 1.8 as indicated in the fourth and fifth column respectively. The final magnitude computed was 4.5 and the preliminary epicentral coordinates were 30.22 S and 71.25 W. The magnitude is reported in the second column, and the latitude and longitude are reported in the sixth and seventh column respectively in Figure 3. Finally, the last seismic recorded event shown at the top of Figure 3 has been computed from 26 available seismic waveforms. With a root mean square travel time residual value (RMS) equal to 0.9 s, the event was moderate, and the magnitude computed was 3.9 (status = "A").



OT (UTC)	M	MType	Phases	RMS (s)	Lat (°)	Lon (°)	Depth	Stat	Agency	Region	ID
2023-02-22 20:14:37	**4.1**	M	14	2.7	35.95 S	72.51 W	10 km	A	USTHB	Near Coast of Central Chile	gfz2023dsof
2023-02-22 18:49:30	**3.9**	M	13	0.9	21.40 S	68.34 W	10 km	A	USTHB	Chile-Bolivia Border Region	gfz2023dslk
2023-02-22 18:18:28	**4.5**	M	20	2.1	35.84 S	72.80 W	10 km	A	USTHB	Near Coast of Central Chile	gfz2023dskk
2023-02-22 18:03:19	**3.8**	M	14	2.1	36.13 S	72.94 W	10 km	A	USTHB	Near Coast of Central Chile	gfz2023dsjx
2023-02-22 17:57:04	**4.1**	M	11	1.9	35.90 S	72.49 W	10 km	A	USTHB	Near Coast of Central Chile	gfz2023dsjr
2023-02-22 17:48:00	**4.2**	M	21	2.3	35.85 S	72.68 W	10 km	A	USTHB	Near Coast of Central Chile	gfz2023dsjk
2023-02-22 15:51:42	**4.7**	M	23	1.2	30.11 S	72.06 W	10 km	A	USTHB	Off Coast of Central Chile	gfz2023dsfo
2023-02-22 15:18:07	**4.5**	M	19	1.5	20.83 S	68.99 W	46 km	A	USTHB	Chile-Bolivia Border Region	gfz2023dsel
2023-02-22 13:42:13	**3.9**	M	15	2.3	30.56 S	71.18 W	10 km	A	USTHB	Near Coast of Central Chile	gfz2023dsbh
2023-02-22 13:31:02	**4.7**	M	16	1.3	24.10 S	66.97 W	177 km	A	USTHB	Salta Province, Argentina	gfz2023dsax
Unassociated	-	-	-	-			-				<>
Origins											
... 15:11:49	-	-	7	1.9	21.90 S	70.34 W	10 km	A	USTHB	*Near Coast of Northern C...*	Origin/20230222200359.338065....
... 15:05:03	-	-	8	1.5	32.95 S	34.16 W	10 km	A	USTHB	*South Atlantic Ocean*	Origin/20230222200353.742553....
... 18:49:38	-	-	9	1.0	21.41 S	68.94 W	19 km	A	USTHB	*Chile-Bolivia Border Region*	Origin/20230222185110.320225....
... 17:53:21	-	-	9	1.1	52.34 S	51.25 W	10 km	A	USTHB	*South Atlantic Ocean*	Origin/20230222180254.470449....
... 17:53:21	-	-	9	1.1	52.34 S	51.25 W	10 km	A	USTHB	*South Atlantic Ocean*	Origin/20230222175957.778044....
... 17:57:04	-	-	8	1.8	35.87 S	72.40 W	10 km	A	USTHB	*Near Coast of Central Chile*	Origin/20230222175846.198495....
... 16:34:09	-	-	6	2.9	24.60 S	69.80 W	213 km	A	USTHB	*Northern Chile*	Origin/20230222163600.052553....
... 15:11:49	-	-	7	1.9	21.90 S	70.34 W	10 km	A	USTHB	*Near Coast of Northern C...*	Origin/20230222163524.411745....
... 13:04:56	-	-	7	1.5	17.14 S	76.59 W	10 km	A	USTHB	*Off Coast of Peru*	Origin/20230222132329.338032....
... 13:03:16	-	-	8	2.9	8.04 S	63.00 W	10 km	A	USTHB	*Western Brazil*	Origin/20230222131622.006142....

Figure 3. *Real-time seismic monitoring using the scolv module of the SeisComP software for the 22 February 2023 earthquake in Talcapana Province (Maule Region, central Chile).*

Figure 4 shows the complexity of this task in the Pacific region. Firstly, a seismic sequence basically includes foreshocks, a main shock and aftershocks. In particular, when the magnitude of the mainshock is important (more than M6.5), the series of aftershocks occurring shortly afterward, even within minutes, can be equally critical for tsunami warnings. The Chilean coast regularly experiences regular moderate earthquakes, which can occur as isolated events or foreshocks. In the example reported in this section, on 22 February 2023, ten events have been reported in South America between 01:30 pm and 08:15 pm (UTC) as moderate events (Figure 4). Seven of these events are localized in the coastal region of Chile with magnitudes ranging between M3.8 to M4.7 (Figure 4). For the M4.7 earthquake, the SeisComP software package here used 23 phases for real-time automatic computation. Events with unassociated origins are also shown in Figure 4.

These results show how significant challenges for earthquake early warning systems and for tsunami warning systems and procedures are raised in particular for (1) strong and destructive earthquakes or/and (2) multiple tsunami sources (complex earthquake

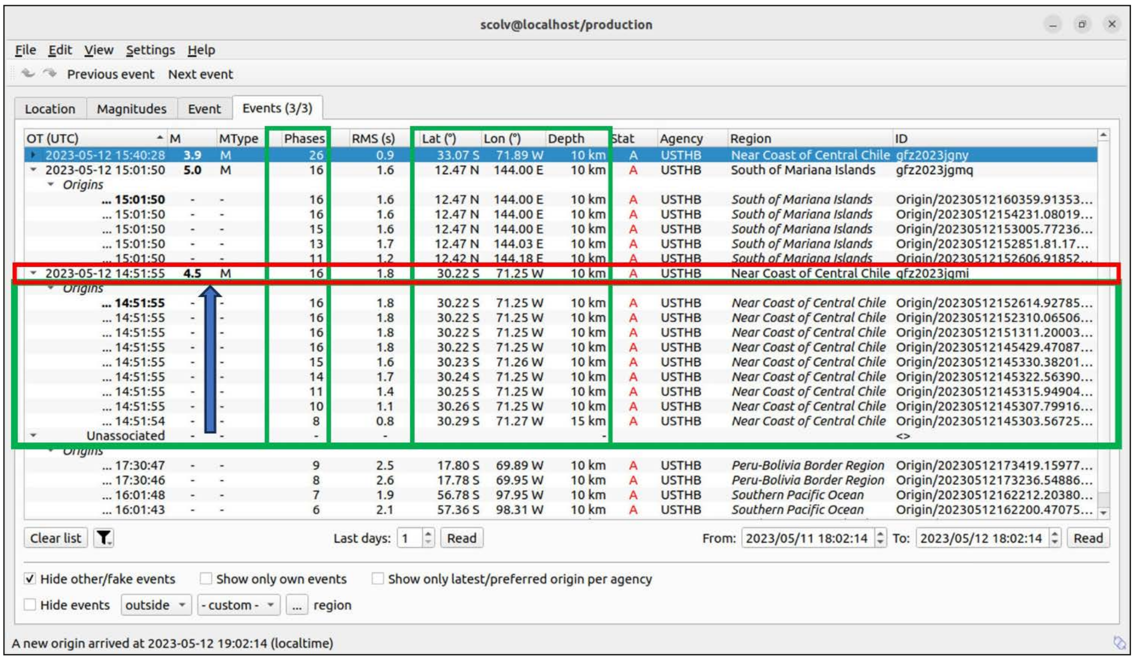


Figure 4. *Real-time seismic event information recorded and reported between 13:30 and 20:15 UTC on 22 February 2023 using the scolv module of the SeisComP software.*

rupture, volcanic collapse, massive submarine landslide generated by the ground shaking). The accuracy of real-time seismic parameters estimations determines the potential of the tsunami hazard triggered in the area hit by the earthquakes.

3.1.2. Example from the French Atlantic coast

The results presented hereafter illustrate the contribution of the Raspberry Shake network (short band, EH) (code: AM) for seismic monitoring of events in Western France (North Eastern Coast of Atlantic). Here, a M5.5 earthquake has been automatically recorded near La Rochelle on 16 June 2023 (Charente Region, West France). There again, the real-time seismic automatic procedure (status "Stat" = A) re-adjusted the seismic location with longitudes and latitudes varying between 0.67 to 0.79 W and 46.23 and 46.27 N respectively (Figure 5). The number of seismic phases acquired for real-time automatic computation increased from 22 to 58 in less

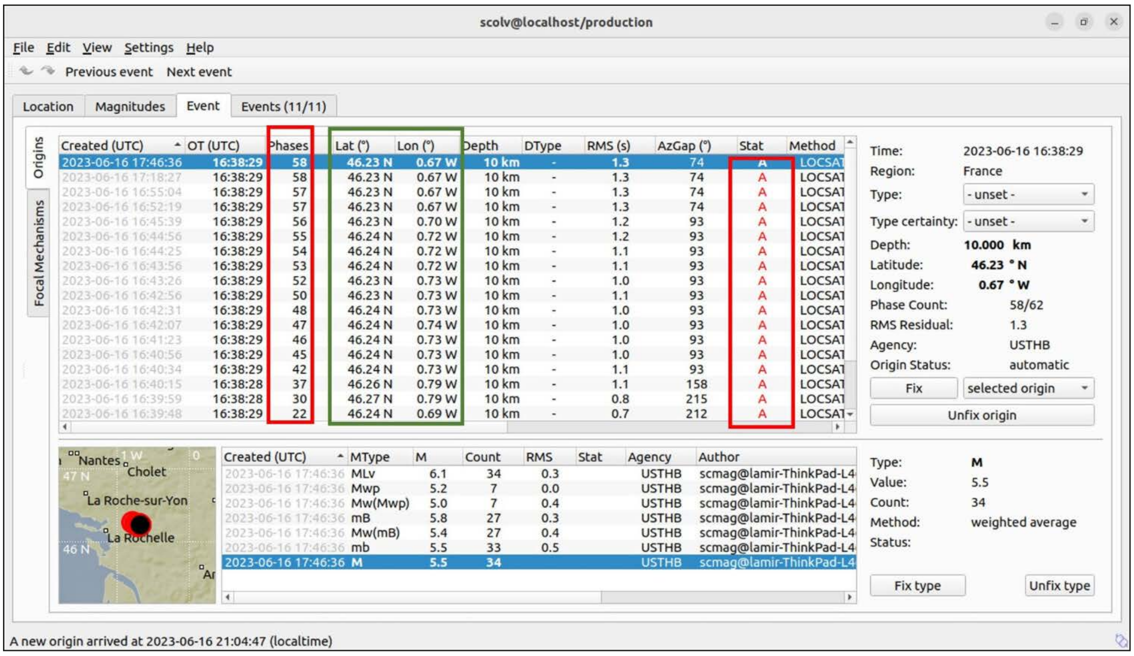


Figure 5. *Real-time data acquisition in the Charente region (western France, northeastern Atlantic): the June 2023 La Rochelle earthquake (using the scolv module of the SeisComP software).*

than two seconds. The depth has been fixed at 10 km. The accuracy of the real-time seismic parameters estimations is well highlighted by the values reported for the AzGap (largest azimuthal gap between two neighboring stations of an origin). While the first estimations were computed with an AzGap of more than 200°, the final automatic solutions have been obtained with an AzGap of 74° (Figure 5, ninth column). Finally, Figure 6 below displays the seismic waveforms traces (AM network) recording real-time seismic activity between 19:00 and 20:20 (UTC) on 16 June 2023, using the scrttv sub-package. Most of the seismic stations involved for real-time monitoring are broadband stations (vertical component, BHZ). In addition, three short-band raspberry shake stations from the Raspberry Shake Citizen network (AM) (R9C8C, R195 D, R63E3) provided seismic waveforms and contributed to the real-time automatic assessment. While belonging to the AM network, R9C8C and R63E3 (located at the Einstein Middle School in Washington and lake forest park, USA respectively) and R195D (located in Mongolia) transmit data via the IRIS/DMC Seedlink protocol through the EarthScope Data Center).

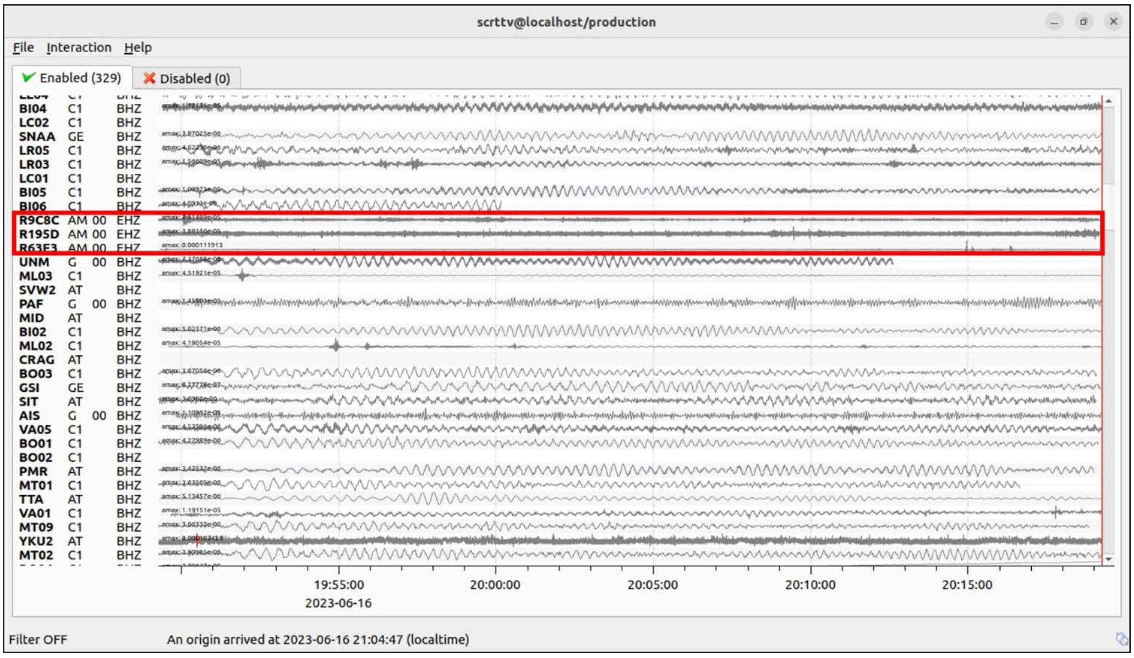


Figure 6. *Real-time seismic monitoring using the AM Raspberry Shake Network and the scrttv module of the SeisComP software between 19:00 and 20:20 UTC.*

3.2. The Raspberry Shake Citizen Network

3.2.1. The Raspberry Shake Network in Northern Africa

In November 2022, for the first time in the history of seismological research in Northern Africa, a low-cost short-band 3-D Raspberry Shake seismic station was deployed in Algiers (Algeria), marking its entry into the Raspberry Shake community (Figure 7a). A few years later, in December 2025, the Raspberry Shake (AM) Network FDSN map showed three Raspberry Shake stations in Algeria, one in Tunisia, and nine in Morocco. Despite this progress, the African continent remained sparsely covered by data from the Raspberry Shake citizen-science network (Figure 7).

3.2.2. Testing urban noise in Algiers (Algeria, North Africa)

Figure 8 illustrates the testing of the 3D Raspberry Shake station R71CB, located in Algiers, Algeria. Real-time online testing was conducted between 17:00 UTC on 23 December 2023 and 04:00 UTC on 24 December 2023 (Figures 8a,b). Figure 8c shows the vertical component of urban noise recorded over a two-hour period on 24 December 2023.
Between 16:00 and 05:00 UTC on 23-24 December 2023, 285 Raspberry Shake stations were actively connected (online) across North Africa and southern Europe (Figure 8a), contributing to real-time earthquake monitoring (Figure 8b). Users may choose to keep their devices hidden and offline, as providing real-time data is optional. They can instead upload and share their recordings later for seismological analysis, rather than transmitting them in real time.
On 25 December 2023, station RC75 was switched from real-time online recording to offline mode (Figures 9a and 9b for the horizontal components and Figure 9c for the vertical component). This offline option is particularly useful when station tests or calibration procedures might otherwise interfere with the real-time monitoring of earthquakes by introducing signals that could distract analysts focused on earthquake detection rather than on calibration signals.

(a)

(b)

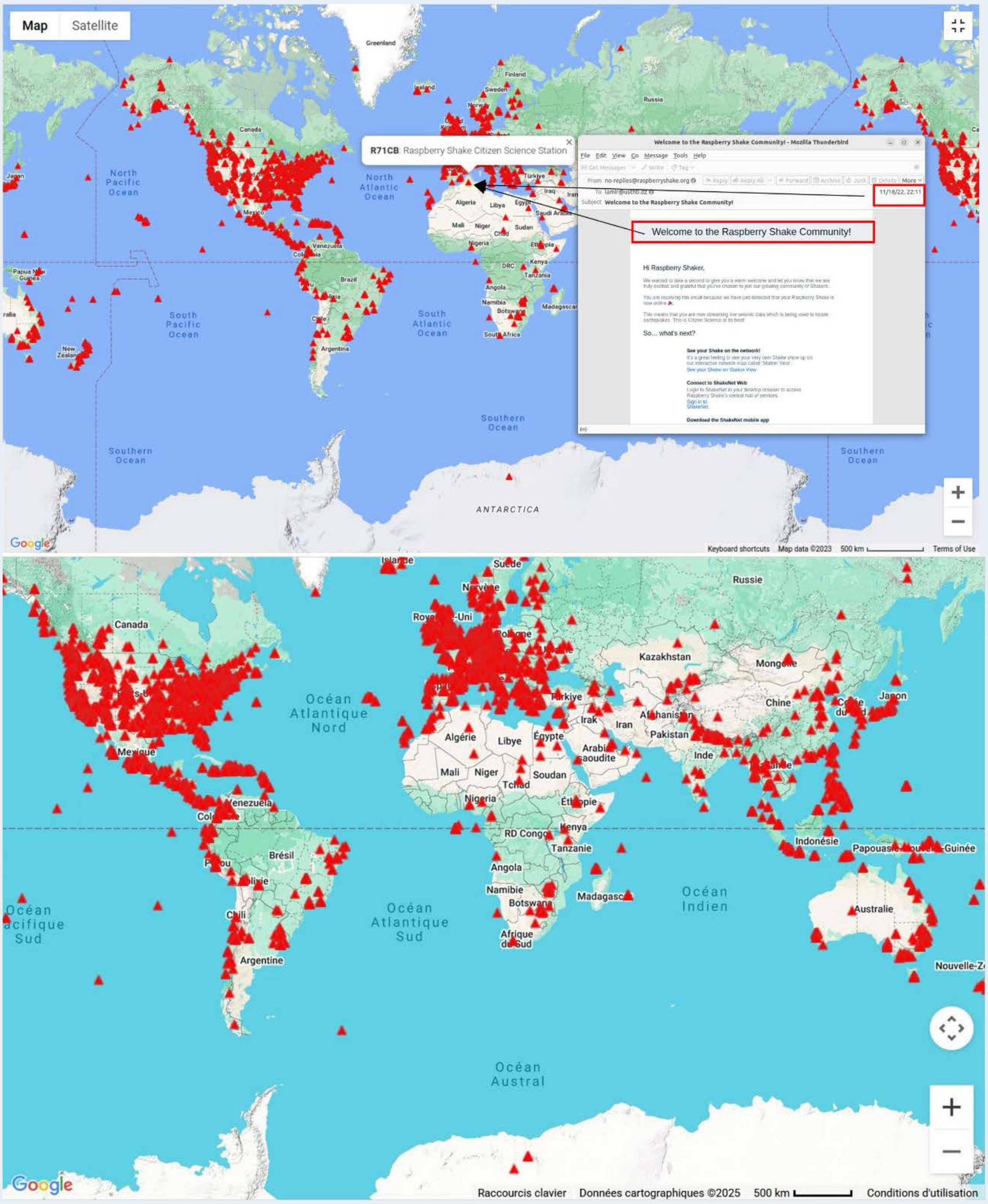


Figure 7. *Distribution of Raspberry Shake seismic stations in the Raspberry Shake (AM) Network: (a) 2023 (FDSN website: https://www.fdsn.org, accessed in 2023); (b) 2025 (FDSN website: https://www.fdsn.org, accessed in December 2025).*

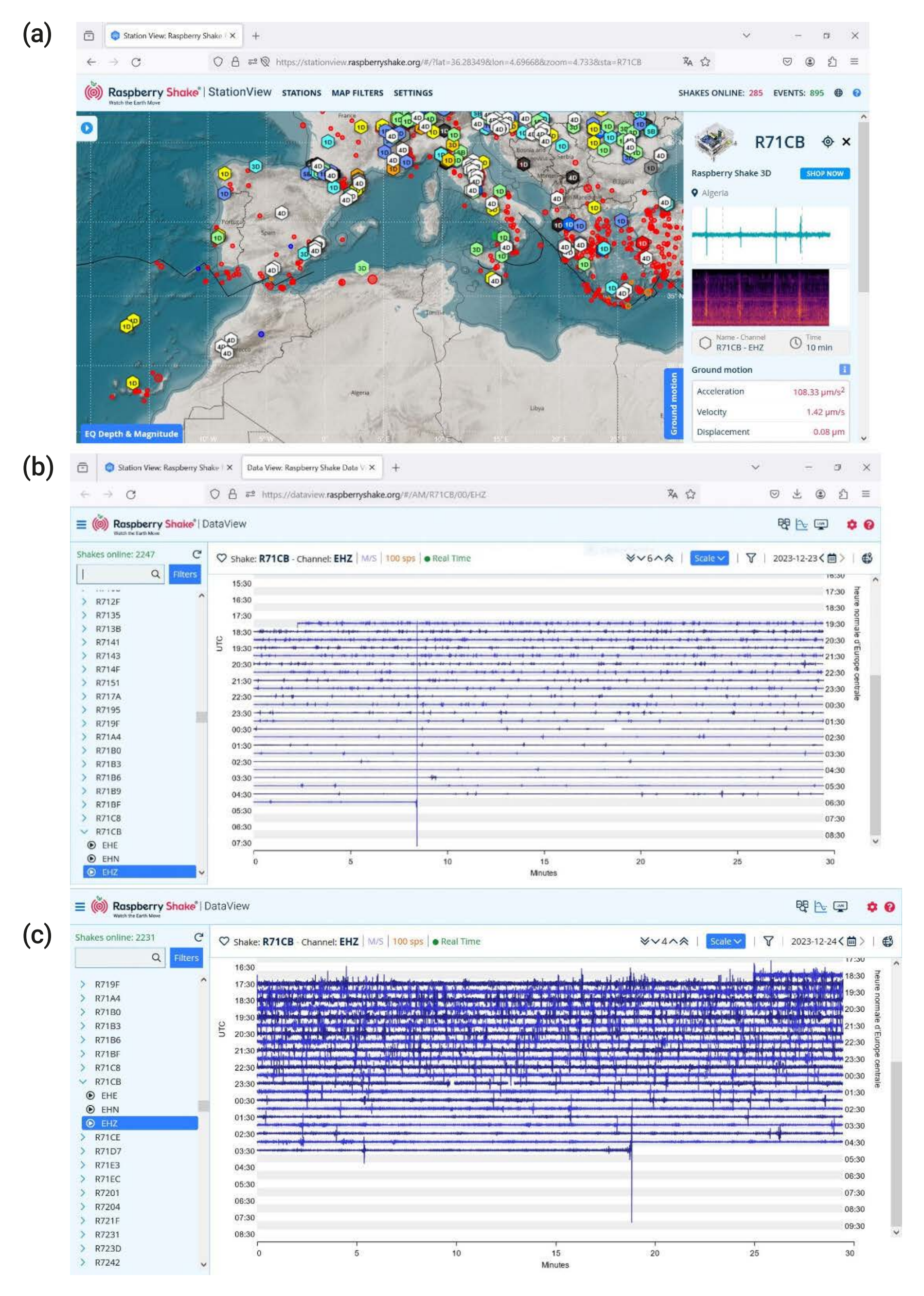


Figure 8. *(a) Distribution of online Raspberry Shake (AM) stations within the zoomed area on 23 December 2023 (Raspberry Shake website, accessed in 2025); (b) Real-time monitoring on 23 December 2025 (vertical component, EHZ); (c) Real-time online monitoring from the Raspberry Shake station R71CB (Algiers, Algeria) on 24 December 2025 (vertical component, EHZ, showing urban noise).*

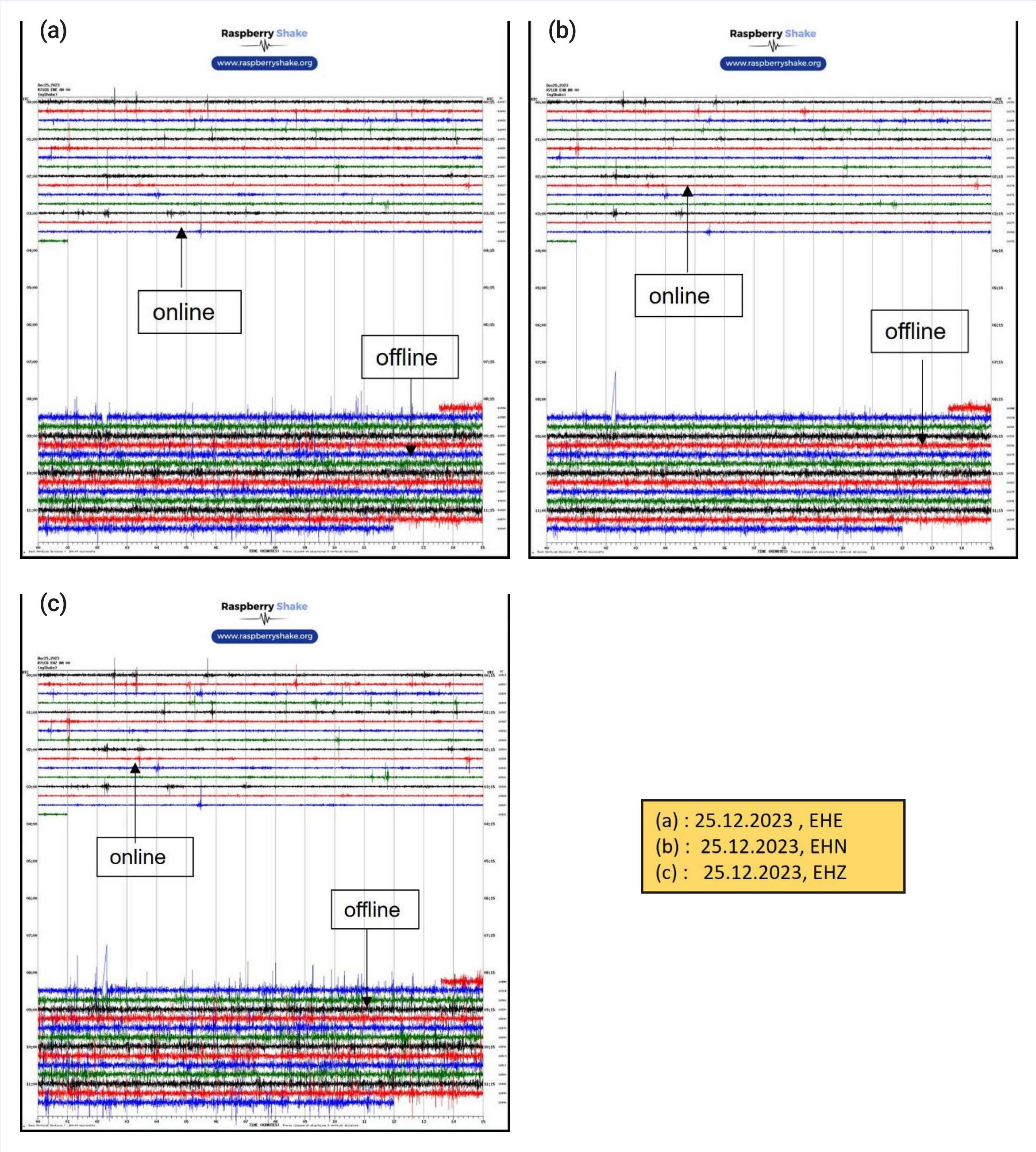


Figure 9. *Testing of the Raspberry Shake station R71CB (Algiers, Algeria). Source: TV broadcasting noise recorded on 25 December 2023. Panels (a) and (b) show the horizontal components (EHN and EHE, respectively), while panel (c) shows the vertical component (EHZ). In each panel, the waveform displayed in the upper section corresponds to real-time online recording, whereas the waveform in the lower section corresponds to offline data recording.*

4. Discussion

4.1. Technical challenges in real-time tsunami FAIR data

4.1.1. Real-time waveform gap issues

This research highlights that forecasting the potential triggering of tsunami waves that can impact both near- and far-field regions is constrained by uncertainties in the real-time automatic assessment of seismic parameters (location, magnitude, depth). Real-time seismic monitoring with SeisComP revealed challenges in data management policies related to tsunami warning systems. Moment magnitudes are defined by the seismic energy released during the tectonic rupture process. Moment magnitude's scales are logarithmic. The difference in the stress relief and the related energy released when dealing with uncertainties for real-time automatic seismic solutions directly impacts the decision for raising warning bulletins and evacuations by stakeholders.

The Pacific Ocean has been the first place where tsunami warnings and messages have been issued to communities at risk. In Western Pacific, the Sanriku Coast is a perfect example of how storytelling, scriptures (landmark stones), and technology have been used since the 1896 Japan tsunami (Bernard and Titov, 2015). Well-documented reports and tsunami stones indicated past highest waves up to more than 38 meters in height during the 1896 Sanriku earthquake and tsunami. However, the 2011 Mw 9 Tohoku earthquake and tsunami led to an unprecedented tragedy. Water waves reached up to 40 meters in height (Satake et al., 2017). This tragedy showed the warning system failed as it underestimated the tsunami height. The agency could not calculate the Mw within 15 minutes because of the scaling off of most broadband seismographs. Here, the community-level response played a crucial role in saving lives. This case study emphasized how community-based tsunami systems could provide a real-time asset for saving life (Ishiwatari, 2012). On 29 July 2025, the eastern coast of the Kamchatka Peninsula (Russia), in the western Pacific, was struck by a powerful earthquake that generated a tsunami propagating across the Pacific Ocean. Tsunami warnings and advisories were issued shortly afterwards for Russia, Japan, North America, Latin America, the Pacific Islands, and the Asia-Pacific region (Benson et al., 2025). The analysis for this event was based on SIFT ("Short-term Inundation Forecasting For Tsunamis"), NOAA'S operational forecast system at Tsunami Warning Centers, led by the NOAA Center for Tsunami Research (NCTR). The preliminary magnitude was understated by roughly an order of magnitude (Wei et al., 2025). Then, using all available data (DART, satellite, seismic), scientists manually revised the seismological parameters using teleseismic data. The earthquake magnitude was upgraded to Mw 8.7 45 minutes later and again to Mw 8.8 1.5 hours later. Millions were asked to evacuate while the tsunami waves were travelling across the Pacific and reached Japan and Hawaii about four hours after the earthquake. The debate definitively raised here is to improve the accuracy for seismological automatic solutions.

In the eastern North Atlantic (western France), the contribution of low-cost Raspberry Shake stations during the 2023 La Rochelle earthquake illustrates how citizen-science initiatives can complement conventional seismic networks by providing waveform data for automatic processing. Several studies on seismic hazards and coastal flooding have highlighted the exposure of this region to storm surges and tidal waves exceeding 6 m in height during spring tides (Amir et al., 2006; Allgeyer et al., 2012; Amir et al., 2014). Furthermore, geological evidence supports the occurrence of far-field effects from tsunamis generated by sources in the eastern Atlantic, as demonstrated by past ocean-wide events such as the 1755 Lisbon tsunami. Deposits attributed to the 1755 Lisbon tsunami have been identified in the Caribbean, the French West Indies, the Brazilian coast, Morocco, Spain, Portugal, Ireland, and the United Kingdom, but not along the western coast of France (Narcisse et al., 2011; Omira et al., 2012; Santos and Rijo, 2022).

4.1.2. Bathymetric and coastal data barriers to tsunami resiliency

Modelling tsunamis requires not only as much seismological waveforms as possible but as well accurate bathymetric data in open sea and near the shoreline. High-resolution for marine bathymetry and tidal gauges data sharing is crucial for tsunami risk assessment and disaster risk reduction. Building multiple grids with bathymetric data combining different resolution scales for numerical modelling tests is crucial to understand water waves propagation processes and paths offshore and nearshore. Multiple reflections and resonance within bays and harbours can only be accurately investigated if the complexity of the marine geology and coastal embayments is incorporated into numerical models.

Finally, inlet geometry and morpho bathymetry are key factors controlling tsunami propagation. Depending on their characteristics, they may either (1) amplify tsunami energy, resulting in greater wave heights and run-up, or (2) dissipate tsunami energy. Coastal topography may also play an important role by shielding the coastline or enclosed bays from tsunami impact. Along the western coast of France, the Pertuis Charentais tidal inlet system (at the entrance to the Charente-Maritime coast) acts as a natural barrier that reduces tsunami hazard (Amir et al., 2014). A similar case of tsunami energy dissipation associated with inlet geometry was reported in northeastern Japan following the 2011 Tohoku tsunami, where the inlet configuration partially protected Matsushima Bay (Ota et al., 2019).

In 2022, the IOC-UNESCO launched a community resilience programme to address societal challenges related to disaster risk reduction. The UNESCO-IOC Tsunami Ready Recognition Programme (TRRP) is a voluntary, collaborative initiative designed to enhance tsunami resilience and strengthen community preparedness (ITIC, 2024). To achieve recognition, communities must demonstrate compliance with twelve indicators covering assessment, preparedness, and response (see Table 1) (UNESCO, 2025).

Tsunami Ready Indicators	
I	**Assessment (Assess)**
1	**Assess-1** Tsunami Hazards zones are mapped and designated
2	**Assess-2** The number of people at risk in the tsunami hazard zone is estimated
3	**Assess-3** Economic, Infrastructural, Political, and Social Resources are identified
II	**Preparedness (Prep)**
4	**Prep-1** Easily understood tsunami evacuation maps are approved
5	**Prep-2** Tsunami information including signage is publicly displayed
6	**Prep-**3 Outreach and public awareness and education resources are available and distributed
7	**Prep-4** Outreach or educational activities are held at least 3 times a year
8	**Prep-5** A community tsunami exercise is conducted at least every two years
III	**Response (Resp)**
9	**Resp-1** A community tsunami emergency response plan is approved
10	**Resp-2** The capacity to manage emergency response operations during a tsunami is in place
11	**Resp-3** Redundant and reliable means to timely receive 24-hours official tsunami alerts are in place
12	**Resp-4** Redundant and reliable means to timely disseminate 24-hours official tsunami alerts to the public are in place.

Table 1. *The Tsunami Ready Programme Indicators (after UNESCO, 2025).*

Therefore, the ethical debate surrounding data-sharing policies for tsunami warning systems has increasingly emphasized the importance of social connectedness and community-driven practices as core components of disaster risk reduction and resilience.

4.2. Social connectedness, ethics, and community-driven practices

4.2.1. Philosophical and sociological roots

The intellectual foundations of both the natural sciences and the social sciences can be traced back to classical Greek philosophy, particularly the works of Plato (428-347 BC) and Aristotle (384-322 BC). While Plato addressed the relationship between society, governance, and the natural world (Plato, 2015), Aristotle sought natural rather than supernatural explanations for earthquakes, floods, celestial bodies, planetary motion, and other natural phenomena (Aristotle, 1952). Their work laid the foundations for later scientific inquiry by promoting rational observation and the search for causal explanations of natural processes and human societies. The intellectual roots of the modern concept of social connectedness can be traced to the fourteenth century through the work of Ibn Khaldun (1332-1406), who is widely regarded as one of the founders of sociology (Ibn Khaldun, 2015). In his *Muqaddimah*, Ibn Khaldun introduced the concept of *asabiyyah* (social cohesion or group solidarity) to explain the rise and decline of societies. He argued that collective solidarity constitutes the social force that enables communities to cooperate, establish political institutions, and respond to internal and external challenges (Sümer, 2012; Korkusuz, 2015). His work represents one of the earliest systematic attempts to understand the dynamics of social organization and collective action. During the nineteenth century, Auguste Comte (1798-1857) further contributed to the development of sociology by introducing the philosophy of positivism, advocating the study of society through observation, empirical evidence, and scientific reasoning, in a manner analogous to the natural sciences (Levin, 2018). Later, David Émile Durkheim (1858-1917) expanded these ideas by examining the role of social cohesion, collective consciousness, and collective effervescence in maintaining social order, particularly through the study of religion and communities (Durkheim, 1915). Modern sociology consequently draws upon several complementary disciplines, including linguistics, anthropology, political economy, and history (Sumpf and Hughes, 1973), recognizing that social processes and institutions evolve within specific cultural and historical contexts.

Taken together, the contributions of Plato, Aristotle, Ibn Khaldun, Comte, Durkheim, and subsequent scholars illustrate the progressive development of an interdisciplinary understanding of the relationships between natural phenomena, social organization, and human behaviour. Within this intellectual framework, Ibn Khaldun's concept of *asabiyyah* provides an important theoretical foundation for contemporary notions of social connectedness, emphasizing that shared values, collective identity, and social solidarity are fundamental to the formation of resilient communities and

institutions. At the same time, historical, cultural, linguistic, political, and economic contexts profoundly influence the ways in which social groups evolve and respond to environmental and societal challenges (Sumpf and Hughes, 1973).
Reconsidering Ibn Khaldun's contribution, Sümer (2012) emphasized his observation that "differences of condition among people were the result of the different ways in which they make their living." Ibn Khaldun compared different societies and concluded that their social organization, political institutions, and historical trajectories were largely shaped by their modes of production and patterns of social cooperation (Sümer, 2012; Ibn Khaldun, 2015; Korkusuz, 2015).

4.2.2. The ethics of community-driven networks

Saunders et al. (2025) highlighted the importance of integrating community-driven data into disaster risk reduction strategies. To strengthen social connectedness within the Sendai Framework, the interdisciplinary dimensions identified by Korkusuz (2015) may be considered as key components: (1) human-nature relationships, (2) human-human relationships, (3) human-economy-society interactions, (4) human-economy-politics interactions, and (5) individual human factors.
The development and implementation of community-driven best practices for FAIR data principles are influenced by a wide range of social, cultural, ethical, institutional, and political factors that shape the ethical governance of geospatial data and disaster risk reduction. Figure 10 summarizes these challenges by distinguishing between social data barriers (Component A, left side) and ethical and political communication factors (Component B, right side), both of which influence the ethical dimension of community-generated and community-shared data. Ultimately, the implementation of the FAIR guiding principles aims to support data-driven decision-making for disaster risk reduction (Figure 10).

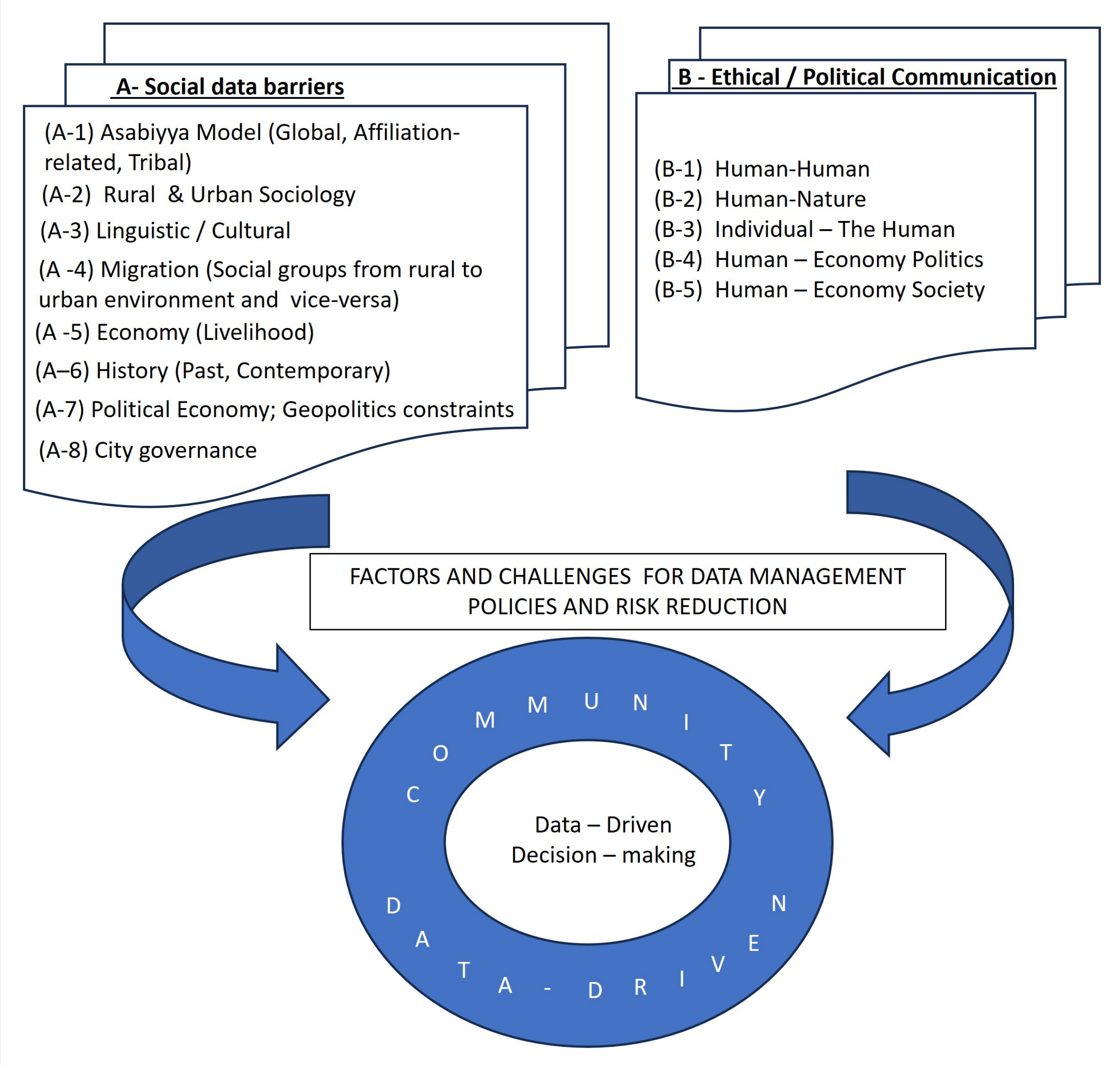


Figure 10. *Factors and challenges in the community-driven implementation of the FAIR guiding principles.*

4.3. Regional application: North Africa and Western Mediterranean

4.3.1. Regional hazards vs. data deficits

A scientometric analysis by Laksono et al. (2024) showed that research on tsunami mitigation in the Mediterranean has increased considerably since the 2004 Indian Ocean tsunami. The geodynamic evolution of the Mediterranean region is highly complex and is largely controlled by subduction rollback, which has led to the formation of several back-arc basins in the western Mediterranean, including the Gibraltar, Balearic, Algerian, and Calabrian basins (Jolivet et al., 2021). In the eastern Mediterranean, subduction along the Hellenic Arc constitutes a major source of destructive earthquakes and tsunamis (Aksoy, 2021; Triantafyllou et al., 2024).

In the western Mediterranean, the most recent instrumentally recorded tsunami-generating earthquakes include the 2003 Mw 6.9 Boumerdès earthquake (Masina et al., 2020) and the 2021 Mw 6.1 Béjaïa earthquake and associated tsunami (Heinrich et al., 2024). Evidence of both prehistoric and historical tsunami events has been documented through the discovery of tsunami boulders and sedimentary deposits along the Algerian coast, southern Spain, and the eastern coast of Tunisia (Roig-Munar et al., 2018; Lario et al., 2023; Bahrouni et al., 2024; Benfedda et al., 2025). Historical records indicate that one of the highest documented tsunami run-ups along the Algerian coast occurred in Béjaïa following the destructive Jijel earthquake of 21-22 August 1856 (Harbi et al., 2011).

The Alboran region has also experienced numerous historical tsunami events, as evidenced by tsunami deposits identified along the Spanish Mediterranean coast (Reicherter and Becker-Heidmann, 2009; Amir et al., 2022). The destructive 1790 Oran earthquake caused damage documented in Spanish historical sources. Several authors have suggested that coastal collapse associated with this earthquake generated local tsunami waves that were observed within the harbour (Amir et al., 2022). In the eastern Mediterranean, the 2020 Samos earthquake demonstrated both near-field and far-field tsunami impacts in Greece and Turkey (Aksoy, 2021).

The North-Eastern Atlantic, the Mediterranean and Connected Seas Tsunami Warning and Mitigation System (NEAMTWS) has been progressively developed since 2005 (Amato, 2020). To support this initiative, the Intergovernmental Coordination Group for the NEAMTWS (ICG/NEAMTWS) was established to coordinate regional tsunami warning activities and to define forecast points along the coast where tsunami warning centres can provide estimates of tsunami arrival times and expected wave heights. Nevertheless, significant gaps remain in North African countries with respect to monitoring infrastructure, warning protocols, and community preparedness. In particular, the limited deployment of Deep-ocean Assessment and Reporting of Tsunamis (DART) buoys, together with restricted access to tide-gauge observations and real-time seismic waveform data, severely constrains tsunami hazard assessment and warning operations throughout the western Mediterranean and the broader NEAM region.

4.3.2. Practical applicability of low-cost stations for ethical and FAIR principles

The critical challenge for tsunami warning systems is to support decision-makers in taking timely actions despite incomplete or uncertain data. As emphasized by Amato (2020), one of the main challenges remains reaching populations at risk and increasing public awareness. Reliable tsunami hazard assessment strongly depends on accurately characterizing the tsunami source and predicting wave propagation. Satake et al. (2020) classified tsunami waveforms into three types according to the duration of the wave train and the timing of the maximum amplitude relative to the arrival of the first wave. Type A is characterized by a few large waves occurring soon after the initial arrival and is commonly observed on isolated Pacific islands and, in some cases, along continental coasts. Type B consists of one or several wave groups and is more typical of continental margins and island arcs. Type C combines the characteristics of Types A and B (Satake et al., 2020). Consequently, the first tsunami wave is not necessarily the largest or the most destructive. At present, Tsunami Service Providers (TSPs) primarily address tsunamis generated by seismic sources (Amato, 2020). Tsunamis triggered by submarine landslides, together with uncertainties associated with the automatic real-time estimation of complex earthquake rupture parameters, are not yet fully incorporated into operational tsunami warning systems.

Robustness and reliability are fundamental requirements for efficient seismic and tsunami warning systems. Operational monitoring networks managed by official institutions rely on a backbone of high-quality, continuously operating seismic stations. Nevertheless, the results presented here for the 2023 La Rochelle earthquake demonstrate the valuable contribution of three low-cost short-period Raspberry Shake stations operated by academic and private institutions in the United States and Mongolia. Although these stations cannot replace national seismic networks, they can complement them by increasing spatial coverage and providing independent waveform observations that support automatic processing.

This study illustrates how community-driven, low-cost seismic stations can enhance real-time automatic seismological monitoring. From a geoethical perspective, reflexivity and ethical responsibility suggest that warning systems should not only rely on technological performance but should also consider the needs and vulnerabilities of exposed communities, including their economic conditions, well-being, health, and existing social vulnerabilities (Amir et al., 2015). Community participation therefore becomes an essential component of resilient warning systems.

Data scarcity and uncertainty in decision-making can be partially mitigated through the integration of crowdsourced observations, low-cost monitoring technologies, and adaptive cost-loss models. Hybrid artificial intelligence approaches may contribute to the development of adaptive cost-loss models capable of supporting more efficient decision-making protocols (Ma et al., 2026). Nevertheless, timely access to high-quality real-time seismic and tide-gauge observations remains essential for reliable operational decisions. As noted by Calais (2019), the Raspberry Shake citizen seismic network helps constrain automatic earthquake solutions while providing an independent stream of observational data.

Similar approaches have already demonstrated their value in other hazard contexts. In North Carolina (USA), Hino et al. (2025) showed that citizen-science initiatives involving low-cost flood sensors complemented conventional tide-gauge observations, improving flood monitoring in coastal communities where available measurements were insufficient to adequately assess sea-level rise and flooding hazards. Likewise, in New Zealand, Prasanna et al. (2022) demonstrated that communication failures and power outages during disasters could compromise the availability of seismic data and contribute to false tsunami alarms. They subsequently developed a low-cost earthquake early warning system based on node-level detection and alert generation, capable of maintaining operational independence during disaster conditions (Prasanna et al., 2022; Hughes et al., 2025).

Within this context, geoethical principles, provide an important framework for promoting FAIR data practices in regions where real-time access to geoscientific data remains limited. Stronger collaboration among public institutions, research infrastructures, and citizen-science networks could facilitate the development of adaptive, low-cost monitoring systems tailored to the economic, political, cultural, and social characteristics of individual countries. Integrating in situ low-cost tide-gauge sensors and Raspberry Shake seismic stations with adaptive cost-loss models could strengthen tsunami warning capabilities, enhance community-driven monitoring, and improve disaster resilience throughout the NEAM region, particularly along the North African coast.

5. Conclusion

Trans-oceanic tsunamis, such as those occurring in the Pacific Ocean and the north-eastern Atlantic, affect both near-field and far-field coastlines. By contrast, the western Mediterranean is characterized by relatively short tsunami travel times, particularly along the North African coast. Consequently, the rapid determination of earthquake location, depth, magnitude, and other key seismological parameters is essential for assessing whether tsunami warning bulletins should be issued.

This study highlights the need to integrate low-cost monitoring technologies and to develop appropriate strategies for the ethical sharing of open geoscientific data that take into account country- and community-specific contexts. Accurate real-time earthquake monitoring depends on automatic processing systems that are capable of collecting and analysing as many seismic waveforms as possible within a few seconds. Citizen-science initiatives, such as the Raspberry Shake community, demonstrate how community-driven data can complement conventional monitoring networks and contribute to disaster resilience.

Social connectedness is a fundamental component of effective disaster risk reduction and real-time crisis management. Continued advances in local-scale tsunami impact assessment will significantly enhance tsunami warning services and improve decision-making under uncertainty. Consequently, future research and policy should promote: (1) the development of adaptive hybrid low-cost monitoring models; and (2) community-driven ethical data-sharing policies aligned with the FAIR guiding principles and adopted by researchers, public institutions, research infrastructures, and the private sector to strengthen the effectiveness of tsunami warning systems.

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